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Secluded in the foothills of the Himalayas between China and India, Bhutan is still subject to many of the same problems facing other developing nations. Environmental degradation is one of these challenging problems, especially due to modernization pressures from urban population growth and economic pressures to generate jobs to accommodate the incoming population. Rural-urban migration analysis is completed by a Geographic Information Systems (GIS) analysis of various 2005 Bhutan census variables from the Population and Housing Census of Bhutan (PHCB). The areas of highest in and out-migration are located, then variables identified as potential push and pull factors for migration (such as health and education) are analyzed. The specific area of interest for this study is Thimphu, the capital of Bhutan.

The primary goal of this research is to identify discrepancies in the national forest inventory and recommend appropriate methodology for using Remote Sensing (RS) and GIS to quantify the amount of forest cover. Political ecology studies show that structural adjustment programs such as land privatization, decentralization, and blueprint based environmental planning exert major impacts on agriculture and land use. In Bhutan, land privatization and decentralization of various administrative boundaries have already caused significant changes to policy regarding forestland in the past two decades. These political and economic impacts affect forest policies in terms of accessibility, control, and management. The land use land cover change was determined using unsupervised classifications, coupled with a post-classification change detection technique, to obtain quantitative change information from Landsat images taken at three different points in time (1990, 1999, and 2007). These techniques were applied at various scales including the city scale and two administrative boundary scales (Dzongkhag and Gewog).

Remote Sensing analysis shows that at the city and geog levels, urban area is increasing, while forested area is decreasing. At the dzongkhag level, however, there was an increase in forested areas. The GIS migration analysis shows that Thimphu dzongkhag has received the highest in-migration, while Trashigang dzongkhag has the highest out-migration. Analysis of the various push variables shows that access to certain amenities, such as health care, electricity, and roads, are major reasons to immigrate to Thimphu dzongkhag. The national government has enacted several policies and programs in an effort to reduce rural-urban migration and to maintain a sustainable forest cover, such as the rural-electrification project and promotion of Non-wooded Forest Products (NWFP), but these policies and programs did not make a significant impact on either of the intended targets. The research finds that GIS and RS are useful tools for analyzing the impact of political, social, and economic modernization pressures on the physical environment.

LAND USE CHANGE IN THIMPHU, BHUTAN FROM 1990 – 2007: EFFECTS OF CULTURAL, POLITICAL, AND ECONOMIC FRAMEWORKS

by

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This dissertation is dedicated to my wife Sonal, whose love, support, and sacrifices never wavered through this incredible journey. My beautiful girls Isha & Maya, whose question “Pappa, to campus thi aiaya?” can now finally cease. My parents Arvind & Usha Gosai, without whose moral and financial support this journey would have been inconceivable.

APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of The Graduate School at the University of North Carolina at Greensboro.

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ACRONYMS

ADB	Asian Development Bank
AOI	Area of Interest
APA	American Planning Association
C-CAP	Coastal Change Analysis Program
CPR	Community Property Rights
DBH	Diameter-at-Breast-Height
DMSP OLS	Defense Meteorological Satellite Program Operational Linescan System
DPT	Druk Phuensum Tshogpa
DUDES	Department of Urban Development and Engineering Services
EOS	Earth Observing System
EROS	Earth Resource Observation and Science
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization
FID	Feature Identification
GCP	Ground Control Point
GDP	Gross Domestic Product
GIS	Geographic Information Systems
GNH	Gross National Happiness
GPS	Global Positioning System
IGBP	International Geosphere-Bioshpere Program
ISODATA	Iterative Self-Organizing Data Analysis Technique
LDC	Less Developed Country
LiDAR	Light Detection and Ranging
LPG	Liquefied Petroleum Gas
LUPP	Land Use Planning Project
MoA	Ministry of Agriculture
MoF	Ministry of Finance
MODIS	Moderate Resolution Imaging Spectroradiometer
MoWHS	Ministry of Works and Human Settlement
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
NDBI	Normalized Difference Built-up Index
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NSB	National Statistics Bureau

NWFP	Non-Wooded Forest Products
OCC	Office of the Census Commissioner
PDP	People's Democratic Party
PHCB	Population and Housing Census of Bhutan
RGoB	Royal Government of Bhutan
RMS	Root-Mean-Square
ROI	Region of Interest
RS	Remote Sensing
SCL	Scan Line Corrector
SPOT	*Satellite Pour l'Observation de la Terre*
TDS	Tripod Data Systems
TM	Thematic Mapper
TSP	Thimphu Structural Plan
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNFPA	United Nations Population Fund
USGS	United States Geological Survey
UTM	Universal Transversal Mercator
WGS	World Geodetic System

PREFACE

After Dr. Susan Walcott and Dr. L. Joe Morgan first visited Bhutan, they recognized the country's need for a unified and dynamic geographic information system for the capital city, Thimphu. Upon their return, Dr. Morgan approached me, and proposed working on a GIS project for the Royal Government of Bhutan (RGoB). Since Bhutan's location is in close proximity to where I was born and spent 10 years of my childhood, I was particularly interested in working on the project. I was interested in learning Bhutan's customs and comparing them to that of India's. I was also interested in examining India's influence on Bhutan and vice versa, especially with regards to geospatial technology, development, and foreign relations.

In March 2008, I had the opportunity to visit Bhutan as part of an NSF funded trip. In preparation for this trip I was in charge of organizing the data and developing a training manual for GPS data collection and fieldwork to be used in the Ministry of Works and Human Settlement and Department of Geography at Sherubste College. I had several opportunities to meet with government leaders in the Ministry of Agriculture to discuss the uses of geospatial technologies and to initiate collaboration between UNCG and various ministries within the RGoB. This trip demonstrated the need and significance for the research my colleagues and I were conducting. Above all, I appreciate the opportunity to be part of a project that has the potential to have a significant impact on the development of such a unique and remote kingdom.

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CHAPTER I

INTRODUCTION

1.1. Overview

Environmental degradation in developing countries often results from modernization pressures to accommodate new population migrating to urban centers and economic pressures to develop quickly in order to generate jobs and raise income levels. Land use changes can be traced by the resulting shift from natural land cover to urban built-up areas. Development policies in the small Himalayan nation of Bhutan present an opportunity for testing the hypothesis that economically driven land use change will occur in spite of government policies and a culture favoring strict land use control in order to avoid environmental degradation. Thus, the primary goal of this study will be to identify discrepancies in the national forest assessment for testing the deforestation process in the Thimphu Valley, site of the capital city of Thimphu. This study will also establish the most suitable methodology for using Remote Sensing (RS) and Geographic Information Systems (GIS) to produce a baseline to quantify the amount of forest cover and human processes involved. The geographic scale of this dissertation will be the administrative boundaries that encompass the Thimphu valley at both dzongkhag and geog scale.

1.2. Land Use and Policy

The Forest Act of 1969 made important changes to pre-existing property rights in Bhutan. These changes modified the incentives for long-term sustainable use, management and protection (RGoB 1969). The Forest Act of 1969 and Land Act of 1978 are further elaborated in section 2.2.1. Rights to the access, use, management, protection and transfer of resources make up the collection of property rights of the person or community for the area in which they live (Messina et. al. 2006). Property rights in Bhutan are a central issue in maintaining the appropriate incentives for people to conserve forests (Dorji 2006). If the property rights of a person or community change through policy formulation or implementation, the incentives for long-term management may change as well. For example, if complete property rights to traditional forest are removed from a community and centralized to the government, then it would be difficult for that community to recognize the security and individuality of future benefits of preserving the forests. Forest environments are associated with approximately ninety percent of Bhutan's economy (RGoB 1999). Dependence on these resources must be incorporated into forest management, conservation, and sustainable strategies, even if the forests are state regulated (RGoB 1969, Messina et. al., 2006). Increasing urbanization is modifying Bhutan's forest in the Thimphu valley (Dema 2007). Long term extraction and exploitation leads to forest fragmentation and degradation (Burgi 2002, Dorji et. al., 2006, Rai 2007).

1.3. Gross National Happiness and the Economy

Gross National Happiness (GNH) is a unique development philosophy that reflects the cultural values of Bhutan. It has served as their guiding principle for socio-economic development since the 1980s. The four major areas identified as pillars are as follows:

1) Equitable economic growth development,
2) Preservation and promotion of cultural heritage,
3) Sustainable use of the environment, and
4) Good governance.

GNH has served as the guiding principle for socio-economic development over the last two decades and current government policy indicates that it will continue to be so in the future (Dorji 2007, Penjore 2007a, Wangmo 2007). A key to GNH-based public policy is the vital search for balance, both within and between the pillars. For example, it is not sufficient that an increased annual economic growth is achieved; it must be accomplished in a manner that protects the environment, preserves the culture and is in harmony with good governance practice.

Since 1999, significant economic and political changes occurred in Bhutan (Dorji 2007). First, the importance of agriculture and forestry in the economy is losing ground (Rai 2007), and is rapidly being replaced by hydropower, construction, and energy-intensive industries. Second, a political transformation process is under way, involving a gradual hand-over of power from the monarchy to a democratically elected parliament and Prime Minister (Wangmo 2007). On April 7, 2007 mock elections were held to prepare for Bhutan's first general election that took place on March 24, 2008. Two parties, Bhutan Peace and Prosperity Party (DPT, for Druk Phuensum Tshogpa) and People's Democratic Party (PDP) were registered. Both parties sought to secure a majority of 47 seats of the National Assembly. Jigme Yoser Thinley from the DPT party was elected the first Prime Minister of Bhutan in a landslide victory for his slate of candidates. Following the elections Jigme Khesar Namgyel Wangchuck was officially crowned king of Bhutan on November 6, 2008. He was the fifth in a line of hereditary monarch since 1907.

Bhutan's economic base is limited. There has been a major shift in national revenue generation from timber to hydropower since the 1990s. Central government support for economic growth comes from the exploitation of hydropower and the utilization of natural resource-based industries that make use of low-priced power. The production of electricity is approximately 457MW but Bhutan exports approximately 78-80% of its total production at a lower than market rate. With several hydropower projects currently under construction, hydropower is projected to remain a critical engine of economic growth (ADB 2007). However, hydropower projects in rural areas provide relatively few employment opportunities.

Due to rural-urban migration, urban areas are witnessing increased rates of population growth, straining urban infrastructure, services and resources (Rosellini et. al. 2006). According to Bhutan's first census in 1969, the total population of Bhutan was 930,614, of which 21% lived in urban centers (RGoB 1999). Censuses prior to 2005 were criticized as inaccurate because the population estimates range from 300,000 to 930,000. A combination of ongoing rural–urban migration and population growth trigger an increased demand for urban services, including roads/streets, water supply and sanitation, public transport, housing, drainage/flood protection and mitigation, solid waste disposal, public markets, street lights, roundabouts/intersections, and other public services (Dorji 2007, Uddin et. al. 2007, RGoB 1999). This in turn, creates land use conversion pressure on forests and other natural lands.

1.4. Statement of Problem

This research is inspired by the need to identify gaps in the national forest assessment for testing the deforestation process in Bhutan and to determine the most appropriate methodology for using Remote Sensing and GIS to create a baseline for measuring the amount of forest cover and human processes involved. Forest environments have historically been closely associated with Bhutan's economy (RGoB 1999). The increasing urban development taking place in Thimphu valley is permanently modifying its forest landscape (Dema 2007). Reliance on the timber industry is also making changes to the forestland. At the national level, wood production potential and extraction is not a major problem. However, at the local level, extraction of wood and the sustainable management of forests is a critical problem due to the concentration of human settlements in valleys and other habitable locations. Continuing reliance on forest resources for heating and cooking fuel also presents a problem in terms of sustainable use of forests. In 1995, the Asian Development Bank (ADB) approved a loan of $7.5 million to the Government of Bhutan towards a Rural Electrification Project to provide electricity to the villages. At the time of project evaluation in 1995, 77% of energy consumption came from firewood and approximately 80% of the population did not have access to electricity. At the end of the project in the year 2000 the rural electrification ratio in the country had increased only 4% from 20% to 24% (ADB 2003). This condition, along with timber as one of the major revenue generating industries, imposes extra strain on forests near settlements. This is especially the case given the development level of Bhutan which places demand on wood for fuel, heat, and construction.

1.5. Research Goals

The primary goal of this research is to identify discrepancies in the national forest assessment for testing the deforestation process in Bhutan and to establish the most suitable methodology for using Remote Sensing and GIS to produce a baseline to quantify the amount of forest cover and human processes involved. One element of the GNH, sustainable use of the environment, is measured. This addresses the disparity realized between government policies on sustainability and the actual practices guiding land use. The study will address three key issues facing Bhutan as an emerging Less Developed Country (LDC):

1. population pressures from rural-urban migration,
2. economic pressure (considering the policies on timber exports, electricity, hydropower generation and exports, security/political needs), and
3. modernization imperatives for urban infrastructures to support rapid resource exploitation in an attempt to raise living standards.

This study utilizes GIS and RS data to analyze how changes in forest cover respond to modernization pressures by examining and assessing land use change from 1990 to 2007. This provides physical evidence of the interlocking cultural, economic and political situation

1.6. Hypothesis and Research Questions

Cultural (GNH), economic (the modernization of Bhutan), and political (Nationalized Forest Program) frameworks play a role in land use change. The major hypothesis of this research is that even under conditions strongly favoring strict land use control (regulations, preservation policies, good intentions, and honest politicians) quantifiable land use change that is environmentally detrimental and economically driven occurs in response to the pressure to modernize. This study will explore GIS data and Remotely Sensed Images to examine the policies that effect cultural, political, and economic frameworks by examining various dependent and independent variables. Using GIS and remote sensing, the two measurable dependent variables are:

1. population growth, and
2. land use land cover change in Thimphu valley.

The first dependent variable, population growth attributable to migration, will be measured by determining the population change in Thimphu due to rural urban migration. It is important to note that since Bhutan conducted its first accurate census in 2005 population change will be difficult to compare. Second, land use change in Thimphu valley will be measured by quantifying the amount of land cover change to the built environment due to roads and buildings, and decrease in agricultural lands and green spaces. Furthermore, this study will determine how Thimphu's observed situation (dependent variables) compares to the hypothetical (independent variable). The independent variables used in this study are the policies governing forestlands and land use.

Crossvergence comes from the choices made to reconcile both convergence and divergence (Chakravorty 2003; Ralston 2007; Witt 2007). Convergence often takes place when a government tries to promote globalization for rapid resource exploitation to raise material standards. An example of this is an increased rate of deforestation that is taking place in Bhutan. Divergence here is seen as created by the political imperative to preserve cultural values and forms. An example of divergence is clearly seen in the form of Gross National Happiness (GNH) which is further elaborated in section 2.3.1. What choices are being made to merge the concepts of crossvergence to blend in the "middle path"? The "middle path" refers to a set of principals based on Buddhist values where moderation and avoiding extremes are practiced in daily life.

1.7. Dissertation Structure

This dissertation is separated into five chapters covering an introductory literature review and theoretical framework, the methods used and sources of data, discussions related to the results of the research, and contributions and recommendations for future study. The contents of the chapters are outlined below.

Chapter 2 describes the background literature of land use change patterns, the three (cultural, political, and economic) frameworks used to analyze development in Bhutan, and the application of GIS and Remote Sensing to detect land use change. The cultural framework covers the origins of Gross National Happiness; the political framework covers several policies in regard to land use and their changes and formulation throughout history; and the theoretical framework of convergence, divergence, and crossvergence demonstrates the interconnection of cultural, political and economic choices.

Chapter 3 explains the methods utilized in this dissertation, detailing the use of Geographic Information System and Remote Sensing approaches. The chapter elaborates on methods and data used to quantify land cover change, such as classification schemes, supervised and unsupervised classifications, and change detection. Accuracy assessment is performed on the imagery using mathematical operations to validate the data and methods.

Chapter 4 discusses the results of the study. Crossvergent practices and ways it is empirically tested in the development process of Bhutan are discussed. The methods used in the development of an accurate GIS database and base map utilizing remotely sensed images are elaborated in chapter 4. Finally, discrepancies in the national forest assessment by the Ministry of Agriculture are examined by comparing rates of deforestation in other developing countries. The chapter also reviews the research limitations and concerns. The final assessment will examine the outcome of:

- migration, especially of young males from rural to urban areas,
- economic utilization of extractive resources such as timber in relationship to development pressures, and
- developed world advice versus divergent factors: GNH, Land Use Act, environmental protection, and government directives which effect land use.

Conclusions of the results of the dissertation, contributions and recommendations for future research are presented in Chapter 5.

This research seeks to contribute to scholarship in three areas. First, contribution to theory comes from empirically testing the use of crossvergent practices in the development process of an emerging nation by comparing the rates of deforestation in other countries. Second, building an accurate GIS base map utilizing remotely sensed images in a developing country poses numerous challenges, but it is crucial for assessing response to modernization pressures such as land use expansion. Issues and problems include the lack of cooperation between departments within the government, obtaining a proper coordinate system of the original data, and the need for an accuracy assessment by ground truthing permanent monuments with high resolution GPS equipment. Construction of an accurate GIS database for Thimphu demonstrates the use of GIS in formulating and monitoring policies towards natural resources and the national forest program and urban development in Thimphu. This enables the third contribution of identifying inconsistencies in the national forest assessment for testing deforestation process in the face of modernization pressures.

CHAPTER II

LITERATURE REVIEW

2.1. Introduction

This literature review investigates the scholarly research conducted by geographers, government officials, political scientists, economists, and others on the subject of land use change with regards to developing countries. This chapter is divided into three sections. Section 1 discusses various challenges when studying land use change. Policies regarding land use in Bhutan are constantly changing, but relatively few studies examine the impact on land use based on policies, and even less studies examine if any significant socio-economic differences exist between land conversions and the policies that governs these land use changes. This section also discusses contemporary literature on methods of detecting land use change using Geographic Information Systems (GIS) and Remote Sensing (RS). Section 2 discusses the three major frameworks of this dissertation. The cultural framework section provides the history of Gross National Happiness (GNH) and the middle path, and how these concepts affect the policies regarding land use and forest rights. The economic framework section explores the modernization of Bhutan and the challenges of shifting from forestry to other means of national revenue. The political framework discusses how the national forest program plays a role in common property rights for much of Bhutan. Section 3 explores the political ecology of land use land cover change in other developing nations.

2.2. Land Use

For years human activities were recognized as a major force in shaping the landscape across the planet. For most of human time, the alteration of earth from human acts mostly involved impacts on the soil and biotic resources that are related to the agricultural activities (White and Whitney 1992). Other negative anthropogenic impacts include species being thinned, exterminated, domesticated, or transplanted across continents; forest being cleared to make room for growth; grasslands being plowed or grazed; cites being expanded to reduce croplands; and wetlands being drained (White and Whitney 1992). Land transformation did not subside, but accelerated and diversified starting with the Industrial Revolution. Other factors in alterations due to land use change include globalization of the world's economy, population growth, and technological advancements.

Almost all of world's lands are being used and managed to some extent (White and Whitney 1992, Millington and Alexander 2000, Gordon 2005). Land demands and the demand for products produced are expected to carry on well into the future. To sustain this kind of demand on land use is the topic of much discussion in both developed and developing countries. Whether it is due to the decreasing capacity of arable lands or the environmental impact that land use change brings, current estimates indicate continued land degradation due to land use change (Mackey and Tudor 2000, Pan et al. 2004, Ustin 2004).

Policy towards Land Use in Bhutan: Historical Context

Prior to 1969 property rights and use of forest resources in Bhutan were loosely interpreted (RGoB 1969, RGoB 1999, Droji et al. 2006, Droji 2007c, Penjore 2007c, Rai 2007). The *Trimshung Chenmo* (constituting law) of 1957 did not contain specific restrictions on the use of forest resources by the local people except on poaching of endangered wild animals. Any acts regarding agricultural lands that took place since 1953 differentiated between private and community property rights. This process did not have negative restrictions on the use and access to forest resources by the population (Dorji et al. 2006). However, this changed in 1969 when the Forest Act was passed. The definition of what constitutes "forest" in the act clearly altered the property regime, particularly in the case of state property. The act brought at least 80% of the land resources under direct government control (RGoB 1969, RGoB 1999, Rai 2007). A decade after the enactment of the Forest Act, the National Assembly passed a resolution to develop a Social Forestry Program in 1979.

The Department of Forestry followed up with decentralization of community forestry and forest fire programs to the *Dzongkhags* (the state level governments). However, this action brought limited improvement in the interaction between the government institutions and the forest resource users, as there was no tenure rearrangement of the forest resources. As a result the forests were managed as defined in the Forest Act and did not make any difference to the farmers. As new roles of forests and forest resources emerged since the enactment of the Forest Act in 1969, the need to involve the local people more closely in the management of forests and forest resources was vital (RGoB 1999, Dorji et al. 2006). The Department of Forest responded by including a chapter on “Community Forestry” in the Forest and Nature Conservation Act 1995. To remove any uncertainty on the status of community forestry and to provide direction, it defined community forestry as “any area of Government Reserved Forest designated for management by local communities in accordance with the rules issued under this act” (RGoB 1995, 1). No formal documentation or analyses have been carried out on the effects of land use based on these policies. An effort is made in this dissertation to document and discuss the policies that govern land use as they function.

Geospatial Technologies in studying land use

Geospatial technologies such as Remote Sensing and Geographic Information Systems have been used for over a century, in the form of aerial photography and surveying, to attain information about land use (Jensen 1996, Green and Hartley, 2000, Ustin 2004, Jensen 2005). The roots of present-day remote sensing lie in the technological advances in photography. Modern photography was introduced in 1839 by Louis Daguerre, and in 1868 one of the first known aerial photographs was taken from a tethered balloon over the city of Paris (Jensen 1996). In recent decades the role has expanded at an accelerating rate as human populations grow and occupy ever-increasing space on the Earth’s surface. The challenge for remote sensing begins with the matter of detection of land use change, followed by the identification and characterization of these changes. From that point on, the challenge is to accurately map then to monitor change over time, and ultimately to model and predict the temporal/spatial dimensions of change (Ustin et. al. 2004, Jensen 1996). Remote sensing offers the potential for multispectral environmental monitoring, with high spatial resolution and periodicity, critical to the scientific understanding of the planet (Jensen 1996, Ustin 2004, Jensen 2005). Geospatial technologies provide a means by which analysts may reach a quantifiable understanding of complex interrelated mechanisms such as human impact on land use and land use change.

2.2.1. Policy

Land and Forest Acts

The Land Act of 1978 and *Thrimshung Chenmo* in 1957 gave tenure rights over the agricultural lands to the farmers (RGoB 1969, RGoB 1999). The Land Act of 1978, Chapter 1, Section (A) 1-4 (a) provides legality for the inherited lands and protects tenure right of the property (RGoB 1969, RGoB 1999). This act also protects a Bhutanese national if for example his or her land was taken over by the Government. Chapter 1 Clause (A) 6-8 and 6-9 states the Government shall compensate by financial support or selected land replacement. To ensure fair distribution of agricultural land the Land Act of 1978, Chapter 1, Clause (A) 3-4 fixed the land ownership at 25 acres per family (RGoB 1969, RGoB 1999). The Forest Act of 1969 gave considerable power to the forest officials to protect, manage, and control access to the forest. It also helped strengthen the natural resource property right regimes. Much of the act's ideologies were carried over from local forest laws in various parts of Bhutan which were aimed at protecting forests from further degradation by the expanding population. One major change to the Forest Act of 1969 gave the government more control at the national (*Dzongkhag*) and local (*Geog* and *Chiwog*) level. Under Chapter 1, Section 4 (e) the word forest was defined as "any land under forest which no person has acquired a permanent, heritable and transferable right of use and occupancy", and all forests as defined under this section are declared as Government Reserved Forestry (RGoB 1969, 4).

National (Dzongkhag) versus Local (Geog/Chiwog) Level Laws

The administrative boundaries of Bhutan are divided into four tiers; international or national, *Dzongkhag*, *Geog*, and *Chiwog*. This schema can be compared to the United States' state level (*Dzongkhag*), county level (*Geog*), and townships (*Chiwog*) administrative boundaries. The Forest and Land acts that preside at *Dzongkhag* level differ slightly from those at *Geog* and *Chiwog* level. The Forest Act 1969 states that "His Majesty's Government reserves the right to the absolute ownership of trees, timber and other forest produce on private land" (RGoB 1969, RGoB 1999, 12). These trees may be made available by a Forest Officer or any officer so empowered by His Majesty's Government. According to the law, sale or barter of timber is strictly prohibited, and a violation "will make the offender liable to imprisonment which may extend to one month or with fine which may extend to Nu. 100 or both" (RGoB 1969, 56). Royal commands and by-laws were distributed in a form of circulars in rural areas to encourage the protection of forests. One such example included a Royal Command to pay fifty percent of the values of illegal forest product seized, with a fine of Nu. 10,000 if the case is detected by a single individual and up to Nu. 20,000 if the case has been detected by more than one person (RGoB 1969, RGoB 1999). The act grants forest officials considerable power to protect forest resources from the local people. Enforcement of regulations has been passed down to local communities by the Government in efforts to promote common property rights to individuals.

Forest Management and Common Property Rights

Local institutions that controlled access and administration of forest resources existed in Bhutan before the *Dzongkhag* (states) were involved in forest management (Burgi 2002, Tempa et. al. 2007). The Forest Act of 1969 made important changes to the pre-existing property rights, which Lam (2006) and others speculate acted to modify the incentives for long-term sustainable use, management, and protection. An important change to the Forest Act of 1969 took place at the Minutes of Seventy Second of National Assembly in 1995. The Forest Act of 1969 was repealed, and its contents were expanded to become the Forest and Nature Conservation Act of 1995 (Turkelboom et al. 2001, Dorji et al. 2006). Most of the Forest Act of 1969 remained unchanged, however, under Chapter 1 Section 3(e) the definition of forest was revised. The forests were now defined as “any land and water body, whether or not under vegetative cover, in which no person has acquired a permanent and transferable right of use and occupancy, whether such land is located inside or outside the forest boundary pillars, and including land registered in a person’s name as *Tsamdog* (grazing land) or *Sokshing* (woodlot for collection of leaf litter)” (RGoB 1995, 1). The new Act recognizes the need to create community forests and contains a chapter on Social and Community Forestry. The Act authorized the Department of Forest and Ministry of Agriculture to make rules on forest management and control. According to Chapter III, Section 11 (a), the Ministry may issue rules to regulate, or prohibit without a permit, any of the following activities (RGoB 1999):

- Entry in designated areas;
- Camping;
- Hiking, or using a vehicle;
- Taking any photograph, video, or sound recording;
- Conducting any scientific research.

Common property privileges in Bhutan are an essential issue in maintaining proper incentives for people to protect and conserve forests. Even though the forests are nationally regulated and controlled, reliance on the resources must be incorporated into forest management and conservation and sustainable strategies at a local level (RGoB 1969, Messina et. al. 2006).

2.2.2. Change Detection

Land Use Land Cover

Land cover is subject to change through natural cycles (floods, fires, volcanic activity, and droughts) and anthropogenic activities (urbanization, agriculture, natural resource management, and shifting cultivation). The doubling of the human population over the past half-century profoundly affected global systems (White and Whitney 1992, Ustin et al. 2004). According to Ustin (2004) and others there are two major forms of land cover changes: (1) conversion and (2) modification. Land cover conversion is most pronounced and is directly observable with remote sensing, such as when a land cover class is changed into another land cover class (e.g., urbanization and deforestation from agricultural) (Jensen 1996, Ustin 2004). "As much as 60% of the global terrestrial surface demonstrates some degree of large-scale conversion, and an important goal of satellite sensor systems is to determine the rate at which anthropogenic land surface alteration is occurring within the global environment" (Artiola et al. 2004, 190).

Methodology

There are substantial studies in which remote sensing is utilized to detect and quantify land cover change. Adams et al. (1995) studied the history of spectral signatures from time-sequence Landsat Thematic Mapper (TM) images in the Brazilian Amazon forest near Manaus, which was converting to secondary forest growth from pasturelands. They applied spectral mixture analyses to measure quantitative changes in land cover. In their study, biophysical processes and human interferences on land use were detected by observing fractional changes from image to image. Imhoff et al. (1997) merged nighttime “city lights” imagery from the Defense Meteorological Satellite Program Operational Linescan System (DMSP OLS) with census data and a United Nations Food and Agriculture Organization (FAO) digital soils maps to determine the amount of build-up land and its probable impact on soil resources in the United States. Their results showed a trend in development that followed soil resources, with the better agricultural soils being where the most urbanized areas were and some soils types (with more organic matter) were almost eliminated by urban sprawl. Although remote sensing offers great potential in monitoring land cover, land use, and land disturbances, there is little understanding of how these changes affect the socio-economic interactions. Other difficulties exist in studying land use and change detection. The challenges that must be addressed include the availability of remotely sensed data in developing nations, varying collection methods, lack of metadata, unwillingness to collaborate within intra-governmental agencies, and corruption.

Technological Challenges in Developing Countries

The improvement of natural resource management aided by Remote Sensing and Geographic Information Systems are crucial prerequisites for the efficient management of land in a developing-world context. However, the transfer or diffusion of geo-technology to developing countries, such as Bhutan, continues to be overwhelmed with many problems and challenges. Taylor (1991) argues that it may be essential for local public and decision makers to have a greater degree of knowledge and control over geo-technology and data. Many developing countries, including Bhutan, are heavily dependent on donor support and development assistance from the West and this presents enormous challenges. However, Taylor (1991) argues that if geo-technology is to be introduced successfully in these countries, it must be developed, modified, and controlled by the native people who understand the social, economic, and political context of the location as well as the technical capabilities. For example, after the Danish consultants left following the end of the Land Use Planning Project (LUPP) in Bhutan, the key problem was that of lack of maintenance and minimal use of equipment following completion of the project.

Taylor (1991) also argues that the lack of technological proficiency will only occur when native people are not fully involved. Yapa (1991) suggests four key points to improving the advancement of technological expertise in developing countries. These are the "establishment of information systems involving strong and local public participation, the development of the public domain, the relaxation of copyrights over existing geo-spatial software and the development of software that takes advantage of existing software infrastructure in the third world" (Yapa 1991, 52).

2.2.3. GIS and Remote Sensing

Integration of GIS and RS

Both GIS and remote sensing are technologies that focus entirely on geographic data. Both are designed to portray the world's geographic features as realistically and reliably as possible. The transition from raw numerical data to geographic data equates to more than simply adding an X, Y dimension. Three basic fundamentally controlled cartographic rules define the value and quality of spatial data: the scale of area of interest; the simplification of feature extents; and the essential description of the earth's surface and atmosphere (Ehlers et al. 1989). These three factors are further emphasized by the need for higher precision and greater accuracy when collecting the exact XY coordinates of geographic features in the real world.

Research in this area incorporated GIS and remote sensing in three ways:

- GIS databases compiled by remote sensing data including the capability to update and authenticate thematic coverage files, using earth observation satellite sensors, aerial photographs, and Light Detection and Ranging (LiDAR)
- Ancillary information using GIS data for image processing such as vector features to identify boundaries between land covers, Ground Control Point support for geo-registration, and assisting classification by in-situ or field work data and categorization of classified pixels.
- Joint analytical functions including fundamental spatial queries, superimposing thematic and statistical attributes from both GIS and remote sensing data, using fuzzy logic, and Boolean (Wilkinson G.G. 1996, Star et al. 1997).

In principle and theory both GIS and remote sensing are founded on diverging ideology in terms of the way data is utilized. Remote sensing is primarily a data collection technology, while GIS is mainly dedicated to data handling.

Varying Datasets and Geospatial Analysis

The integration of GIS and remote sensing basically involves combining both data to create a hybrid, or fusion, dataset. Integration of GIS and remote sensing data presents various challenges that need to be addressed. Three problems in data fusion include the following:

1. GIS and remote sensing data are provided by agencies and companies which do not agree on collection standards;
2. Differences in cartographic symbols and legends within separate information sources, for example, the concept of street is viewed differently in a municipal database from a topological database;
3. Combining real-time satellite or on-ground sensor based data to a vector database; for example, meteorological data from NOAA sensors to ground weather stations or real-time traffic measurements from street sensors (Verma et al. 2003).

One way to integrate remote sensing data into GIS is to convert interpreted or classified remotely sensed data into a layer, such as a classification scheme in a thematic map with each layer representing a particular class. Hasse (2008) applied an object extraction and identification method to develop an image classification algorithm. GIS spatial information assisted in reference to object identification in the classification algorithm. In remote sensing terminology this is commonly used as object supervised classification, where mean gray and texture values of each pixel are assigned to each class (Jensen 1996, Jensen 2005). In another study Mason et. al. (1997) used an artificial intelligence system combining remotely sensed and GIS data to study informal settlements. Three-dimensional data showing shelters and shacks were extrapolated from aerial photography and combined with socio-economic data to understand the dynamics of rapidly changing suburban and deprived areas. GIS and Remote Sensing technologies have been successfully applied for studying urban land use and land cover and their change patterns with approximately 80% accuracy (Mason et. al. 1997).

Urban Socio-Economic Analysis

Urbanization often leads to loss of green space, increasing impervious surface, lack of utilities and resources, increasing traffic congestion, and non-point environmental pollution (White and Whitney 1992, Rocheleau 1996). These problems linked with urbanization impact economic development and the quality of life in urban areas (Rocheleau 1996, Robbins 2007). It is vital to understand the dynamic interactions between human actions within urban environments with land use change and patterns of socio-economic activity.

Recent development in socio-economic research using GIS and remote sensing can be divided into two groups: activity modeling and information estimation (Taylor 1991, Yapa 1991, Wilkinson 1996, Taylor 1998). For socio-economic modeling group the focus is on modeling socio-economic activity by utilizing various environmental factors in an urban setting. This analysis is carried out in a GIS (vector) format to model socio-economic activity. For the information estimation group, the focus is on estimating socio-economic activity through complex regression analysis using remotely sensed imagery. Lo (1986a, 1986b) counted the number of houses then took a survey of approximate household size to estimate total population. While this study produces accuracy, it is labor intensive and time consuming because it involves manual photo interpretation. This study was the earliest application of remote sensing in estimating total population using household size by counting the number of houses.

Another study utilized population density to design a transportation infrastructure and plan bus routes that serviced libraries, public schools, and hospitals (Benn 1995). This study involved using both raster (imagery to estimate population density) and vector (road networks, locations of libraries and hospitals) datasets. Site evaluation and business feasibility studies often utilize population information linked with socio-economic attributes (Plane and Rogerson 1994). Socio-economic information relies on censuses that are conducted every five to ten years for most of the developed world. However, for some developing countries such as Bhutan, census information is not readily available due to lack of census data, tight government control, and lack of standards or consistency in collection methods. In such cases remote sensing can be an alternative means for estimating population, based on estimated occupancy per structure given its perceived size and identified function.

2.3. Frameworks

Cultural, economic, and political frameworks play an important role in land use change. The cultural framework includes the four pillars of the unique Gross National Happiness (GNH) philosophy. The economic framework consists of the exploitation of natural resources and modernization of Bhutan. Finally, the political framework consists of forest and land acts of Bhutan.

Gross national happiness is the unique development philosophy of Bhutan. It recognizes the need to balance material well-being with the spiritual, emotional, and cultural well-being of the individual and society for holistic development (RGoB 1999, Kezang 2004, Rossellini 2006, Wangchuck 2007a, Wangchuck 2007b). The four major areas identified as pillars are:

1. Sustainable and equitable socio-economic development,
2. Conservation of environment,
3. Preservation and promotion of culture and
4. Promotion of good governance (RGoB 1999).

Gross national happiness has been the guiding principle for socio-economic development over the last two decades and will continue to be so in the future (Dorji 2007c, Penjore 2007b, Wangmo 2007).

Bhutan's economic base is limited, with the central support for economic growth coming from the exploitation of hydropower and the utilization of natural resource-based industries that make use of low-priced power. Hydropower accounted for 12% of their GDP in 2003 (Rosellini et. al. 2006, Uddin 2007). Its exports accounted for about 45% of government revenues (Rosellini et. al. 2006, Uddin 2007). With several hydropower projects currently under construction, hydropower is projected to remain a critical engine of economic growth. However, hydropower and its related industries generate very few jobs.

Forest environments are associated with approximately ninety percent of Bhutan's economy (RGoB 1999). Increasing urbanization is modifying Bhutan's forest in the Thimphu valley (Dema 2007). At the national level, wood production potential and extraction is not a major problem. However, at the local level, extraction of wood and the sustainable management of forests is a critical problem due to the concentration of human settlements in valleys and other habitable locations. This condition imposes extra strain on forests near settlements, given the development level of Bhutan which places demand on wood for fuel, heat, and construction. Long term extraction and exploitation leads to forest fragmentation and degradation (Burgi 2002, Dorji et. al. 2006, Rai 2007).

2.3.1. Cultural

Gross National Happiness

Gross national happiness is the unique development philosophy of Bhutan. It recognizes the need to balance material well-being with the spiritual, emotional, and cultural well-being of the individual and society for holistic development (RGoB 1999, Kezang 2004, Thinley 2005, Rossellini et. al. 2006, Wangchuck 2007b). His majesty King Jigme Singye Wangchuck, the Fourth King of Bhutan, first announced the principles of the philosophy of Gross National Happiness in the late 1980s. The concept however, is referenced much earlier. Gross National Happiness promoters suggest that while Gross National Product is used to measure economic development does not take in consideration the real policy on the ground (Thinley 2005). GNH has guided socio-economic development in Bhutan since its declaration.

Four Pillars

In the first pillar, sustainable and equitable socio-economic development, it is of "absolute necessity to eradicate poverty," and it is a reality that must be faced in many developing countries where "physical survival is an everyday challenge, economic policies are what matters most" (Thinley 2005, 7). Very few studies exist in measuring happiness against environmental variables (Thinley 2005). It is especially important for the Bhutanese to promote the conservation of environment "given that [their] health and aesthetic experiences depend on the quality of physical environment around us"

(Thinley 2005, 7). This is true for the farming communities, “such as majority of Bhutanese, living not only close to, but in nature, livelihood depends directly on richness of their immediate natural environment which bestows on them free, wholesome foods, medicines, pleasure and a host of essential materials” (Thinley 2005, 8). The preservation and promotion of culture is seen throughout Bhutan’s countryside in the forms of traditional architecture to the dress code of government employees in the capital city of Thimphu. Thinley (2005, 10) argues that “a state which does not preserve its cultural richness is one where the choices and well-being of its citizens are diminished and greatly constrained” The final pillar, promotion of good governance, greatly affected implementation of the Gross National Happiness philosophy. His Majesty the King “has recently circulated the Draft Constitution of the Kingdom of Bhutan that opts for liberal democratic institutions” and a move towards decentralization of *Dzongkhag* administration (Thinley 2005, 10).

The Middle Path

A key to Gross National Happiness-based public policy is the vital search for balance, both within and between the pillars. For example, it is not sufficient that an increased annual economic growth is achieved; it must be accomplished in a manner that protects the environment, preserves the culture, and is in agreement with good governance practice. As one of the four pillars of Gross National Happiness, ensuring the long term sustainability of the environment has been a priority in Bhutan (Droji et.

al. 2006). However, due to growing economic activities and population, particularly in urban areas, there is increasing pressure on the environment. It is important to sustain the national efforts to follow "The Middle Path" in order to fulfill policy goals affecting land use/land cover (Thinley 2005). The middle path refers to the Bhutanese government's approach to natural resource management. This middle path focuses on the concept of "sustainable development, which recognizes the need to develop the economy, to progress technically, medically, and scientifically, while maintaining the rich cultural heritage," with traditional values and the natural resources as the base (Turkelboom 2001, 21). This prompted the National Assembly in 1973 to enact a mandate to maintain a forest cover of at least 60% nationwide at all times (RgoB 1974).

2.3.2. Economic

Challenges facing Bhutan

The bigger issue facing Bhutan is that, while there is a major scarcity of human resources to address rural development, the increasing countrywide urban workforce is untrained and limited in skill sets needed to meet the demands of the market. According to the Common Country Assessment report by the United Nations (2000) one of the key issues is the lack of employment opportunities. It has been equally difficult for Bhutan to absorb the loss to the agriculture sector as it is to have such a substantial unemployment rate in the urban areas (especially for the young cohort). Yeshi Zimba, the Finance Minister of Bhutan, stated that one of the biggest economic challenges facing his country is finding employment for 40 percent of the younger generation (Lawson 2002). Much of this unemployment (or underemployment) Zimba describes is found among those either in the rural areas or migrants from the rural areas. Private sector development also faces numerous challenges. One challenge is the lack of an entrepreneurial culture in the country. Add to this other externalities, such as infrastructure inaccessibility and the rural communities become seriously restrained from participation in mainstream development. With the continued loss of the younger more productive work force, some village officials indicated a slowed progress toward development and a weakening of family cohesion, which has traditionally been extremely important to the Bhutanese culture and the aspirations toward Gross National Happiness.

As the overall national population increases, different parts of the country bear different kinds of hardships. Scattered population is intensified by migration of people from the least developed to the more heavily developed areas. Much of this migration is caused by people's response to the limited access to resources and economic opportunities, along with "spatial variations such as the distribution of natural endowment", including land that is sustainable for agricultural use (United Nations, Bhutan 2000, 5). Other significant pull factors are job opportunities and better standard of living in urban areas.

Hydropower

Many rural areas in Bhutan are adapting to micro hydropower, which is considered a low cost environmentally conscious renewable source of energy. Micro hydropower is generally defined as a decentralized small-scale water power plant producing less than 100 kW. It can provide electricity to rural communities which otherwise might take years to be served by national electricity services in the Himalayas (Abdallah et. al. 2009). The components of micro hydropower can be manufactured and the systems built locally. The challenge of micro hydropower dams lies in the wide disparity between the monsoonal and the regular flows of rivers (Rosellini 2006). These dams are unable to operate at full capacity at all times due to seasonally varying water availability. Construction and maintenance of micro hydropower plants generate very few jobs in rural communities throughout Bhutan.

Challenges in Agriculture

In prior generations, younger persons would supplement their families' labor needs on the farm and in all likelihood become farmers themselves. One of the major disadvantages in Bhutan is that farming is much more difficult to mechanize. Though in some cases the Ministry of Agriculture (MoA) supplied motorized tillers for communities (first introduced to Bhutan by the Japanese, who faced a similar problem of inadequate rural labor left after urban migration), many of these machines are used for transportation rather than for direct farming needs doing little to sustain or enhance farm production. This difficulty in mechanization results in more work for fewer (and older) people when the younger cohort leaves the farm. Mechanization is also difficult in the Bhutanese landscape due to the practice of terrace based soil conservation methods. A terrace based agricultural practice is a leveled section of a hilly cultivated area, considered to be a sustainable method of soil conservation to slow or prevent the rapid surface runoff of irrigation water (Carman 2005). In mountainous regions, such as Bhutan, land is formed into multiple terraces, giving a stepped appearance. These challenges make it difficult to maintain current production levels and even greater difficulty to increase farm production or to make it commercially and economically viable.

Rural-Urban Migration Issues

Due to rural-urban migration in response to modernization opportunities, urban areas are witnessing increased rates of population growth, straining urban infrastructure, services, and resources (Rosellini et. al. 2006). In 2002, the population was estimated at 734,340, of which 21% lived in urban centers (RGoB 2005). A combination of ongoing rural–urban migration and population growth trigger an increased demand for urban services, including roads, water supply and sanitation, public transport, housing, drainage and flood protection and mitigation, solid waste disposal, public markets, street lights, roundabouts/intersections, and other public services (RGoB 1999, Dorji 2007b, Uddin et. al. 2007). Developing safe, healthy, and well-managed urban settlements is critical to promote social development, and to assist in an economic growth process that successfully balances and anticipates the future needs of the rural and urban populations (Epstein and Jezeph 2001, Zhang and Song 2003, Goldsmith et. al. 2004).

Excessive rural-urban migration tends to exacerbate the rural-urban structural imbalance, as noted in the Todaro Thesis (Todaro 1997). This imbalance is a supply side/demand side dichotomy. On the supply side, rural-urban migration disproportionately increases the growth rate of urban job seekers (relative to urban population growth). This in turn results in an over abundance of the urban labor supply while depleting the rural human capital. In the case of Bhutan, as is likely in many other poorer developing countries, the poverty that exists in the rural areas (a major push factor for the younger rural population) is further heightened as a result of the out migration. Though providing substantial labor for the urban or industrial sector Bhutan initially faces two major problems which is contrary to Arthur Lewis' two sector model of development for Less Developed Countries (Lewis 1954). First, much of the labor resulting from this migration is not employed in the receiving sector. Second, a large percentage of the labor that is migrating is in fact the potentially more productive segment for the rural areas.

According to the Asian Development Bank (ADB 2001), 79% of the Bhutanese population is an agrarian based rural society. These populations generally exist by subsistence farming along with animal husbandry, classic in the Lewis model for Low Developing Countries (LDCs). They face many problems such as market access, insufficient means of transportation, lack of business expertise, low levels of literacy, acute shortages in modern skills, poor nutrition and health indictors, gender disparities, and inequitable access to better paying employment opportunities within their environment (ADB 2001, UNESCO 2006). Facing economic and educational problems in the remote rural areas, the younger generation believes that it is necessary to leave their communities in order to accomplish their economic and social goals. Many migrants consider relocation to urban centers as a measure of success (UNESCO 2006).

2.3.3. Political

Shift in government and policy

Since 1999, significant political changes have occurred in Bhutan. A political transformation process started in early 2008, involving a gradual hand-over of power from the monarchy to a democratically elected parliament and a prime minister. At the same time, decentralization efforts have proceeded at the sub national level. This has transferred the authority of local planning and construction projects to each of the twenty *Dzongkhags*.

Forest programs and management

The Forest Act of 1969 made important changes to the pre-existing property rights, which could modify the incentives for long-term sustainable use, management, and protection as described in section 2.2.1 (RGoB 1969a). Rights to the access, use, management, protection, and transfer of resources make up the collection of property rights of the person or community for the area in which they live. If the property rights of a person or community change through policy formulation or implementation, the incentives for long-term management may change as well. For example, if all of the property rights to traditional forest are taken away from a community that previously possessed complete ownership rights, then it is difficult for those users to recognize the security and individuality of future benefits. Those individuals are less likely to have any incentive to invest time and effort in management of the forest. Given insufficient regulations over property rights, resources may be considered open domain and susceptible to degradation and pilferage with no incentive towards sustainability. Local institutions that regulated access and management of forest resources existed in Bhutan before state involvement in forest management (Burgi 2002, Tempa et. al. 2007). One possible solution in maintaining incentives for people to use the forests in a sustainable manner is to closely monitor property rights.

Common Property Rights

The loss of rights over resources may eventually result in attitudes within individuals to act independently in their own self-interest further causing the loss of incentives for management and more incentive for short-term gains (Hardin 1968). Several South American and African nations demonstrated that providing fair rights to traditional users is an important component of a national forestry strategy (Atkinson 2000; Seeland, 2000; Messina 2006). Similarly south and south-east Asian nations implemented policies that claim ultimate property rights (eminent domain) over forests. Examples exist throughout India (1878 Indian Forest Act), Indonesia (1967 Basic Forestry Law No. 67), Nepal (1957 Private Forests Act) and Thailand (1913 Forest Protection Act). Vandergeest (1996) and Ma (1999) discovered that the major factor in deforestation was lack of land tenure or a sense of common property in both Nepal and Thailand. Property rights in Bhutan are a central issue in maintaining the appropriate incentives for people to conserve forests. Dependence on the resources must be incorporated into forest management and conservation and sustainable strategies, even if the forests are state regulated (RGoB 1969a, Messina et. al. 2006).

2.4. Political Ecology

Theory in Conservation and Resource Management

Studies of political ecology in the field of geography were traditionally seen as "utiliz[ing] ecosystems that are, by nature, in ever-changing interaction with human activities," for example, the interaction of people with vegetation or people with wildlife (Zimmerer and Bassett 2003, 8). Bassett and Zueli's study incorporated both geographic and social science knowledge to analyze the relationships of land use and human interactions in Western Africa. In this study the authors followed three sets of integrated methods popular in political ecological research:

1. Ecological analysis (vegetation transects);
2. Related image analysis (aerial photo interpretation, geographical information systems [GIS] analysis, ground truthing); and
3. Corresponding social-scientific and humanistic approaches (household surveys, oral histories, and discourse analysis).

Other political ecology studies show that "structural adjustment programs" such as "land privatization, decentralization, and blueprint based environmental planning exert major impacts on agriculture, livestock raising, and land use" (Zimmerer and Bassett 2003, 9). In Bhutan, land privatization and decentralization of national, *Dzongkhag*, and *Geog* level administration already caused significant changes to policy regarding forestland in the past two decades (Afshar and Jimba 2001). These political and economic impacts affect forest policies in terms of accessibility, control, and management. Methods of geospatial technologies merged with social sciences are used to better understand these complex issues in political ecology.

Geospatial Technologies in Political Ecology

Geospatial technologies such as GIS, remote sensing, use of geographic positioning systems (GPS) devices, mapping, and data analysis software are “increasingly common elements in the methodological toolkit of political ecologist interested in understanding the multi-scale dynamics of nature-society relations” (Zimmerer and Bassett 2003, 11). These technologies are used to understand land use and land cover changes at a regional-scale with a global linkage such as global warming. Numerous studies investigate the “relationships between geospatial technology to knowledge, and representations of landscapes” that broaden the use of geospatial technologies in the social science arena (Zimmerer and Bassett 2003, 12).   Brent McCusker and Daniel Weiner (2003) used a combination of “survey research techniques, oral histories, group transect walks, and archival research” to reveal “landscape power relations” that helped to explain land use change in Africa (Zimmerer and Bassett 2003, 23). Integrating geospatial technologies and political ecological investigations has produced land use land cover maps that often differed from those produced using strictly GIS and remote sensing. Furthermore, the authors discovered hidden political ecologies by which political economic strategy was used to make up land use claims for personal gains (Weiner and Harris 2003).

A study by Paul Robbins (2007) compares interpretations of land cover from two opposing parties in a semi-arid region of Rajasthan, India. On one side, for their economic and bureaucratic gains Indian foresters must show an increase in forests. To do this certain invasive species (such as *Prosopis juliflora*) are planted to reflect the “greenness” when viewing the landscape through satellite sensors. On the other side the agriculturists argue that these species do not necessarily contribute to the forests. Instead they classify them as degraded rangeland due to its low forage potential (Robbins et al. 2007). Robbins’s research highlights the highly objective nature of image processing and map making and the challenges between true land use and what is seen from satellite sensors.

CHAPTER III

METHODOLOGY

3.1. Study Area and Data

Overview

The geographic focus of this study is the Thimphu valley in Bhutan (27° 28’60” N, 89° 35’60” E). Several raster and vector datasets were utilized for the analysis of land use land cover. The raster datasets, which are further elaborated in section 3.1.2, include: Landsat 1990, 1999, and 2007, SPOT 2006, and QuickBird 2006. Vector datasets, also discussed in more detail in section 3.1.2, include: Thimphu city boundary, road centerlines, building footprints, bus stops, and enumerations zones.

3.1.1. Area of Interest

Administrative Boundaries

Known for its unique culture and values, Bhutan is a small, landlocked country located between China to the north and India to the south (Figure 3.1).

Figure 3.1: Bhutan General Location Reference Map.
*Source: Environmental Systems Research Institute, 2008.

Though about the size of Switzerland, it only has about a tenth of Switzerland's population, with a population of only 691,141 (RGoB 2005). Estimates of Thimphu's population vary. The Common Country Assessment by the United Nations claims that Thimphu's population is approximately 54,300, and is growing nearly 10% annually

(Rosellini, et. al. 2006). According to the Thimphu Municipal Corporation, the present population of Thimphu is 43,479 persons, based on a survey conducted in the year 2000 by the National Statistics Bureau. Thimphu currently accommodates one third of the total urban population in the country, which was 137,864 in the year 2000 (RGoB 2005). With regards to its administrative boundaries, Bhutan is subdivided into 20 *Dzongkhags*, which are structurally similar to states in the United States (Figure 3.2).

Figure 3.2: Dzongkhag locator map.
*Source: Ministry of Agriculture, Thimphu, Bhutan.

Dzongkhags are further subdivided into 205 *Gewogs* (which are structurally analogous to counties in the United States), which are even further subdivided into 1906 Chiwogs (Figure 3.3). The boundaries of the *Gewogs* are ever-changing, as well. In early 2008, *Toepisa* and *Bapisa Gewogs* were removed from Thimphu *Dzongkhag* and given over to *Punakha Dzongkhag*.

Thimphu Valley

Thimphu is located in the west-central part of the country, on the Thimphu River at an elevation of approximately 7,000 feet (2,000 m) above sea level. The national capital city, Thimphu, is located in the *Dzongkhag* of the same name, and it also serves as the capital of that *Dzongkhag*. With a population of just over 98,000, Thimphu is the most densely populated urban area in the country (RGoB 2005). The population for Thimphu *Dzongkhag* is estimated to be 116,000, indicating the concentration in the urban area (RGoB 2005). It was made the permanent capital in 1952-3, but this was at a time when the city consisted of a "*dzong* surrounded by some huts" (Pommaret 2003, 151). These "huts" were spread throughout Thimphu valley, and were organized into hamlets, whose names correspond to the names of Thimphu's current districts (e.g. *Motithang* and *Langchupakha*).

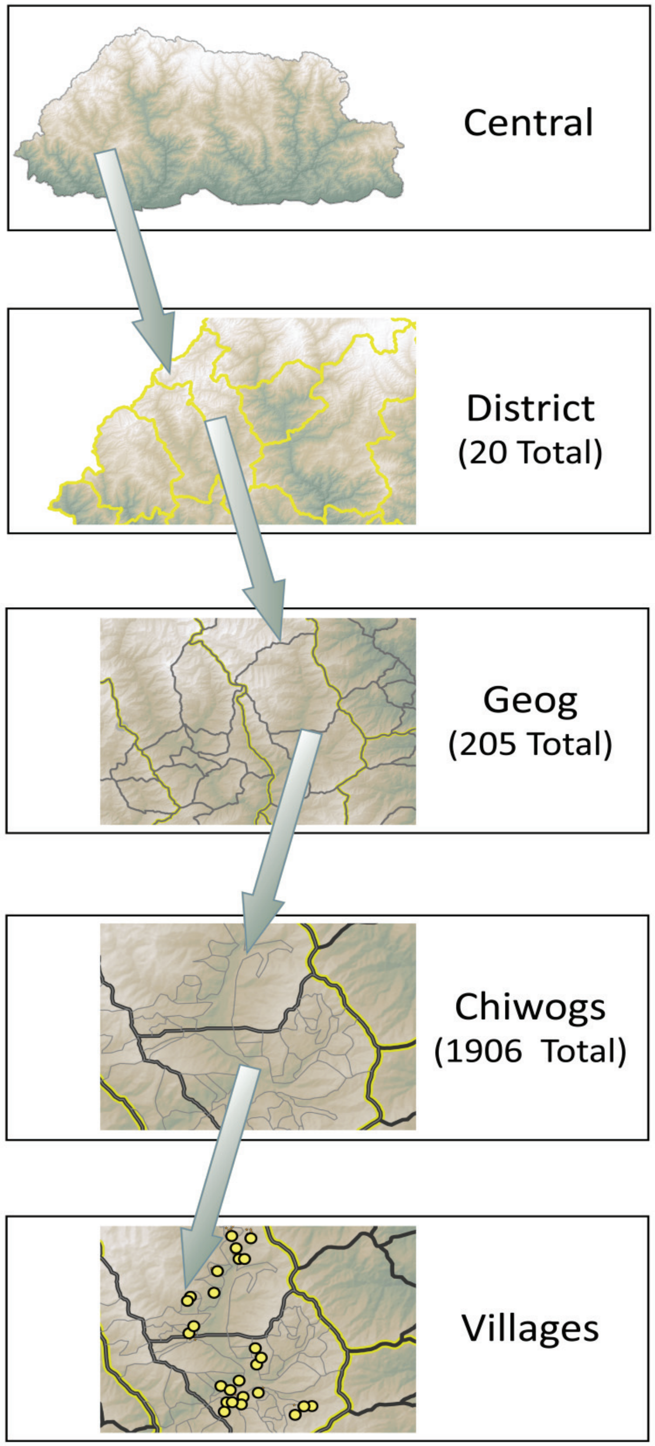


Figure 3.3: The five levels of geographic hierarchy of the PHCB, from largest to smallest.

It was not until recently that Thimphu started to develop into the Thimphu of present. A real estate boom occurred in the 1980s, which was followed by an influx of businesses, hotels, restaurants, and dance clubs in the 1990s. Likely due to the additional increase in automobile use in the 1990s, street names have also slowly begun to be developed and used (Pommaret 2003). The *Tashichhodzong*, one of the most prominent features in the city, serves as a meeting place for the National Assembly in one portion, as well as a monastery in the other half of the building, separated by a central plaza. Because the monastery is housed in the *Tashichodzong* and the monk body resides there, they have an inevitable influence on policy decisions.

The city is also considered to be the main marketing center for agricultural goods produced in the surrounding valley and on terraced hill slopes. Power is supplied by a hydroelectric station constructed in 1966. Major industries include sawmilling, wood products, and food processing (RGoB 1999). Transportation infrastructure is sparse, as there is only one road into Thimphu. The Indo-Bhutan Highway, constructed in 1968, is the main route into Thimphu from India via the Indian border town of *Phuntsholing* (176 kilometers or 109 miles) and passing through the site of the sole national airport in *Paro* (72 kilometers or 44 miles).

3.1.2. Raster and Vector Datasets

Raster Data Overview

Multiple raster datasets were used in this study. Land use change will be assessed from Landsat Thematic Mapper (TM) satellite imagery. One advantage of using Landsat imagery for a land use change analysis is the availability of comparable data from the past. The Landsat Program is a series of Earth-observing satellite missions jointly managed by the National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey (USGS). Since 1972, Landsat satellites have collected information about Earth from space. In this study Landsat imagery from 1990, 1999, and 2007 was utilized. Other years were available for download; however, because of a malfunction in Scan Line Corrector (SCL) the available Landsat Enhanced Thematic Plus (ETM+) imagery after 2003 would introduce error in a change detection analysis (Covington 2004, Maxwell 2007, Bedard 2008, USGS 2009). Acquisition dates for Landsat images utilized for this study are shown in Table 3.1.

Other raster datasets utilized in this study are QuickBird and *Satellite Pour l'Observation de la Terre* (SPOT) imagery. The QuickBird sensor is located on a spacecraft which collects high resolution commercial imagery of the earth. The source of the QuickBird imagery is DigitalGlobe located in Longmont, Colorado. QuickBird orbits at an altitude of 450 kilometers, in a 98 degree, sun-synchronous orbit. The 60 centimeter (0.60 meter) resolution of QuickBird images allows objects on the ground as small as 60 cm or approximately 2 feet across to be identified. SPOT is also a high-resolution, optical imaging Earth observation satellite system operating from space. SPOT satellite sensors are owned and operated by SPOT Image in Toulouse, France. The constellation of SPOT satellites offers imagery with spatial resolutions of 20m, 10m, 5m, and 2.5m. The SPOT image used in this study includes a 2.5m panchromatic image. The SPOT image is primarily used for accuracy assessment.

Vector Data Overview

Vector datasets included GIS shapefiles and tabular Excel spreadsheets used to generate the attributes data for shapefiles. Table 3.2 shows a list of vector datasets utilized in this study. Data from the Population and Housing Census of Bhutan (PHCB) served as a base for much of the vector analysis. PHCB data comes from the Office of the Census Commissioner (OCC) in *Langjuphakha*, Thimphu. Though Bhutan's first census was conducted in 1744 – 1766, PHCB of 2005 is regarded as country's first "official" census (RGoB 2008). The geographic hierarchy identified in the PHCB consists of five levels (Appendix A). The background and history of PHCB is further elaborated in section 3.2.1. This dissertation utilizes Dzongkhag and Gewog level census data to address rural-urban migration. The tabular data is available for download at the Bhutan portal website (http://www.bhutan.gov.bt).

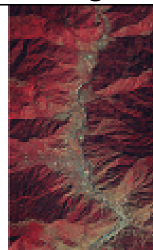
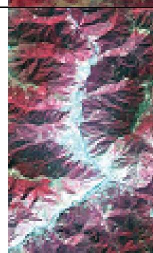
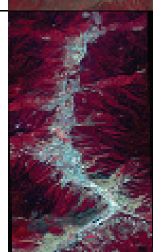
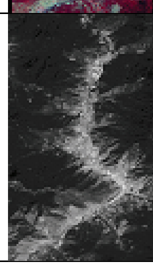
Image	Satellite	Source	Acquisition Date
	Landsat	EROS Explorer USGS	11.14.1990
	Landsat	EROS Explorer USGS	10.30.1999
	Landsat	EROS Explorer USGS	05.05.2007
	IKONOS (QuickBird)	DigitalGlobe	03.27.2006
	SPOT	*Satellite Pour l'Observation de la Terre*	02.06.2006

Table 3.1: Remote Sensing imagery utilized, with its source and date of acquisition. The source of Landsat imagery is the USGS Earth Resource Observation and Science (EROS) in Sioux Falls, South Dakota. The imagery has 7 spectral bands with 28.5 meter spatial resolution.

Name	Geometry	Description	Source	Creation Date	Projection
Thimphu City Boundary	Polygon	Converted from original CAD file	Bhutan Survey	2007	WGS-1984, UTM Zone 46N
Enumeration Zones	Polygon	Digitized from Thinley map (JPEG Static)	Bhutan Survey	2008	WGS-1984, UTM Zone 46N
Building Footprints	Polygon	Converted from original CAD file	Bhutan Survey	2007	WGS-1984, UTM Zone 46N
Road Centerlines	Polyline	Digitized from 2006 Quickbird	Quickbird Image	2008	WGS-1984, UTM Zone 46N
Bus Stops	Points	Digitized from static maps	Road Safety & Transport Authority (RSTA)	2008	WGS-1984, UTM Zone 46N

Table 3.2: Vector data utilized and attribute information associated with the datasets.

3.2. Addressing Rural Urban Migration

Migration Overview

Addressing the rural urban migration issue involves examining several GIS and tabular datasets. This is not only to organize the data for assessment, but to analyze and understand those findings. The analysis includes tabular to GIS shapefile joining, examining several variables from the PHCB. The tabular data is downloaded in a PDF format from the Government of Bhutan portal website. The data is then converted from PDF to excel spreadsheets, and then finally into DBF (database) format for use in

ESRI's ArcMap software. This tabular data is joined to GIS shapefiles using a unique ID that matches both the shapefile and tabular data. Data from three major categories (health, education, and household/housing characteristics) are extracted and examined from the PHCB in order to examine population pressures from rural-urban migration. Rural urban migration at a *Gewog* and Thimphu city scale is further elaborated in section 4.1.1.

3.2.1. Background on Census of Bhutan

The need for population and housing census in Bhutan was recognized by the government in March 2003. The Ministry of Home Affairs received an order from the Royal Government to conduct a nationwide census. Prior to the 2005 census, the country's population was based on estimates from various surveys and administrative (*Dzongkhag*) records (Dorji 2007a). The ministry consulted the United Nations Population Fund (UNFPA) and submitted a proposal that followed international standards of conducting a census. His Majesty approved the proposal and authorized the Office of the Census Commissioner (OCC) to conduct the PHCB by the end of 2005. The OCC employed demographers, statisticians, cartographers, communication experts, and senior staff from other ministries to complete a nationwide survey within two years.

The OCC provided training workshops prior to conducting the survey and after the survey was complete to process the data. The workshops included: manual methods of data collecting, using GPS units, and processing data using GIS. The data collection and processing was handled in a hierarchy. To ensure complete coverage, the whole country was segregated into 6800 enumeration area maps. Every structure (temporary, permanent, caves, shelters) was plotted with a GPS. The National Statistics Bureau (NSB) was in charge of processing the data collected for the census. NSB's objectives for processing and analyzing the data in GIS were:

- Generation of Geo-database for PHCB 2005,
- Processing the PHCB data from Dzongkhag to enumeration level,
- Producing socio-economic maps using census data for all categories,
- Data dissemination for various governmental organizations, and
- Creating a bench mark for future censuses of Bhutan (NSB, 2005).

The raw census data collected information using forms (i) PHCB 2A (household list), (ii) PHCB 2B (Household member list), (iii) PHCB 2C (Individual details), (iv) PHCB 2D (Household information). Household to Gewog aggregated census data was collected for the following categories:

- Demographic and general characteristics
- Migration (Dzongkhag and Gewog)
- Education
- Health (accessibility and distance)
- Employment
- Fertility of women 15-45 years of age
- General population mortality
- Infant and child mortality
- Maternal mortality
- Health professional attendance
- Ownership of housing
- Lighting
- Cooking fuel
- Toilet facility
- Source of drinking water
- Number of rooms occupied by the household

These categories were further grouped into six major clusters in the PHCB 2005 report:

1. population characteristics
2. migration
3. health
4. education
5. labor and employment
6. household and housing characteristics

The PHCB of 2005 was conducted over the course of two days (30 and 31 May 2005). A total of 7,500 enumerators, supervisors, and administrators were involved throughout the country in the census enumeration (RGoB 2005). Data editing was done in several stages. The first editing of data was done by the field supervisors and then followed by the manual editing at the *Dzongkhag* level immediately after the field operation. The final manual editing was done at the NSB center in Thimphu. This was followed by data entry and encoding of census forms. Numerous computer operators, supervisors, and assistants were involved in data processing for six months. The first set of data processing began on 15 July 2005 and was completed on 30 October 2005. As recommended by the database consultant and technical group of the UNFPA, each record was entered again for 100% verification of the data. This began on 1st November, and the entire PHCB data processing and verification was completed on 30 January 2006.

3.2.2. Shapefile Generation

Digitizing and Rectifying

Much of the detailed data for Bhutan is not available for download from any of the government departments, so it needed to be manually created. First, a geog scale map from the PHCB was rectified (for a more in depth discussion of rectification, see Section 3.3.2) to the most recent shapefile of the dzongkhag boundaries (Figure 3.4). Using the dzongkhag boundary shapefile as the basis for the rectification made sure that the geog shapefile was using the same projection as the dzongkhag shapefile and allowed it to be used as a base for easily digitizing the geogs.

Once the map was rectified to the shapefile, both files were opened in ArcMap. One more shapefile, edited to create the geog shapefile, was also added. This shapefile was created in ArcCatolog using the same projection as the dzongkhag shapefile (WGS_1984_UTM_Zone_46N). Utilizing the “Editor Toolbar” in ArcGIS, new features were created for each individual geog (Figure 3.5). The geogs were snapped to the dzongkhag boundaries, using the “trace” features, to ensure that any common boundaries between the dzongkhags and the geogs were not misaligned. In total, all 205 geogs were manually digitized.

Joining Data and Attributes

Once all of the geogs were digitized, the different variables from the PHCB were joined to the geogs. The tabular data was obtained from the National Statistic Bureau's ArcIMS website (http://203.175.8.86/website/bhutangeogs/viewer.htm), where it was extracted from tables that were opened when a particular geog was selected and placed into an excel spreadsheet. Some of the variables extracted include population, in-migration, out-migration, net-migration, rural population, urban population, water facilities, toilet facilities, access to health care, distance to motor road, source of lighting, and source of cooking fuel.

Each geog feature had a unique identifying number (FID) in the shapefile, which is also a column in the in the tabular data. These unique identification numbers were used to join each geog to its respective data. For example, if the FID for Thimphu was 2, all of the attributes in the "2" row of the tabular data would be joined to the shapefile feature of the same number.

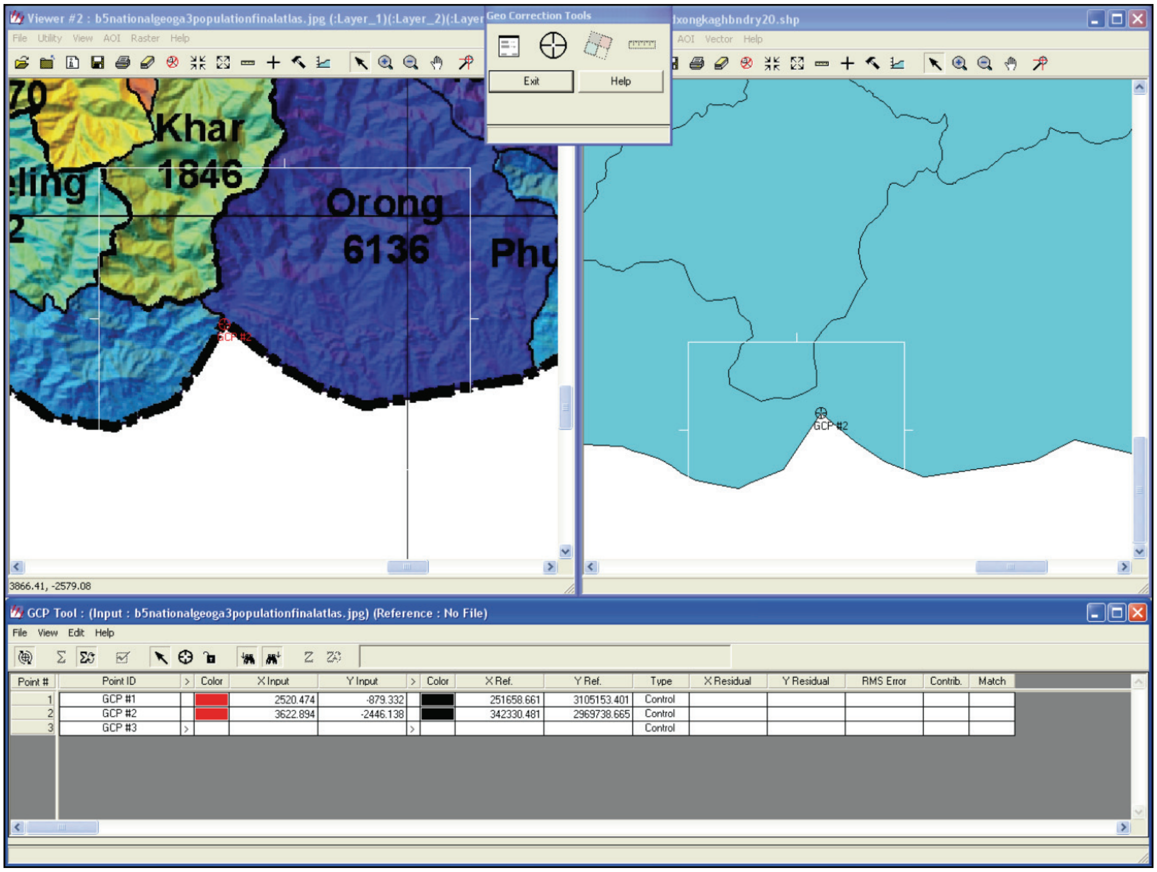


Figure 3.4: Map-to-Map rectification required for the digitization of geogs from the PHCB geog population map.

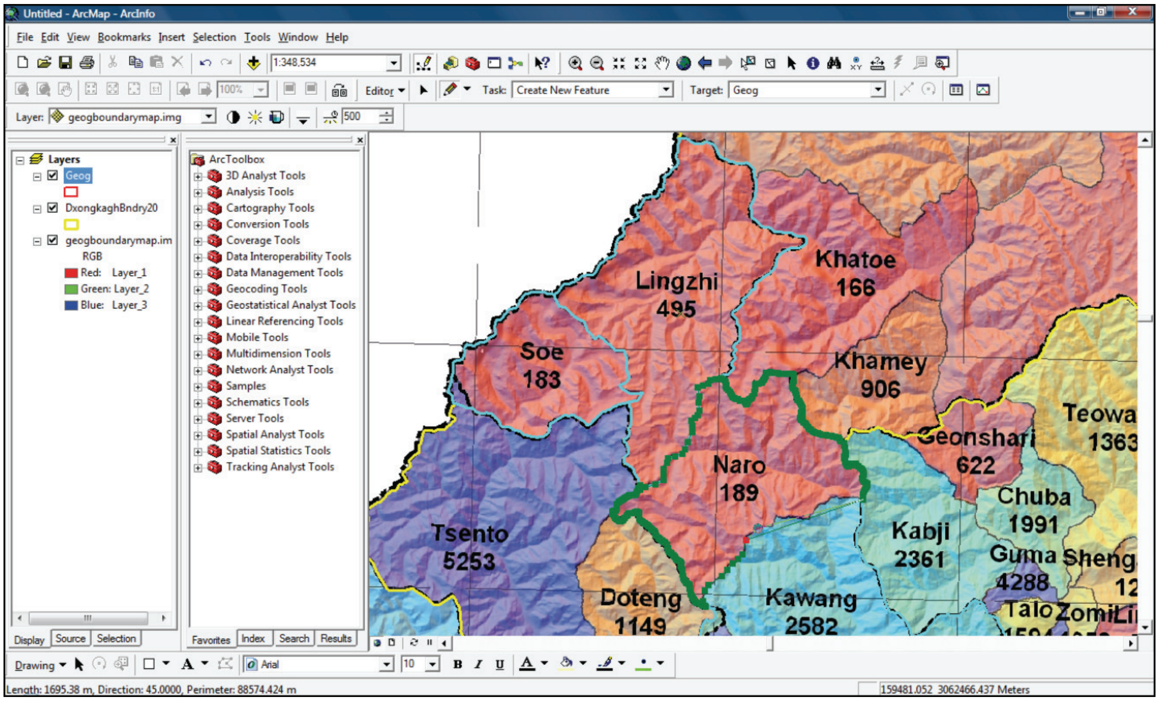


Figure 3.5: Digitizing geogs in ArcMap using a rectified PHCB geog map and an existing dzongkhag shapefile as a base.

*Required utilization of:

- The snap to vertex tool
- The trace tool
- The modify feature tool

3.3. Land Conversion From 1990-2007

Analysis Overview

Land conversion analysis involves a number of steps to not only prepare the imagery for analysis, but to analyze and interpret those findings. These steps include image preprocessing, image enhancement, thematic information extraction, change detection, and accuracy assessment. Preprocessing refers to the Radiometric and

Geometric corrections that are needed for a proper cartographic projection. The SPOT image used in this study includes a 2.5m panchromatic image. Image enhancements include image indices, such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Built-up Index (NDBI), and are used to improve the appearance of an image. The subsequent analysis includes thematic information extraction, such as supervised and unsupervised classifications, and change detection. Finally, it is necessary to perform accuracy assessments on all classified images to inform potential users of the data of the accuracy of each classification (Jensen 2005).

3.3.1. Ground Control Points

Geometric distortions caused by sensor system movements (roll, pitch, and yaw) and/or altitude changes can be compensated for by using ground control points and various mathematical models (Bernstein 1983, Millington and Jehangir 2000). A Ground Control Point (GCP) is a location on the surface of the Earth (e.g., corner of a building or a road intersection) that can be identified on the imagery and located accurately on a map. The photogrammetric specialist must be able to obtain two individual sets of coordinates associated with each GCP.

- Image coordinates specified in *i* rows and *j* columns, and
- Map coordinates (e.g., *x, y* measured in degrees of latitude and longitude, feet in a state plane coordinate system, or meters in a Universal Transverse Mercator projection).

The matching coordinates (*i, j,* and *x, y*) from GCPs can be utilized to obtain geometric transformation coefficients. These coefficients may then be used to geometrically rectify the remotely sensed data to a standard datum and map projection such as Universal Transverse Mercator projection (Jensen 2005).

Georeferencing was performed to overlay GIS data (such as building footprints, road centerlines, and building centroids) to the Thimphu QuickBird image. Generally, georeferencing is performed on a raster dataset using existing spatial data (target data), such as a vector feature class, that resides in the preferred map coordinate system. The process involves identifying a series of ground control points, known x,y coordinates, that link locations on the raster dataset with locations in the spatially referenced data (target data). The GCPs are used to build a polynomial transformation that will shift the raster dataset from its existing location to the spatially correct location. The connection between one control point on the raster dataset and the corresponding control point on the aligned target data registers the known point to both the image and the collected GCP.

GCPs were collected and utilized to correct geometric distortions for the Thimphu QuickBird image. With the assistance from DUDES, GCPs were collected during an NSF funded trip to Bhutan in March 2008 (Appendix B). A Trimble XH Pro receiver with a Hurricane pole mounted antenna and a Tripod Data Systems (TDS) Recon handheld computer were used to collect 15 points throughout the city (Figure 3.6).

Figure 3.6: The Trimble XH Pro receiver with a Hurricane pole mounted antenna and a Tripod Data Systems (TDS) Recon used to collect 15 GCP throughout Thimphu, as shown in the top left photograph (photo credit: Mayur A. Gosai).

Because of time constraints and government regulations on collecting spatial data only 15 points were collected (RGoB 1999). GCPs were collected in WGS_1984 (World Geodetic System) coordinate systems. The QuickBird image's native projection was in Universal Transversal Mercator (UTM) Zone 45N. All of the GIS data obtained from the various government departments were in a projection identified as *DRUKREF* projection. *DRUKREF* projection is a modified Geographic Coordinate System Everest 1962 definition. *DRUKREF* was created by the NSB to conform to national standards of GIS data collection and warehousing. Once the QuickBird image was aligned with GCPs it was reprojected to *DRUKREF* to overlay the GIS data acquired from DUDES in MoWHS. Because of the limited number of GCPs collected, the image overlay was offset by ±3 meters, (Figure 3.7). Before proceeding with the classification and change detection analysis, the Landsat images needed to be rectified and registered to a known location on the ground. Because of its high resolution QuickBird was used to rectify Landsat imagery.

3.3.2. Image Registration and Rectification

Image to Image Registration

Image to image registration is the "translation and rotation alignment process by which two images of like geometry and of the same geographic area are positioned coincident with respect to one another so that corresponding elements of the same ground area appear in the same place on the registered images" (Jensen 1996, 125). This type of geometric correction is used when it is not necessary to have each pixel assigned a unique *x, y* coordinate in a map projection such as the procedure described in GCPs section. Image to image registration is performed especially if one wants to compare two images obtained on different dates to see if any change has taken place.

Figure 3.7: After rectifying the image using the collected GCPs, the image overlay was offset by approximately 3 meters. The red point indicates the point location on the images after the image was rectified, and the yellow point indicates where the point should be located on the ground.

Image to Map Rectification

Image to map rectification is the process by which the geometry of an image is aligned to GCPs collected in the field (Figure 3.8). Whenever accurate area, direction, and distance measurements are required, image to map geometric rectification is performed.

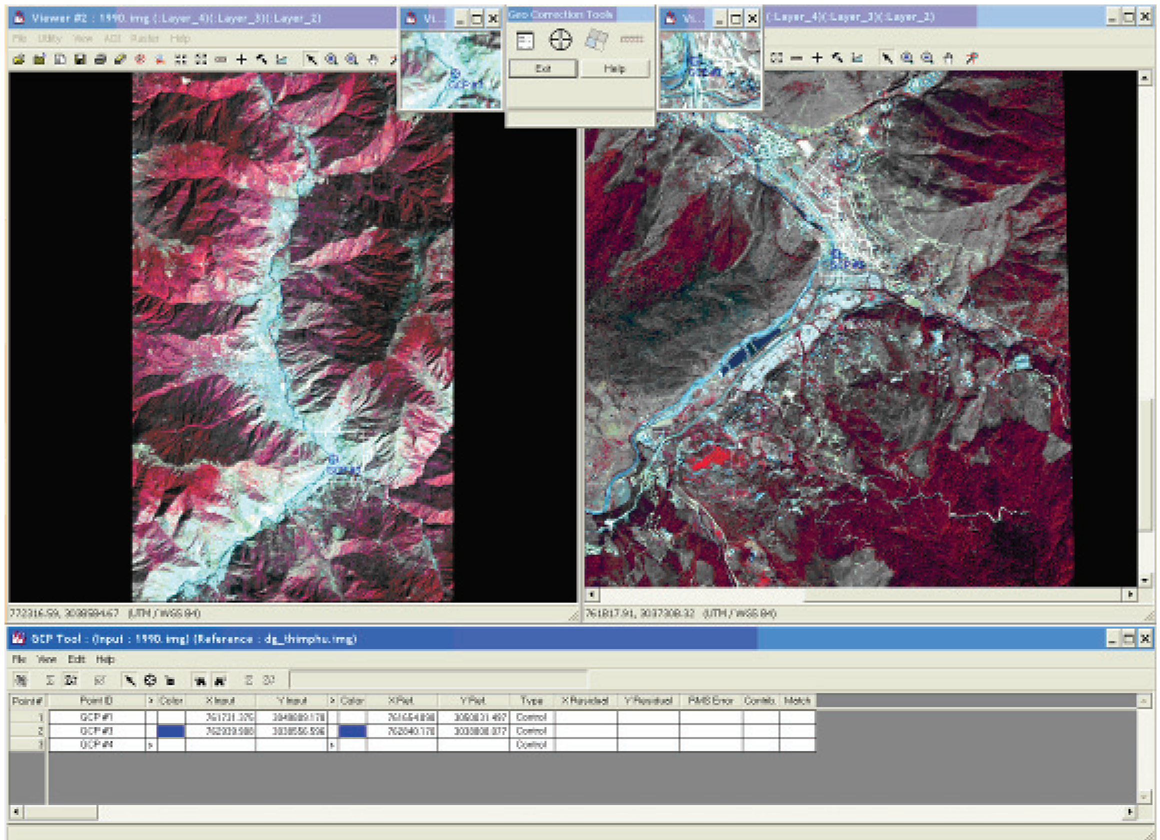


Figure 3.8: Image –to-image rectification: The misaligned 1990 Landsat image being rectified to the same projection as the 2006 QuickBird image.

Global positioning system (GPS) instruments may be taken into the field to obtain the coordinates of objects such as road intersections, building corners, or other identifiable feature in the imagery to be rectified. GPS collection of map coordinates to be used for image rectification is especially useful in poorly mapped regions of the world or where rapid change has made existing maps obsolete, such as in Thimphu (Figure 3.9).

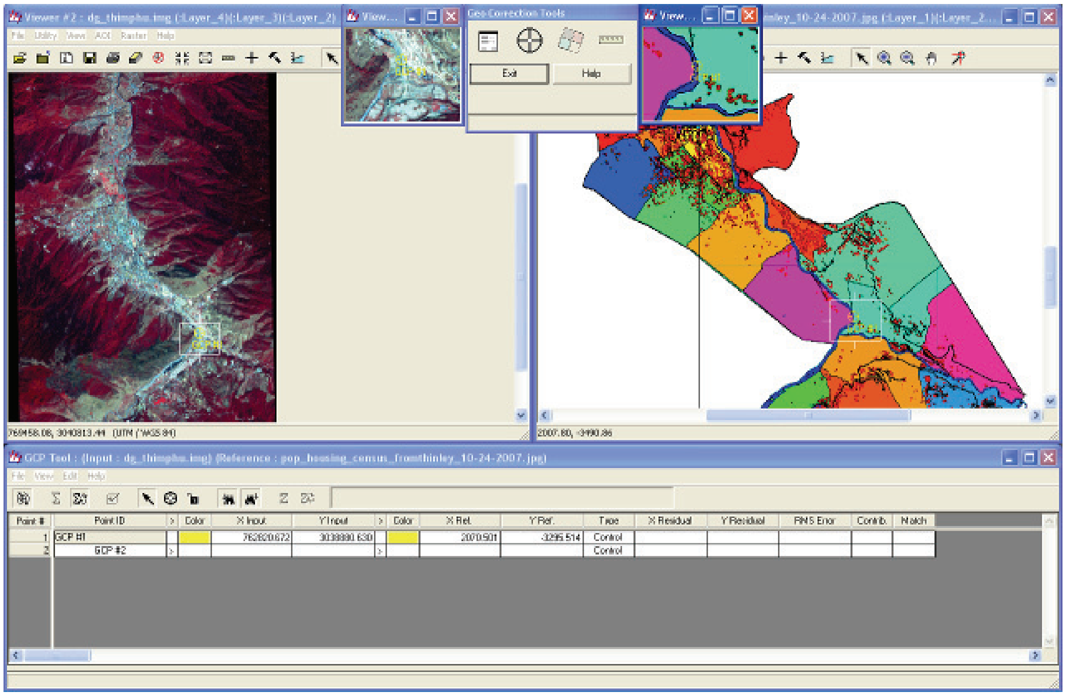


Figure 3.9: Image-to-Map Rectification – rectifying the Thimphu enumeration zones to the 2006 QuickBird Image.

Hybrid Approach

Because of inherit geometric errors of using an image to image rather than a map, a hybrid approach is used as suggested by Jensen (1996). Furthermore, “when conducting rigorous change detection between two or more dates of remotely sensed data, it may be useful to select a *hybrid* methodology involving both image to map rectification and image to image registration” (Jensen 1996, 126).

Root Mean Square Error (RMS_{error})

The root-mean-square (RMS) error for all GCPs is computed to measure the geometric distortions. One way to measure such distortion is to calculate the RMS_{error} for each GCP by using the equation:

$$RMS_{error} = \sqrt{\left(x' - x_{orig}\right)^2 + \left(y' - y_{orig}\right)^2}$$

Where X_{orig} and Y_{orig} are the original row and column coordinates of the GCP in the image and x' and y' are the computed or estimated coordinates in the original image (Jensen 2005). The square root of the squared deviations represents a measure of the accuracy of this GCP in the image. The user specifies a certain amount of acceptable total RMS_{error} (for Thimphu Landsat - 30 m). If an evaluation of the total RMS_{error} reveals that a given set of control points exceeds this threshold, it is common practice to:

1. Delete the GCP that has the greatest amount of individual error form the analysis,
2. Recomput the six coefficients, and
3. Recomput the RMS_{error} for all points.

The RMS_{error} all three Landsat imagery was in between 24.5 to 28.5 (Figure 3.10). Once image registration and rectification was complete classification scheme and number of classes was defined.

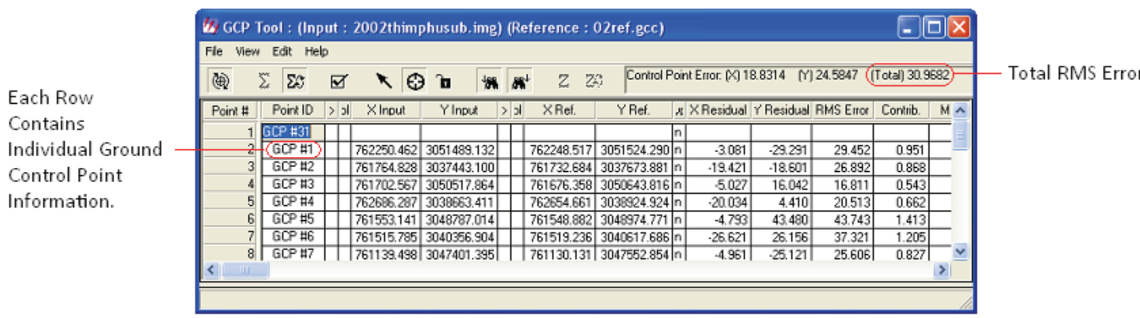


Figure 3.10: Ground Control Point window in ERDAS Imagine. It displays the Point information, including the X and Y input and Reference locations as well as the root mean square errors.

3.3.3. Classification Scheme

Hard versus Fuzzy Classification

A classification scheme contains taxonomically correct definitions of classes of information that are organized according to logical criteria. Classes of interest must be selected and defined carefully to classify remotely sensed data successfully into land use land cover information. There are two major types of logic in classifying data: hard and fuzzy logic (Figure 3.11). This dissertation utilizes hard classification because the scheme consists of hard, discrete categories.

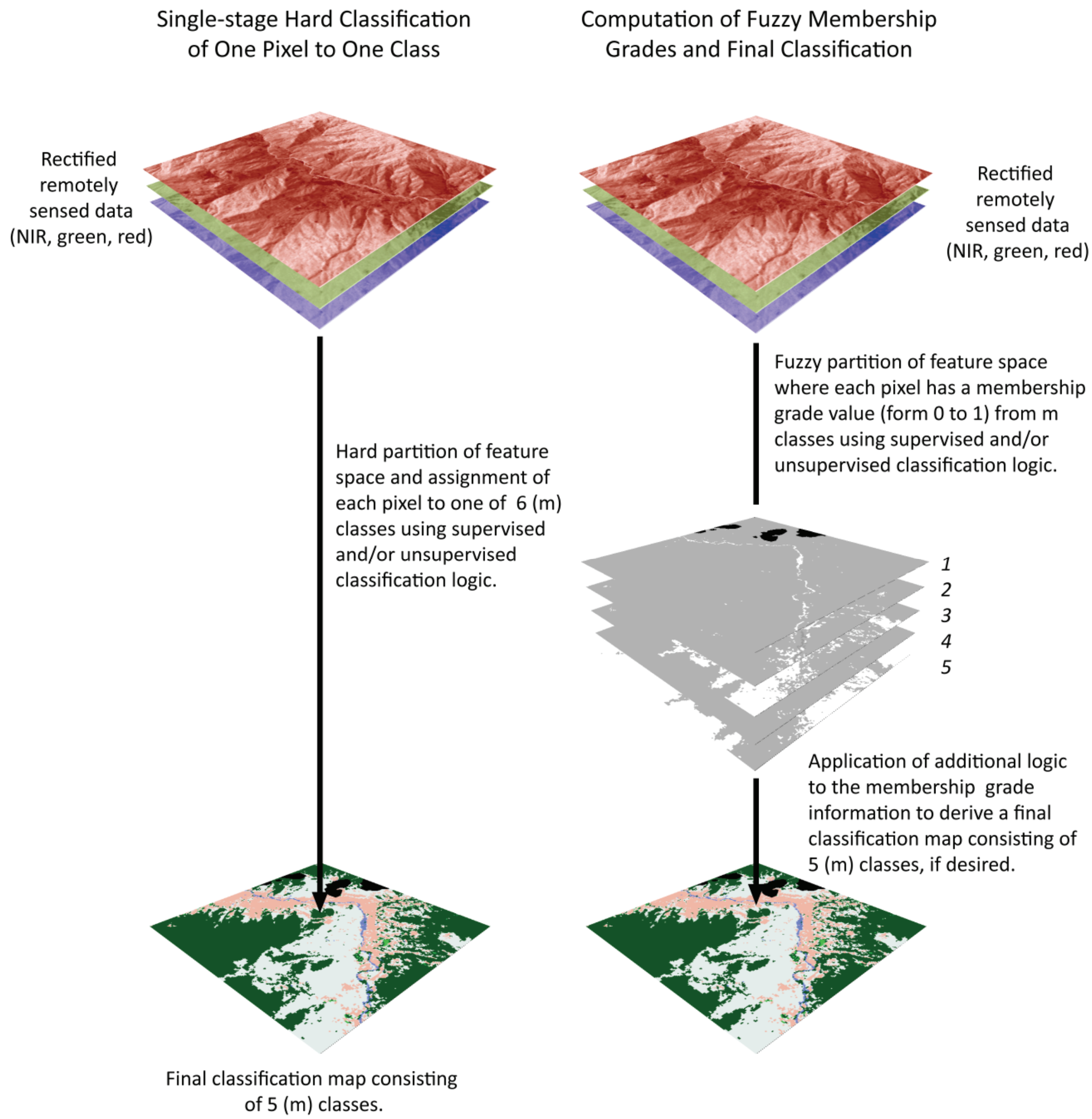


Figure 3.11: A comparison of hard classification to fuzzy classification (adapted from Jensen 2005, p. 340).

Fuzzy classification produces thematic output products that contain fuzzy information and it is based on the premise that remote sensing detectors "record the reflected or emitted radiant flux from heterogeneous mixtures of biophysical materials"

(Jensen 2005, 338). If hard classification is to be performed, then the classes in the classification scheme should be:

- Mutually exclusive,
- Exhaustive, and
- Hierarchical.

When there is no taxonomic overlap (or fuzziness) of any classes in the scheme, it is considered mutually exclusive. For example, deciduous forest and evergreen forest have distinct classes. It is considered exhaustive only if all land cover classes that are present in the study area are accounted for. Hierarchical means that sub-level classes (e.g., single-family residential, multiple-family residential) may be hierarchically combined into a higher-level category (e.g., residential). It is critical to keep in mind the difference between information classes and spectral classes. Information classes (such as single-residential housing) are those that human beings define, and spectral classes (such as concrete and asphalt) are those that are in the remote sensor data, must be identified, and then labeled by the analyst.

Examples of Land-Cover Characterizations

Certain hard classification schemes have been developed that are considered the industry standard and can readily be incorporated to land-use and/or land-cover data that is obtained by remotely sensed data. In the United States five classification characterizations widely used are:

- American Planning Association (APA) Land-Based Classification System – oriented toward detailed land-use classification;
- United States Geological Survey (USGS) Land-Use/Land-Cover Classification System for Use with Remote Sensor Data. It is adapted for use by U.S. National Land Cover Dataset and National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP);
- U.S. National Vegetation and Classification System;
- International Geosphere-Bioshpere Program (IGBP) Land Cover Classification System modified for the creation of MODIS land-cover products (USGS 2009).

The American Planning Association land-based classification standard utilizes high-spatial resolution imagery and is primarily used for urban/suburban land-use. The U.S. Department of Interior Fish and Wildlife Service classification of wetlands and deepwater habitats primarily focuses on inland and coastal wetland areas, and the U.S. national vegetation classification system only focuses on classifying vegetation. The IGBP land-cover classification system, on the other hand, utilizes Moderate Resolution Imaging Spectroradiometer (MODIS) of NASA's Earth Observing System (EOS) providing global land-surface information at spatial resolutions of 250-1000 meters.

This dissertation uses a modified level-1 USGS land-use/land-cover classification system (Figure 3.12). Its focus is resource-oriented classification rather than people or activity-oriented land-use classification. The resource-oriented land use in the US makes up for 95% of the total land area therefore, there is an obvious need for a resource-based classification. Since this study seeks to quantify land use change from forested to urban this classification is well suited in terms of resource oriented classification scheme. Though intended for use in the U.S., its basic levels can be utilized for other areas of the world, such as Bhutan, with the removal of classes not present in the AOI.

Classes Defined

The USGS land-use/land-cover classification system contains nine categories that are sub-divided further ranging from 2 to 7 categories within each class (Figure 3.13). Because Landsat imagery is used, this dissertation utilizes a modified Level 1 USGS land-use/land-cover classification system. Five classes are defined for a change detection analysis in Thimphu valley, which include:

1. Forest Land
2. Urban or Built-up Land
3. Barren Land
4. Agricultural Land
5. Water

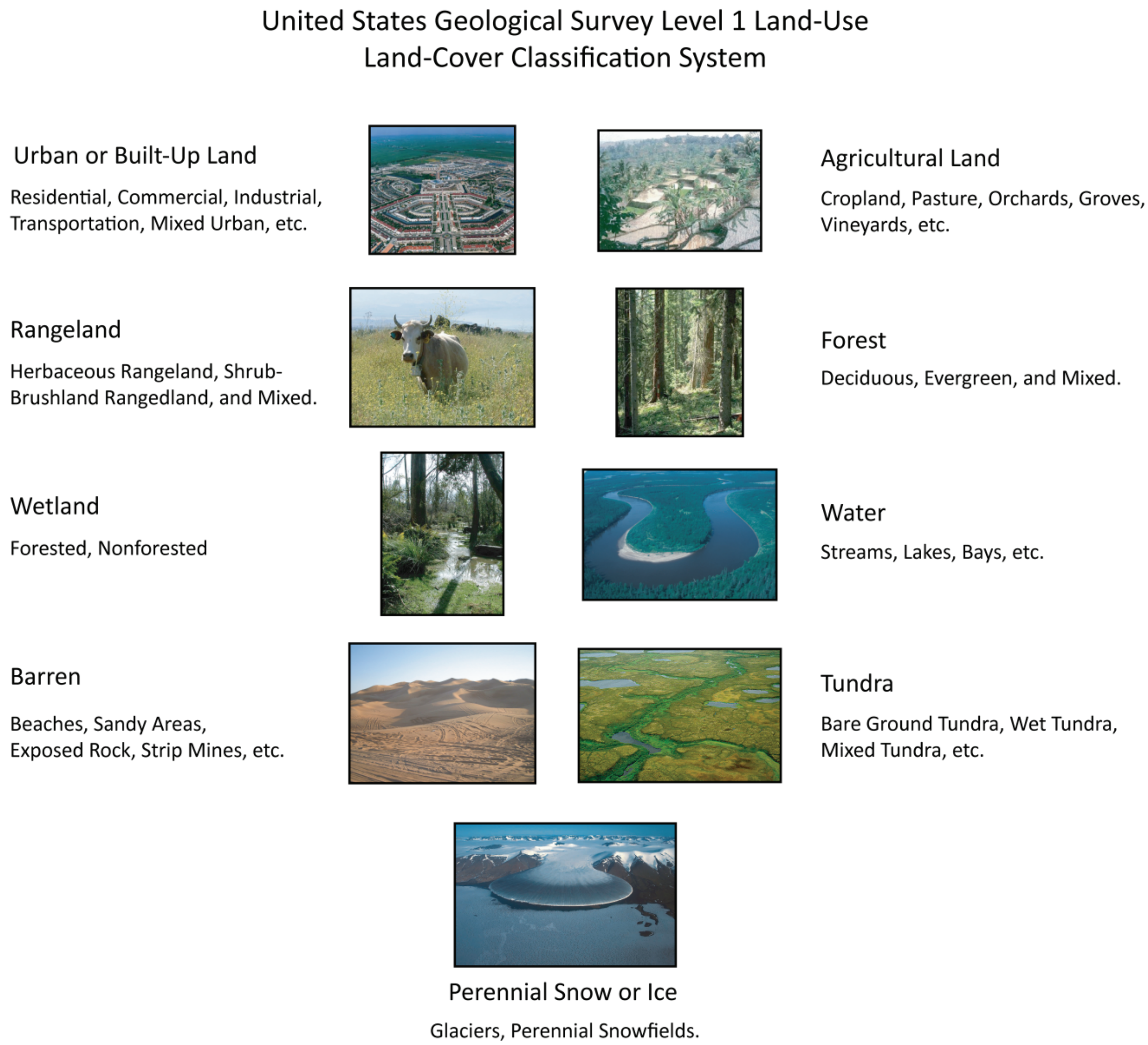


Figure 3.12: The Level 1 United States Geological Survey Land-Use Land-Cover Classification System, with examples of features included in each category.

1. Urban or Built-up Land
    1.1 Residential
    1.2 Commercial and Services
    1.3 Industrial
    1.4 Transportation, Communications, and Utilities
    1.5 Industrial and Commercial Complexes
    1.6 Mixed Urban or Built-up
    1.7 Other Urban or Built-up Land
2. Agricultural Land
    2.1 Cropland and Pasture
    2.2 Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas
    2.3 Confined Feeding Operations
    2.4 Other Agricultural Land
3. Rangeland
    3.1 Berbaceous Rangeland
    3.2 Shrub-Brushland Rangeland
    3.3 Mixed Rangeland
4. Forest Land
    4.1 Deciduous Forest Land
    4.2 Evergreen Forest Land
    4.3 Mixed Forest Land
5. Water
    5.1 Streams and Canals
    5.2 Lakes
    5.3 Reservoirs
    5.4 Bays and Estuaries
6. Wetland
    6.1 Forested Wetland
    6.2 Nonforested Wetland
7. Barren Land
    7.1 Dry Salt Flats
    7.2 Beaches
    7.3 Sandy Areas Other Than Beaches
    7.4 Bare Exposed Rock
    7.5 Strip Mines, Quarries, and Gravel Pits
    7.6 Transitional Areas
    7.7 Mixed Barren Land
8. Tundra
    8.1 Shrub and Brush Tundra
    8.2 Herbaceous Tundra
    8.3 Bare Ground Tundra
    8.4 Wet Tundra
    8.5 Mixed Tundra
9. Perennial Snow or Ice
    9.1 Perennial Snowfields
    9.2 Glaciers

Figure 3.13: An exhaustive list of the United States Geological Survey's Land Use-Land Cover Classification system, including all sublayers.

Sub-classes were omitted due to the coarse resolution of Landsat. Forest class includes deciduous, evergreen, and mixed forests. The sub-classes for Urban or Built-up Land that were grouped into a single class include residential, commercial and services, industrial, transportation, communications, and utilities, industrial and commercial complexes, mixed urban or built-up, and other urban or built-up land. Barren land class includes bare exposed rock, transitional areas, and mixed barren land. Agricultural land includes cropland, pasture, and land used for any other agricultural purpose. The water class includes streams and canals.

3.3.4. Unsupervised Classification

There are two methods, unsupervised and supervised, to partition remote sensor image data to extract land cover information. Both classifications were performed for this dissertation since there is limited literature available on the choice of classification for a Bhutanese context. Supervised classification is discussed in section 3.2.5. Unsupervised classification is the process where mathematical operations are executed that search for homogonous grouping of the spectral similarities of pixels (Loveland et. al., 1999, Huang 2002, Lo and Yeung 2002). This method of classification requires only a minimum amount of initial input from the analyst; however, the analyst must understand the spectral characteristics of the study area well enough to be able to identify specific class information. Some spectral clusters may be meaningless, because they represent mixed classes of land cover material. For example, it may be difficult to differentiate between barren and urban built-up areas such as the case in Thimphu (Figure 3.14).

Many clustering algorithms have been developed. The two most commonly used are the chain method and Self-Organizing Data Analysis Technique (ISODATA) (Figure 3.15). This dissertation utilizes the ISODATA method, because it is not dependent on any particular region or data distribution, it is iterative, and requires relatively minimum input from the analyst.

ISODATA Method of Clustering

ISODATA represents a comprehensive set of rules that have been incorporated into an iterative classification algorithm (ERDAS 2008). It is self-organizing because it requires relatively minimum human input. An ISODATA algorithm usually requires the analyst to identify the following criteria:

- C_{max}: the maximum number of clusters to be identified by the algorithm (e.g., 20 clusters). However, it is not uncommon for fewer to be found in the final classification map after splitting and merging take place
- T: the maximum percentage of pixels whose class values are allowed to be *unchanged* between iterations (convergence threshold). When this number is reached, the ISODATA algorithm terminates. Some datasets may never reach the desired percentage. If this happens, it is necessary to interrupt processing and edit the parameter.

- *M*: the maximum number of times ISODATA is to classify pixels and recalculate cluster mean vectors (iterations). The ISODATA algorithm terminates when this number is reached.
- *Minimum members in a cluster (%)*: If a cluster contains less than the minimum percentage of member, it is deleted and the members are assigned to be an alternative cluster. This also affects whether a class is going to be split. The default minimum percentage of members is often set to 0.01.
- *Maximum standard deviation (σ_{max})*: when the standard deviation for a cluster exceeds the specified maximum standard deviation and the number of members in the class is greater than twice the specified minimum members in a class, the cluster is split into two clusters. The mean vectors for the two new clusters are the old class centers ±1 σ. Maximum standard deviation values between 4.5 and 7 are typical.
- *Split separation value*: if this value is changed from 0.0, it takes the place of the standard deviation in determining the locations of the new vectors plus and minus the split separation value.
- *Minimum distance between cluster means (C)*: clusters with a weighted distance less than this value are merged. A default of 3.0 is often used.

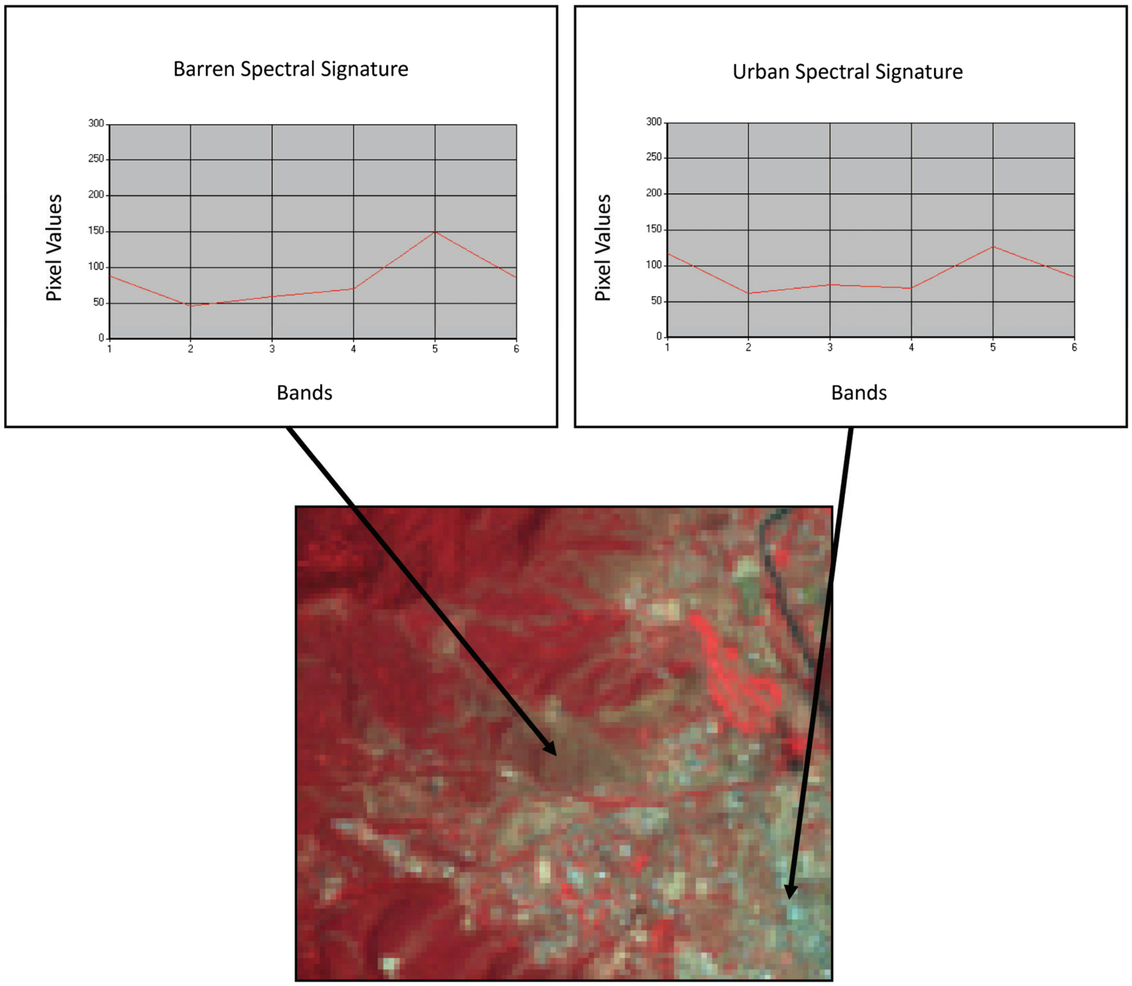


Figure 3.14: Barren and urban areas were often confused during classification due to their similar spectral signature. The spectral signature on the left is that for a barren area (indicated by the arrow), while the right one indicates a similar spectral signature but for an urban area.

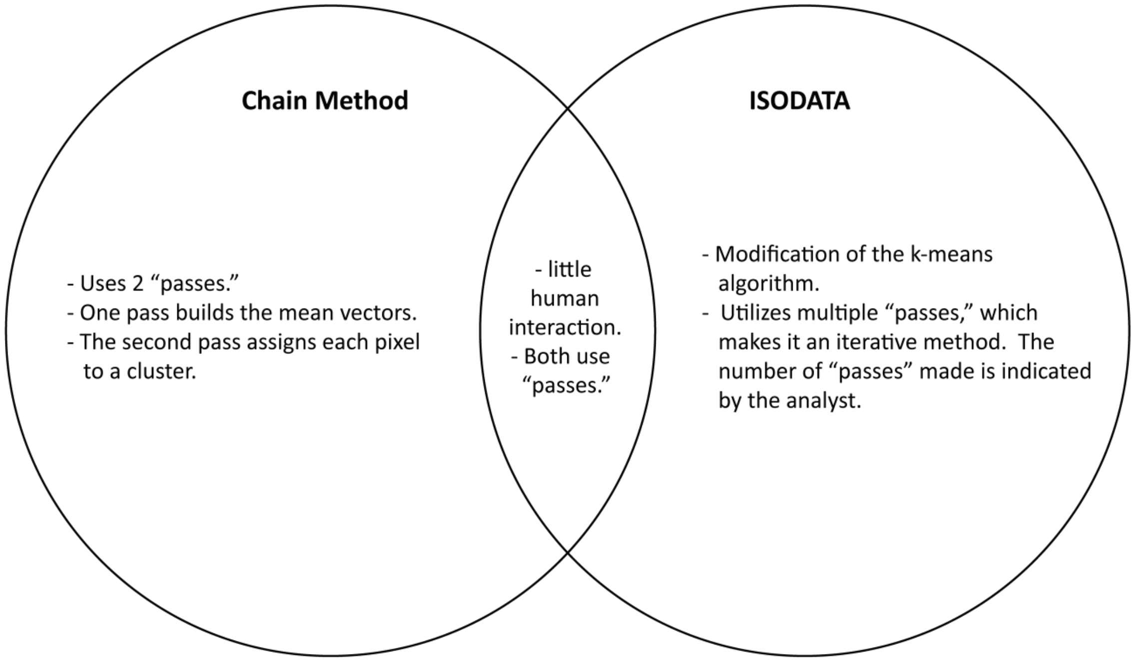


Figure 3.15: A comparison of the similarities and differences between the Chain Method and ISODATA procedures for unsupervised classification to help determine which method would be most advantageous.

For this study the ten iterations were run with *T* value of 0.95 or 95 percent. This means that the application tries to reach a convergence threshold of 95 percent before it reaches ten passes. When initiated in ERDAS Imagine software, ISODATA runs through two phases: 1) cluster building using many passes (iterations) through dataset, and 2) assignment of pixels to one of the clusters using the minimum or Euclidean distance method. ISODATA is iterative, because it makes a large number of passes through the remote sensing dataset until specified results are obtained, instead of just two passes such as in chain method. In the initial iteration, “each candidate pixel is compared to each cluster mean and assigned to the cluster whose mean is closest in Euclidean distance" (Jensen 2005, 386). During the second iteration, "a new mean is calculated for each cluster based on the actual spectral locations of the pixels assigned to each cluster", instead of the first random calculation (Jensen 2005, 386). This involves analysis of several parameters (*Minimum members in a cluster - %, Maximum standard deviation -* σ_{max}*, Split separation value, Minimum distance between cluster means - C)* to merge or split clusters. After the new cluster mean vectors are selected, every pixel in the scene is assigned to one of the new clusters (Figure 3.16). This split, merge, and assign process continues until there is relatively little change in number of classes between iterations (the *T* threshold is reached) or the maximum number of iterations is achieved (*M*).

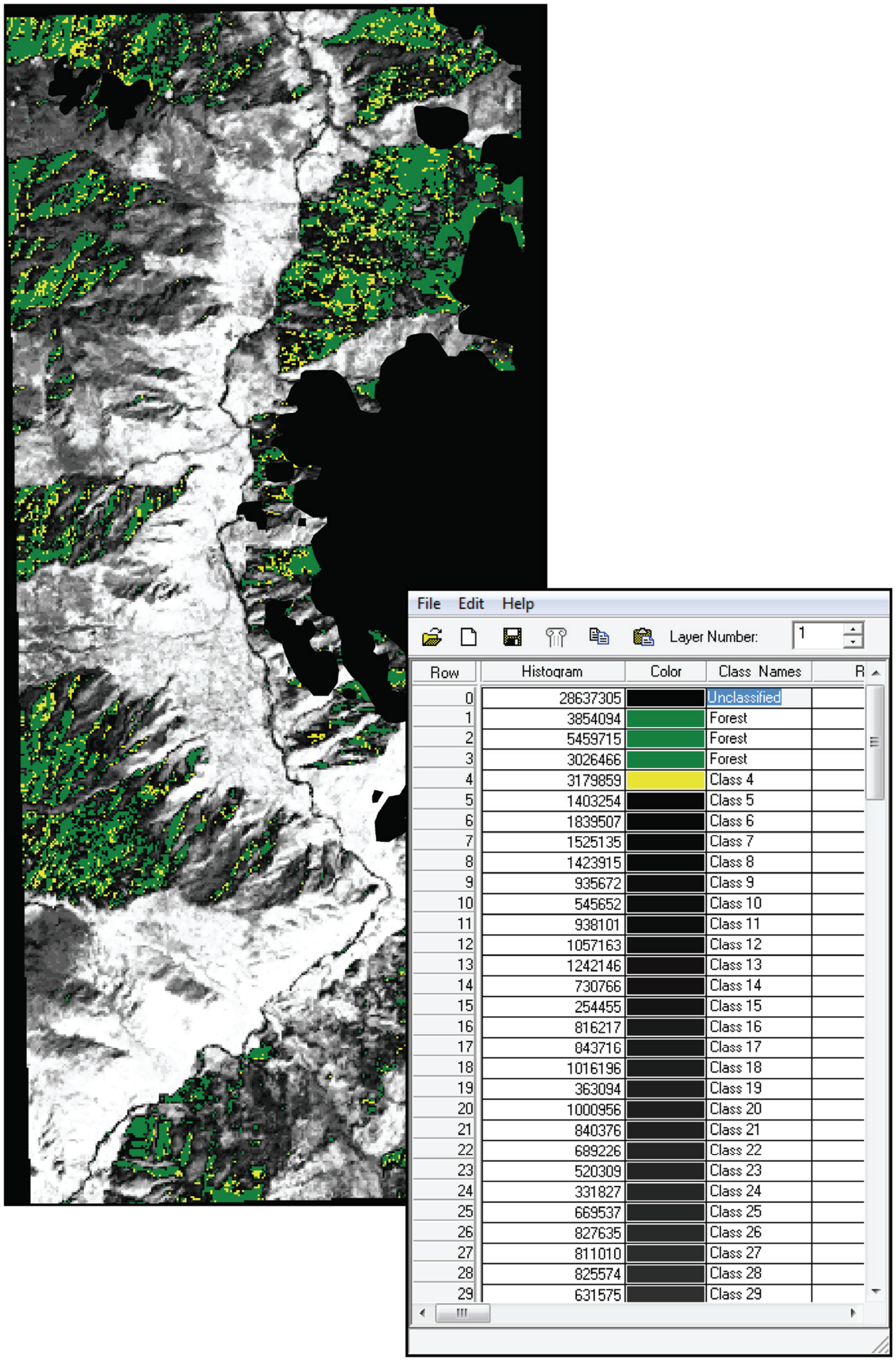


Figure 3.16: Assigning classes to the 150 clusters of the Thimphu city unsupervised classification. The yellow indicates a cluster that is currently being assessed.

Running Iterations

The iterative process in ISODATA algorithm is time consuming. To run ten iterations for Landsat 1999 Thimphu image it took the computer approximately 45 minutes. This is after the image was subset to Thimphu valley and clouds and shadows removed. To produce effective results the ISODATA algorithm needs to iterate enough times. Jensen (2005) used 20 iterations to demonstrate ISODATA classification for Charleston, SC using band 3 and 4 data. For this dissertation 10 iterations yielded convergence threshold of 94.4 to 94.8 percent for all three Landsat images. The 150 mean vectors shown in (Figure 3.17) were used in the 10^{th} pass of the ISODATA algorithm to create a thematic map consisting of 5 spectral classes. These spectral classes were investigated and labeled as the 5 information classes. The final step in the process is to recode the 150 information clusters into just 5 classes, to create a 5-class legend, and to compute the hectares in each land-cover class.

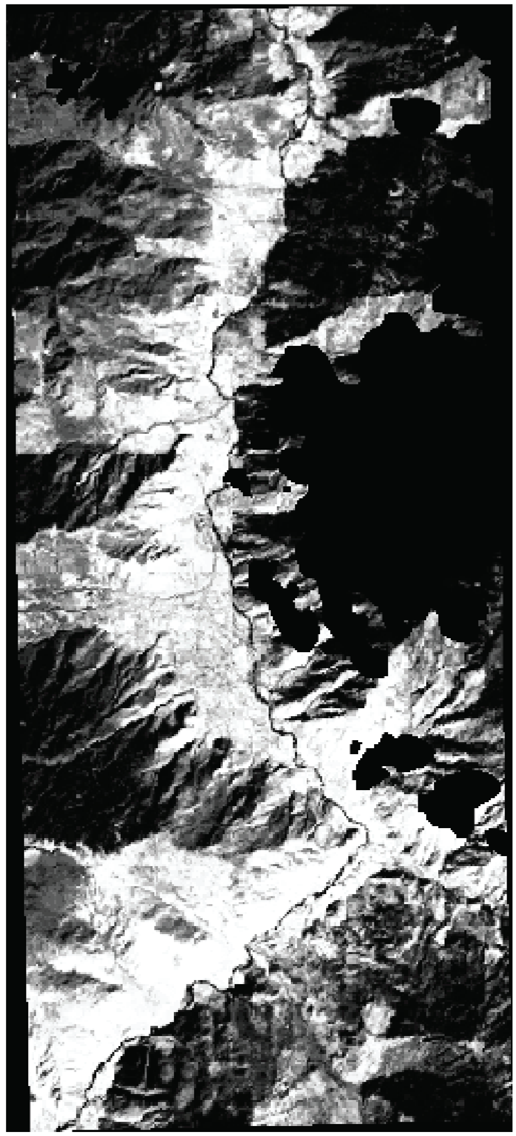


Figure 3.17: 150 mean vectors (clusters) for the 1990 Thimphu city unsupervised classification.

Cluster Busting

When running an unsupervised classification certain pixels may get confused and the result is misclassification (Figure 3.18). For Thimphu there were two sets of classes that were misclassified: forest/agriculture and urban/barren. To achieve better accuracy Jensen (1996 and 2005) recommends using the cluster busting process to reduce the confusion. The reasons for pixels to be misclassified are:

1. The terrain within the field of view of the sensor system contained at least two type of terrain, causing the pixel to exhibit spectral characteristics unlike either of the two terrain components, or
2. The distribution of the mean vectors generated during the unsupervised classification process was not good enough to partition certain importation portions of feature space.

When performing a cluster busting procedure for Thimphu Landsat imagery the pixels that were difficult to label were recoded and a binary mask was created. The pixels needing cluster busting were extracted, creating a new multiband image file consisting of only the pixels that could not be effectively labeled during the initial unsupervised classification (Figure 3.19). A final unsupervised classification was performed on those pixels and merged with the original classification to form a classification with better results than just the original classified image alone. The final cluster map was then recoded to create the final classification image of Thimphu.

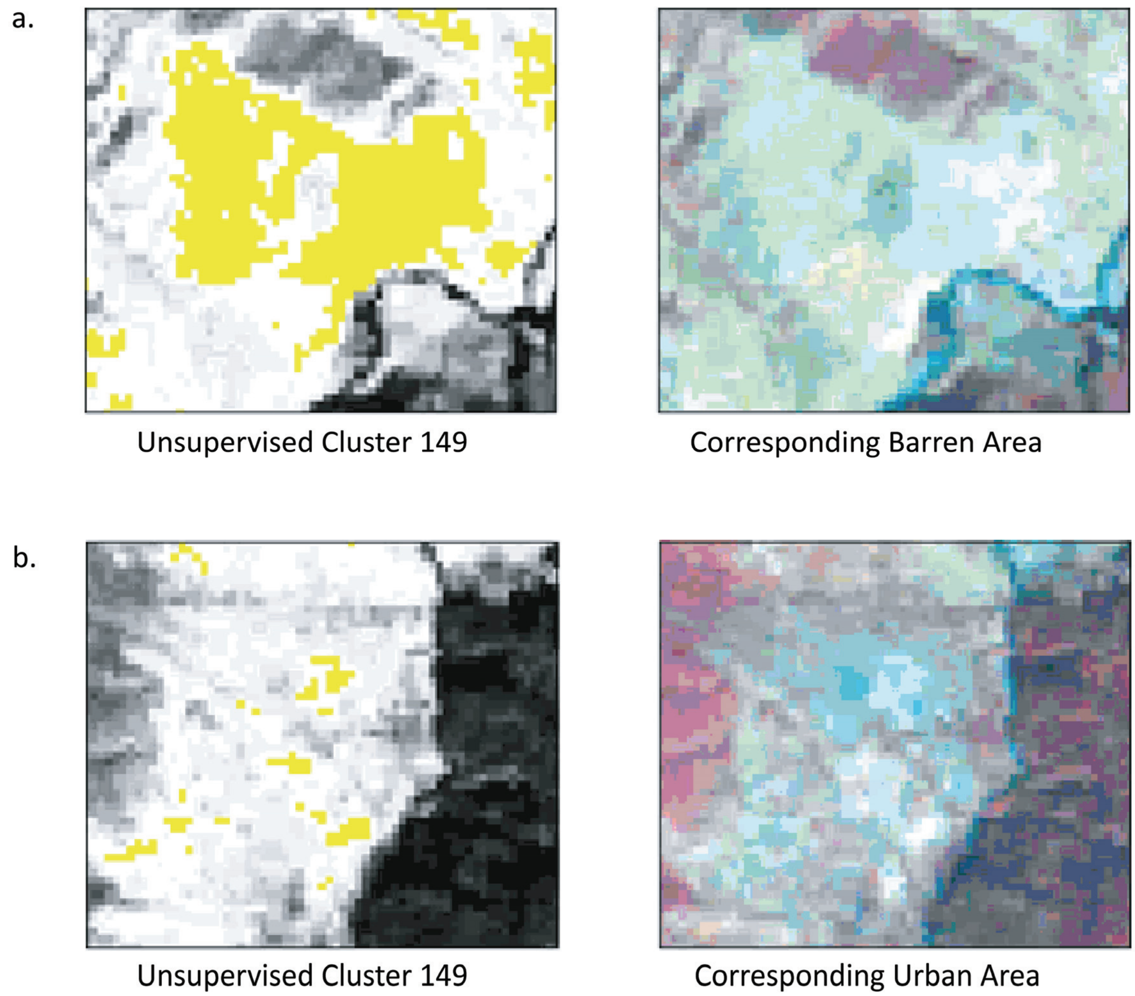


Figure 3.18: Urban and barren clusters were often confused. In this particular case, cluster 149 included both urban and barren areas, so this cluster needed to be cluster busted.

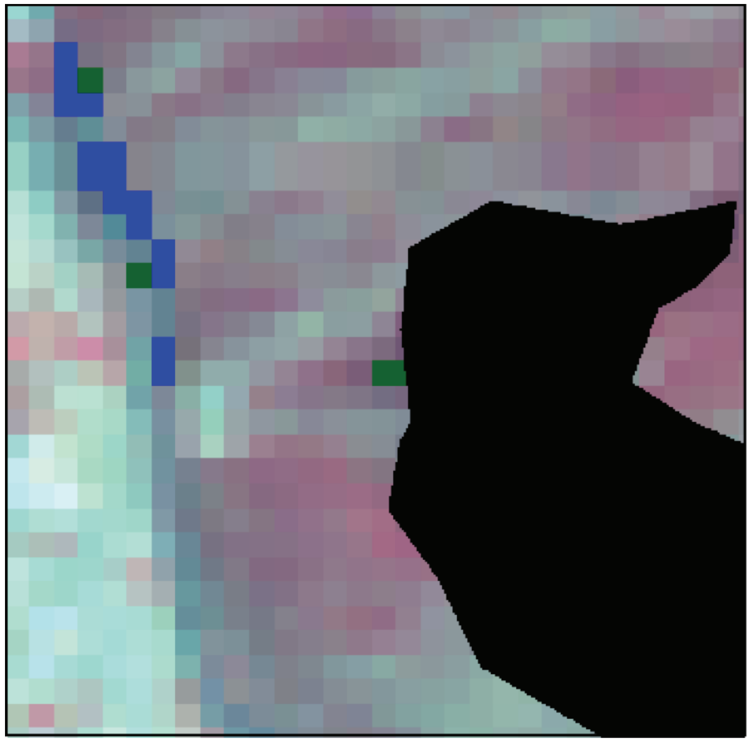


Figure 3.19: Once a cluster has been "busted," the different classes can be classified out. With this particular cluster, water and forest were combined, so once busted, those two classes were separated.

3.3.5. Supervised Classification

Unlike the unsupervised classification, the supervised classification gives greater control to the analyst. Since the analyst is directly involved in selecting the pixels represented in each class, it is considered to be supervised by the user. The analyst first defines the geographic region of interest (ROI). The classes are then defined in a classification scheme as discussed in section 3.2.3 (classification schemes). Next, the analyst obtains the appropriate digital remote sensor data and performs corrections as discussed in section 3.2.2 (image registration and rectification). A correct classification algorithm is then selected and preliminary training data are collected. Feature band selection is performed to determine the multispectral bands most appropriate for discerning one training class from another (Han et. al. 2007). Additional training data and algorithm are collected and applied before producing a final classification map. The final step in supervised classification is to do an accuracy assessment.

Training Sites Selection

After a classification scheme is adopted, training sites within the image are selected. Training site selection for this study was done in ERDAS using various polygons and area of interest (AOI) tools (Figure 3.20). The training data is considered valuable "if the environment from which they were obtained is relatively homogenous" (Jensen 2005, 350). Selecting sites in homogenous areas is critical especially since this study utilizes only 5 classes. There are 3 primary ways of collecting training sites:

1. Collection of *in situ* information such as tree type, height, percent canopy closure, and diameter-at-breast-height (dbh) measurements,
2. On-screen selection of polygonal training data and/or
3. On-screen seeding of training data.

When training site selection is done in ERDAS the seed program begins at a single x, y location and evaluates neighboring pixel values in all bands of interest. Depending on the criteria defined by the analyst, “the seed algorithm expands outward like an amoeba,” looking for pixels with spectral signatures similar to the selected or trained seed pixel (Jensen 2005, 352). Every pixel in the training site linked with a particular class (*c*) is represented by a *measurement vector;* X_c*:*

$$X_c = \begin{bmatrix} BV_{ij1} \\ BV_{ij2} \\ BV_{ij3} \\ \vdots \\ BV_{ijk} \end{bmatrix}$$

Where BV_{ijk} is the brightness value for the *i,j*th pixel in band *k.* The brightness values for each pixel in each band in each training class can then be analyzed statistically to generate a mean measurement vector, M_c, for each class:

$$M_c = \begin{bmatrix} \mu_{c1} \\ \mu_{c2} \\ \mu_{c3} \\ \vdots \\ \mu_{ck} \end{bmatrix}$$

Where μ_{ck} indicates the mean value of the data acquired for class *c* in band *k*. The raw measurement vector can also be analyzed to generate the covariance matrix for each class *c*:

$$V_c = V_{ckl} = \begin{bmatrix} Cov_{c11} & Cov_{c12} & \dots & Cov_{c1n} \\ Cov_{c21} & Cov_{c22} & \dots & Cov_{c2n} \\ \vdots & \vdots & \vdots & \vdots \\ Cov_{cn1} & Cov_{cn2} & \dots & Cov_{cnn} \end{bmatrix}$$

Where Cov_{ckl} is the covariance of class *c* between band *k* through *l*. For simplicity, the notation for the covariance matrix for class *c* (i.e. V_{ckl}) will be shortened to just V_c and similarly for the covariance matrix class *d* (i.e., $V_{dkl} = V_d$) (Pontius et. al. 2004). The mean, standard deviation, variance, minimum value, maximum value, variance-covariance matrix, and correlation matrix for the training statistics of five Thimphu land-cover classes (barren, forest, urban, water, and agriculture) are listed in Appendix C.

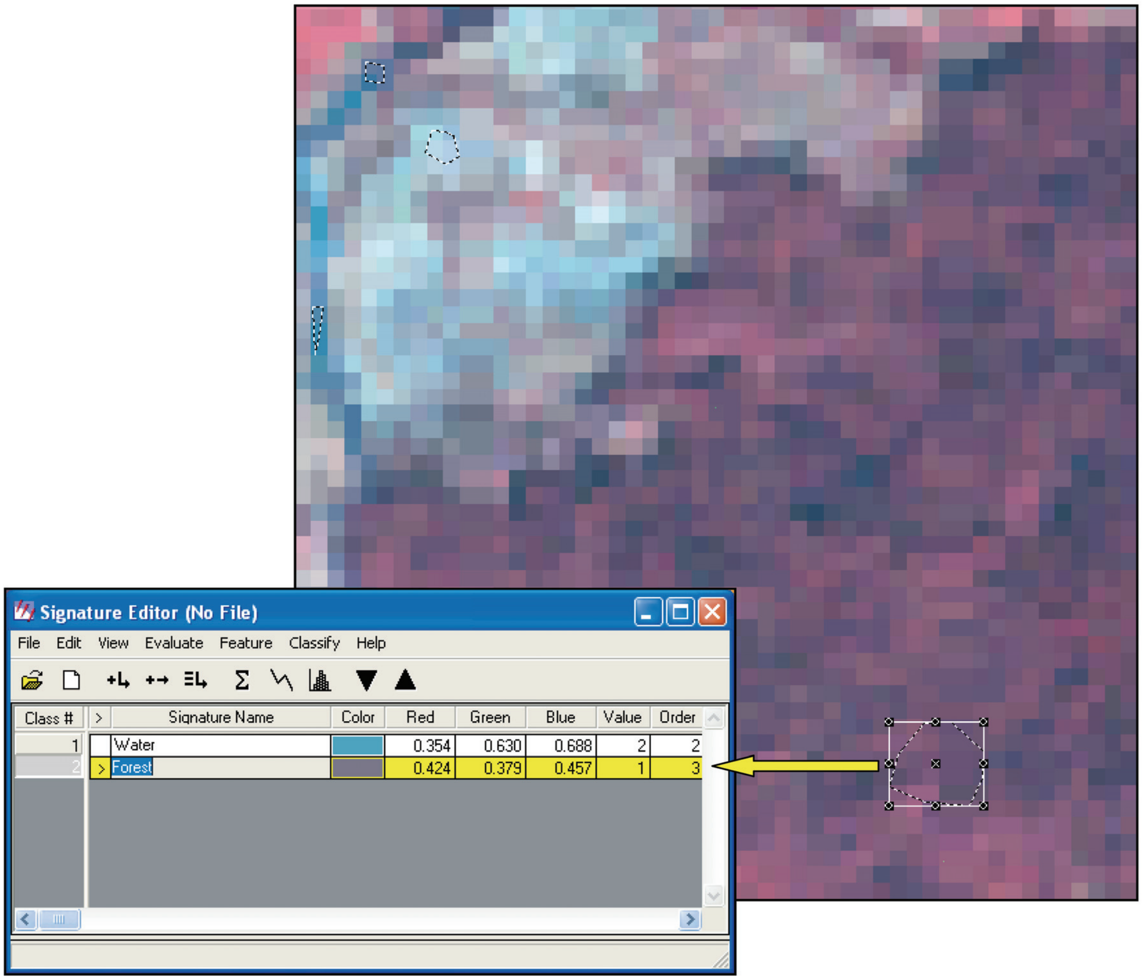


Figure 3.20: Supervised classifications require the selection of relatively homogeneous training sites for each class. This training site is for the “Forest” class.

Feature Selection and Spectral Signatures

Once training statistics are created, judgment on feature selection must be made. Feature selection is a process that determines the bands that are most effective in discriminating each class from all other classes (Armitage et. al. 2000, Duda et al. 2001). The objective is to discard the bands that provide redundant spectral information from the analysis. This process minimizes the cost of the digital image classification process because the dimensionality or the number of bands to be processes is reduced.

Selecting the Appropriate Algorithm

There are two groups of algorithms available for a supervised classification, parametric and nonparametric. Parametric classification algorithms assumes that the observed measurement vectors X_c obtained for each class in each spectral band during the training phase of the supervised classification are Gaussian. In other words, the selected polygons in a supervised training session are assumed to be normally distributed. Nonparametric algorithms do not make these assumptions. There are five widely used supervised classification algorithms in the nonparametric group:

- One-dimensional density slicing (e.g., using a single band of imagery),
- Parallepiped,
- Minimum distance,
- Nearest-neighbor, and
- Neural network and expert system analysis

The choice of a particular algorithm depends on the nature of the input data and the desired output. For the Thimphu Landsat imagery, a nonparametric algorithm (minimum distance) was used because of its simplicity and the results in classification accuracy are "comparable to other more computationally intensive algorithms such as the maximum likelihood algorithm" (Jensen 2005, 372).

To perform a minimum distance classification, the program must calculate the distance to each mean vector μ_{ck} from the training data. This measurement is calculated using Euclidean distance based on the Pythagorean Theorem. The computation of the Euclidean distance from point to point relies on the equation:

$$Dist = \sqrt{(BV_{ijk} - \mu_{ck})^2 + (BV_{ijk} - \mu_{cl})^2}$$

Where, μ_{ck} and μ_{cl} represent the mean vectors for class *c* measured in bands *k* and *l*. Minimum distance algorithm let the analyst "specify a distance or threshold from the class means beyond which a pixel will not be assigned to a category even though it is nearest to the mean of that category" (Jensen 2005, 373).

3.3.6. Built-up Indices

Normalized Difference Built-up Index (NDBI)

The NDBI is used by scientists studying urban/suburban problems and are interested in monitoring the spatial distribution and growth of urban built-up areas (Deering et al. 1975, Running et al. 1994). The built-up data can be used to calculate impervious surface for watershed runoff prediction and other planning purposes (Jensen 2005).

Zha et al. (2003) calculated the NDBI by:

$$NDBI = \frac{MidIR_{TM5} - NIR_{TM4}}{MidIR_{TM5} + NIR_{TM4}}$$

Where, Landsat TM near- and middle-infrared bands are normalized to generate this index. This index uses Landsat TM near- and middle-infrared bands and is more sensitive to changes in plant biomass and water stress than NDVI (Zha et al. 2003). When running the model (Figure 3.21) in ERDAS for Thimphu Landsat, the generated output image contained only built-up and barren pixels having positive values while other classes had a value of 0 or -254 (Figure 3.22).

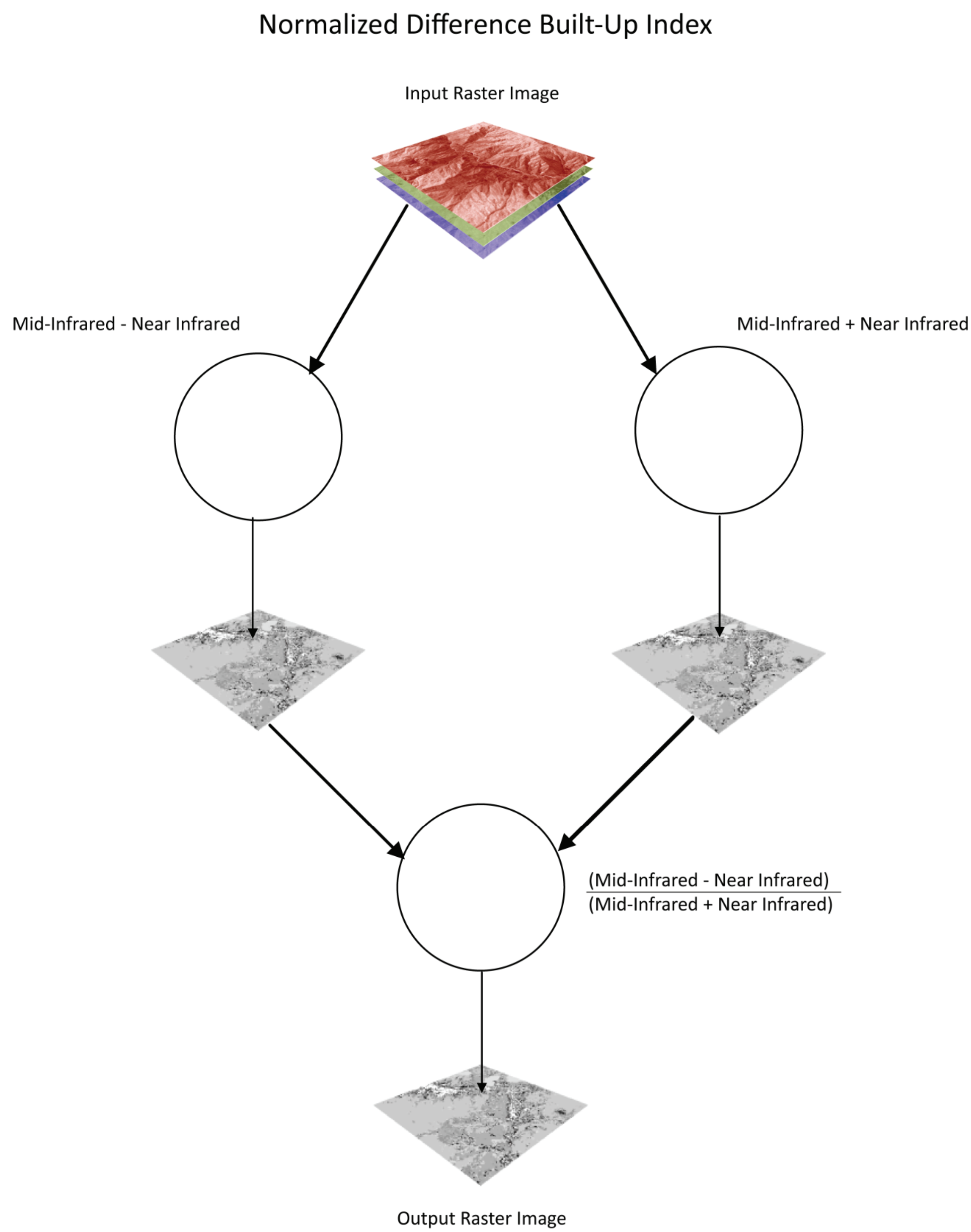


Figure 3.21: ERDAS Imagine's Model Maker was used to create this model that generated the NDBI output emulated that of Zha et al (2003).

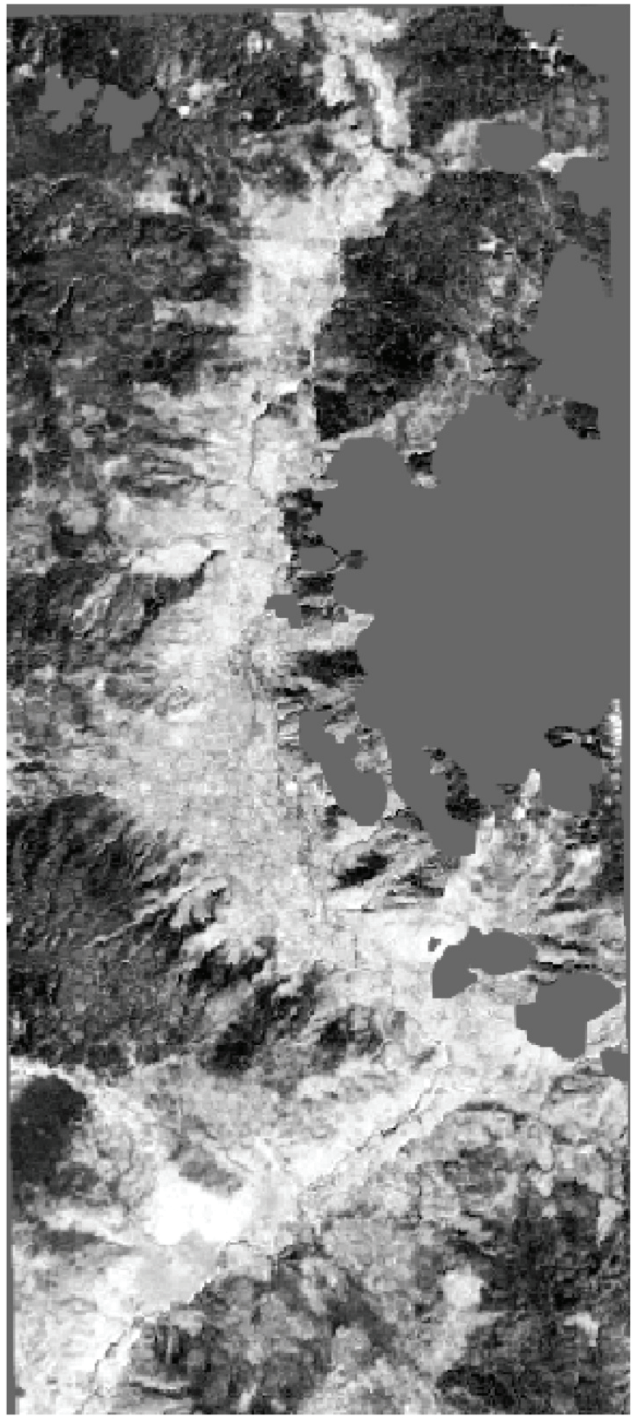


Figure 3.22: An example of the NDBI output as generated from the model created in Model Maker.

3.3.7. Change Detection

Steps Towards Change Detection

Land cover refers to the type of material present on the landscape, for example water, sand, crops, forest, and wetland. Land use refers to what people do on the land surface such as agriculture, commerce, and settlement. In this research land use and land cover in Thimphu valley are inventoried, and changes are documented using remote sensing techniques. Some of the data are static and do not change over time, for those that are dynamic, careful consideration must be taken when selecting the proper method for change detection. It is believed that land use land cover change is taking place at a global scale and “significant effort has gone into the development of change detection methods using remotely sensed data” (Jensen 2005, 467). When conducting a land conversion or change detection study there are set of steps (Figure 3.23) that need to be followed as outlined by Cakir et. al. 2006. The geographic AOI (area of interest) is important in a change detection study, because imagery must exist for dates being studied.

In this study Landsat imagery for Thimphu was available for 1990, 1999, and 2007. Other years were available for download however, because of a malfunction in Scan Line Corrector (SCL) the available Landsat Enhanced Thematic Plus (ETM+) imagery after 2003 would introduce error in a change detection analysis (Covington 2004, Maxwell 2007, Bedard 2008). The change detection time period depends on the availability of data and the nature of the study.

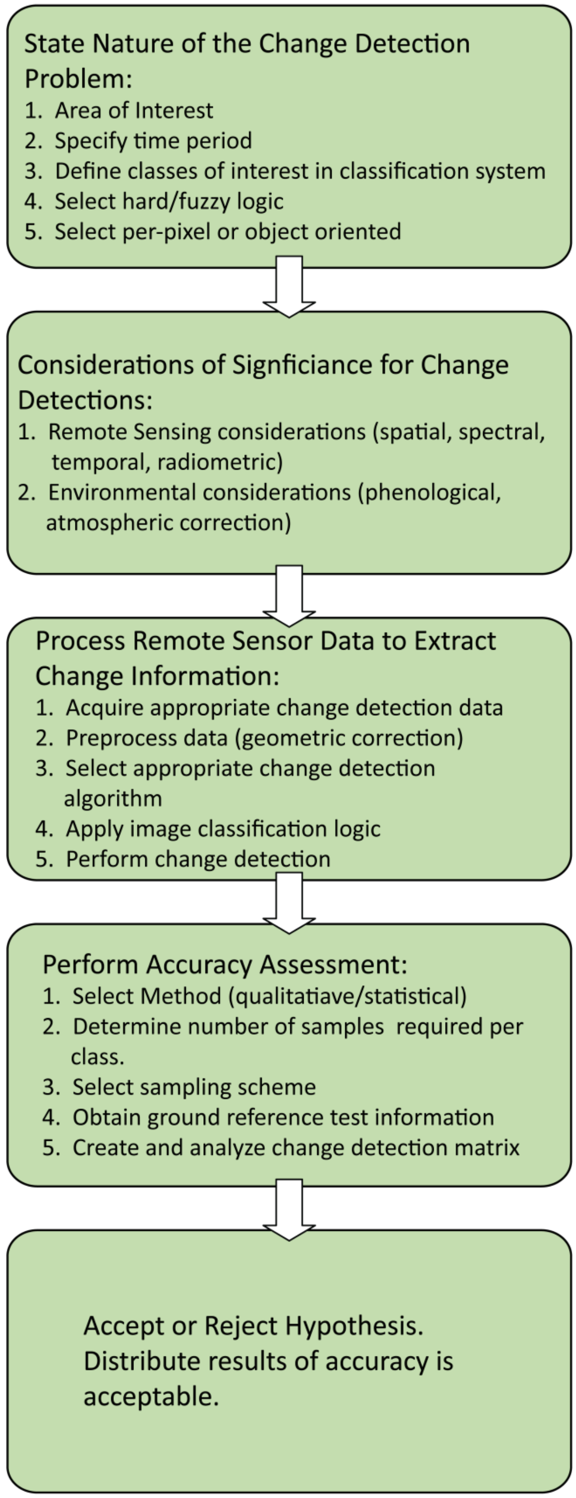


Figure 3.23: Change detection process as prescribed by Jensen (2005).

Transportation analysis studies for example require the change detection data to be within hours or minutes. In this study there were two major reasons for selecting 1990, 1999, and 2007 for a change detection analysis. First, data available for 1990, 1999, and 2007, allows this research to examine two decades of change, with a snapshot in between (in 1999). Because of SCL-off errors majority of the data from 2003 to 2008 would result in mis-classification of pixels. For other years (1991 to 1998) the acquisition dates are not broad enough or the time span between the images was too close to detect any significant change. Second, according to MoWHS and DUDES (2004) majority of land use conversion in Thimphu started taking place after 2000. This would not only allow for an examination of a before and after snapshot, but also the identification of a trend in growth of build-up areas or reduction in forested areas.

There are many classification systems (schemes) available, as described in section 3.2.3. This study utilizes a USGS (Land-Use/Land-Cover Classification System for Use with Remote Sensor Data). It is important to use a standardized classification system because this allows for a comparative study with other regions. Remote sensing systems and environmental considerations must be taken into account to reduce errors in a change detection study (Dobson et al. 1995, Yuan and Elvidge 1998).

Sensor and Environmental Considerations

Various parameters in temporal, spatial, spectral, and radiometric resolutions in a remote sensing system must be examined carefully. It is important to keep temporal resolution constant for the imagery on the same date. In this study Landsat 1990 and 1999 imagery for Thimphu was taken in fall, and the 2007 image was taken in summer. For the 2007 imagery, a fall acquisition date was not available, and similarly summer dates were not available for earlier years. Accurate spatial resolution registration of at least two images is vital for change detection (Pontius et. al. 2004). All Landsat imagery was rectified with the QuickBird as described in section 3.2.2, with an RSME ≤ 28.5 pixels. Spectral resolution refers to the "reflected radiant flux in spectral regions that best capture the most descriptive spectral attributes of the object" (Jensen 2005, 470). Many of the change detection algorithms do not function well when bands form one sensor system do not match those of another sensor system (differing in spectral resolution). For example, utilizing the Landsat TM band 1 (blue) with either SPOT or Landsat MSS would not be effective. Change detection analysis for Thimphu consisted of using only Landsat imagery. When the radiometric resolution of data acquired by one system (6-bit lower resolution) is compared with data acquired by a higher radiometric resolution instrument (8-bit higher resolution), the lower-resolution data should be decompressed to 8-bit resolution (Congalton 1991). All imagery for this study consists of Landsat TM therefore the radiometric resolution is consistent with all imagery.

Other environmental parameters, such as atmospheric conditions, soil moisture conditions, phonological cycle characteristics, vegetation phenology, and urban-suburban phenological cycles, also must be taken into consideration when conducting change detections. When considering atmospheric conditions there should be no clouds or extreme humidity when the imagery was collected. Even a thin haze can modify spectral signatures in a satellite image. Therefore 0% cloud cover is preferred however it is often difficult to obtain imagery with minimum cloud cover. Landsat 1990 and 1999 imagery for Thimphu contained 0% cloud cover, 2007 imagery contained 15.2%.

Natural ecosystems go thru repeatable, predictable cycles of development just as human beings modify the landscape in repeatable, predictable stages (Congalton 1991). These stages are referred to as phenological cycles (Green et. al. 1994, Dobson et. al. 1995, Foody 2001). Jensen (1996) identified 10 stages of residential development in a region based on evidence of clearing, subdivision, transportation, buildings, and landscaping (urban-suburban phenology). Many of these stages of development may appear spectrally similar if coarse resolution imagery, such as MSS (80 meter), is used. Therefore, the analyst must be aware of the phenological cycle of all urban phenomena being investigated, as well as the natural ecosystem. Algorithms are developed to aid in change detection when examining these phenological cycles.

Selecting the Appropriate Algorithm

It is important to select an appropriate change detection algorithm, because it dictates whether important from-to change information can be extracted from the imagery (Dodson et. al. 1995). Change detection algorithms commonly used include:

- Write function memory insertion
- Multi-date composite image
- Image algebra (e.g., band differencing, band ratioing)
- Post-classification comparison
- Binary mask applied to date 2
- Ancillary data source used as date 1
- Spectral change vector analysis
- Chi-square transformation
- Cross-correlation
- Visual on-screen digitization
- Knowledge-based vision systems

Each algorithm has pros and cons (Table 3.3), and it is important to examine these change detection options when choosing the appropriate one. To detect and quantify land use/land cover change in Thimphu, the post-classification comparison algorithm was selected. In this study it was necessary to quantify land use/land cover change to test government policies. Post-classification comparison has three advantages:

- Does not require atmospheric correction
- Provides “from-to” change class information
- Next base year map is already completed

Method	Advantages	Disadvantages
Write Function Memory Insertion	• Visual examination of 2 or 3 years of nonspecific change. • Does not normally require atmospheric correction.	• Non-quantitative. • No “from-to” change class information.
Multi-Date Composite Image	• Requires single classification. • Does not normally require atmospheric correction.	• Difficult to label change classes. • Little “from-to” change class information available.
Image Algebra	• Normally does not require atmospheric correction. • Efficient method of identifying pixels that have change in brightness values between dates.	• No “from-to” change information available. • Requires careful selection of “change/no change” threshold.
Post-Classification Comparison	• Does not require atmospheric correction. • Provides “from-to” change class information. • Next base year map is already created.	• Dependent on accuracy of individual date classifications. • Requires two separate classifications.
Binary Mask Applied to Date 2	• May reduce change detection errors. • Provides “from-to” change class information.	• Requires a number of steps. • Dependent on quality of “change/no change” binary mask.
Ancillary Data Source Used as Date 1	• May reduce change detection errors. • Provides “from-to” change class information. • Requires a single classification.	• Depends on quality of ancillary information.
Spectral Change Vector Analysis	• Provides information about the type of change and magnitude.	• Results depend on the threshold set.
Chi-Square Transformation	• Works with any type of imagery.	
Cross-Correlation	• Not necessary to atmospherically correct or normalize Date 2 image data. • Requires a single classification.	• Depends on quality of Date 1 classification. • Does not provide “from-to” change class information.
Visual On-Screen Digitization	• Useful for high resolution imagery, which is often difficult to classify.	• Time-consuming.
Knowledge-Based Vision Systems	• Requires very little human interaction.	• Still in development.

Table 3.3: Advantages and disadvantages associated with different change detection methods.

Post-classification comparison requires rectification and classification of each remotely sensed image (Figure 3.24). The two images are then compared and quantified on a pixel-by-pixel basis using a change detection matrix (Table 3.4). When a change detection matrix is created, it represents a practical solution visualizing how land use conversion has taken place on pixel by pixel basis. The quantitative from-to information ascertained from the post-classification comparison algorithm is a major advantage for its use. This information can be used for further statistical analyses (Dobson et. al 1995, Yuan and Elvidge 1998). The disadvantage of this method is that any errors inherent in the classifications may appear in the final result of the change detection. Since this method heavily relies on imagery that is classified, it is imperative that the individual classification method be as accurate as possible (Arzandeh and Wang 2003). The next Section (3.2.8) discusses accuracy assessment of classified imagery.

3.3.8. Accuracy Assessment

Any remote sensing analysis is subject to error due to data acquisition process, inaccurate measurements, environmental conditions, or erroneous commands by the analyst (Congelton 1988). Image analysts who create remote sensing derived data should recognize the "sources of the error, minimize it as much as possible, and inform the user how much confidence he or she should have in the data" (Jensen 2005, 495). Remote sensing analysis should be subjected to a careful accuracy assessment before being used for scientific examination or any policy decisions.

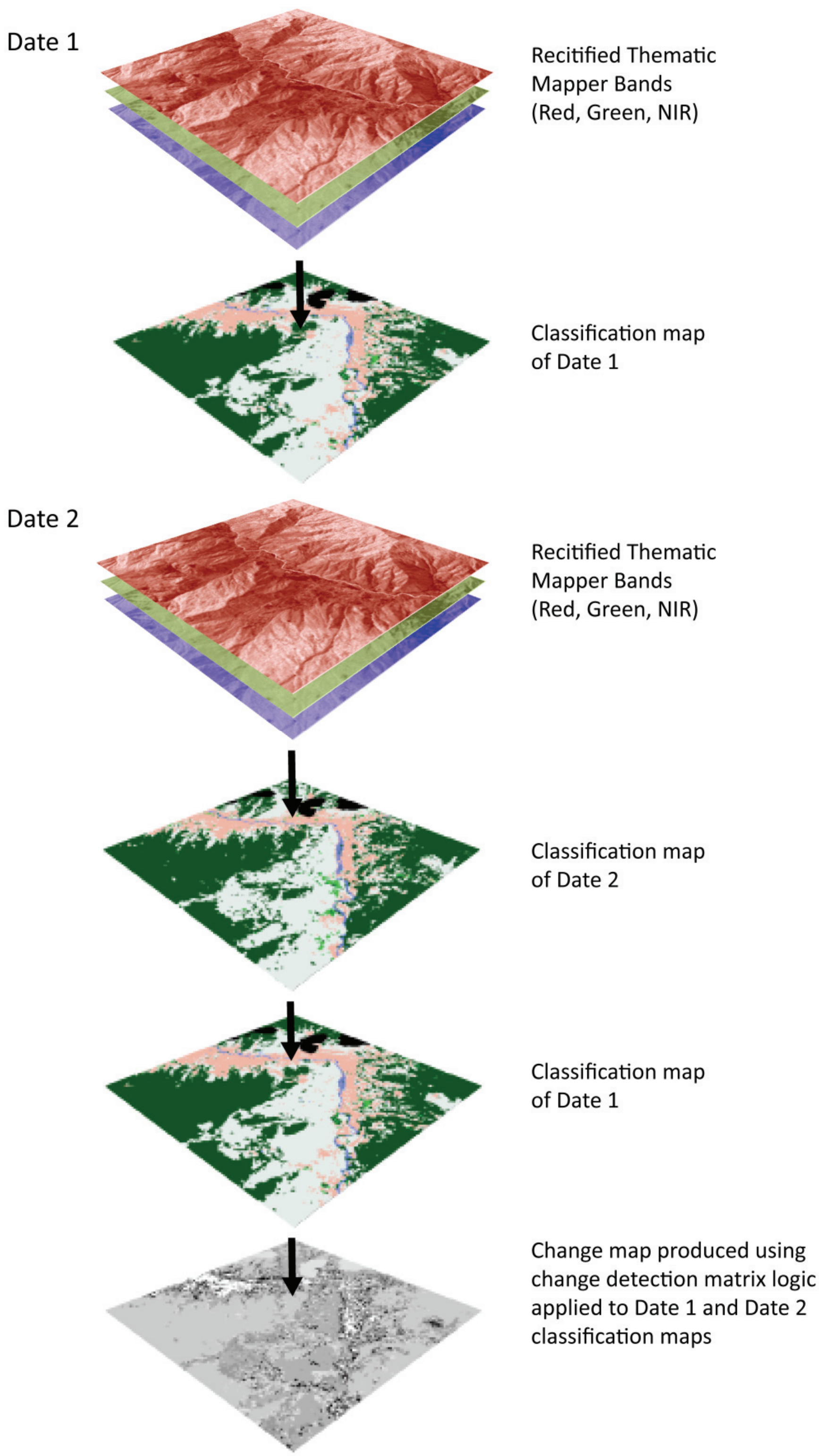


Figure 3.24: Post-Classification change detection process.

		To (2007)					
		Forest	**Agriculture**	**Barren**	**Urban**	**Water**	**Totals**
From (1990)	**Forest**	6713.01 (60.73)	18.95 (0.17)	824.6 (7.46)	139.76 (1.26)	23.15 (0.21)	7719.47 (69.84)
	Agriculture	4.48 (0.04)	0.04 (0.00)	2.45 (0.02)	0.27 (0.00)	0.14 (0.00)	7.38 (0.06)
	Barren	491.17 (4.44)	26.94 (0.24)	1244.32 (11.26)	450.51 (4.08)	17.86 (0.16)	2230.8 (20.18)
	Urban	118.55 (1.07)	11.67 (0.11)	335.39 (3.03)	521.94 (4.72)	23.97 (0.22)	1011.52 (9.15)
	Water	16.15 (0.15)	0.95 (0.01)	23.05 (0.21)	26.62 (0.24)	17.25 (0.16)	84.02 (0.76)
	Totals	7343.36 (66.44)	58.55 (0.53)	2429.81 (21.98)	1139.1 (10.31)	82.37 (0.75)	11053.19 (100)

Table 3.4: 1990 – 2007 Change Detection Matrix (Top numbers are area in hectares (ha) and bottom numbers are percents of total).

Land Use Land Cover Map Accuracy Assessment

There are set of standards or steps that need to be followed during accuracy assessment process. It is important to clearly state the nature of accuracy assessment problem in the study. The objectives of the accuracy assessment should be clearly identified and:

- What the accuracy assessment is expected to accomplish,
- The classes of interest (discrete or continuous), and
- The sampling design and sampling frame (consisting of area and list frames

Accuracy assessment process follows a sampling design or a protocol that contains sampling frame and sampling units. Sampling frame consists of "the material or devices which delimit, identify, and allow access to the elements of the target population" (Jensen 2005, 496). Two important elements associated with sampling frame are the area frame and the list frame. The area frame represents the exact geographic dimension of the study area. The list frame is a list of all the possible sampling units within the area frame. The accuracy assessment is dependent on two types of sampling units: point and areal. There is no areal extent in point sampling units. Typically there are three types of areal sampling units when conducting remote sensing-related accuracy assessment; individual pixels (e.g., Thimphu Landsat TM of 30x30 m pixels), polygons, or fixed-area plots (Congelton 1991). Two methods, qualitative confidence-building assessment and statistical measurements, are used to validate the accuracy assessment once the problem has been stated.

Sources of Error

There are several sources of error in remotely sensed analysis. Error maybe introduced during the remote sensing data acquisition process (Figure 3.25). Remote sensing sensors and equipment often become miscalibrated, resulting in inaccurate measurements. Additionally, the aircraft or spacecraft may roll, tilt, or yaw during data acquisition, which may create error in the resulting image. Ground control personnel may input erroneous commands from inertial navigation systems. Environmental conditions (i.e., haze, smog, fog, dust, high, relative humidity or sunlight) during the acquisition can significantly affect the quality and accuracy of remote sensing data.

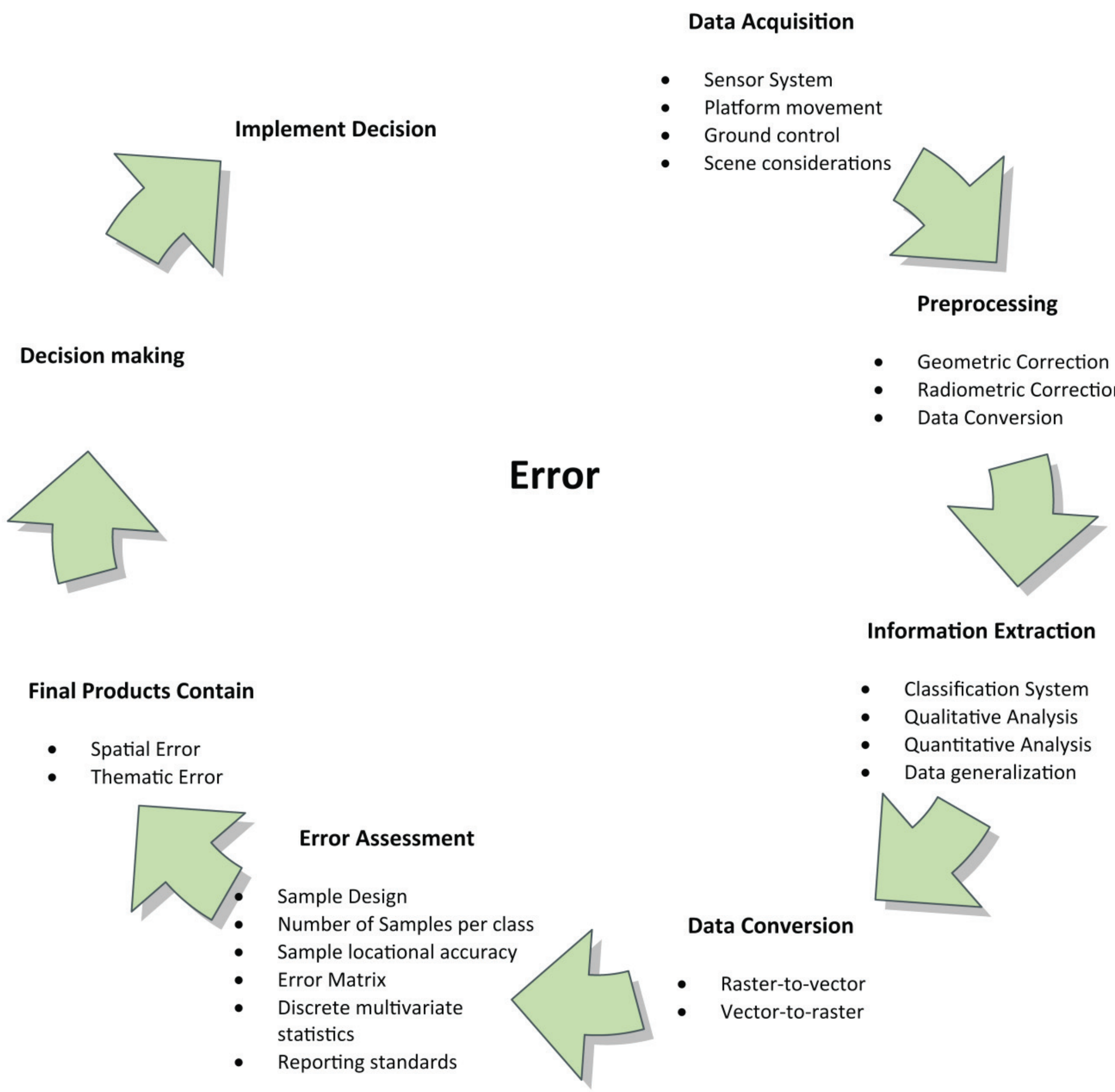


Figure 3.25: Error assessment process as described by Jensen (2005).

Even optimal atmospheric correction may not result in an error free relationship between reflectance measured on the ground and percent reflectance measured by an optical remote sensing system for the same geographic region (Foody 2002). Sometimes there is a flaw in the logic when employing qualitative or even quantitative methods. For example, a hard land-cover classification scheme may include classes that are homogenous and are not mutually exclusive. In a supervised classification method training sites or clusters may be incorrectly labeled. Finally, the policy makers often do not understand the amount of error that has accumulated in the remote sensing analysis. It is critical that they should be educated about the amount of error and be cautioned not to overstate the level of accuracy.

Error Matrix

To perform a classification accuracy assessment, it is essential to thoroughly compare pixels or polygons and ground reference test information. The relationship between these two sets of information is referred to as error matrix (Pontius et. al. 2004). The error matrix is used to assess the remote sensing classification accuracy of *k* classes (Table 3.5).

		Reference Data						
		Forest	**Agriculture**	**Barren**	**Urban**	**Water**	**Totals**	**User's Accuracy (%)**
Classified Data	**Forest**	96	0	1	0	0	97	98.97
	Agriculture	11	4	1	1	0	17	23.53
	Barren	16	1	34	11	0	62	54.84
	Urban	0	0	1	13	0	14	92.86
	Water	3	0	0	1	6	10	60
	Totals	126	5	37	26	6	200	
	Producer's Accuracy (%)	76.19	80	91.89	50	100		

Table 3.5: 1990 supervised classification error matrix (numbers are indicative of points used in the accuracy assessment).

The columns of the matrix represent the ground reference test information and the rows correspond to the classification generated from analysis of the remotely sensed data. Each error contains “both an omission from the correct category and a commission to a wrong category” (Jensen 2005, 499). The intersection of the rows and columns summarize the number of sample units (i.e., pixels for Thimphu Landsat) assigned to a particular category (class) relative to the actual category as verified in the field. The diagonal of the matrix summarizes those pixels or polygons that were assigned to the correct class. To obtain unbiased ground reference test information when comparing to remotely sensed classification, Jensen (2005) recommends applying appropriate descriptive and multivariate statistics to assess the accuracy of the remote sensing analysis.

Ground Reference Test Information and Training Pixels

Often the analyst performs accuracy assessment based solely on training pixel that was used to train or seed a supervised or unsupervised classification algorithm. These locations are usually not random and are biased by the analyst's prior knowledge of where certain land-cover types exist in the study area. The ideal situation is to locate ground reference test pixels in the study area. The ground reference data can be obtained by visiting the site on the ground and making observations that can then be compared with remote sensing data for the exact location. During the NSF funded March 2008 trip to Bhutan 14 ground control points (GCPs) were collected in Thimphu (Figure 3.26). Of the 14 GCPs one was collected on an agricultural field, seven were collected in an urban setting, and one was collected in a forested area. Out of five classifications three (agricultural land, built-up, and forestland) can be verified with these GCPs. However, seven GCPs are not enough to produce reliable accuracy assessment. Therefore, higher spatial resolution remotely sensed data was used as a substitute for ground reference test information. The imagery used to attain the ground reference test information "should be substantially higher in spatial and/or spectral resolution than the imagery used to derive the original thematic information" (Jensen 2005, 500). This study uses a QuickBird (0.6m resolution) with an acquisition date of 2006 to extract ground reference test information that is then compared with thematic data produced using Landsat TM imagery (30x30m resolution).

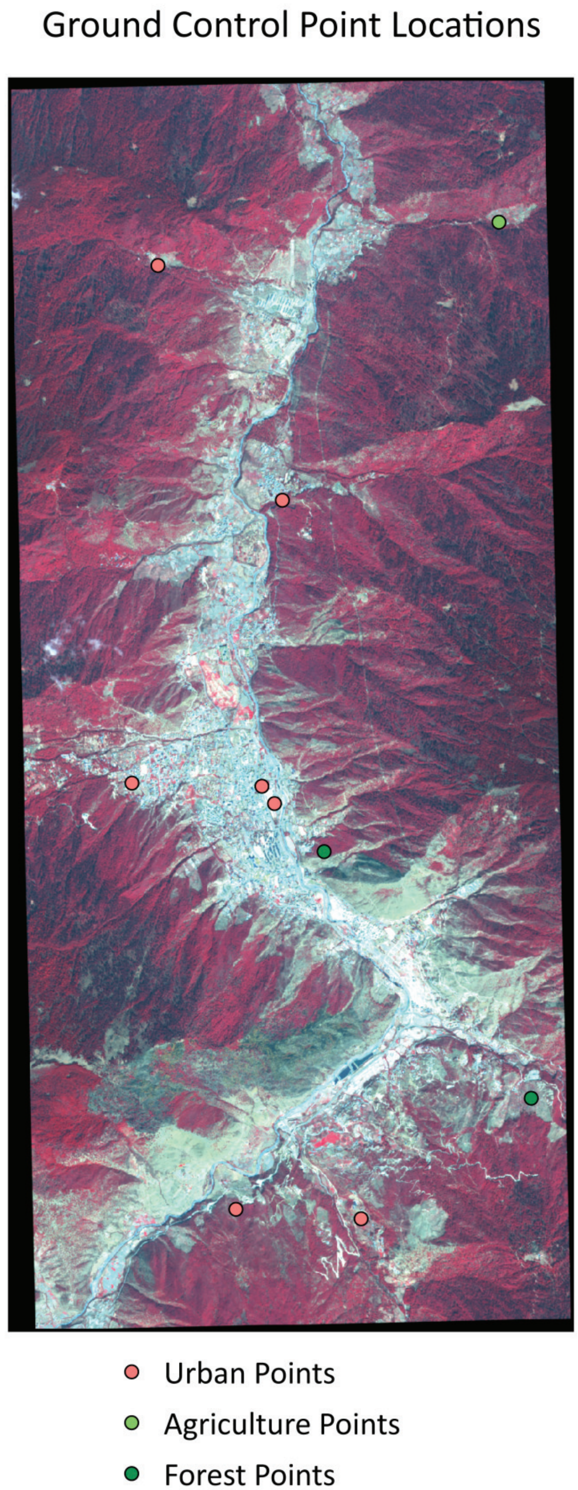


Figure 3.26: Distribution of GCPs used for accuracy assessment and their classification per the classification scheme used for Thimphu city.

When comparing the results of the ground reference test information with remotely sensed data, Jensen (2005) suggests examining pixels that are surrounding the location of the ground reference test information by eight pixels.

In this study a sample size based on binomial probability theory was utilized. In the binomial probability theory formula the sample size *N* is used to assess the accuracy of a land-use classification map (Fitzpatrick-Lins 1981).

$$N = \frac{Z^2(p)(q)}{E^2}$$

Where *p* is the expected percent accuracy of the entire study area *q-100, E* is the allowable error, and *Z* represents the standard normal deviate of 1.96 for the 95% two-sided confidence lever. So, for the Thimphu Landsat's expected accuracy of 85% and allowable error of 5% the number of points would be:

$$N = \frac{2^2(85)(15)}{5^2} = a\ minimum\ of\ 203\ points$$

In the binomial probability theory "the lower the expected percent accuracy (*p*), and the greater the allowable error (*E*), the fewer ground reference test samples that need to be collected" to calculate the classification accuracy (Jensen 2005, 501).

Kappa Statistics

Kappa analysis was first introduced in 1981 and published in 1983 (Congalton 1988, Jensen et. al. 2007). It is a discrete multivariate technique for use in accuracy assessment. It is a measure of accuracy between the remote sensing data and the reference data. K_{hat}, Coefficient of Agreement, or the Kappa statistics is calculated using:

$$\widehat{K} = \frac{N\sum_{i=1}^{k} x_{ii} - \sum_{i=1}^{k}(x_{i+}\mathrm{X}x_{+i})}{N^2 - \sum_{i=1}^{k}(x_{i+}\mathrm{X}\mathrm{x}_{+i})}$$

Where k is the number of land-cover classes in the matrix, x_{ii} is the number of observations in row i and column i, and x_{i+} and x_{+i} are the marginal totals for row i and column i, respectively, and N is the total number of observations. $\widehat{K}$ values > 0.80 (i.e., > 80%) represent strong agreement or accuracy between the classification map and the ground reference information. $\widehat{K}$ values between 0.40 and 0.80 (i.e., 40% to 80%) represent moderate agreement. $\widehat{K}$ values <0.40 (i.e., < 40%) represent poor agreement (Jensen 2005).

Similarly the Conditional K_{hat} Coefficient of Agreement can be used to calculate agreement between the reference and remotely sensing data with change agreement eliminated for an individual class using the equation:

$$\widehat{K}_{\iota} = \frac{N(x_{ii}) - (x_{i+}\mathrm{X}\mathrm{x}_{+\mathrm{i}})}{N(x_{i+}) - (x_{i+}\mathrm{X}x_{+i})}$$

Where x_{ii} is the number of observations correctly classified for a particular category (summarized in the diagonal of the matrix), x_{i+} and x_{+i} are the marginal totals for row i and column i associated with the category, and N is the total number of observations in the entire error matrix. For example, the conditional *Ki* coefficient of agreement for the unsupervised forest class of the 1990 Thimphu Landsat is:

$$\hat{\mathrm{K}}_{\iota} = \frac{(200)(78) - (89)(84)}{(200)(84) - (89)(84)} = 0.8713$$

Both of these procedures permit land-use maps resulting from remotely sensed to be "quantitatively evaluated to determine overall and individual category classification accuracy" (Jensen 2005, 508). Quantitatively evaluated accuracy assessment such as Kappa analysis enhances the reliability of using remotely sensed derived land-cover data.

3.3.9. Summary

This research methodology required a combined knowledge of GIS and remote sensing methods. It was essential to create the data necessary to examine population trends and potential variables that may influence on which this research is based using GIS technology. Even more essential to the land use analysis of the research was the remote sensing analysis. The remote sensing analysis included geo-rectification of images, examination of image indices, supervised classification, unsupervised classification, change detection, and accuracy assessment. Each process added to the wider goal of an accurate land cover classification for Thimphu city, Thimphu dzongkhag, and Kawang and Chang geogs.

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1. Remote Sensing Results

The remote sensing analysis performed in the methodology provides the dependent variable in this research. Due to the lack of literature with regards to remote sensing in the region, different classification methods needed to be assessed to find those best suited to this rather mountainous region. The Normalized Difference Barren Index (NDBI) method proposed by Zha et al (2003) was also assessed as a potential method of documenting Bhutan's urban growth. Once these methods were assessed, the quantitative land use change analysis using the post-classification change detection method was performed, identifying and locating the areas of urban growth in Thimphu. Forest cover trends were also identified at three scales: Dzongkhag, Geog, and Thimphu city level. These remote sensing analyses are the basis for assessing the population and economic pressures discussed throughout this chapter.

4.1.1 Unsupervised versus Supervised Classifications

There is little literature describing which classification method would be most accurate to use for classifying the study area. Bhutan is a unique place, including its architecture and building materials (Watson and Bertaud, 1976). One of the four pillars of GNH includes the preservation and promotion of culture, which requires all construction to follow the traditional style of architecture. In many cases these buildings are constructed of local materials, such as straw, wood, bamboo, and mud, which gives Bhutanese urban areas a spectral signature that is unique from many of the western cities more commonly studied. Potential misclassifications could occur with urban and barren classes due to the mountainous terrain. Due to the difficulties associated with remote sensing in the study area, this research utilized both methods to determine which would be the best method to use in the assessment of land use changes in Bhutan.

Accuracy assessments were performed for each of the three Thimphu city images for both the unsupervised and supervised classifications to ascertain which classification method is superior. For the 1990 supervised classification, the overall accuracy was 76.5%, with a kappa statistic of 0.62356 (Table 4.1). The kappa statistic represents a moderate agreement, though two classes represent excellent agreement (forest and urban), with kappa values above 0.90 (90%). The unsupervised classification for 1990 yielded a slightly higher accuracy of 78.5% and kappa statistic of 0.6993 (Table 4.2). Though the overall accuracy and kappa statistic were higher than the supervised classification, the forest and urban kappa statistic were considerably lower (0.8713 and 0.7871, respectively). The 1999 supervised classification yielded an overall accuracy of 72% (Table 4.3), with a kappa statistic of 0.5096, while the unsupervised classification yielded an overall accuracy of 82% and a kappa statistic 0.7072 (Table 4.4).

		Reference Data						
		Forest	**Agriculture**	**Barren**	**Urban**	**Water**	**Totals**	**User's Accuracy (%)**
Classified Data	**Forest**	96	0	1	0	0	97	98.97
	Agriculture	11	4	1	1	0	17	23.53
	Barren	16	1	34	11	0	62	54.84
	Urban	0	0	1	13	0	14	92.86
	Water	3	0	0	1	6	10	60
	Totals	126	5	37	26	6	200	
	Producer's Accuracy (%)	76.19	80	91.89	50	100		

Overall Accuracy	76.50%

Overall Kappa	0.6236

Class	**Kappa**
Forest	0.9721
Agriculture	0.2157
Barren	0.4459
Urban	0.9179
Water	0.5876

Table 4.1: 1990 Supervised Accuracy Assessment

		Reference	Data				
	Forest	**Agriculture**	**Barren**	**Urban**	**Water**	**Totals**	**User's Accuracy (%)**
Forest	78	0	3	2	1	84	92.86
Agriculture	7	8	5	0	0	20	40
Barren	2	0	35	9	0	46	76.09
Urban	1	0	4	24	0	29	82.76
Water	1	0	5	3	12	21	57.14
Totals	89	8	52	38	13	200	
Producer's Accuracy (%)	87.64	100	67.31	63.16	92.31		

Classified Data

Overall Accuracy	78.50%

Overall Kappa	0.6993

Class	**Kappa**
Forest	0.8713
Agriculture	0.375
Barren	0.6769
Urban	0.7871
Water	0.5416

Table 4.2: 1990 Unsupervised Accuracy Assessment

		Reference Data					
	Forest	Agriculture	Barren	Urban	Water	Totals	User's Accuracy (%)
Forest	107	1	5	4	1	118	90.68%
Agriculture	1	4	3	2	0	10	40.00%
Barren	21	1	13	10	0	45	28.89%
Urban	0	2	0	14	1	17	82.35%
Water	2	0	2	0	6	10	60.00%
Totals	131	8	23	30	8	200	
Producer's Accuracy (%)	81.68%	50.00%	56.52%	46.67%	75.00%		

Classified Data

Overall Accuracy	72.00%

Overall Kappa	0.5096

Class	Kappa
Forest	0.7298
Agriculture	0.375
Barren	0.1956
Urban	0.7924
Water	0.5833

Table 4.3: 1999 Supervised Accuracy Assessment

		Reference	Data				
	Forest	**Agriculture**	**Barren**	**Urban**	**Water**	**Totals**	**User's Accuracy (%)**
Forest	104	0	0	5	0	109	95.41%
Agriculture	1	1	5	3	0	10	10.00%
Barren	12	1	29	5	1	48	60.42%
Urban	0	0	2	21	0	23	91.30%
Water	0	0	0	1	9	10	90.00%
Totals	117	2	36	35	10	200	
Producer's Accuracy (%)	88.89%	50.00%	80.56%	60.00%	90.00%		

Classified Data

Overall Accuracy	82.00%

Overall Kappa	0.7072

Class	**Kappa**
Forest	0.8895
Agriculture	0.0909
Barren	0.5173
Urban	0.8946
Water	0.8947

Table 4.4: 1999 Unsupervised Accuracy Assessment

Both of the kappa statistics indicate that the classifications are moderate representations of what is on the ground. However, the unsupervised classification has a 20% greater kappa statistic and a 10% greater overall accuracy. Additionally, nearly every producer and user accuracy was higher in the unsupervised over the supervised classifications, except for the agriculture class. The supervised classification for 2007 had an overall accuracy of 68.5% and a kappa statistic of 0.5042 (Table 4.5), while the unsupervised classification had an accuracy of 92% and a kappa statistic of 0.8664 (Table 4.6). Both the producer's and user's accuracies were greater for the unsupervised classification over the supervised, as were all of the kappa statistics for the individual classes. For all of the images used, the unsupervised classification yielded a higher overall classification accuracy and kappa statistic. Based on these results, the unsupervised classifications for Thimphu City, Thimphu *Dzongkhag*, and both the Chang and Kawang *Geogs* were utilized for the quantification of the land use change in this research.

		Reference	Data					
		Forest	**Agriculture**	**Barren**	**Urban**	**Water**	**Totals**	**User's Accuracy (%)**
Classified Data	**Forest**	91	0	2	0	0	93	97.85%
	Agriculture	2	5	2	1	0	10	50.00%
	Barren	34	4	20	10	0	68	29.41%
	Urban	0	2	2	14	0	18	77.78%
	Water	4	0	0	0	7	11	63.64%
	Totals	131	11	26	25	7	200	
	Producer's Accuracy (%)	69.47%	45.45%	76.92%	56.00%	100.00%		

Overall Accuracy	68.50%

Overall Kappa	0.5042

Class	**Kappa**
Forest	0.9377
Agriculture	0.4709
Barren	0.1886
Urban	0.746
Water	0.6232

Table 4.5: 2007 Supervised Accuracy Assessment

	Reference	Data					
	Forest	Agriculture	Barren	Urban	Water	Totals	User's Accuracy (%)
Forest	111	0	1	1	0	113	98.23
Agriculture	0	8	0	2	0	10	80
Barren	11	0	31	1	0	43	72.09
Urban	0	0	0	25	0	25	100
Water	0	0	0	0	9	9	100
Totals	122	8	32	29	9	200	
Producer's Accuracy (%)	90.98	100	96.88	86.21	100		

Classified Data

Overall Accuracy	92.00%

Overall Kappa	0.8664

Class	Kappa
Forest	0.9546
Agriculture	0.7917
Barren	0.6678
Urban	1.00
Water	1.00

Table 4.6: 2007 Unsupervised Accuracy Assessment

4.1.2. Normalized Difference Built-Up Index

As this research seeks to quantify the urban expansion that is currently underway in Thimphu, the NDBI serves as an ideal way to rapidly measure the increased urban area in numerous images. Though Zha et al. (2003) were able to obtain accuracies of 92.6% using the NDBI and achieve higher accuracies than those yielded by a supervised classification, their study area was a Chinese city, with little barren area. Due to the similar spectral signatures of the urban and barren classes in this research, it was difficult for the model designed for this dissertation to differentiate between the two classes (Figure 4.1). In many cases, barren would be included in the urban boundary, while a large portion of the core of the city (urban built-up area) was not included. This would make for an inaccurate portrayal of the city limits and urban area. Due to these issues, the NDBI could not be used in this study and it is not recommended for use in other mountainous regions.

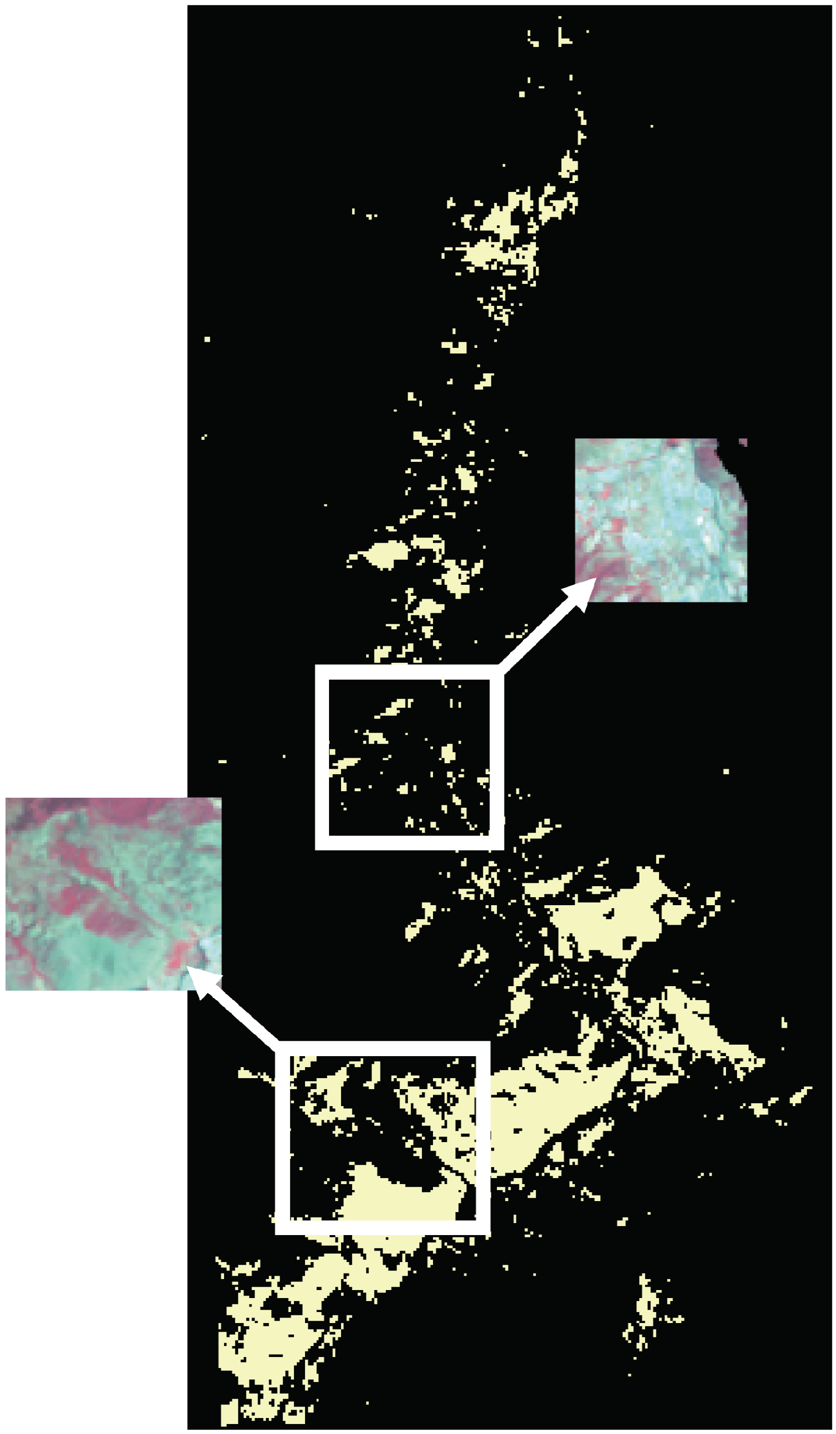


Figure 4.1: The NDBI model at times classified barren area as "urban," while excluding areas of the core from the "urban areas."

4.1.3. Cross-Tabulation Metrics

Cross-Tabulation Matrices were created based on the unsupervised classifications (Figures 4.2, 4.3, 4.4) for the Thimphu city images. Three matrices were generated: one for the 1990 and 1999 classifications (Table 4.7), one for the 1999 and 2007 classifications (Table 4.8), and one for the 1990 and 2007 classifications (Table 4.9).

The 1990 to 1999 matrix shows an increase in urban area (28.62 ha). The majority of the urban area came from what was barren in 1990 (387.09 ha), comprising 37.2% of the total urban area in 1999. Much of the urban growth took place on the periphery of the city, as shown in Figure 4.5. Forest area decreased during this time period, by 261.82 ha, yielding a total forest cover of 67.47%, down by 2.37% from the 69.84% it was in 1990. The majority of the change in forest was to the barren class, as such the 1990 to 1999 matrix also showed an increase in barren area of 174.45 ha.

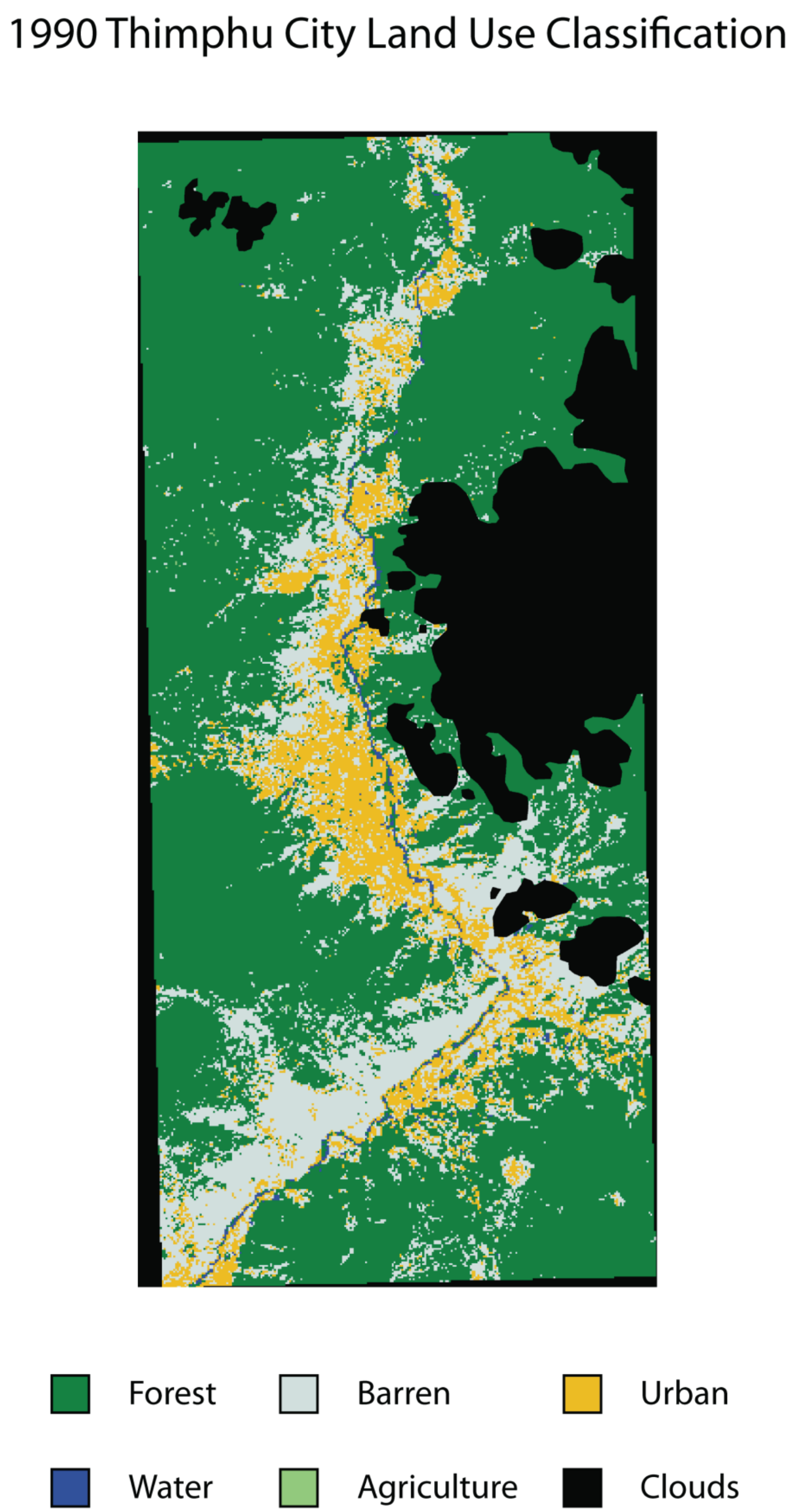


Figure 4.2: 1990 Thimphu city unsupervised classification.

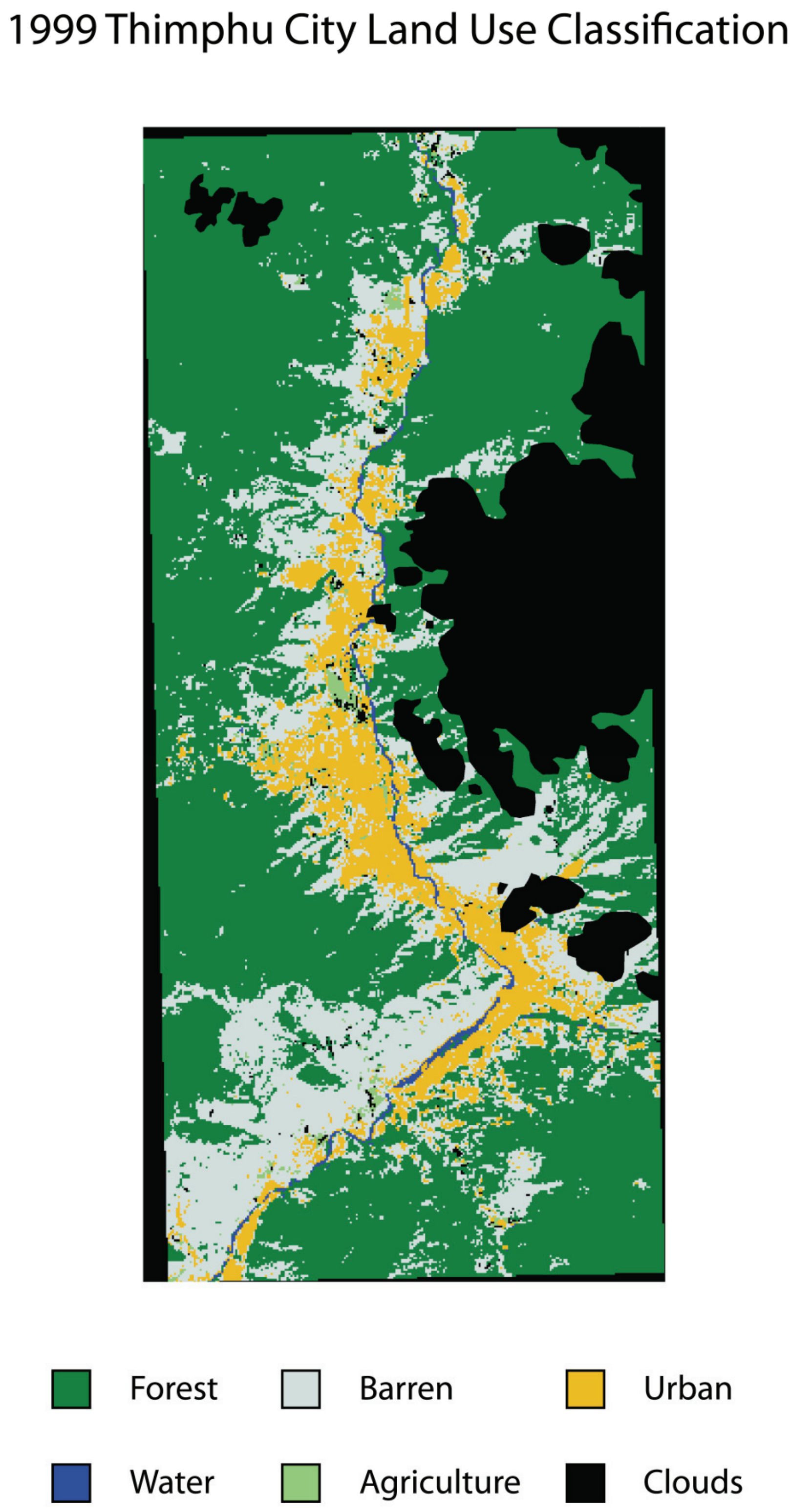


Figure 4.3: 1999 Thimphu city unsupervised classification.

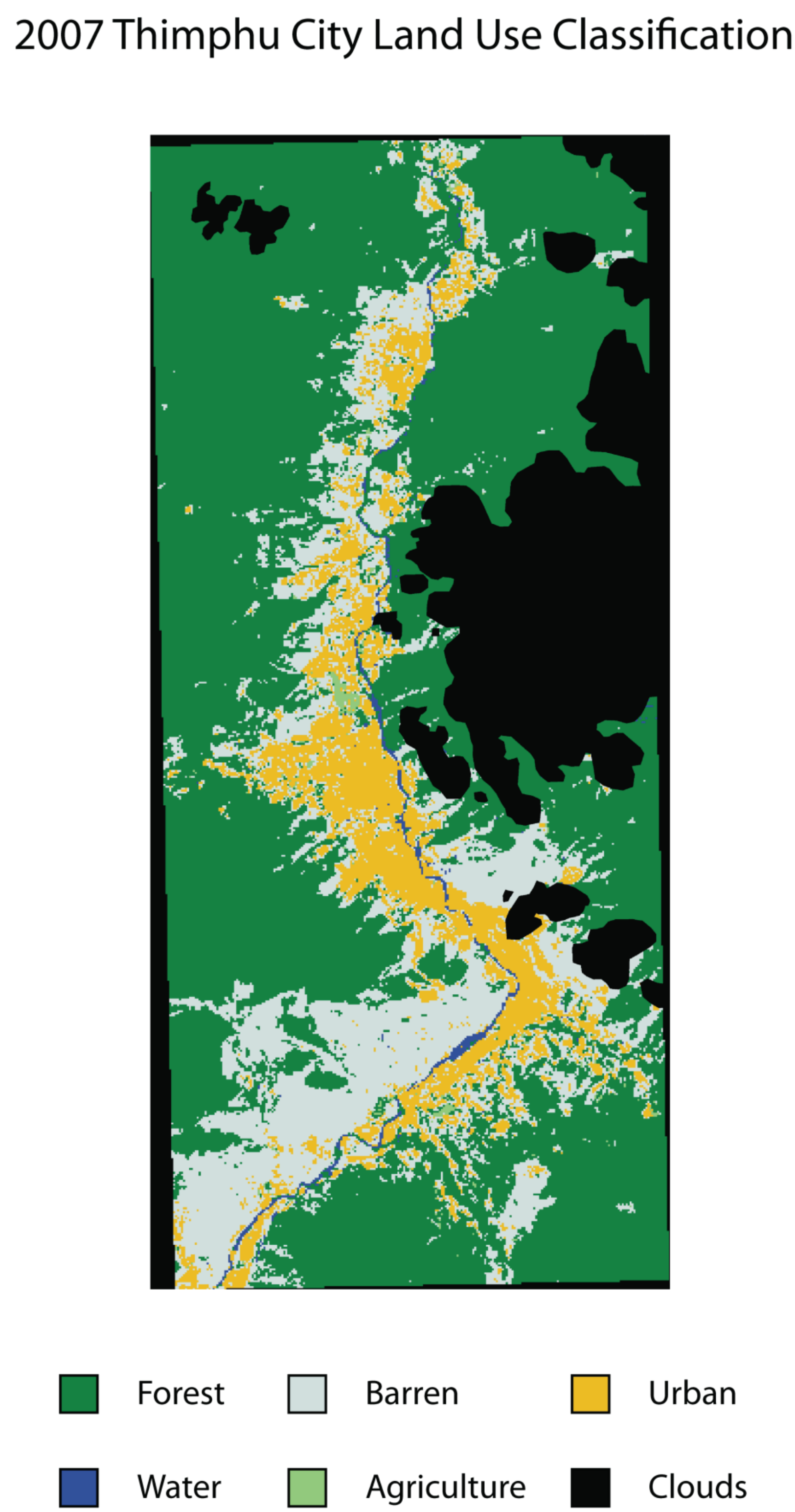


Figure 4.4: 2007 Thimphu city unsupervised classification.

1990 – 1999 Expansion

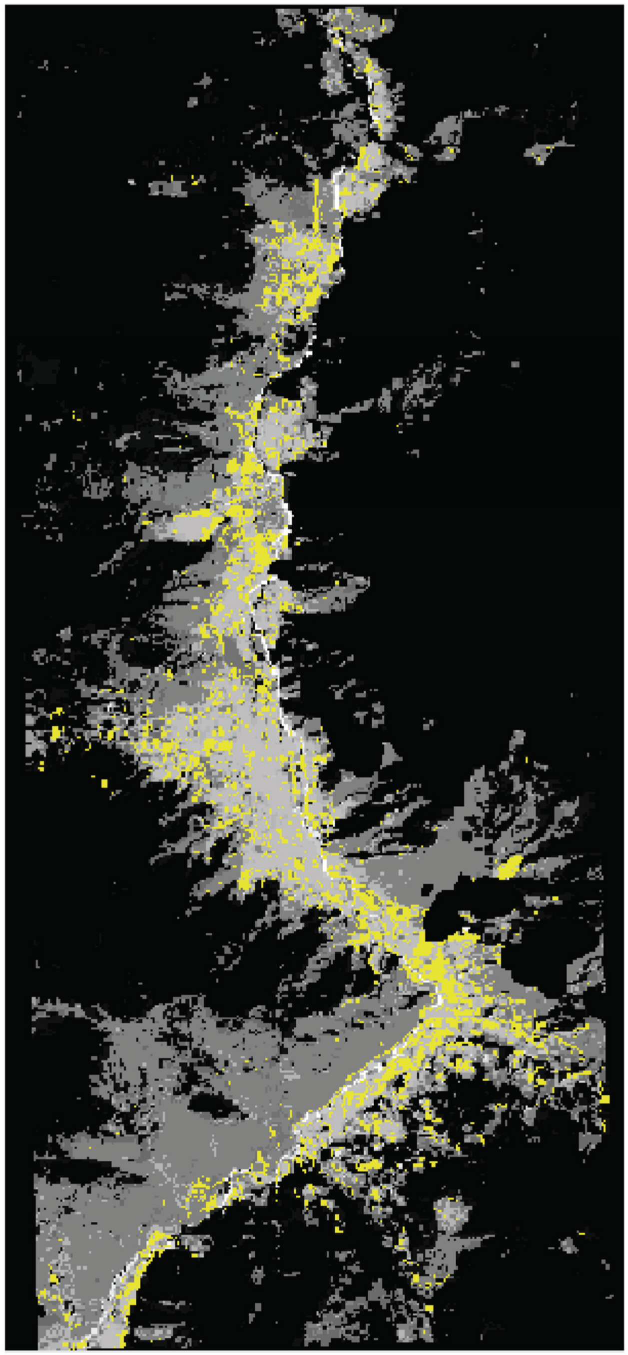


Figure 4.5: Areas in yellow are urban expansion in 1990 – 1999 as indicated by the change matrix.

		To (1999)					
		Forest	Agriculture	Barren	Urban	Water	Totals
	Forest	6679.55 (60.43)	23.17 (0.21)	894.91 (8.10)	111.16 (1.01)	10.68 (0.10)	7719.47 (69.84)
	Agriculture	4.69 (0.04)	0.68 (0.00)	1.92 (0.02)	0.10 (0.00)	0 (0.00)	7.3892 (0.06)
From (1990)	Barren	591.23 (5.35)	64.11 (0.58)	1178.57 (10.66)	387.09 (3.50)	9.81 (0.09)	2230.81 (20.18)
	Urban	157.96 (1.43)	13.78 (0.12)	307.98 (2.79)	514.32 (4.65)	17.46 (0.16)	1011.51 (9.15)
	Water	24.22 (0.22)	0.53 (0.00)	21.88 (0.20)	27.47 (0.25)	9.93 (0.09)	84.02 (0.76)
	Totals	7457.65 (67.47)	102.27 (0.92)	2405.26 (21.76)	1040.13 (9.41)	47.88 (0.43)	11053.19 (100)

Table 4.7: 1990-1999 Thimphu City Cross-Tabulation Matrix

		To (2007)					
		Forest	Agriculture	Barren	Urban	Water	Totals
	Forest	6517.08 (58.86)	20.04 (0.18)	752.39 (6.80)	155.14 (1.40)	29.11 (0.26)	7473.76 (67.51)
From (1999)	Agriculture	16.02 (0.14)	12.87 (0.12)	44.47 (0.40)	27.74 (0.25)	1.17 (0.01)	102.27 (0.92)
	Barren	733.56 (6.63)	14.13 (0.13)	1341.7 (12.12)	299.29 (2.70)	18.11 (0.16)	2406.79 (21.74)
	Urban	86.13 (0.78)	11.43 (0.10)	281.83 (2.55)	639.66 (5.78)	21.12 (0.19)	1040.17 (9.40)
	Water	7.2 (0.06)	0.09 (0.00)	10.45 (0.09)	17.28 (0.16)	12.87 (0.12)	47.89 (0.43)
	Totals	7359.99 (66.48)	58.56 (0.53)	2430.84 (21.96)	1139.11 (10.29)	82.38 (0.74)	11070.88 (100)

Table 4.8: 1999-2007 Thimphu City Cross-Tabulation Matrix.

From (1990) \ To (2007)	Forest	Agriculture	Barren	Urban	Water	Totals
Forest	6713.01 (60.73)	18.95 (0.17)	824.6 (7.46)	139.76 (1.26)	23.15 (0.21)	7719.47 (69.84)
Agriculture	4.48 (0.04)	0.04 (0.00)	2.45 (0.02)	0.27 (0.00)	0.14 (0.00)	7.38 (0.06)
Barren	491.17 (4.44)	26.94 (0.24)	1244.32 (11.26)	450.51 (4.08)	17.86 (0.16)	2230.8 (20.18)
Urban	118.55 (1.07)	11.67 (0.11)	335.39 (3.03)	521.94 (4.72)	23.97 (0.22)	1011.52 (9.15)
Water	16.15 (0.15)	0.95 (0.01)	23.05 (0.21)	26.62 (0.24)	17.25 (0.16)	84.02 (0.76)
Totals	7343.36 (66.44)	58.55 (0.53)	2429.81 (21.98)	1139.1 (10.31)	82.37 (0.75)	11053.19 (100)

Table 4.9: 1990-2007 Thimphu City Cross Tabulation Matrix

The 1999 to 2007 change matrix shows a similar trend as the 1990 to 1999 matrix. This matrix, too, showed an increase in urban area of 98.84 ha, which is over double the increase seen from 1990 to 1999. This may be indicative of the major land use conversion described by MoWHS and DUDES (2004) in the Thimphu Structural Plan (TSP) reports. A structure plan was prepared in 1986 that guided the development of Thimphu through 1990s. In 1998 a strategic plan was prepared in collaboration with urban planning departments (MoWHS and DUDES) and external contractors and architects. Because of growth the TSP recognized “the need for extending the municipal boundary covering a larger area” that will expand the city’s “corridors, public transport systems, and underground utilities” (Dorji 2004, np). The role of Thimphu’s growth and TSP is further elaborated in section 4.1.5. As was true with the 1990 to 1999 matrix, from 1999 to 2007, barren area was a major contributor to the increase in urban area.

Additionally, this increase in urban area is continuing to expand outward from the 1999 periphery (Figure 4.6). Similarly, forest area also decreased by113.77 ha. The increase in barren area was smaller than shown in the 1990 to 1999 matrix, with an increase of only 24.05 ha. Once again, the major contributor to the increase in barren area was the forest class, which declined a total of 66.48%.

The final matrix gives an overall view of the changes from 1990 to 2007. Once again, these results are similar to those exhibited in the previous two matrices. The urban area had a net increase of 127.58 ha, extending the periphery of Thimphu city onto the slopes of the valley (Figure 4.7). Forest area also had a net decrease of 376.01 ha, and barren area had a net increase of 199.01 ha. Table 4.10 shows the general trends exhibited by the classifications.

1999 – 2007 Expansion

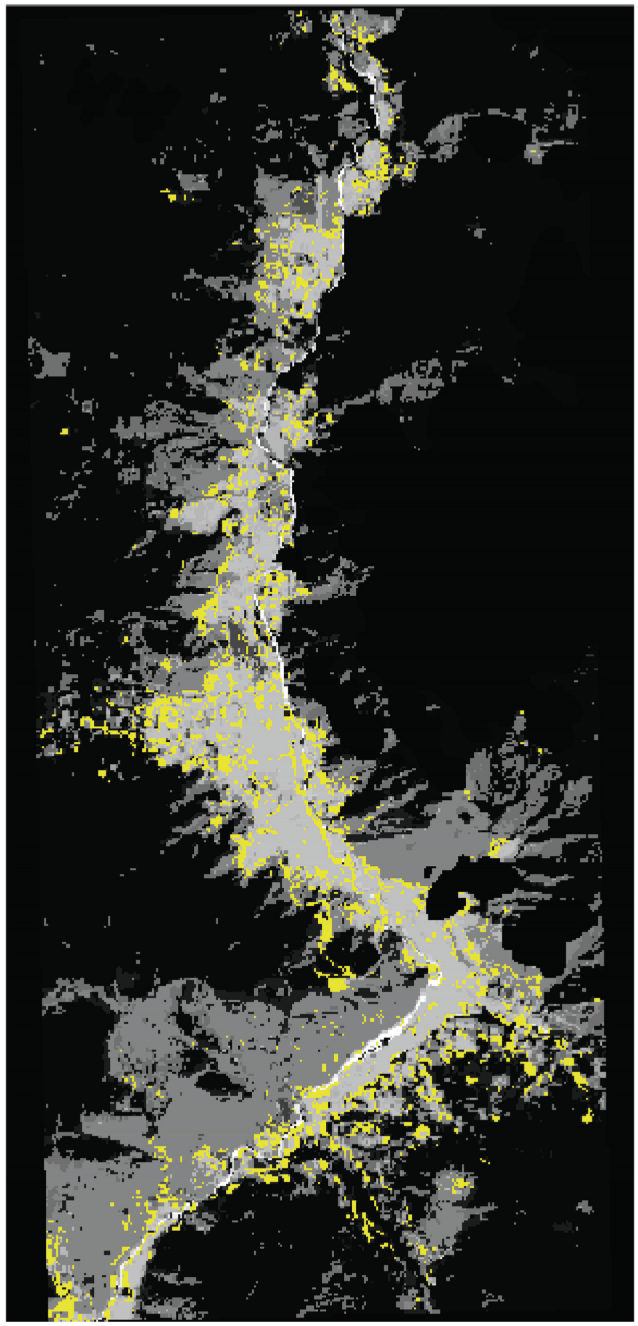


Figure 4.6: Areas in yellow are urban expansion in 1999 – 2007 as indicated by the change matrix.

1990 – 2007 Expansion

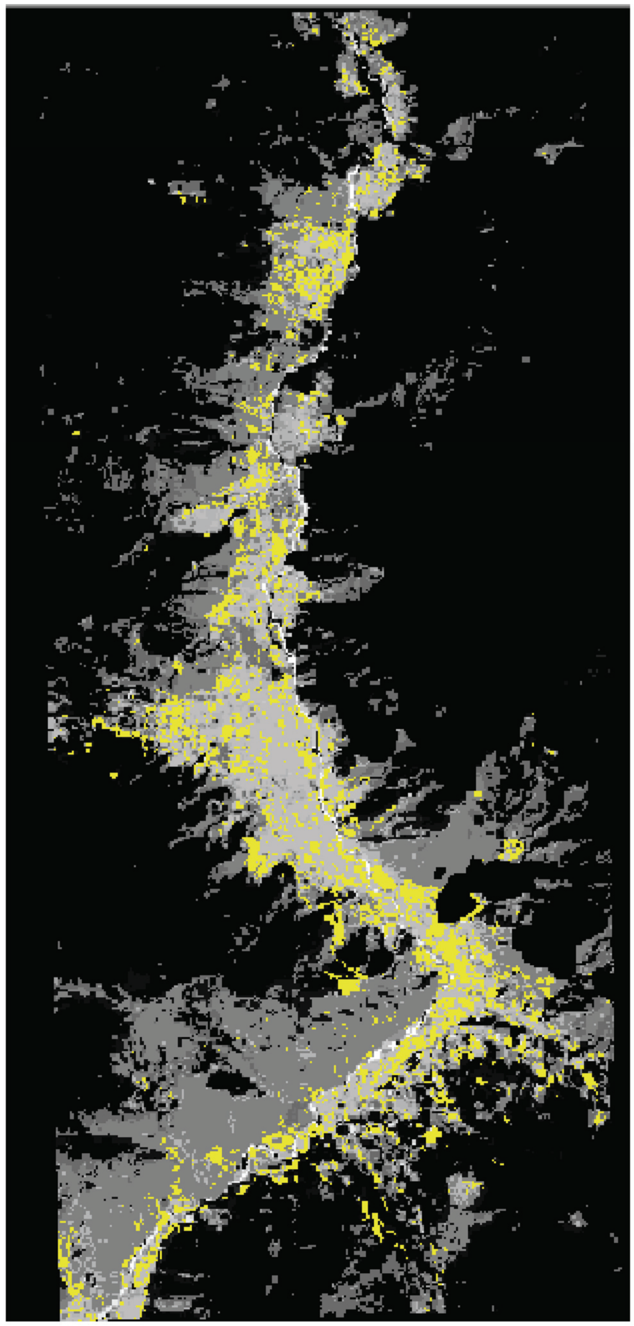


Figure 4.7: Areas in yellow are urban expansion from 1990 – 2007 as indicated by the change matrix.

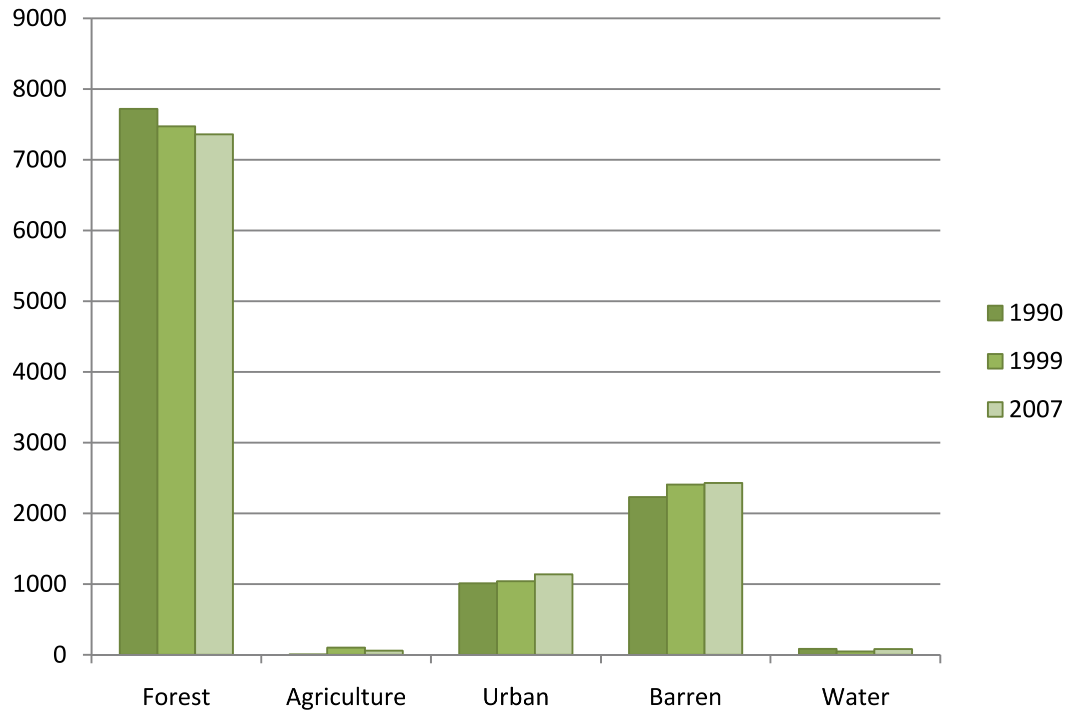


Table 4.10: Thimphu city unsupervised classification trends (hectares on the y axis, class on the x axis).

4.1.4. Dzongkhag and Geog Analyses

Since the area of interest (AOI) for the Thimphu city analysis was an arbitrary boundary, drawn from the extent of the QuickBird Image, two other analyses were performed to make certain the trends exhibited by the Thimphu city classifications were also shown in the administrative boundaries of Thimphu *Dzongkhag* and *Kawang* and *Chang Geogs*. Since the geographic area is much larger than that of Thimphu city for both of these administrative areas, the classification scheme needed to be adapted. With the additional extent of the AOI, a perennial ice class was added to the scheme. Table 4.11 shows land use as the percentage of total area for all three scales utilized in this study. It is important to examine all three scales to test the validity of the remote sensing analysis employed in this study. Furthermore, examining all three scales helps to understand that land use change as percent total can vary from one scale to another. For example the forested area for 1990 at a city scale is 69.8% and at dzongkhag scale it's 38.51%.

The Thimphu Dzongkhag analysis yielded slightly different results than the Thimphu city analysis (Table 4.12). Instead of showing a decrease in forest cover, the classifications showed an increase in forest cover of 14,370.8 ha from 1990 to 2002 (Figures 4.8 and 4.9). In conjunction with the increase in forest cover, the classification indicates a decrease in the amount of barren area. One potential reason for the increase in forest cover could be that after the Nature Conservation Act of 1995 was passed, the government initiated forest regeneration methods which further restricted

Community Property Rights (CPRs) by limiting the forest cover to "official" use only. Furthermore, the rural-electrification project took away part of the need for firewood. Because the rural electrification project reports on nationwide assessment it is difficult to single out a dzongkhag when discussing forestland and firewood consumption.

The Kawang and Chang *Geog* analysis yielded results that were similar to that of the Thimphu city analysis (Table 4.13). The amount of forest area decreased by 4,312.88 ha (8.62%), which is offset by increases in urban and barren areas (Figures 4.10, 4.11, 4.12). The decrease in forest area may be explained by the cutting of forests, which leaves barren areas that are then set aside for future construction projects recommended by the TSP. This is demonstrated by the increase in barren areas on the periphery of the city boundary. Decrease in forested areas can also partially be explained by the fact that the Thimphu city urban built-up area makes up a larger portion of the land use when compared to the *Dzongkhag* analysis.

1990

	City	Geog	Dzongkhag
Forest	69.8	80.94	38.51
Agriculture	0.07	0	0.04
Barren	20.18	14.58	24.28
Urban	9.15	1.8	0.46
Water	0.76	0.1	0.38

1999

	City	Geog	Dzongkhag
Forest	67.51	76.74	51.8
Agriculture	0.92	0.32	0.04
Barren	21.74	14.44	30.11
Urban	9.4	1.85	0.65
Water	0.43	0.11	0.36

2007 (2002 for Geogs and Dzongkhag)

	City	Geog	Dzongkhag
Forest	66.48	72.32	58.04
Agriculture	0.53	0.02	0.16
Barren	21.96	20.21	25.23
Urban	10.29	2.86	0.65
Water	0.74	0.09	0.16

Table 4.11: Land use percentage of total area for three study scales.

*all numbers are percents of total area
**Geog and Dzongkhag numbers will not equal 100% due to the exclusion of the Ice category.

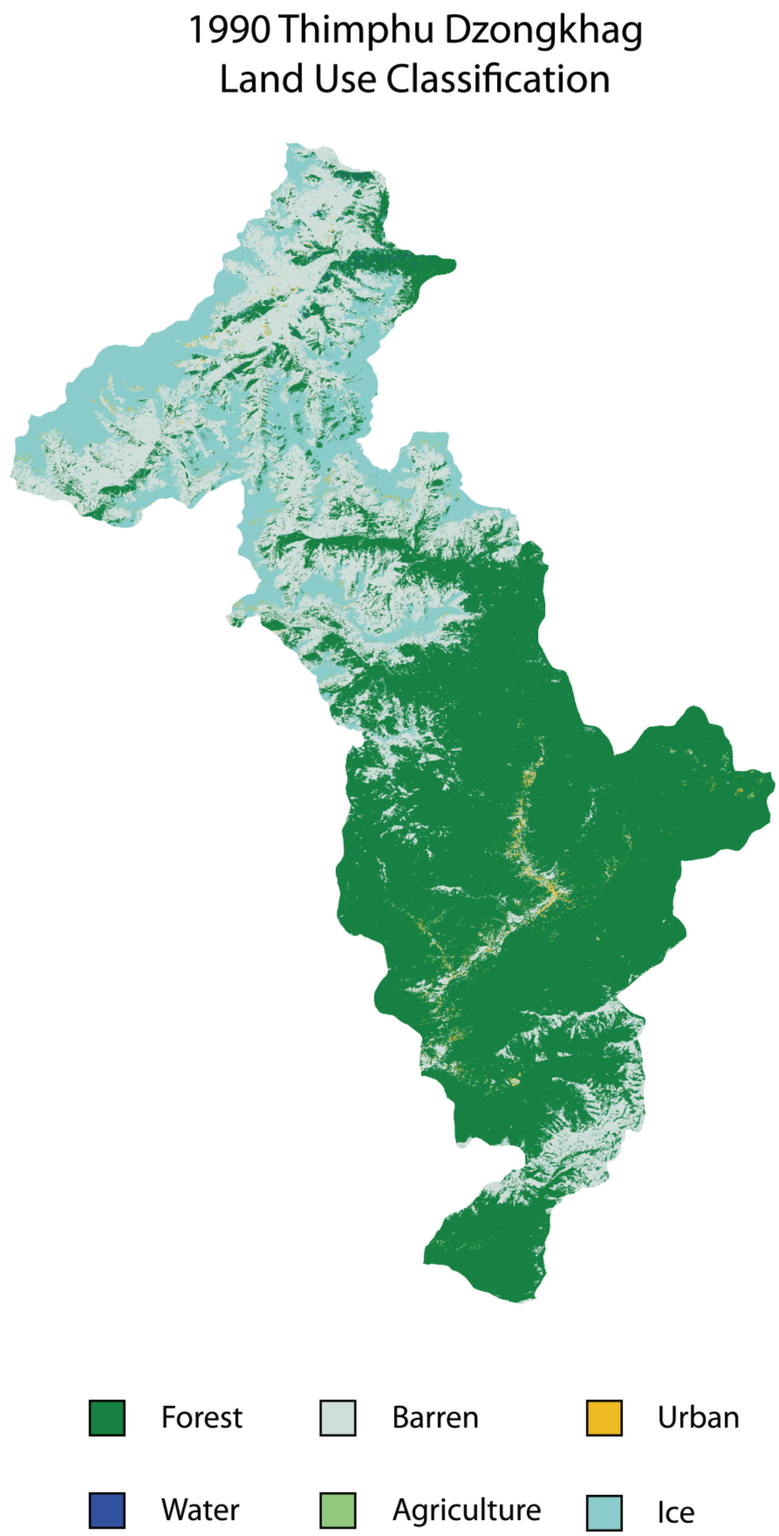


Figure 4.8: 1990 Thimphu dzongkhag unsupervised classification.

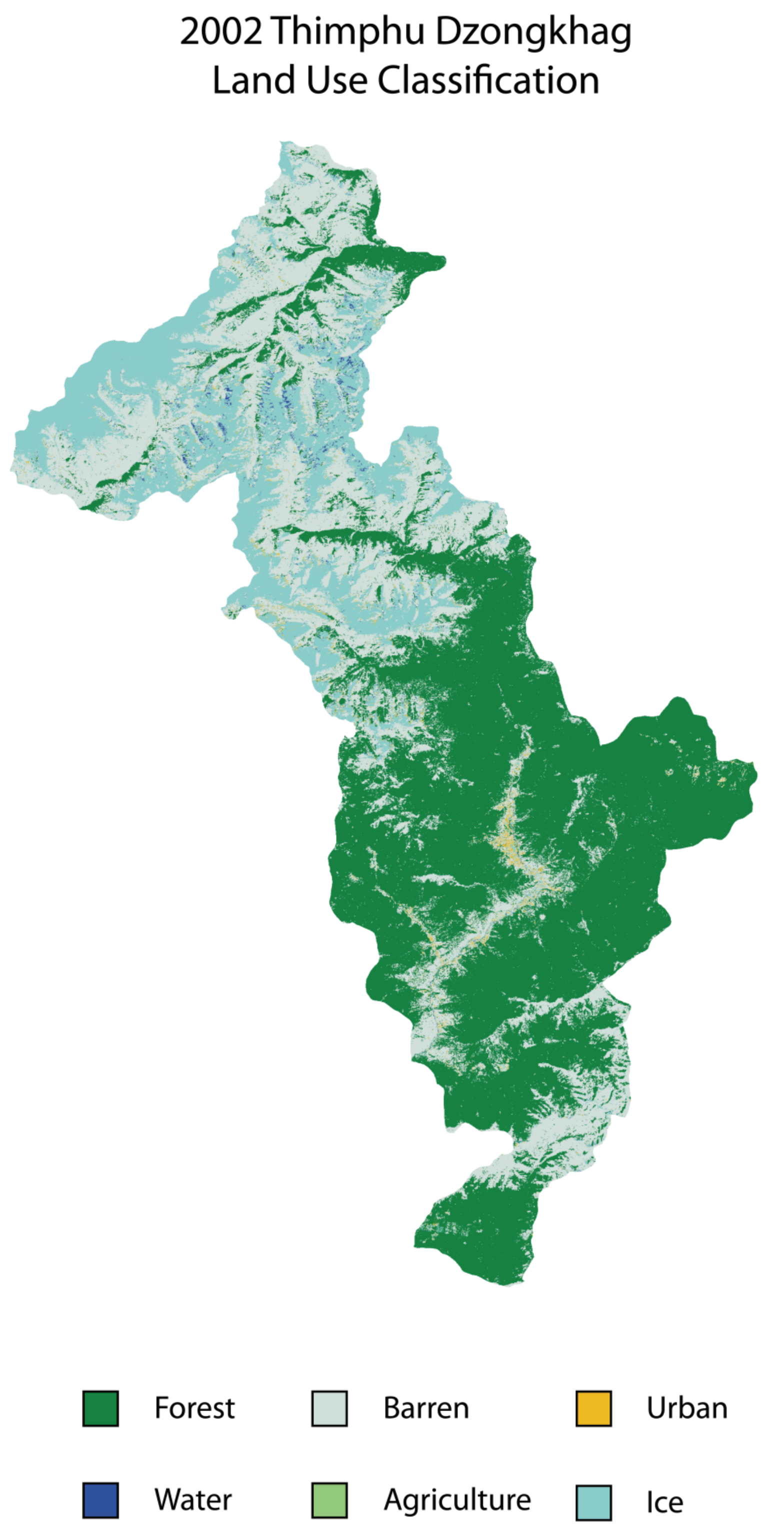


Figure 4.9: 2002 Thimphu dzongkhag unsupervised classification.

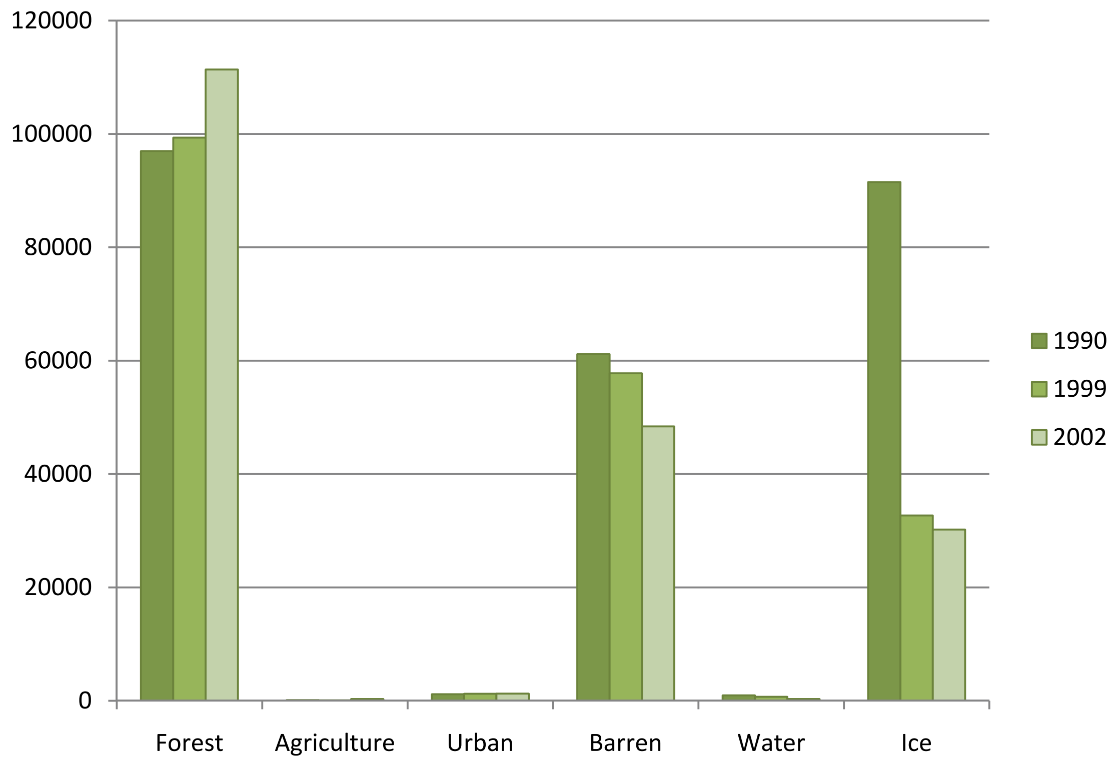


Table 4.12: Thimphu dzongkhag unsupervised classification trends (hectares on the y axis, class on the x axis).

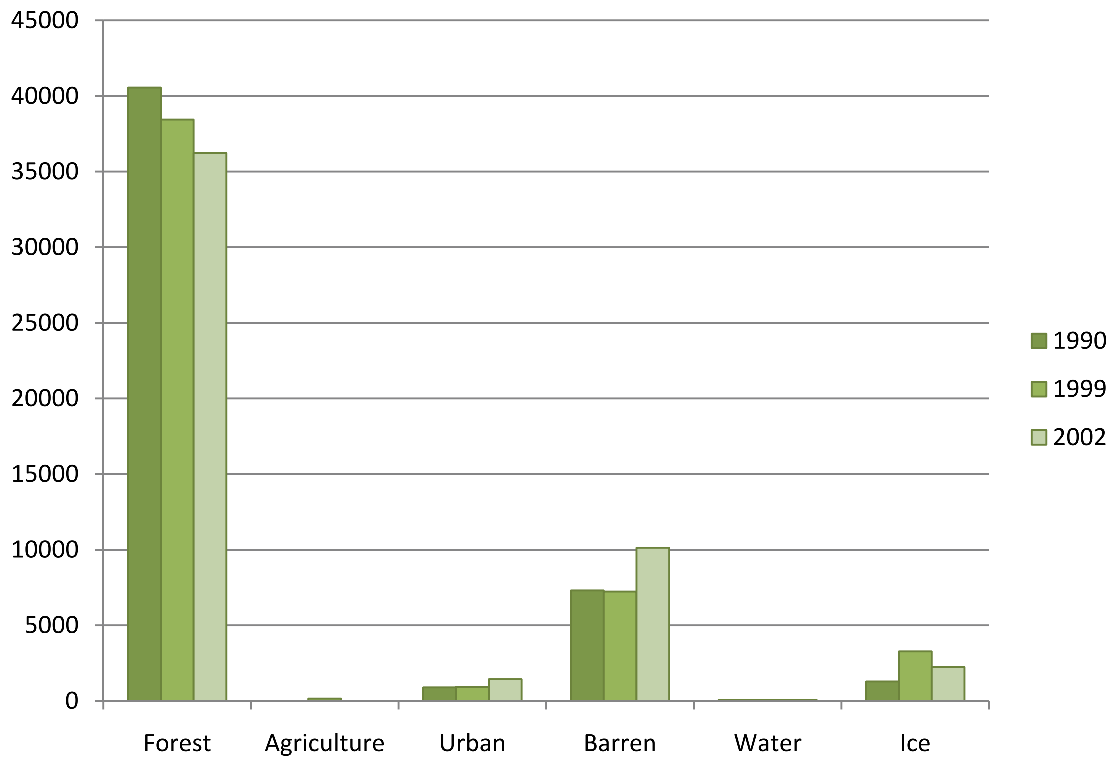


Table 4.13: Kawang and Chang geog unsupervised classification trends (hectares on the y axis, class on the x axis).

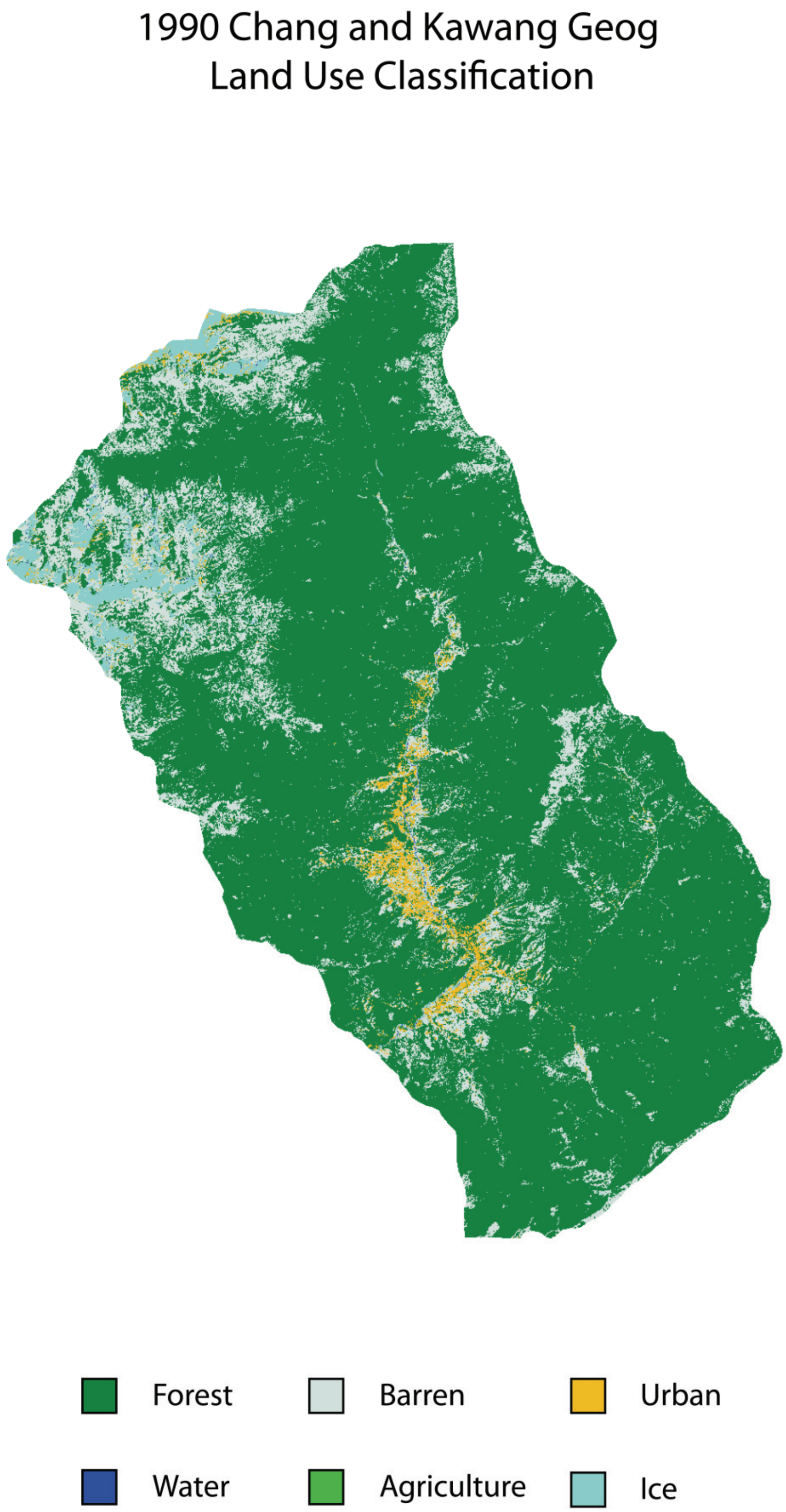


Figure 4.10: 1990 geog unsupervised classification.

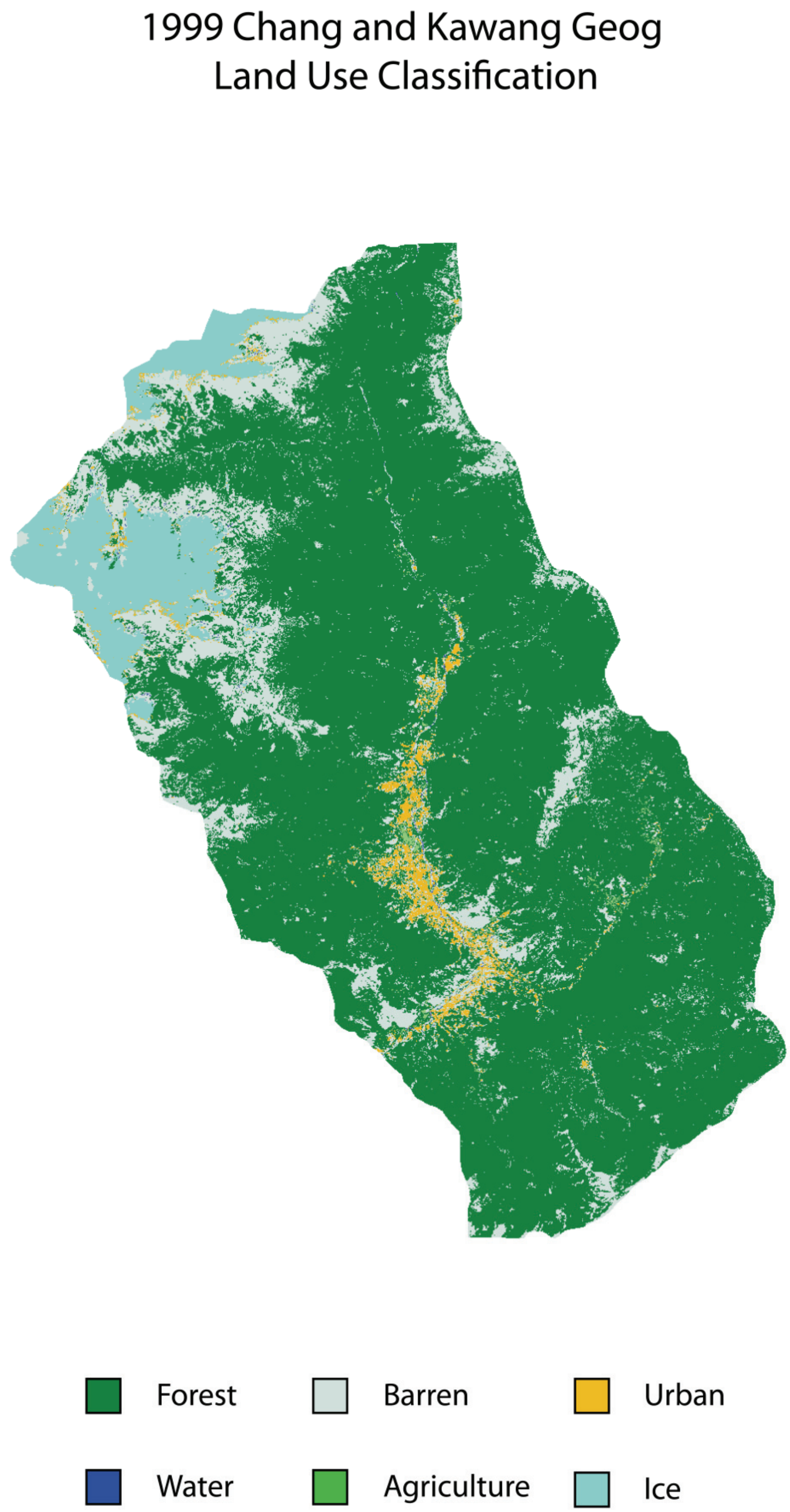


Figure 4.11: 1999 geog unsupervised classification.

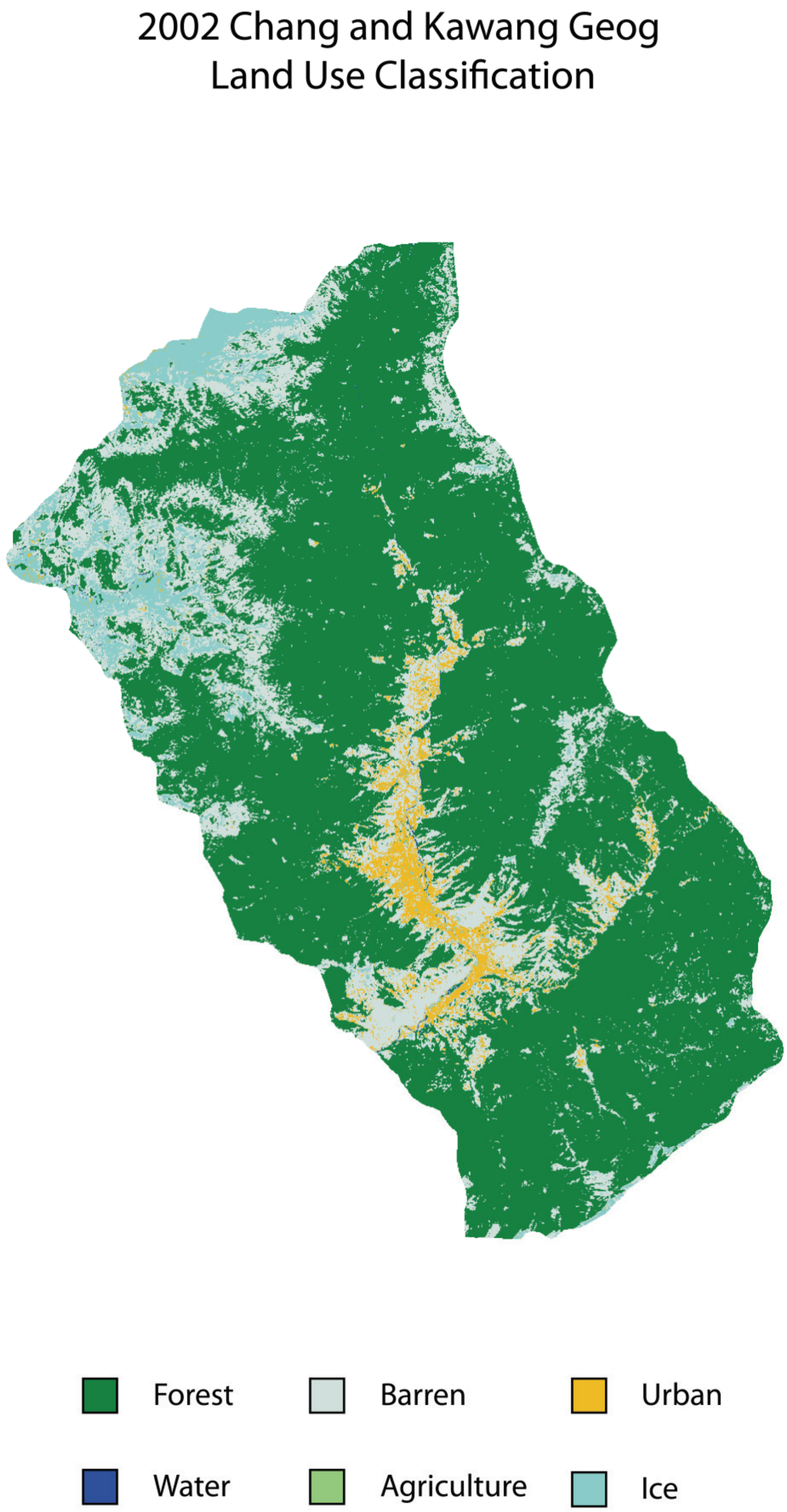


Figure 4.12: 2002 geog unsupervised classification.

4.1.5. Land Use from 1990 to 2007

Major Land Conversions: Barren to Urban

The remote sensing analysis revealed that the biggest land conversion took place from barren to urban built-up areas. From 1990 to 1999, 8.10% of forested areas converted to barren areas. From 1999 to 2007, a 6.8% conversion from forested areas to barren took place. One possibility for an increase in barren areas is that forests are thinned to make room for future growth. Evidence of this is demonstrated in *Motithang* (west), *Dechencholing* (north), and *Simtokha* (south) for years 1999 to 2007. Other evidence is present in the 2002-2027 TSP, the new structural plan laying out Thimphu city growth patterns for the future. As the population increases in the city, more roads and housing are needed. In the last two decades the MoWHS (2004) approved construction projects that include government housing projects, road and parking lot expansion, and conference centers.

Two of the four pillars of GNH, conservation of environment and preservation and promotion of culture, state that the environment must be used in a manner where it is not only sustainable but must take in consideration local customs to preserve cultural heritage. Clearly if there is a reduction of forests, then GNH policy is not working. Furthermore, the guidelines of traditional architecture stated in the pillar promotion of cultural heritage are not met with large construction projects such as the *Taj Tashi*. The *Taj Tashi* is a 6-story 133 room luxury hotel located at the heart of Thimphu. It is an investment by an Indian Taj Hotels Resorts and Places group to accommodate an influx of tourists visiting Bhutan every year (www.tajhotels.com). A modernization imperative by the government is recognized here to “allow” such large scale construction to take place.

Other examples of how the government has turned a blind eye to development is seen in the growth that is taking place in districts to the north (*Dechencholing*), west (*Motithang*), and south (*Simtokha*) of the Thimphu core area. In *Dechencholing* there is a large military installation, in *Motithang* there is substantial presence of affluent residences, and in *Simtokha* the majority of land use is subsidized government housing and a new auto industry plant (Figure 4.13).

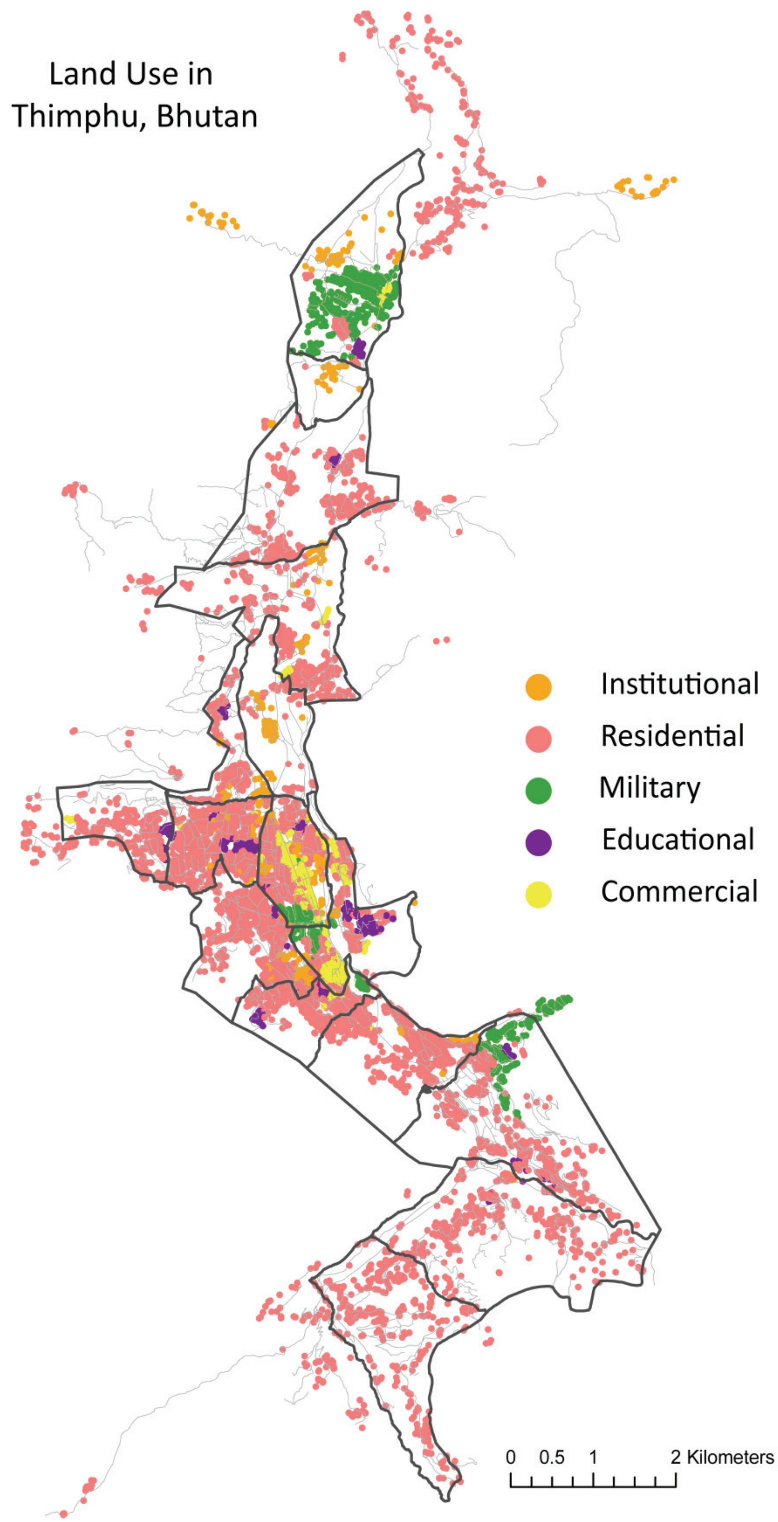


Figure 4.13: Thimphu city land use classification.
*Source: Ministry of Agriculture, Thimphu, Bhutan.

Global Deforestation

It is important to examine deforestation in other countries for comparison of developed and developing world policies to that of Bhutan's forest policies. There are many causes of deforestation at a global scale; rapid population growth, expansion of cropland, and intensive harvesting of forests for fuel wood and wood exports. It is not the scope of this study to examine the causes and effects of deforestation at a global scale. The Forest Resources Division of the U.N. Food and Agriculture (FAO) made available the results of a global inventory of tropical forests areas in Africa, Asia, and Latin America for the first time (Allen and Barnes 1985). Table 4.14 shows total forest cover and deforestation from 1990 to 2005 in various parts of the globe. Countries with the highest levels of deforestation were; Tanzania, Zambia, Zimbabwe, Sudan, Congo (DR), Nigeria, Indonesia, Myanmar, Philippines, Mexico, Bolivia, Brazil, Venezuela, and Australia. For regional and local comparison India, Nepal, Pakistan, and Thailand were added. Deforestation when compared to other countries Bhutan's loss of forestlands seem minimum as shown in Table 4.15. For example, the loss of forest cover in Indonesia was greater than 28 million hectares and in Brazil (over 42 million hectares). It is not reasonable to compare deforestation in Bhutan with countries that are much larger such as the US. However, this comparison provides a sense of scale when examining policies that affects forestlands. Sustainable use of forests is often not familiar to many developing countries where the policy emphasis has been on production rather than protection (Allen 1983). This is the case with majority of African nations (such as Tanzania, Zambia, Zimbabwe, Sudan, Congo (DR), and Nigeria) where forest losses have been greater than 6 million hectares from 1990 to 2005. Even when forest management practices are well known, institutions for forest management are poorly supported such as those in Mexico, Bolivia, and Venezuela. For many years, government of Mexico realized a huge income from logging activities, none of which was reinvested in improved forest management or in the local communities (Bray et. al. 2005). These problems are compounded when local people, due to lack of community property rights, do not cooperate with forest management programs. In Bhutan lack of local participation may be an indication of poorly designed policy or a warning that rural communities have other economic or development agendas as described in section 4.3.

Country	1990 Forest Cover	2000 Forest Cover	2005 Forest Cover	1990-2000 Change	2000-2005 Change	1990-2005 Change	1990-2005 % Change
Nigeria	17,234	13,137	11,089	-4,097	-2,048	-6,145	-35.7
Philippines	10,574	7,949	7,162	-2,625	-787	-3,412	-32.3
Pakistan	2,527	2,116	1,902	-411	-214	-625	-24.7
Nepal	4,817	3,900	3,636	-917	-264	-1,181	-24.5
Indonesia	116,567	97,852	88,495	-18,715	-9,357	-28,072	-24.1
Zimbabwe	22,234	19,105	17,540	-3,129	-1,565	-4,694	-21.1
Myanmar	39,219	34,554	32,222	-4,665	-2,332	-6,997	-17.8
Tanzania	41,441	37,318	35,257	-4,123	-2,061	-6,184	-14.9
Zambia	49,124	44,676	42,452	-4,448	-2,224	-6,672	-13.6
Bhutan	3,495	3,141	3,035	-354	-106	-460	-13.2
Sudan	76,381	70,491	67,546	-5,890	-2,945	-8,835	-11.6
Thailand	15,965	14,814	14,520	-1,151	-294	-1,445	-9.1
Venezuela	52,026	49,151	47,713	-2,875	-1,438	-4,313	-8.3
Brazil	520,027	493,213	477,698	-26,814	-15,515	-42,329	-8.1
Mexico	69,016	65,540	64,238	-3,476	-1,302	-4,778	-6.9
Bolivia	62,795	60,091	58,740	-2,704	-1,351	-4,055	-6.5
Congo (DR)	140,531	135,207	133,610	-5,324	-1,597	-6,921	-4.9
Australia	167,904	164,645	163,678	-3,259	-967	-4,226	-2.5
USA	298,648	302,294	303,089	3,646	795	4,441	1.5
India	63,939	67,554	67,701	3,615	147	3,762	5.9

Country	1990 Forest Cover	2000 Forest Cover	2005 Forest Cover	1990-2000 Change	2000-2005 Change	1990-2005 Change	1990-2005 % Change
Pakistan	2,527	2,116	1,902	-411	-214	-625	-24.7
Nepal	4,817	3,900	3,636	-917	-264	-1,181	-24.5
Myanmar	39,219	34,554	32,222	-4,665	-2,332	-6,997	-17.8
Bhutan	3,495	3,141	3,035	-354	-106	-460	-13.2
Thailand	15,965	14,814	14,520	-1,151	-294	-1,445	-9.1

Table 4.14: Global deforestation (showing top 15 countries and others as reference) and forest cover from 1990 to 2005.

*Source: “Forest Resources Assessment 2005" by the Food and Agriculture Organization (FOA) of the United Nations.

Table 4.15: Global deforestation (1000 hectares) for top 15 countries and other countries for regional and local reference.

*Source: "Forest Resources Assessment 2005" by the Food and Agriculture Organization (FOA) of the United Nations.

The next several sections discuss in depth some of the reasons for land use changes evident in the remote sensing analyses presented in section 4.1. It is important to understand the socio-economics of both rural and urban Bhutan in order to assess the policies that might help meet the goal of sustainable forested land cover.

4.2 Rural Urban Migration and Population Pressures

In the case of Bhutan, as is likely in many other poorer developing countries, the lack of employment and other similar rural issues (which are major push factors for the younger rural population) are further heightened as a result of the out migration. The research conducted in this dissertation revealed that Thimphu *Dzongkhag* received the highest number or percentage of migrants followed by Chhukha. In these *Dzongkhags* the urban centers, Thimphu and Phuntsholing, are ranked highest in population nationwide. In terms of *Geog* migration patterns Kawang and Chang *geogs* had the highest number or percentage migrants. Kawang and Chang *Geogs* are located in Thimphu *Dzongkhags* and Thimphu city is located in the two *Geogs* (Figure 4.14).

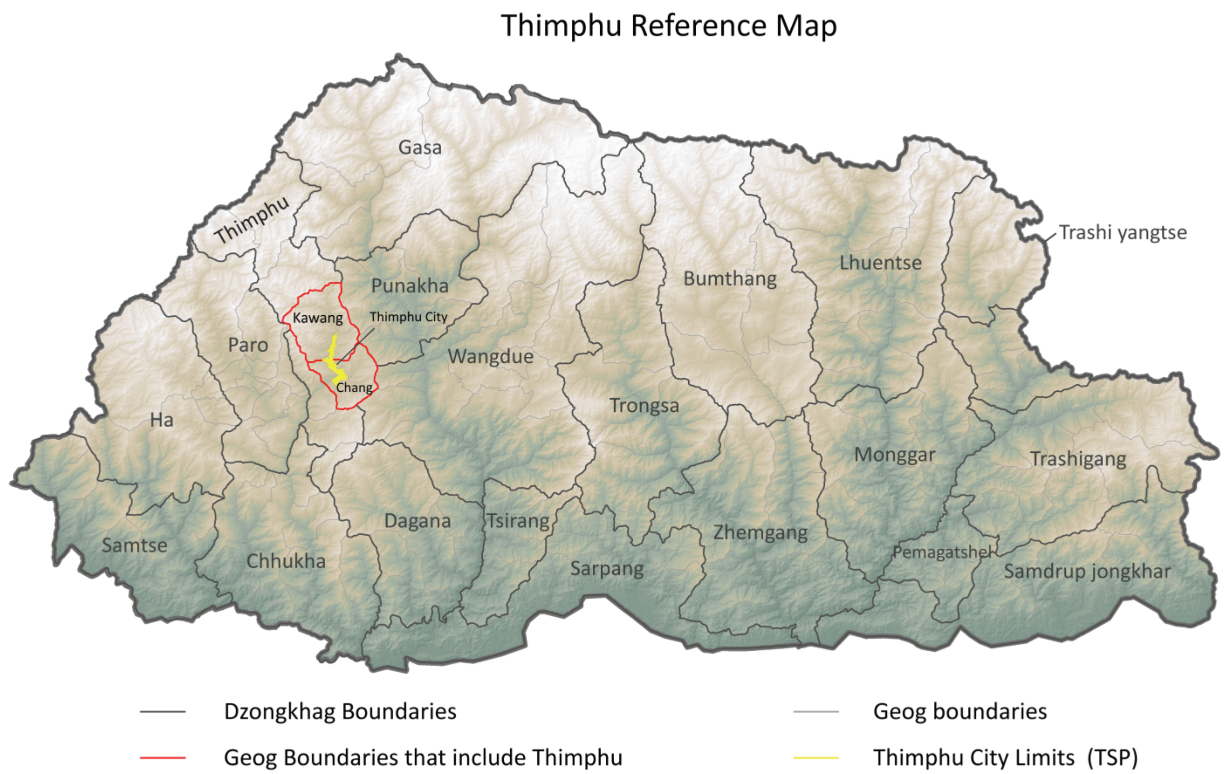


Figure 4.14: Thimphu city and geogs reference map.
*Source: Ministry of Agriculture, Thimphu, Bhutan.

4.2.1. Spatial Distribution of Migration Patterns

Migration Overview

Among the *Dzongkhags*, Thimphu has received the highest number (54,685) of migrants, followed by Chhukha (25,951) and Sarpang (17,997). In terms of out-migration, Trashigang, with a total of 23,802, is the highest, followed by Monggar with 12,871 persons (Figure 4.15). There were a total of 111,770 migrants who have moved from rural areas to the urban, while 19,992 have moved from urban to rural areas. Net-migration in Thimphu has the highest net gain with 39,770 persons, and Trashigang has the highest net loss of 16,697 persons as shown in Figure 4.16 (PHCB 2005).

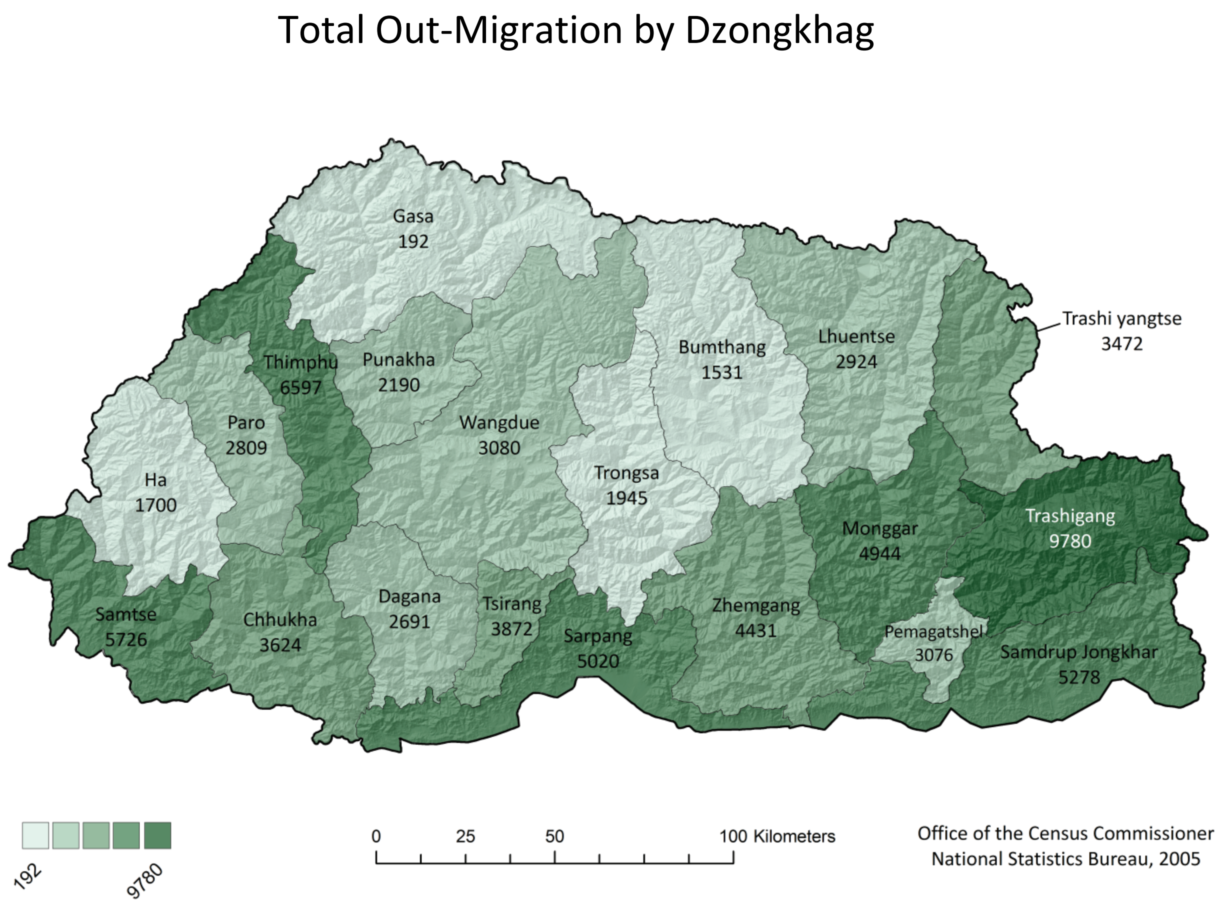


Figure 4.15: Out-migration by dzongkhag using data from the PHCB (2005).
*Source: Ministry of Agriculture, Office of Census Commissioner, Thimphu, Bhutan.

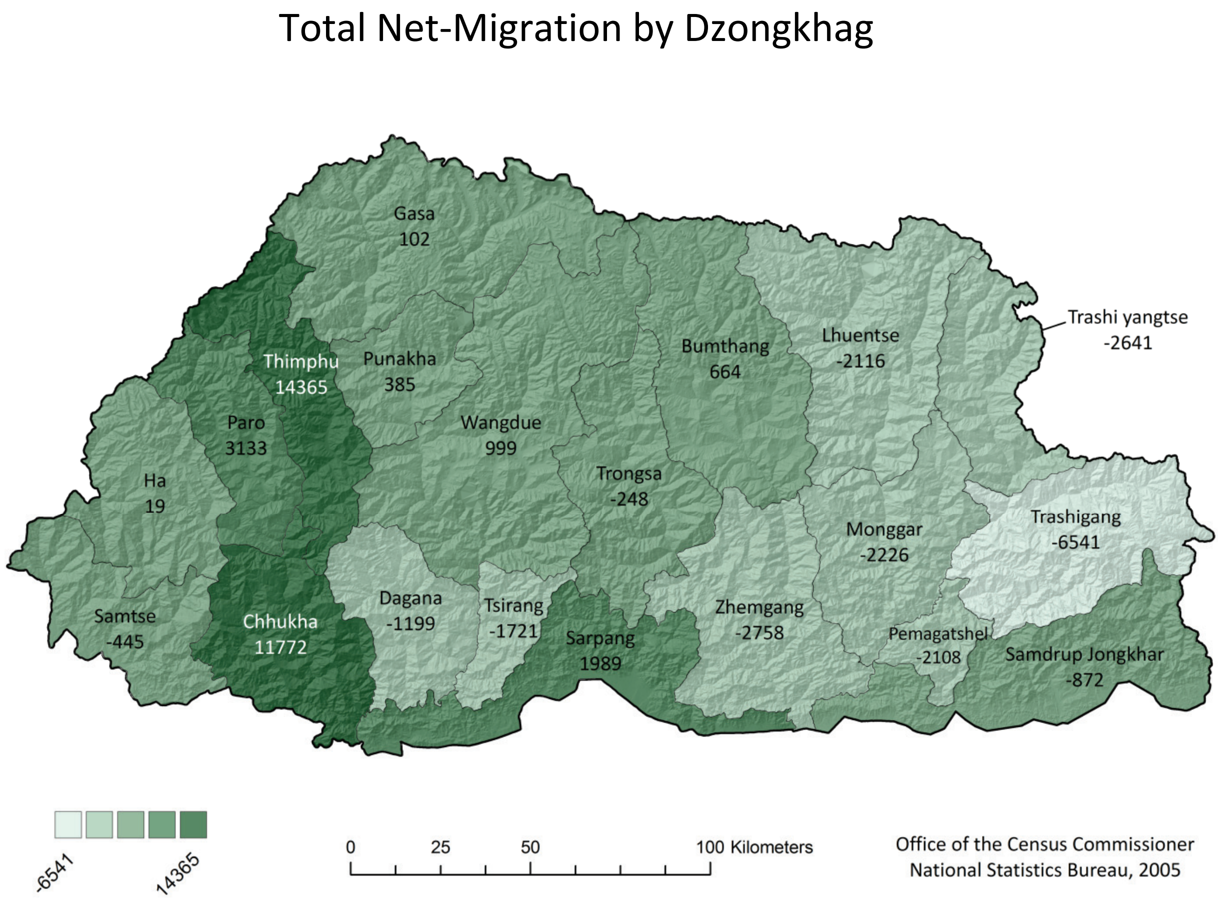


Figure 4.16: Net-migration by dzongkhag using data from the PHCB (2005).
*Source: Ministry of Agriculture, Office of Census Commissioner, Thimphu, Bhutan.

A study by the MoA (2005) describes several reasons for migration in Bhutan. Two broad categories, push and pull factors exists in rural urban migration. On the receiving end, such as Thimphu and other urban areas, pull factors accelerate the process of rural-urban migration. Opposite of that, in the rural areas, push factors are the main motivators. The lack of educational facilities (46%) is the most common push factor. Other reasons for leaving rural areas include; lack of job opportunities (17%), inadequate service facilities (15%), and small land holdings (7%). In terms of pull factors the primary reason for migrating into the city was better employment opportunities (33%). Many of these migrants live with relatives or friends. Other pull factors include; spouse relocated (24%), religious pursuits (9%) and better business opportunities (4%).

Dzongkhag Migration Patterns

It is important to understand the population demographics before discussing migration issues in Bhutan. The actual resident population of Bhutan, using the definition of the PHCB 2005 which stated it measured "population that is known to occupy a specific area for at least a part of the year", surveyed on the census day of April 30, 2005 stood at 634,982 persons, out of which 333,595 persons (52.5%) were males and 301,387 persons (47.5%) were females (PHCB 2005, 17). The most populated *dzongkhag* is Thimphu, with 98,676 persons, accounting for 15.5 percent of the total population, followed by Chhukha, with 74,387 persons (11.7%), and Samtse with 60,100 persons (9.5%). These three most populous *dzongkhags* together account for 36.7% of the total population of Bhutan. The least populated *dzongkhag* is Gasa*,* with 3,116 persons (0.5%), followed by *Haa,* with 11,648 persons (1.8%), and Pemagatshel with 13,864 persons (2.2%). These three *dzongkhags* are all considered to be rural *dzongkhags*. Rural *dzongkhags* primarily have settlements that are less than 10,000 households. Agriculture is the main source of income (PHCB 2005).

Thimphu *dzongkhag* has the largest urban population, with 79,185 persons residing in Thimphu city, accounting for 80.3% of the *dzongkhag's* total population. Thimphu is followed by Chhukha and Sarpang *dzongkhags*, with urban populations of 32,926 (44.3%) and 12,596 (30.3%), respectively (DUDES 2003). With a total surface area of 38,816 sq. km. and a total population of 634,982, the population density of Thimphu is 54 persons per sq. km. Thimphu is the most densely populated *dzongkhag* while the least populated is Gasa with a population of 1 person per square kilometer (PHCB 2005). However, it is important to note that nearly one-third of Gasa *dzongkhag* is covered by perennial snow and ice. Population density of 54 persons per sq. km. is relatively small compared to other capitals around the world. For example, Washington DC's population density is 3,722 sq. km. with the area size of 177 sq. km (US Census Bureau 2008).

Gewog Migration Patterns

The migration trends at both *Dzongkhag* and *Gewog* scale follow similar patterns on the receiving end. At the *Gewog* scale Kawang and Chang located in Thimphu *Dzongkhag* had the highest in-migrants similar to the *Dzongkhag* patterns. The population demographics differ slightly at *Gewog* scale in terms of density along the main road connecting western Bhutan to the east. As noted earlier, the most populated *dzongkhag* is Thimphu and within this *dzongkhag,* Thimphu city is located in two *Gewogs,* Chang *and* Kawang. Chang's total population is 38,586 and Kawang's total population is 38,599. Together, both *Gewogs* account for 83% of the total population for Thimphu *Dzongkhag* (Figure 4.17).

Figure 4.17: Thimphu city population by urban village.
*Source: Ministry of Agriculture, Thimphu, Bhutan.

4.2.2. Push Factors in Migration

Examining the Census Variables

The preliminary examination of several variables in the PHCB can be useful for understanding the push factors of migration. However, it is not in the scope of this study to examine every possible reason as to why rural to urban migration is taking place in Bhutan. The rural communities face many problems such as market access, insufficient means of transportation, lack of business expertise, low levels of literacy, acute shortages in modern skills, poor nutrition and health indictors, gender disparities, and inequitable access to better paying employment opportunities within their environment (ADB 2001). Facing economic and educational problems in the remote rural areas, the younger generation believes that it is necessary to leave their communities in order to accomplish their economic and social goals (MoA 2005).

The study undertaken by UNESCO (2006) indicates that many migrants consider relocation to urban centers as a measure of success. Seven variables were examined from the PHCB at a *Dzongkhag* scale to assess the quality of life in rural area and possible reasons for migration to urban areas. These variables include water facilities, toilet facilities, health care facilities, distance to major motor roads, source of lighting, source of cooking, and media access.

A total 84.2% of the households in Bhutan have access to piped water facilities (22.7% within the house and 61.5% outside the house). In the urban areas, 53.7% of household reported that they have piped water within the house, but only 9.2% do so in the rural areas. Of the total rural households 69% have access to piped water outside the home and 19.9% still depend on spring, river, or pond as their main source of drinking water. With limited access to water indoors, water facilities and access to these facilities can be considered a push factor from rural areas.

In terms of toilet facilities it is reported that 89.2% of the total households in Bhutan have access. According to the census 49.8% of the households that have access to toilet facilities use pit toilet followed by independent flush toilet inside house. Among the households that use independent flush toilet inside house, 32.3% are in Thimphu *dzongkhag* and 22.4% are in Chhukha *dzongkhag*. Majority of these are in urban areas of Thimphu and Phuentsholing cities. In the rural areas, 64.1% of the households use pit, which is equivalent to an outhouse with a hole dug in ground.

ADB (2001) identified lack of access to health care may be another major push factor for persons to move from rural areas to urban areas. PHCB's data on visits to a health care facility indicate at least one member of the household that visited a health facility for any treatment in the past year. If there were no visit, they were asked the main reason for not visiting the facility. It is observed that 91.1% of the households in Bhutan visited health facilities in the past one year, of which 89.9% are in urban areas as compared to 1.2% of the households in the rural areas visited health facilities. Of the

10.1% households that did not visit, majority of the households reported that the facilities were too far.

Distance from motor road has the potential to be a major factor in persons desiring urban living over rural life (ADB 2001). Distance from motor road in the PHCB refers to an approximate time taken to get from the nearest motor road to the respondent's house. Among the households, Samdrupjongkhar, Samtse and Trashigang *dzongkhags,* many were reported to be more than six hours walking distance from the nearest motor road. In the urban areas, 99.5% of the households are within half an hour walking distance from the motor road, where as only 47.1% of the total population in the rural areas are within a half hour walking distance. There are 13.9% of the rural households which are more than six hours walking distance from the nearest motor road.

Another major push factor to move from rural to urban areas is access to using electricity as a source of lighting. It is reported that 57.1% of the total households in Bhutan use electricity as their main source of lighting followed by firewood and kerosene with 36.5%. In the urban areas, 96.4% of the households reported that they use electricity as their main source of light in comparison to 3.6% of the rural households. The PHCB (2005) reported that most households in rural areas depend on firewood as their main source of lighting.

With regards to the source of cooking fuel, two main sources were considered since many households use more than one source. Majority of households in Bhutan use firewood (37.3%) either as the primary source or as a secondary source. This is followed by electricity (30.6%) and Liquefied Petroleum Gas (LPG) (25.6%). In the urban areas, electricity is used by 46.5% of the households while LPG is used by 43.6% of the households. Among the rural households, 56.4% use firewood while 21.4% use other sources (Appendix D).

Western and Eastern National Region Dilemma

Other influences in rural-urban migration potentially come from the fact that the country of Bhutan is divided into a more developed western portion and a rural, less developed eastern portion. The majority of urban centers such as Thimphu, Phuntsholing, and Paro are located in western Bhutan. It is much more difficult to travel in eastern Bhutan because of the terrain and road conditions – and lack of roads - than it is to travel in the western part of the country (Figure 4.18). The government tries to mitigate this imbalance by concentrating economic development projects, such as micro-hydropower production, in the rural eastern part of the country. In general road construction is funded by grants from India and other outside entities such as the Asian Development Bank, pursuant to the relevant Five Year Plan developed in conjunction with outside consultants and planners. Roads are largely constructed by Indian work crews, maintained by Bhutanese under the auspices of the MoWHS.

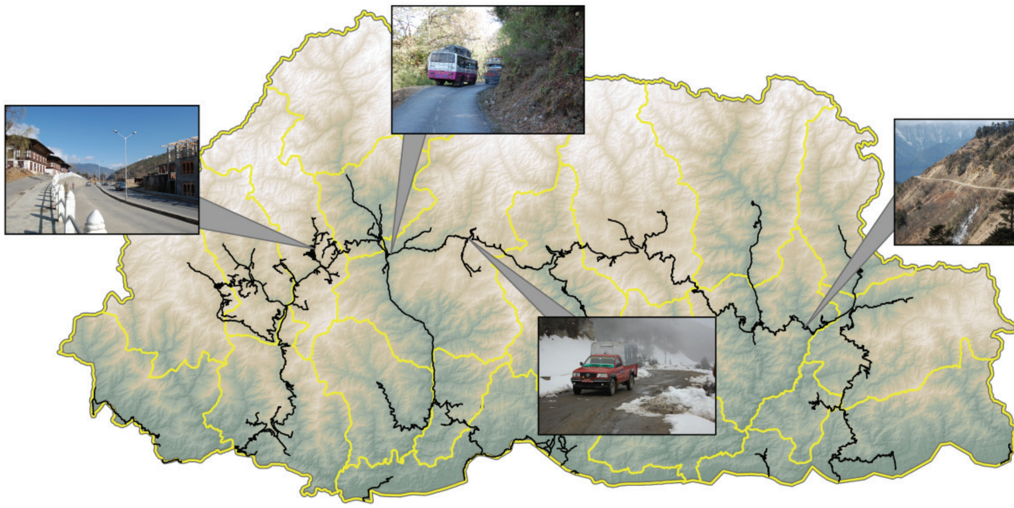


Figure 4.18: Illustrations of Bhutan's rugged terrain over its limited infrastructure system (Source: Ministry of Agriculture, Thimphu, Bhutan; Photo credits: Mayur A. Gosai).

4.2.3. Migration and Development Policy

Micro-Hydropower Generation

Support from the central government for reducing rural-urban migration comes from hydropower and construction projects throughout rural Bhutan. While there are no "official" policies or national decrees in place that clearly state that hydropower construction projects will reduce migration, it is inferred in final project reports by the Ministry of Finance (MoF 2007). There are two key issues when examining hydropower and employment in the rural areas. First, hydropower generates too few jobs for the growing number of young job seekers. Second, Bhutan uses large amounts of external migrant labor. The proximity and relationship of India to Bhutan has significantly impacted the Bhutanese labor supply. Much of the construction work is being done by Indian migrant labor. Alistair Lawson of the BBC News (2002) indicated that, "Many young Bhutanese consider themselves too well-educated to do menial work, which is why the country has employed thousands of Indian expatriates to do blue-collar, building and road construction work." More private sector activity is essential, both for jobs and economic diversification. Until Bhutan employs Bhutanese, it will be difficult to address migration in terms of employment in rural areas. Furthermore, while micro-hydropower projects addressed sustainable use of land, it did very little in terms of providing employment in the rural areas.

Rural-Electrification Project

The rural electrification program under the Government's Seventh 5-Year plan was funded by the Asian Development Bank (ADB) during the period 1992–1997. The Ministry of Agriculture (MoA) recognized the need to conserve natural resources and reduce the rate of forest depletion. The primary goal of this project was to provide a gradual replacement of electricity for other types of fuel in rural areas. The majority of people living in rural areas depended on pinesap, wood, and imported kerosene for cooking, heating, and lighting. The secondary objective was to provide a basic infrastructure to support Bhutan's transformation from a subsistence economy to a market economy. The lack of electric power is a major bottleneck in achieving the country's development goals. Bringing electricity to the rural areas would improve the living standards of rural communities and possibly minimize the rate of migration. At the time of project assessment in 1995, firewood accounted for about 77% of energy consumption; 80% of the population did not have access to electricity (ADB 2003). Providing electricity from the grid to remote villages would be expensive as shown in Figure 4.19, primarily due to the fact that villages are scattered throughout rural Bhutan. This project's primary goal was achieved only in those rural areas where electricity was able to be provided however majority of rural areas do not have electricity. At the end of the project in 2000 the rural electrification ratio in the country increased only 4% from 20% to 24%. Notably the project did not have a significant impact in other rural parts of Bhutan.

Despite the government's best efforts with policy and other means migration still continues. To discourage and slow migration, government policies need to address issues such as: access to land, microfinance, and skills development. If poverty reduction and migration reduction are key objectives, the project needs to be accompanied by other efforts that increase their access to markets, skills, and seed capital.

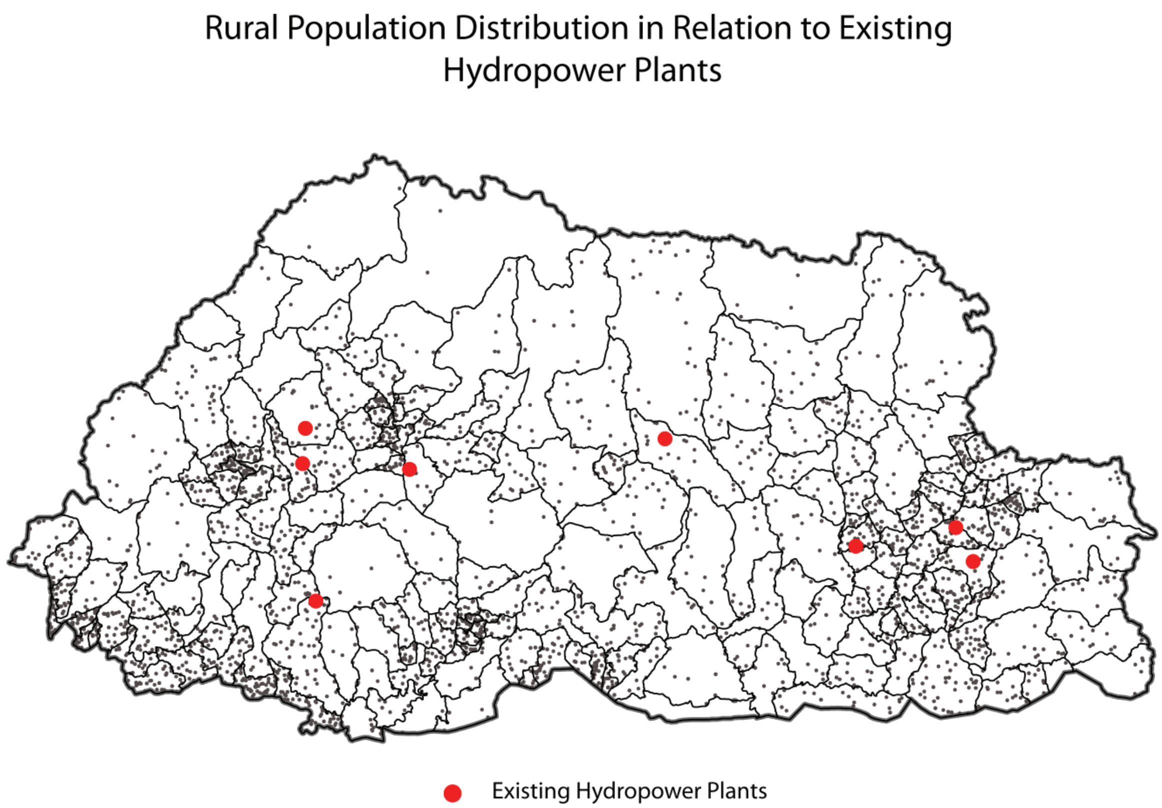


Figure 4.19: Rural geog population distribution in relation to existing hydropower plants. (Source: Ministry of Agriculture, Thimphu, Bhutan).

Mechanization

As stated earlier, many young Bhutanese consider themselves too well-educated for blue-collar work. One solution to this issue was to mechanize the farming industry. One of the major disadvantages in Bhutan is that farming is much more difficult to mechanize given the very steep hillsides used for many farms, limited quantity of flat riverside land, and shallow, rocky soils. The Ministry of Agriculture supplied motorized tillers for communities. These were introduced to Bhutan by the Japanese, who faced a similar problem of inadequate rural labor after rural urban migration. Many of these machines are used for transportation rather than for direct farming needs, reducing their impact on sustaining or enhancing farm production (Figure 4.20). This difficulty in mechanization results in more work for fewer (and older) people when the younger cohort leaves the farm. It introduces significant challenges to maintain current production levels and even greater challenges to increase farm production or to make it commercially viable.

The Department of Agriculture has undertaken some demonstration programs in model fields to introduce more commercially oriented, lower labor intensive farming such as fruit trees whose produce is destined for export. In rural areas, there is a need to encourage farm households to shift from subsistence to a commercial orientation, develop agro processing, and expand off-farm employment in cottage industries, local handicrafts, and textiles. These measures can only be achieved by improvements in the transport and communications sectors. The national economy needs to be integrated with the private sector, which will enable the environment to boost the efficiency of the financial sector and develop human resources which will potentially reduce rural-urban migration.

Figure 4.20: Examples of mechanization in Bhutan.
(Photo credits: Mayur A. Gosai)

4.3. Economic Pressures

Due to the unique GNH philosophy and the importance of forest resources in increasing the GDP, Bhutan is in a unique situation. The country must try to decrease their dependence on forest resources (maintain a national forest cover of 60%), while working towards increasing their economic status, which requires a delicate balance between government policies and open market access. The Bhutanese have tried a number of alternatives to their timber economy, including hydropower and non-wooded forest products (NWFPs), and their advantages and disadvantages are described in further detail in this section.

4.3.1. Timber Exports

Issues of Sustainability in Timber Exports

The need to promote sustainable uses has led to more flexible provisions in the forestry legislation. Since the creation of the Forest Act of 1969, the National Forest Policy of 1974, and the Forest and Nature Conservation Act of 1995, the government and the national assembly appropriated multiple roles for forest resources. None of these acts addressed other complex issues such as timber harvesting under government subsidiary programs, leases for commercial plantations, and supply of raw material to wood based industries. These acts however, gave substantial power to the forest officials to protect, manage, and control access to the forests. Furthermore, Section 1.1 (Proportion of Forest Area) in the National Forest Policy of 1974 stated that a minimum of 60% of total land area must remain as forests. The Ministry of Agriculture (MoA) was given the authority to complete a comprehensive survey of land use in Bhutan for the first time.

The MoA took 15 years to complete a national land use inventory using ground based surveys and basic remote sensing techniques, the results from which are shown in Figure 4.21.

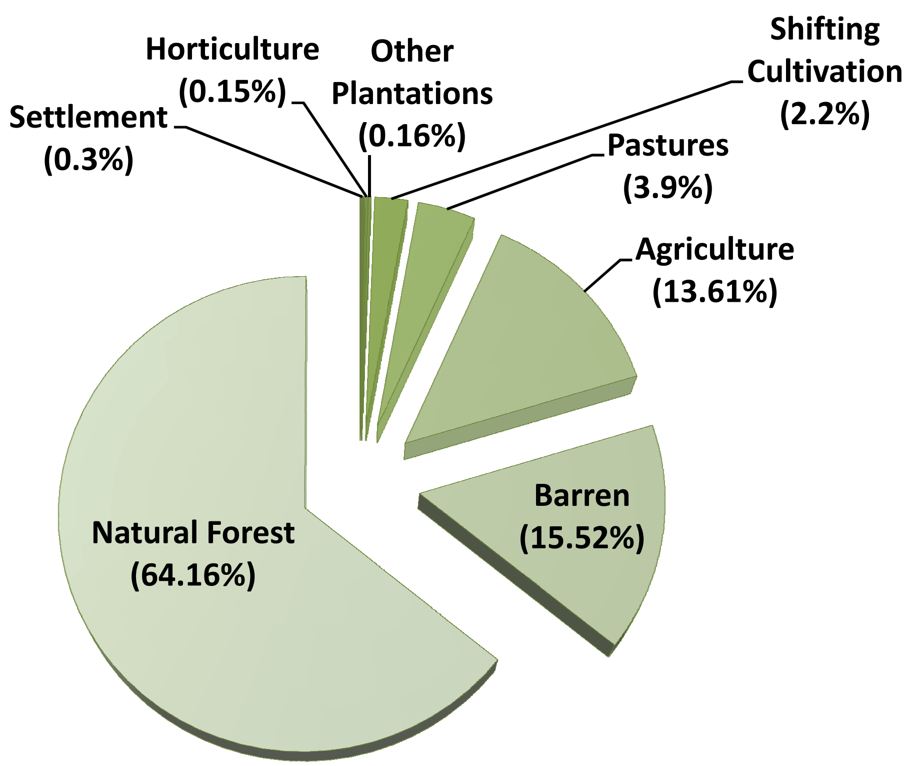


Figure 4.21: National Land Use from the Ministry of Agriculture.
*Source: Ministry of Agriculture, Thimphu, Bhutan.

Forest is the main land use (64.16%) followed by agriculture (13.62%). Though the MoA has shown that a minimum of 60% is met, it has carefully defined what it considers as "National Forests". As seen in Figure 4.22, the *Jigme Dorji* National park's boundary extends into Thimphu city boundary. Furthermore, the MoA's basic definition of "National Forests" does not consider canopy cover, tree height, harvested forests, or species in their national assessment. Since enacting the National Forest Policy of 1974 the government is contemplating the idea of generating greater revenues from forest products.

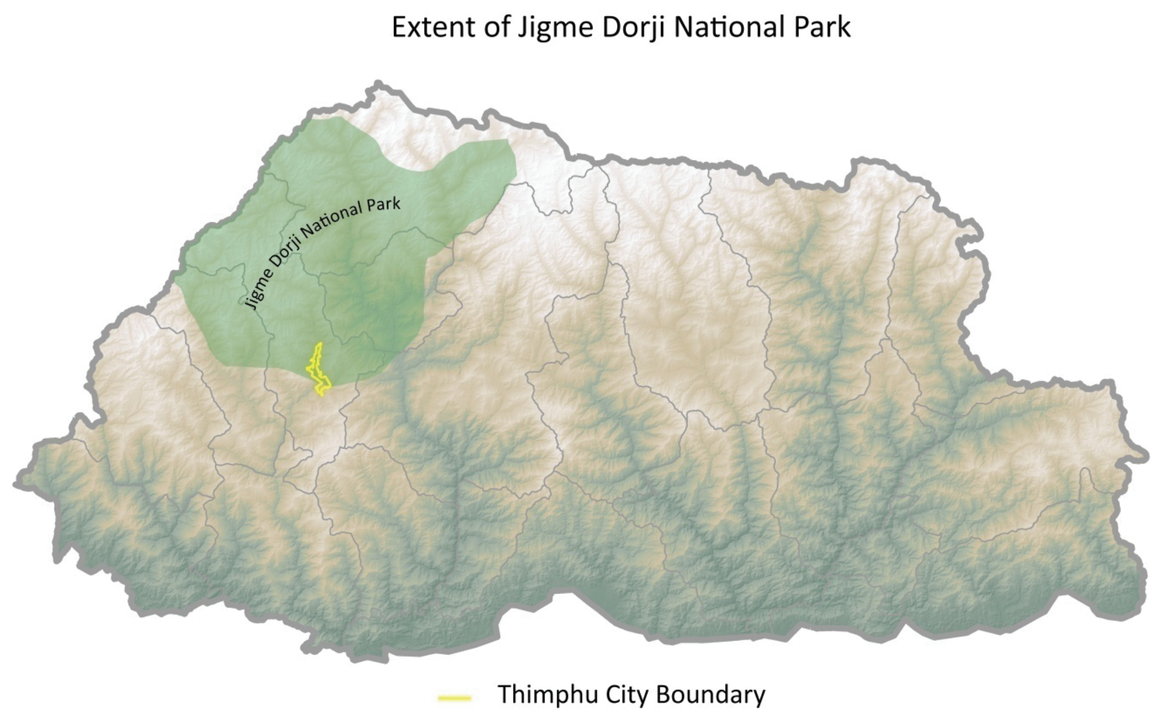


Figure 4.22: Reference map of Jigme Dorji National Park extending into the Thimphu city boundary.
(Source: Ministry of Agriculture, Thimphu, Bhutan).

Table 4.16 shows income from forests from 1963 to 1974. The Forest and Nature Conservation Act of 1995 recognizes that the current trend of deforestation cannot continue if the forested areas are to remain at the mandated level of 60%. To replace the timber industry the government started to look towards hydropower generation for exports in the early 90s. Hydropower is generally considered to be more sustainable than the timber industry in terms of protecting forested areas; however, it does not come without costs.

Revenues from Forests (1964 - 1974)

Year	Ngultrums	Dollars
1964	1002000	74960
1965	882000	53760
1966	803000	61400
1967	1085000	41400
1968	1207000	44400
1969	904000	36160
1970	1110000	48280
1971	1035000	43400
1972	1535000	32120
1973	1344000	35280
1974	1874000	40080

Table 4.16: Revenues from forests in Ngultrums and Dollars.
*Source: Ministry of Agriculture, Thimphu, Bhutan.

Hydropower and the Economy

Prospects for future hydropower exports are promising (ADB, 2007). Located in the Himalayas and close to India with its growing demand for power, Bhutan is planning to capitalize on its hydropower potential (Figure 4.23). After construction began for the Tala hydropower plant in 1997, the construction industry dominated the GDP (Gross Domestic Product) and its growth until 2006.

When the Tala hydropower plant was fully operational, additional power production added to GDP growth. The internal revenue collected during the fiscal year (FY) 2006-2007 was Nu 10,082 million ($214 million US dollars) as compared to Nu 6,902 million ($146 million US dollars) of FY 2005-2006. The increase in internal revenue of Nu 3,179 million ($67 million US dollars) over the previous FY is an increase of about 46% adding 6.8% to the GDP. The increase is credited mainly to the Tala hydropower project which alone contributed Nu 1,800 million ($38 million US dollars) to government revenues by way of exporting hydropower to India (RGoB 2008). There are other hydropower projects under construction throughout the country.

Power Plant and Line Distribution

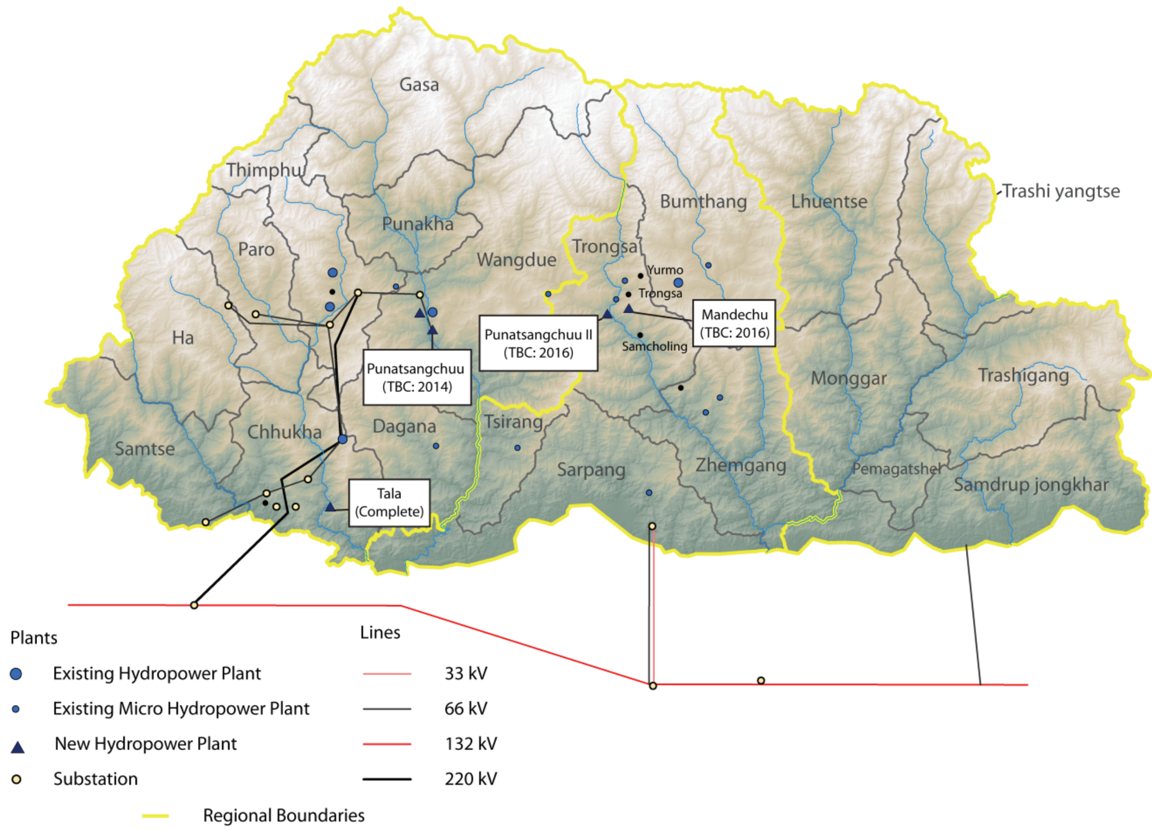


Figure 4.23: Bhutan power plant and power line distribution.
*Source: Ministry of Agriculture, Thimphu, Bhutan.

Punatsangchhu I hydropower project (1,095 MW) is under construction, scheduled for completion in 2014. The Punatsangchu hydroelectric project runs along the course of the Punatsangchu river, downstream from Wangduephodrang town. Mangdechu (670 MW) and Punatsangchhu II (990 MW) projects will be completed by 2016. These projects will be located at Chuenjugpang, about 5 kilometers from Trongsa towards Zhemgang. The main power house for Mangdechu and Punatsangchhu will be located at Yurmo and the power shafts at Samcholing (MoF 2006). These three projects will eventually take total national generation capacity to 4,235 MW. Assuming that Tala's full operation and the building of the new projects progresses on schedule, the Ministry of Finance predicts GDP growth should stay in double digits, at 14.4% in fiscal year 2009 but fall to 7.2% by FY2016. The main reason for the decline is the lack of revenues from the construction industry. The MoF anticipates that the new hydropower stations (Punatsangchhu I, Mangdechu, and Punatsangchhu II*)* will be drivers of growth as demonstrated by the construction of Tala hydropower plant.

Even with a substantial increase in GDP, because the hydropower sector employs few people, job generation in other economic sectors will remain crucial for development and stability. Unemployment is likely to increase especially among the growing number of young people entering the labor force. The private sector needs to be a key source of job generation, but the government first needs to tackle a variety of obstacles including: lack of skilled labor, cumbersome labor practices, inadequate infrastructure, difficult access to land, and the high cost of finance (Kuensel Online, 2007, 2009).

Timber Exports and GNH

Gross National Happiness (GNH) serves as a guiding principle for socio-economic development. To summarize, these principles include the four major areas identified as pillars. They are;

1. Sustainable and equitable socio-economic development,
2. Conservation of environment,
3. Preservation and promotion of culture, and
4. Promotion of good governance.

A focus in GNH-based public policy is the fundamental search for balance, both within and between the pillars. For example, it is not satisfactory that an increased annual economic growth is achieved; it must be accomplished in a manner that protects the environment, as stated in "conservation of environment" pillar. The National Forest Policy of 1974 recognizes forests as one of the major natural resources of Bhutan and they play a critical role in the physical balance with economic development of the country. As stated earlier the government took measures to protect the forests by diverting national revenues from timber industry to hydropower generation. Other means of generating revenue such as the exports of non-wooded forest products (NWFP) were explored.

4.3.2. NWFP Exports

Identifying NWFP in Rural Bhutan

With 69% of the population living in rural areas, the non-wooded forest products (NWFPs) play an important role in the daily lives and overall well being of the Bhutanese people, especially among the rural farming community. NWFPs are a major source of income for these people. Other incentives include: food, medicinal and aromatic products, fodder, fiber, and even local construction. The MoA (2000) identified that 42% of households in Bhutan use bamboo resources for a variety of purposes, with 21% of households harvesting mushrooms from the wild, and 38.6% of households engaging in fern top harvest during summer months. Farmers from Monggar, Lhuentse, Trashigang, and Trashiyangtse earned an income worth Nu. 51,247,045 (approximately $1,281,176 US dollars) over a period of 10 years (1994-2004) from the sale of lemon grass oil according to reports from the MoA (2006).

However, NWFP development is constrained by four major factors. First, the limited arable land (8% of the total land area) is further restricted along with the loss of some of the most productive agricultural lands to urban development. Second, most agricultural lands are spread around small, remote settlements on hill slopes and valleys. Thus a limited access to markets is realized, with a low potential for mechanization as described in section 4.1.3. Third, the rural population of Bhutan has to make a living on an average income of less than half of that of the urban population (IMF 2004). This is potentially leading to rural-urban migration thus creating shortages of labor, which subsequently increases the cost of production of agricultural goods as described in Section 4.1. Fourth, the possibility of natural disaster (monsoon, floods, and landslides) further reduces the margin for the highly integrated, diverse, and labor-intensive farming systems creating issues in production, access, and market.

Production-Access-Market Issues

Bhutan is landlocked, with a rugged terrain of high mountains and deep gorges that pose unique transport challenges. Roads are the only means of surface transport for goods and passengers. Certain roads become difficult to drive on during winter months on mountain passes and during the rainy (monsoon) season (June, July, August, and September). Landslides are common during the monsoons, further restricting access to remote and rural areas. The two aircraft fleet of Druk Air, the only national flight carrier, is the only means of air transport to world markets. One issue with Druk Air is that it has a single runway and airport operating in Paro, which is located in western Bhutan. Because of rugged terrain, a journey from Trashigang (eastern Bhutan) to Paro can take up to two days, even in fair weather. So, even if a farmer can bring the product to Paro it would be rather expensive to fly it to world markets – hence the importance of alternative transportation such as roadways for truck transport.

Community Property Rights

An effort to decentralize the management of forest and natural resources in Bhutan is underway (Rizal 2001). However, decentralization efforts are restricted by policies such as the National Forest Policy of 1974 that are decades old. Often, these policies clearly state that the government assumes total control over all forest lands that are not registered as plots. For example, part one of the National Forest Policy of 1974 states that "the entire forests belong to the State and there should not be any private right to any part of them", clearly strips communities of any property rights (MoA 1974, p. 1). Furthermore, part 1.2. (Demarcation) states that "the present hindrance in implementing quick and efficient demarcation has been the existence of local rights. These local rights vested with the population will be purchased, denied or admitted in whole or in part as deemed necessary by the Government for facilitating the programs of demarcation," give evidence that the government at anytime can deny rights to any property. The loss of community property rights in resource management weakens a sense of social structure and often leads to a process of negligence or misuse. Parts of the rural community no longer feel concerned about environmental matters. They migrate to other areas or try to assimilate within urban settings. The result of this process weakens the social structure of a community, which in turn leads to fragmentation of society and degradation of cultural values (Thinley 2005).

4.4. Summary

In summary, examining the three focus areas in this research project serves several purposes. First, it was necessary to use remote sensing for identifying areas that underwent land use change at both the *Dzongkhag* and city scale. The remote sensing analysis results were examined in conjunction with several policies to making an assessment of land use in Thimphu *Dzongkhag*, *Gewog,* and city scales. Results indicated an increase in urban built up areas of 28.62 ha, and a decrease in forests by 261.82 ha, which was projected to be linked based on the idea that forested areas are being reduced to facilitate urban expansion to accommodate the population increase from both in-migration from rural areas and basic population increase. Second, examining rural-urban migration using GIS helped to identify *Dzongkhags* and *Gewogs* with the highest and lowest number of migrants as discussed in section 4.2.1. The methodology utilized in the shapefile and data generation was elaborated in section 3.2.2. The continued reduction of the younger, more productive work force from the rural areas to the urban areas is a proxy measure for slowed progress toward development and a weakening of family cohesion. Both of these have traditionally been extremely important to the Bhutanese culture and the aspirations toward GNH (Thinley 2005). Within the next decade rural areas of Bhutan will see a dramatic reduction in population while the urban areas will continue to increasing in population (Samten Wangchuck 2007). PHCB data from three major categories (health, education, and household/housing characteristics) were analyzed to examine population pressures from rural-urban migration. GIS was used to generate maps showing total and net migration at both *Dzongkhags* and *Gewogs* scales. Finally, land use land cover accuracy assessment was crucial in determining the effectiveness of government policies and practices essential in directing sustainable forest cover in the Thimphu valley. The final chapter of this research will illustrate how the hypotheses proposed in Chapter 1 and theoretical frameworks based on the literature review in Chapter 2 were tested by the methodology projected in Chapter 3 to conclude this research.

CHAPTER V

CONCLUSIONS

Government policies on land use in Bhutan sought to dramatically impact the sustainability of forest cover. To test the proposed hypothesis on land use change, it was necessary to identify discrepancies in the national forest assessment for testing the deforestation process in Bhutan. Forest environments are closely associated with Bhutan's economy; however, increasing urban development taking place in Thimphu valley is permanently modifying its forest landscape. The recent and ongoing population growth along with timber as one of the major revenue generating industries places extra strain on forests near settlements, especially given the development level of Bhutan which places demand on wood for fuel, heat, and construction.

GIS and Remote sensing techniques were used to evaluate changes in land use for the Thimphu Valley from 1990 to 2007. Reduction in forest cover and the subsequent growth in urban land cover demonstrate pressures of modernization on the environment. Those pressures may be viewed as indicators of economic, political and cultural change taking place in Bhutan. Specifically, this dissertation addressed two key questions regarding land use and sustainable use of forestlands.

First, the research identified areas that had the largest land conversions, specifically in terms of reduction in forested areas. Both unsupervised and supervised classifications were utilized to determine which would be the best method to use for assessing land use changes. Accuracy assessments of three Thimphu valley images determined the method of classification best suited for this rather difficult mountainous region. Unsupervised classification yielded a higher overall classification accuracy and Kappa statistics; therefore, it was used for Thimphu valley, Thimphu *Dzongkhag*, and Chang and Kawang *Geogs* to measure the land use change in this research. The results of the 1990 to 1999 remote sensing analysis showed an increase in urban built-up areas of 28.62 ha. The majority of the urban built-up area came from what was classified as barren in 1990.

Additionally, the remote sensing analysis showed that much of the urban growth was on the periphery of the city. This growth outward expansion may be due to the GNH philosophy requiring that all buildings be built in traditional architecture. It is difficult for the Bhutanese to build up while keeping in mind the traditional architectural style, so they build out on the periphery, perhaps even onto the more dangerous valley slopes. The 1999 to 2007 analysis showed an increase in urban built-up area of 98.84 ha, which was twice as much from 1990 to 1999. These urban increases were shown not only at the city level, but also at the Dzongkhag and Geog levels. Increases at the Geog and city level were combined with a decrease in overall forest area and increases in barren area. This may be indicative of a larger pattern in urban areas of movement from forest areas to barren, where areas are made barren to make room for future urban area growth.

For comparison this study examined deforestation at a global scale and found that there are many reasons for forestland reduction; rapid population growth, expansion of cropland, and intensive harvesting of forests for fuel wood and wood exports. The Forest Resources Division of the U.N. Food and Agriculture (FAO) recognized that African nations have the highest rates of deforestation. Based on this comparison lack of local participation may be an indication of poorly designed policy in Bhutan. Moreover, the rural communities of Bhutan have shown more concerns towards economic development rather than addressing sustainability issues.

Second, this research identified the areas of highest in-migration (Thimphu with 54,685 migrants) and the areas of highest out-migration (Trashigang with 23,802 out-migrants), providing evidence of the significant population growth in Thimphu city and reasoning for its examination with remote sensing. Examination of the various socio-economic variables using GIS provided insight into the push and pull factors that might be behind rural-urban migration, and compliments and adds to the remote sensing analysis by illustrating the luxuries Thimphu dzongkhag residents enjoy, thus providing potential reasoning for its urban expansion.

This research also determined that the governments' measures to reduce rural-urban migration did not make a significant impact. An attempt to address the rural-urban migration issues and an attempt at crossvergence was made in the form of increased hydropower construction projects and disincentives for exports of non-wooded forest products (NWFP). While hydropower exports replaced the declining revenues from the timber industry, and thus promoted the GNH principle of sustainable and equitable socio-economic development (divergence), it did very little in terms of addressing unemployment in the rural areas and providing electricity to the rural areas (convergence). Similarly, the NWFPs exports proved to be difficult due to rugged terrain, lack of access, and lack of support in the private sector.

Contributions

This research makes a contribution by identifying discrepancies in the national forest assessment for testing the deforestation process in Bhutan. Methods of geospatial technologies merged with social science insights were used to better understand complex issues in political ecology. Building an accurate GIS database for Thimphu demonstrated the usefulness of Remote Sensing and GIS in formulating and monitoring policies towards natural resources, specifically the national forest program, and urban development in Thimphu. In Bhutan, land privatization and decentralization efforts of national, *Dzongkhag*, and *Geog* level administration caused significant changes to policy regarding forestland in the past two decades.

This dissertation examined the political and economic impacts that affect forest policies in terms of accessibility, control, and management. This research adds to the literature on both land use change and Bhutan. Within the land-use change literature, few studies have been conducted tying the results in with political ecology; convergence, divergence, and crossvergence principles; cultural aspects; and census results, and then combining them all to establish the most suitable methodology for using Remote Sensing and GIS to produce a baseline to quantify the amount of forest cover and human processes involved. There is also scarce literature studying the national forest assessment and inventory of Bhutanese policies from a forest cover and land use perspective.

Recommendations

Bhutan is making great strides towards their “middle path” modernization; however, the government still has many challenges it needs to address in order to achieve this ideal. One major issue is unemployment, especially in the rural areas of the country. The government needs to promote the private sector for job generation, but there are many issues associated with promotion of the private sector that the government must confront. These issues include: lack of skilled labor, cumbersome labor practices, high cost of finance, inadequate infrastructure, and difficult access to land (production-access-market issues).

With regards to forest policy, the government needs to focus more on decentralization efforts of community property rights (CPRs). If the government hands over the CPRs to the individual communities, they will be more likely to start protecting the resources that belong to them. Unemployment and CPRs are to larger extent national level issues; however, forest issues extend down to the local level. The Thimphu city planners must view the Thimphu Structural Plan (TSP) with caution because while it promotes green space in the form of parks it does not necessarily increase forest cover. Since it does not add to forest cover, green space and parks could alter the spectral signature of the city and give a false impression of increased forest areas as described in a study in Rajasthan, India (Robbins 2007).

Future Research

The absence of research on land use change and policy in low developed countries offers numerous opportunities for future research endeavors for geographers and scientists in other disciplines. This dissertation provides a first glance at analyzing the national forest program and how they affect sustainable use of forest lands in Bhutan. Future research could include assessment of policy effects on deforestation, since not enough time has elapsed to quantify the effects of the ongoing transition to modernization development.

Second, a temporal analysis of land use derived from higher resolution imagery such as SPOT. Imagery from different sensors could help refine a more current and robust land use inventory. Higher resolution imagery with ground based surveys could help to determine precise pockets and rates of land use conversion.

Third, future research should include a more detailed examination of rural urban migration to all major urban centers of Bhutan. Statistical examination of pull and push factors for urban centers such as Thimphu, Phuntsholing, Paro, Wangdi Phodrang, and Trashigang, should also be included in future research. Additionally, an examination of factors that influence land use and forest policy subsequently promoted by the newly elected government could help test the efficacy of absolute monarchy versus a constitutional democratic monarchy political systems.

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Appendix A: Dzongkhag and Geog numerical geographic hierarchy as prescribed by the NSB for dissemination of PHCB data.

District Code	District Name	Geog/Town Code	Geog Name
11	Bumthang	1102	Chhumey
11	Bumthang	1104	Ura
11	Bumthang	1101	Chhokor
11	Bumthang	1103	Tang
12	Chhukha	1211	Phuntsholin
12	Chhukha	1201	Balujhora
12	Chhukha	1209	Lokchina
12	Chhukha	1206	Dungna
12	Chhukha	1210	Metakha
12	Chhukha	1207	Geling
12	Chhukha	1204	Chapcha
12	Chhukha	1202	Bjachho
12	Chhukha	1205	Darla
12	Chhukha	1203	Bongo
12	Chhukha	1208	Getana
13	Dagana	1301	Dorona
13	Dagana	1309	Tsendagang
13	Dagana	1308	Tashiding
13	Dagana	1304	Goshi
13	Dagana	1303	Gesarling
13	Dagana	1305	Kana
13	Dagana	1306	Khibisa
13	Dagana	1302	Drugyelgang
13	Dagana	1310	Tsangkha
13	Dagana	1307	Lajab
13	Dagana	1311	Tseza
14	Gasa	1401	Goenkhame
14	Gasa	1402	Goenkhatoe
14	Gasa	1403	Laya
14	Gasa	1404	Lunana
15	Haa	1505	Sombaykha

15	Haa	1501	Bji
15	Haa	1504	Samar
15	Haa	1502	Eusu
15	Haa	1503	Katsho
16	Lhuentse	1604	Kurtoe
16	Lhuentse	1601	Gangzur
16	Lhuentse	1607	Metsho
16	Lhuentse	1602	Jarey
16	Lhuentse	1608	Tshenkhar
16	Lhuentse	1605	Menbi
16	Lhuentse	1606	Minjey
16	Lhuentse	1603	Khoma
17	Monggar	1711	Saleng
17	Monggar	1713	Silambi
17	Monggar	1706	Gongdue
17	Monggar	1707	Jurmey
17	Monggar	1708	Kengkhar
17	Monggar	1705	Drepung
17	Monggar	1714	Thangrong
17	Monggar	1703	Chaskhar
17	Monggar	1709	Monggar
17	Monggar	1702	Chali
17	Monggar	1716	Tsamang
17	Monggar	1715	Tsakaling
17	Monggar	1710	Ngatshang
17	Monggar	1712	Sermung
17	Monggar	1701	Balam
17	Monggar	1704	Dremitse
18	Paro	1809	Tsento
18	Paro	1802	Doteng
18	Paro	1804	Lamgong
18	Paro	1808	Dopshari
18	Paro	1810	Wangchang
18	Paro	1803	Hungrel
18	Paro	1805	Lungnyi
18	Paro	1807	Shaba
18	Paro	1801	Doga
18	Paro	1806	Naja
19	Pemagatshel	1903	Dungmien

19	Pemagatshel	1901	Chimung
19	Pemagatshel	1906	Yurung
19	Pemagatshel	1902	Chongshing
19	Pemagatshel	1904	Khar
19	Pemagatshel	1905	Shumar
19	Pemagatshel	1907	Zobel
20	Punakha	2002	Goenshari
20	Punakha	2001	Chhubu
20	Punakha	2004	Kabjisa
20	Punakha	2003	Guma
20	Punakha	2007	Talo
24	Punakha	2410	Toepisa
24	Punakha	2401	Bapisa
20	Punakha	2009	Dzome
20	Punakha	2005	Lingmukha
20	Punakha	2006	ShengaBjim
20	Punakha	2008	Toewang
21	SamdrupJongkhar	2107	Norbugang
21	SamdrupJongkhar	2103	Dechiling
21	SamdrupJongkhar	2108	Orong
21	SamdrupJongkhar	2104	Gomdar
21	SamdrupJongkhar	2106	Martshala
21	SamdrupJongkhar	2105	Lauri
21	SamdrupJongkhar	2111	Serthi
21	SamdrupJongkhar	2109	Langchenphu
21	SamdrupJongkhar	2110	Samrang
21	SamdrupJongkhar	2102	Pemathang
21	SamdrupJongkhar	2101	Phuntshotha
22	Samtse	2201	Bara
22	Samtse	2216	Tendru
22	Samtse	2202	Biru
22	Samtse	2214	Sipsu
22	Samtse	2209	Lhareni
22	Samtse	2203	Chargharey
22	Samtse	2208	Ghumauney
22	Samtse	2211	Nainatal
22	Samtse	2204	Chengmari
22	Samtse	2213	Samtse
22	Samtse	2212	Pagli

22	Samtse	2215	Tading
22	Samtse	2206	Dorokha
22	Samtse	2207	Dungtoe
22	Samtse	2205	Denchuka
22	Samtse	2210	Mayona
23	Sarpang	2309	Lhamoyzingk
23	Sarpang	2304	Deorali
23	Sarpang	2310	Nichula
23	Sarpang	2313	Sengye
23	Sarpang	2307	Hilley
23	Sarpang	2311	Shompangkha
23	Sarpang	2303	Dekiling
23	Sarpang	2305	Dovan
23	Sarpang	2301	Bhur
23	Sarpang	2306	Gelephu
23	Sarpang	2312	Serzhong
23	Sarpang	2302	Chhuzagang
23	Sarpang	2315	Umling
23	Sarpang	2314	Taklai
23	Sarpang	2308	Jigmecholin
24	Thimphu	2409	Soe
24	Thimphu	2406	Lingshi
24	Thimphu	2408	Naro
24	Thimphu	2405	Kawang
24	Thimphu	2407	Mewang
24	Thimphu	2402	Chang
24	Thimphu	2404	Geynekha
24	Thimphu	2403	Dagala
25	Trashigang	2516	Yangner
25	Trashigang	2501	Bartsham
25	Trashigang	2502	Bidung
25	Trashigang	2509	Phongmi
25	Trashigang	2511	Sakteng
25	Trashigang	2507	Merak
25	Trashigang	2510	Radhi
25	Trashigang	2504	Kangpara
25	Trashigang	2514	Thrimshing
25	Trashigang	2508	Nanong
25	Trashigang	2506	Lumang

25	Trashigang	2505	Khaling
25	Trashigang	2515	Udzorong
25	Trashigang	2513	Shongphu
25	Trashigang	2512	Samkhar
25	Trashigang	2503	Kanglung
26	Trashiyangtse	2602	Jamkhar
26	Trashiyangtse	2604	Ramjar
26	Trashiyangtse	2607	Yalang
26	Trashiyangtse	2605	Thetsho
26	Trashiyangtse	2603	Khamdang
26	Trashiyangtse	2606	Tongzhang
26	Trashiyangtse	2608	Yangtse
26	Trashiyangtse	2601	Bumdeling
27	Trongsa	2704	Nubi
27	Trongsa	2705	Tangsibji
27	Trongsa	2701	Dragten
27	Trongsa	2703	Langthil
27	Trongsa	2702	Korphu
28	Tsirang	2807	Patale
28	Tsirang	2812	TsirangTeo
28	Tsirang	2811	Tsholingkha
28	Tsirang	2804	Goseling
28	Tsirang	2805	Kikorthang
28	Tsirang	2808	Phuntenchhu
28	Tsirang	2810	Semjong
28	Tsirang	2803	Dunglegang
28	Tsirang	2809	Rangthangli
28	Tsirang	2806	Medrelgang
28	Tsirang	2801	Barshong
28	Tsirang	2802	Beteni
29	Wangduephodrang	2907	Gatseshoom
29	Wangduephodrang	2906	Gatseshogom
29	Wangduephodrang	2909	Nahi
29	Wangduephodrang	2915	Thedtsho
29	Wangduephodrang	2911	Phangyul
29	Wangduephodrang	2903	Daga
29	Wangduephodrang	2901	Athang
29	Wangduephodrang	2913	Ruepisa
29	Wangduephodrang	2902	Bjena

29	Wangduephodrang	2905	Gangte
29	Wangduephodrang	2912	Phobji
29	Wangduephodrang	2914	Sephu
29	Wangduephodrang	2904	Dangchhu
29	Wangduephodrang	2910	Nyisho
29	Wangduephodrang	2908	Kazhi
30	Zhemgang	3008	Trong
30	Zhemgang	3006	Pangkhar
30	Zhemgang	3005	Ngangla
30	Zhemgang	3002	Bjoka
30	Zhemgang	3003	Goshing
30	Zhemgang	3001	Bardo
30	Zhemgang	3004	Nangkor
30	Zhemgang	3007	Shingkhar

Appendix B: Ground Control Point Collection and fieldwork in Thimphu and Kanglung, Bhutan (March 2008).

Figure B.1: Permanent landmarks were selected to achieve better accuracy.

Figure B.2: Mayur A. Gosai and Joe Morgan collecting a GCP in Thimphu periphery.

Figure B.3: Joe Morgan and Sangay Dorji of MoWHS collecting and documenting a GCP to be located on the 2006 QuickBird image.

Figure B.4: Sangay Dorji, Joe Morgan, and Mayur A. Gosai collecting a GCP near Motithang, Thimphu.

Figure B.5: Photographs were used not only to document the GCPs but also to find landmarks on the QuickBird image and on the ground.

Figure B.6: GPS data collection and fieldwork training provided to the Department of Geography faculty and students at Sherubtse College, Kanglung, Bhutan.

Figure B.7: Faculty and staff of the Department of Geography at Sherubtse College with Leanne Sulewski, Dr. Susan Walcott, Joe Morgan, and Mayur A. Gosai, Kanglung, Bhutan.

Appendix C: Thimphu City Supervised Classification Training Site Statistics

C.1: 1990 Supervised Classification Training Site Statistics

1. **Water**

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	53.457	23.23	24.194	21.144	29.493	13.962
Std. Deviation	3.238	1.94	3.686	5.524	10.728	5.398
Minimum	45	16	13	11	5	4
Maximum	60	27	30	40	64	30

Variance – Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	10.486	5.71	10.327	3.242	19.979	12.912
Band 2	5.71	3.763	6.654	2.535	11.205	8.199
Band 3	10.327	6.654	13.589	5.882	23.685	15.92
Band 4	3.242	2.535	5.882	30.511	43.726	17.863
Band 5	19.979	11.205	23.685	43.726	115.082	49.872
Band 7	12.912	8.199	15.92	17.863	49.872	29.141

2. Urban

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	78.426	38.303	50.718	47.539	99.006	60.456
Std. Deviation	7.122	3.681	4.931	5.29	13.272	9.142
Minimum	67	32	42	39	75	41
Maximum	92	46	59	56	117	79

Variance-Covariance Matrix

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	50.724	21.614	31.194	-6.878	-20.535	28.15
Band 2	21.614	13.548	17	0.886	-16.407	4.893
Band 3	31.194	17	24.31	0.169	-17.391	13.12
Band 4	-6.878	0.886	0.169	27.983	45.608	7.47
Band 5	-20.535	-16.407	-17.391	45.608	176.147	80.147
Band 7	28.15	4.893	13.12	7.47	80.147	83.574

3. **Forest**

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	45.334	17.107	16.618	37.513	36.908	12.948
Std. Deviation	3.717	3.068	5.935	17.716	18.773	8.782
Minimum	40	12	8	7	11	3
Maximum	62	27	40	85	121	59

Variance-Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	13.817	9.983	20.525	24.165	59.391	29.086
Band 2	9.983	9.413	16.54	33.488	51.106	22.648
Band 3	20.525	16.54	35.22	39.865	99.903	49.092
Band 4	24.165	33.488	39.865	313.852	207.425	54.755
Band 5	59.391	51.106	99.903	207.425	352.424	154.75
Band 7	29.086	22.648	49.092	54.755	154.75	77.118

4. Barren:

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	56.136	24.387	32.659	42.376	78.618	36.038
Std. Deviation	5.845	4.307	9.047	12.517	32.464	16.516
Minimum	46	17	18	25	35	12
Maximum	70	34	56	70	150	75

Variance-Covariance Matrix

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	34.162	24.149	50.547	65.529	177.282	89.755
Band 2	24.149	18.55	37.893	50.488	132.019	66.737
Band 3	50.547	37.893	81.855	107.021	281.851	140.753
Band 4	65.529	50.488	107.021	156.67	388.846	191.331
Band 5	177.282	132.019	281.851	388.846	1053.918	527.686
Band 7	89.755	66.737	140.753	191.331	527.686	272.786

5. **Agriculture:**

Univariate Statistics:

	Band 1	**Band 2**	**Band 3**	**Band 4**	**Band 5**	**Band 7**
Mean	56.964	27.125	31.672	75.451	93.171	34.599
Std. Deviation	1.046	0.937	1.54	3.14	3.055	1.969
Minimum	56	25	29	71	86	32
Maximum	60	29	35	80	103	32

Variance-Covariance Matrix:

	Band 1	**Band 2**	**Band 3**	**Band 4**	**Band 5**	**Band 7**
Band 1	1.094	0.693	1.243	-1.696	1.016	0.958
Band 2	0.693	0.879	1.227	-1.951	1.192	0.946
Band 3	1.243	1.227	2.37	-3.794	2.526	1.705
Band 4	-1.696	-1.951	-3.794	9.859	-1.897	-2.845
Band 5	1.016	1.192	2.526	-1.897	9.334	4.709
Band 7	0.958	0.946	1.705	-2.845	4.709	3.877

C.2: 1999 Supervised Classification Training Site Statistics

1. **Water**

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	66.972	58.523	58.287	52.249	48.367	36.712
Std. Deviation	5.172	4.902	7.422	5.701	12.547	10.939
Minimum	57	49	44	38	35	25
Maximum	76	67	70	78	102	70

Variance – Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	26.75	24.988	36.917	3.387	22.192	31.52
Band 2	24.988	24.028	35.35	3.301	20.933	29.878
Band 3	36.917	35.35	55.091	10.699	40.744	51.836
Band 4	3.387	3.301	10.699	32.499	57.681	44.449
Band 5	22.192	20.933	40.744	57.681	157.42	132.25
Band 7	31.52	29.878	51.836	44.449	132.25	119.659

2. **Urban**

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	75.01	68.365	77.074	85.191	104.296	72.923
Std. Deviation	4.968	5.034	6.724	5.782	7.956	6.094
Minimum	66	60	63	66	77	56
Maximum	83	75	86	100	118	82

Variance-Covariance Matrix

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	24.681	22.11	27.967	-2.758	14.794	23.92
Band 2	22.11	25.341	32.005	5.183	25.422	25.317
Band 3	27.967	32.005	45.217	12.268	34.506	34.27
Band 4	-2.758	5.183	12.268	33.428	33.427	11.015
Band 5	14.794	25.422	34.506	33.427	63.291	35.692
Band 7	23.92	25.317	34.27	11.015	35.692	37.131

3. Forest

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	49.244	37.484	31.961	61.451	44.151	26.235
Std. Deviation	2.322	4.731	4.856	23.457	16.614	8.275
Minimum	44	30	23	33	19	14
Maximum	70	61	61	127	109	74

Variance-Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	5.39	8.856	9.042	34.82	27.821	14.531
Band 2	8.856	22.386	21.363	98.533	70.434	33.83
Band 3	9.042	21.363	23.584	92.97	73.781	37.18
Band 4	34.82	98.533	92.97	550.235	361.123	160.581
Band 5	27.821	70.434	73.781	361.123	276.035	132.803
Band 7	14.531	33.83	37.18	160.581	132.803	68.48

4. Barren:

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	56.136	24.387	32.659	42.376	78.618	36.038
Std. Deviation	5.845	4.307	9.047	12.517	32.464	16.516
Minimum	46	17	18	25	35	12
Maximum	70	34	56	70	150	75

Variance-Covariance Matrix

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	34.162	24.149	50.547	65.529	177.282	89.755
Band 2	24.149	18.55	37.893	50.488	132.019	66.737
Band 3	50.547	37.893	81.855	107.021	281.851	140.753
Band 4	65.529	50.488	107.021	156.67	388.846	191.331
Band 5	177.282	132.019	281.851	388.846	1053.918	527.686
Band 7	89.755	66.737	140.753	191.331	527.686	272.786

5. **Agriculture:**

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	56.964	27.125	31.672	75.451	93.171	34.599
Std. Deviation	1.046	0.937	1.54	3.14	3.055	1.969
Minimum	56	25	29	71	86	32
Maximum	60	29	35	80	103	32

Variance-Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	1.094	0.693	1.243	-1.696	1.016	0.958
Band 2	0.693	0.879	1.227	-1.951	1.192	0.946
Band 3	1.243	1.227	2.37	-3.794	2.526	1.705
Band 4	-1.696	-1.951	-3.794	9.859	-1.897	-2.845
Band 5	1.016	1.192	2.526	-1.897	9.334	4.709
Band 7	0.958	0.946	1.705	-2.845	4.709	3.877

C3: 2007 Supervised Classification Training Site Statistics

1. **Water**

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	72.091	35.280	34.973	42.542	56.182	29.412
Std. Deviation	4.365	2.903	4.046	7.284	14.609	7.519
Minimum	61	28	25	25	28	17
Maximum	82	43	45	61	84	51

Variance – Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	19.049	11.302	16.596	2.441	23.283	20.315
Band 2	11.302	8.43	11.265	7.052	23.803	15.551
Band 3	16.596	11.265	16.372	6.595	30.955	21.324
Band 4	2.441	7.052	6.595	53.054	62.928	20.793
Band 5	23.283	23.803	30.955	62.928	213.289	92.096
Band 7	20.315	15.551	21.324	20.793	92.096	56.540

2. Urban

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	101.052	54.002	64.91	78.462	153.992	94.778
Std. Deviation	10.922	5.261	7.204	6.630	18.477	9.839
Minimum	77	42	46	64	104	67
Maximum	143	71	84	96	188	114

Variance – Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	119.296	52.792	65.732	-14.148	-82.418	-2.466
Band 2	52.792	27.679	35.247	1.643	-17.831	9.158
Band 3	65.732	35.247	51.891	9.758	-3.260	21.161
Band 4	-14.148	1.643	8.758	43.955	88.760	34.884
Band 5	-82.418	-17.831	-3.260	88.760	341.405	154.539
Band 7	-2.466	9.158	21.161	34.884	154.539	96.804

3. Forest

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	56.850	26.565	22.459	66.505	60.208	22.313
Std. Deviation	1.972	1.821	1.502	11.150	10.076	3.537
Minimum	50	21	18	44	40	15
Maximum	62	30	27	101	90	33

Variance – Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	3.889	2.543	2.091	11.618	8.721	2.603
Band 2	2.542	3.317	2.205	16.857	13.831	4.031
Band 3	2.091	2.205	2.256	11.639	10.334	3.349
Band 4	11.618	16.857	11.639	124.318	96.529	26.862
Band 5	8.721	13.831	10.334	96.529	101.522	32.990
Band 7	2.603	4.031	3.349	26.862	32.990	12.510

4. Barren

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	74.308	38.573	42.636	74.100	114.800	56.529
Std. Deviation	12.867	7.772	15.087	8.022	37.274	26.869
Minimum	57	27	24	50	55	20
Maximum	99	53	67	93	171	99

Variance – Covariance Matrix:

	Band 1	**Band 2**	**Band 3**	**Band 4**	**Band 5**	**Band 7**
Band 1	165.547	98.839	191.450	-21.873	451.217	327.769
Band 2	98.839	60.410	114.893	-8.889	267.623	194.359
Band 3	191.450	114.893	227.622	-35.900	543.473	396.233
Band 4	-21.873	-8.889	-35.900	64.358	-110.85	-89.456
Band 5	451.217	267.623	543.473	-110.86	1389.33	990.788
Band 7	327.769	194.359	396.233	-89.456	990.788	721.969

5. Agriculture

Univariate Statistics:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Mean	75.442	40.161	39.964	128.850	128.658	51.150
Std. Deviation	0.547	0.754	1.863	5.051	6.861	4.948
Minimum	73	39	37	108	114	44
Maximum	79	43	47	139	139	60

Variance – Covariance Matrix:

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
Band 1	0.299	0.078	0.770	-1.329	1.367	1.422
Band 2	0.078	0.568	0.293	-0.809	4.143	2.902
Band 3	0.770	0.293	3.471	-5.659	2.860	2.833
Band 4	-1.329	-0.809	-5.659	25.509	-6.483	-5.173
Band 5	1.367	4.143	2.860	-6.483	47.071	31.638
Band 7	1.422	2.902	2.833	-5.173	31.638	24.479

Appendix D: Geographic distribution of potential push/pull factors affecting rural-urban migration.

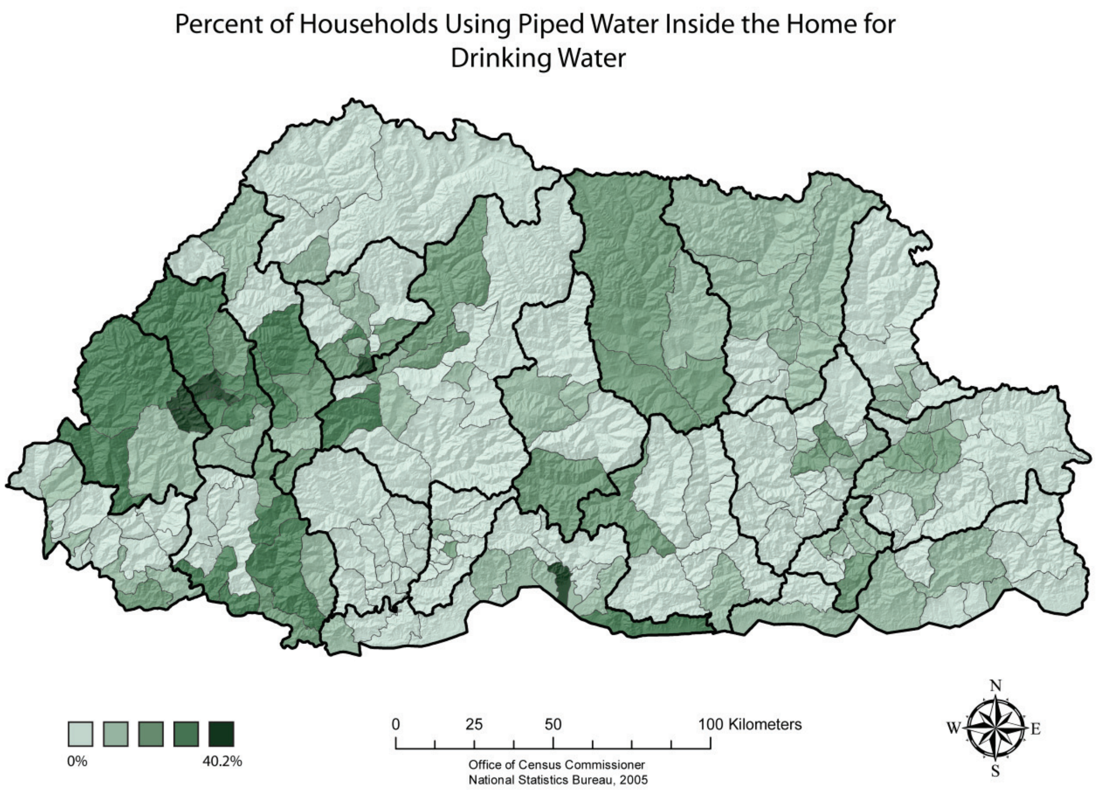

Figure D.1: The vast majority of households using piped water inside the home are in the west, where most of the large cities are located.

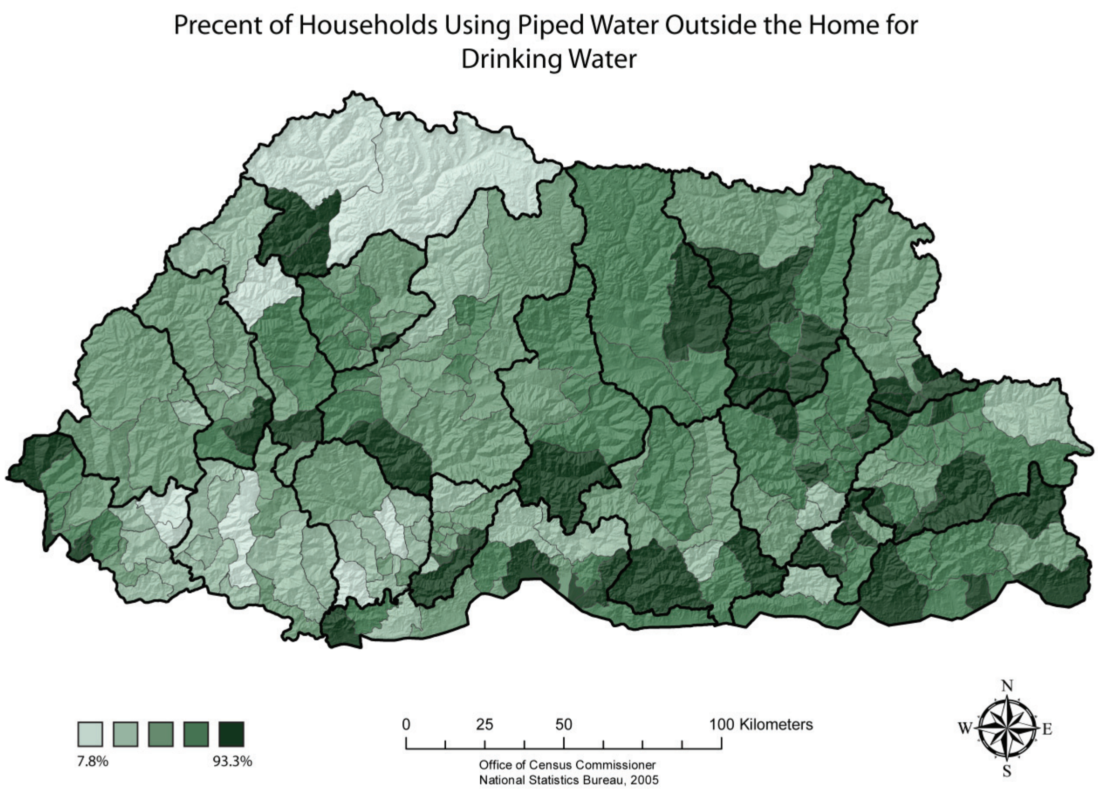

Figure D.2: There are a much great percentage of households using piped water outside the home than inside the home, and it is more widely distributed across the country.

Percent of Households Using Spring Water for Drinking Water

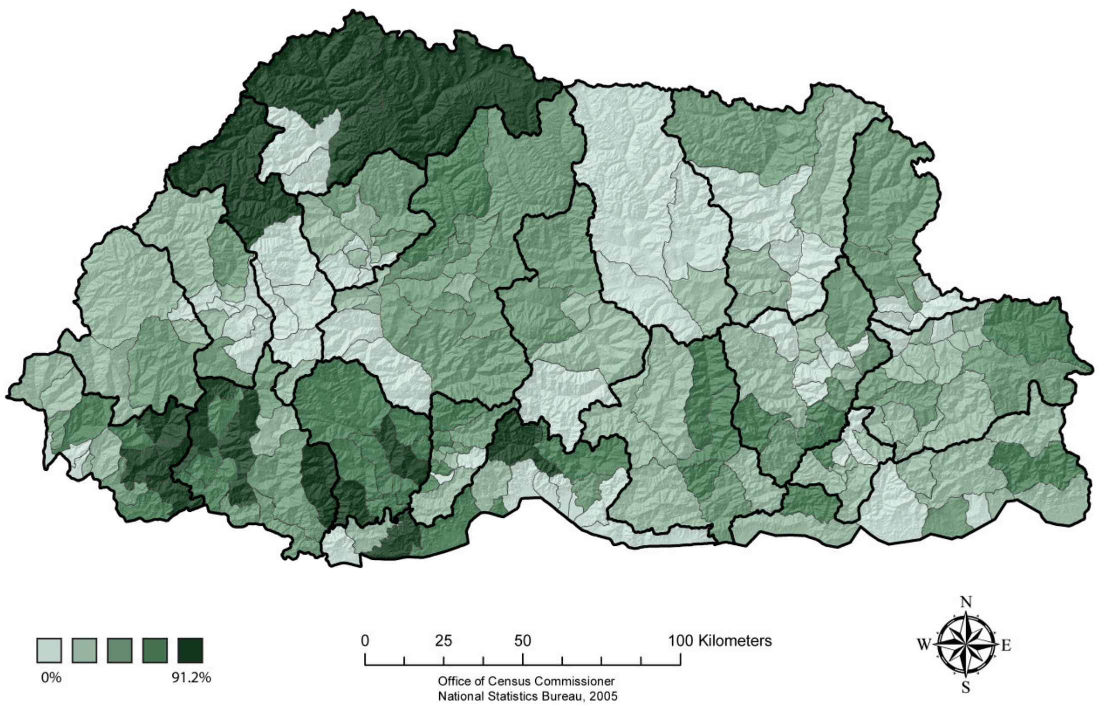

Figure D.3: Northern Thimphu dzongkhag and most of Gasa dzongkhag have the highest percentage of households using spring water for their drinking water.

Percent of Households Using a Pit for Toilet Facilities

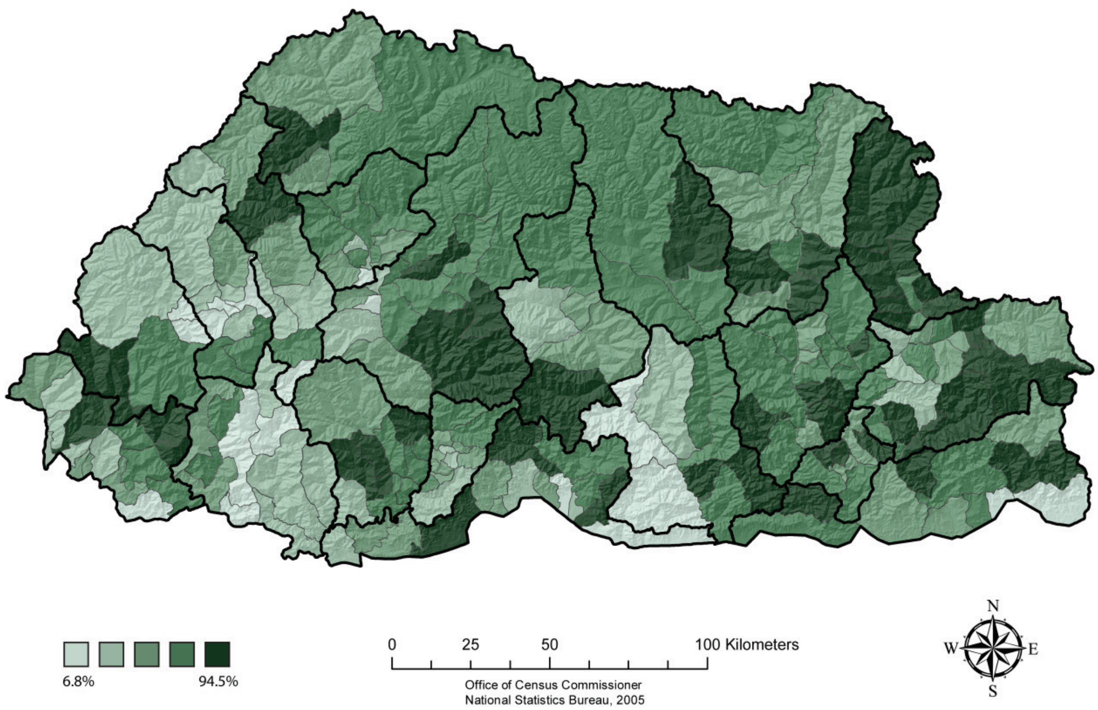

Figure D.4: The percentage of households using pits as toilet facilities are mainly concentrated in the eastern half of the country.

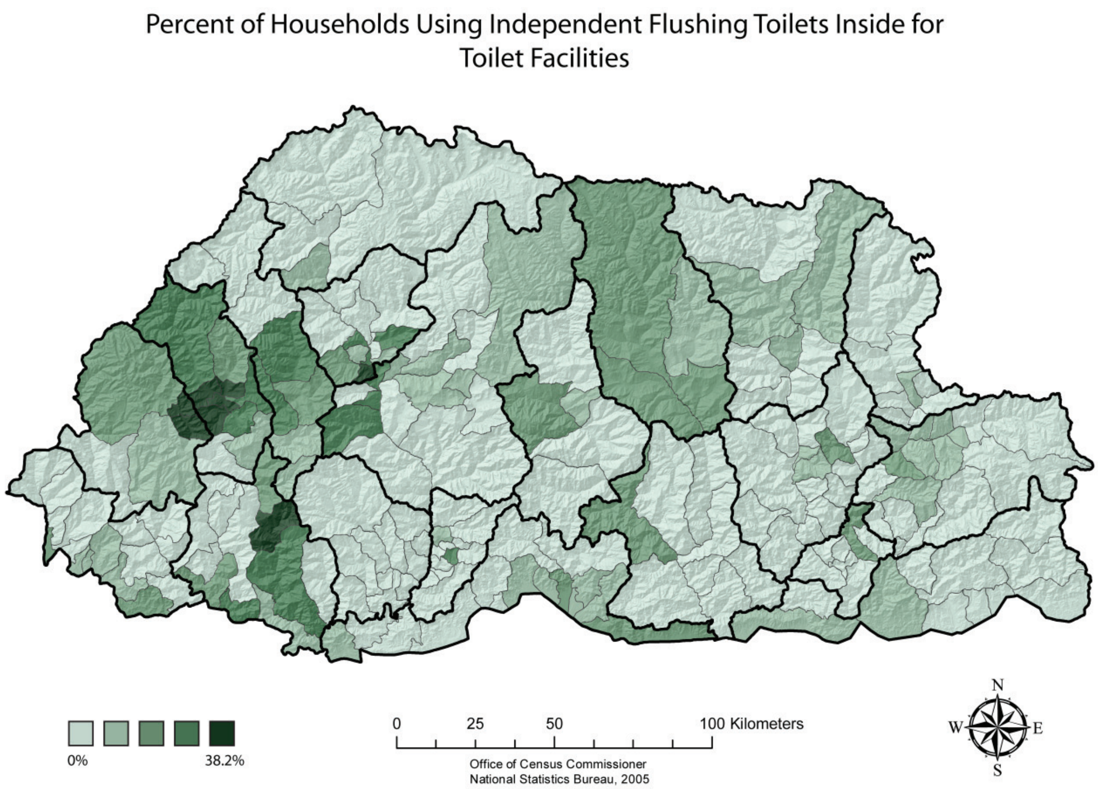

Figure D.5: Very few households across Bhutan use independent flushing toilets inside their home, concentration of households is in the western half of the country, near the cities, Thimphu and Paro.

Percent of Households With Access to Health Care Facilities

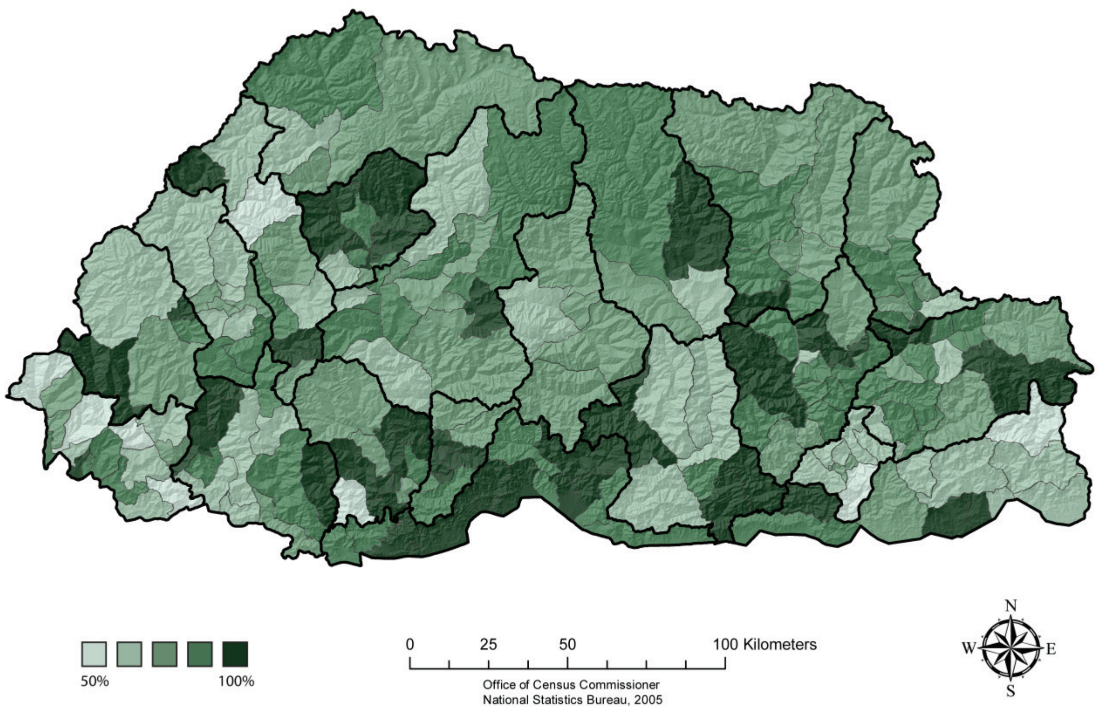

Figure D.6: Most households all across Bhutan have some degree of access to health care facilities.

Percent of Households Without Access to Health Care Facilities

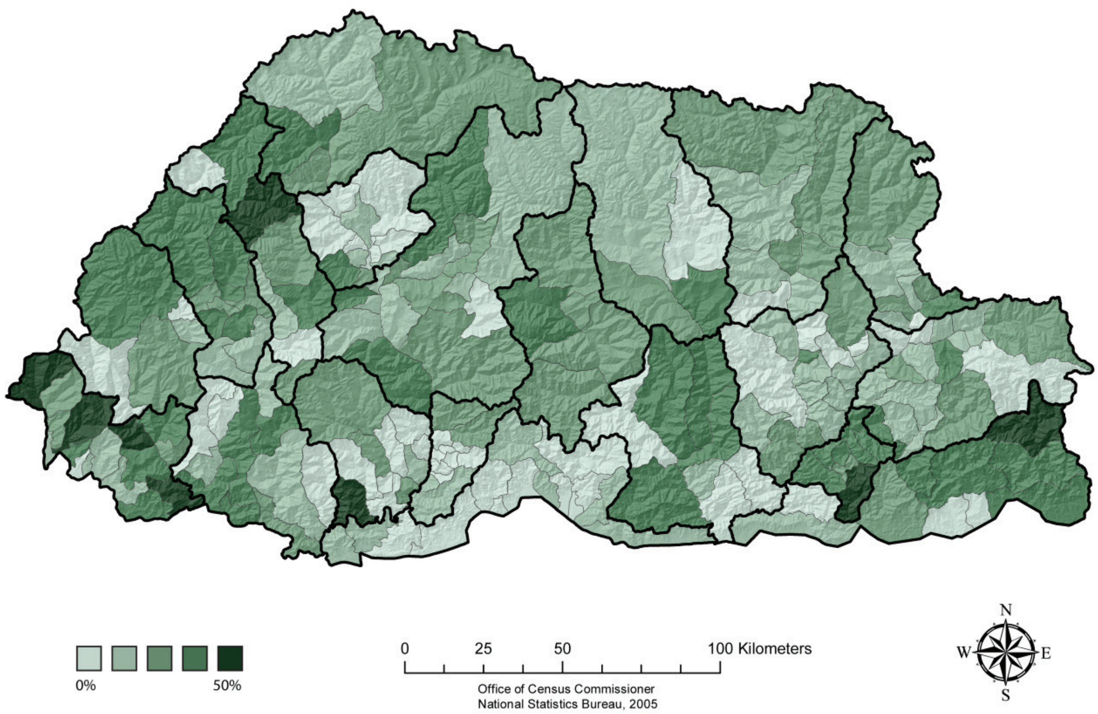

Figure D.7: The majority of areas that do not have access to health care facilities are located on the southern border of Bhutan.

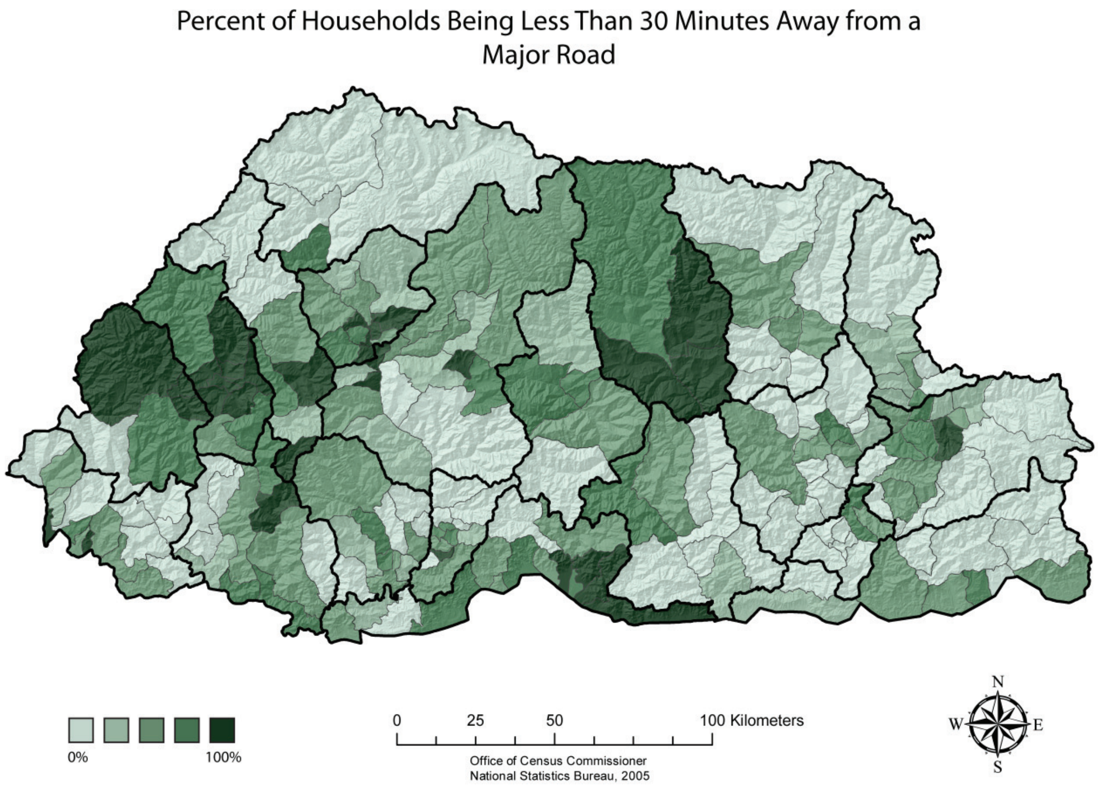

Figure D.8: The eastern half of the country has the majority of households that are less than 30 minutes away from a major road, and it is concentrated near the cities Paro and Thimphu.

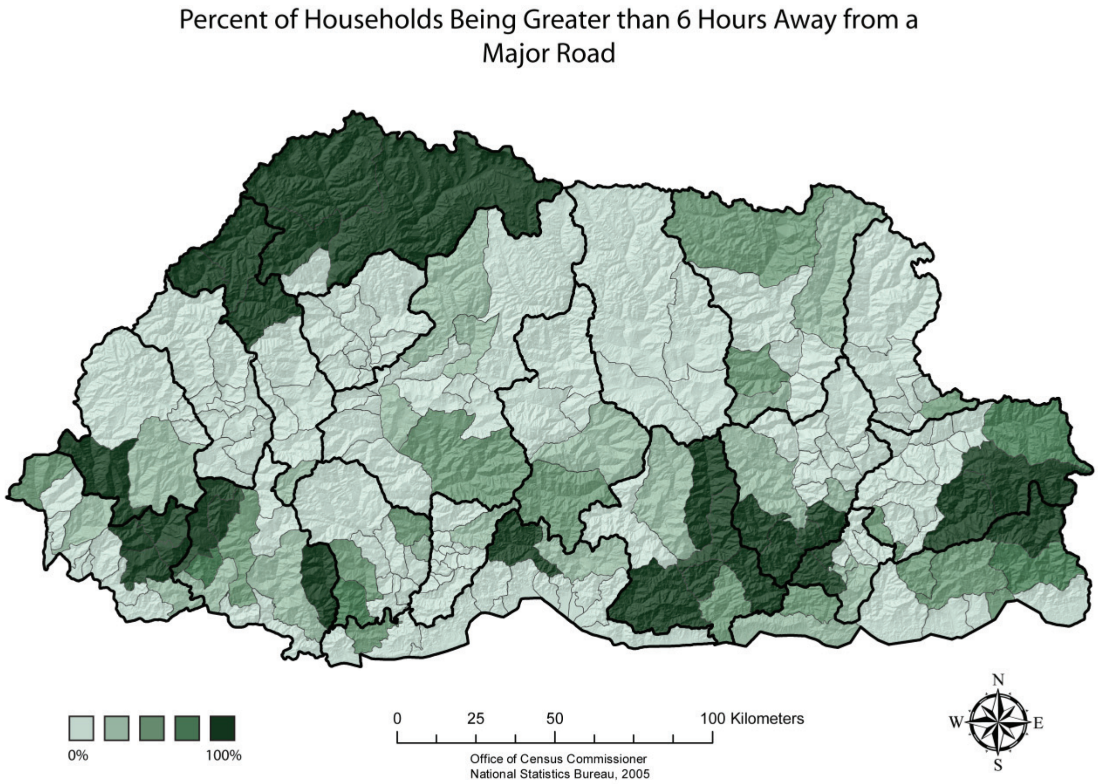

Figure D.9: The households with greater than 6 hours away from a major road are mainly in the rural areas, such as northern Thimphu and northern Gasa dzongkhags.

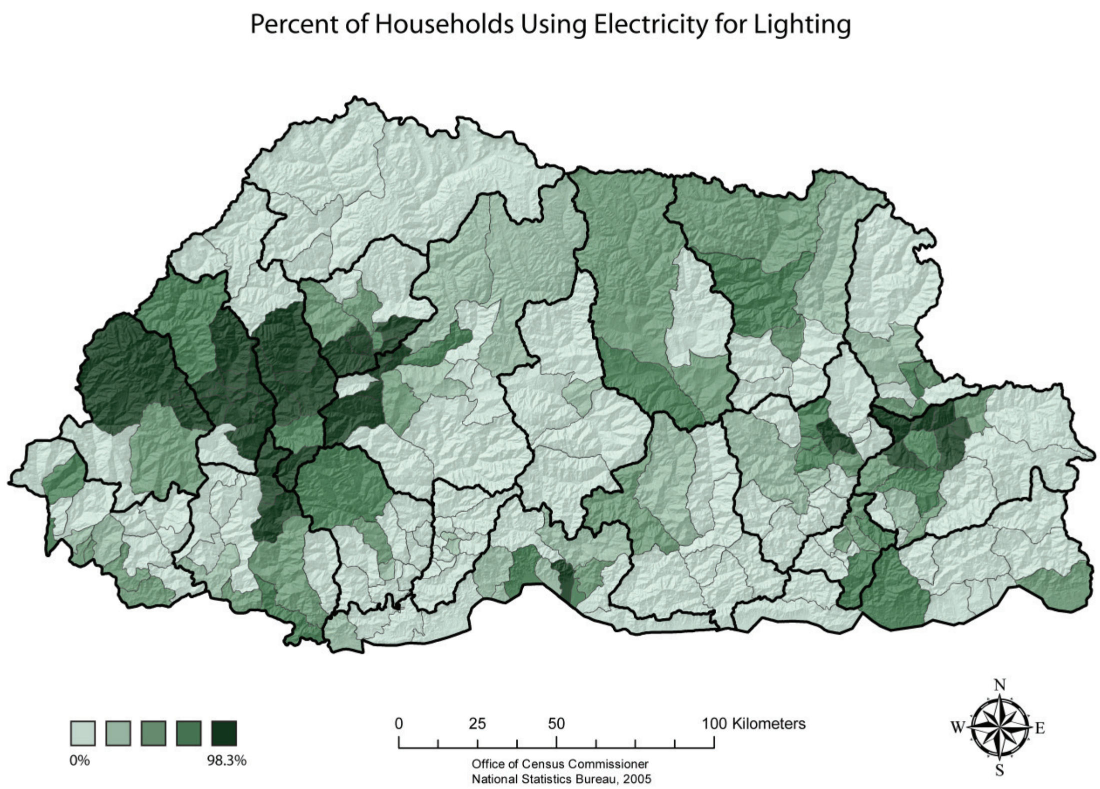

Figure D.10: Using electricity for lighting is clustered in the western section of the country, near major populated centers.

Percent of Households Using Firewood for Lighting

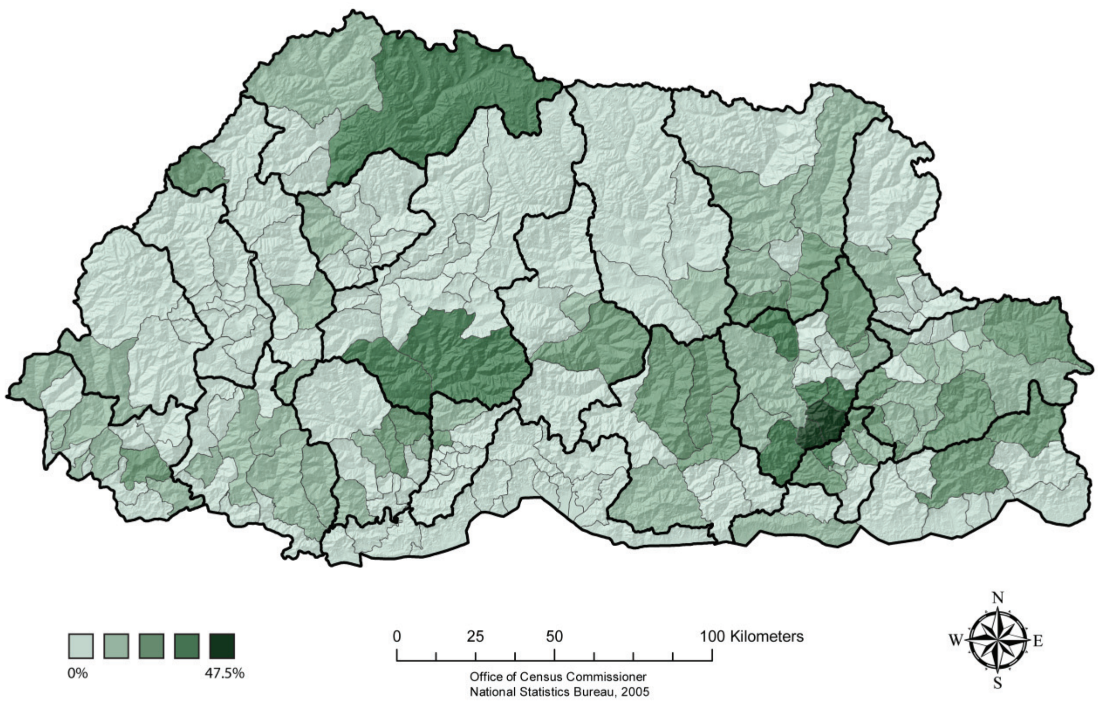

Figure D.11: The use of firewood for lighting is not very widespread across Bhutan.

Percent of Households Using Kerosene for Lighting

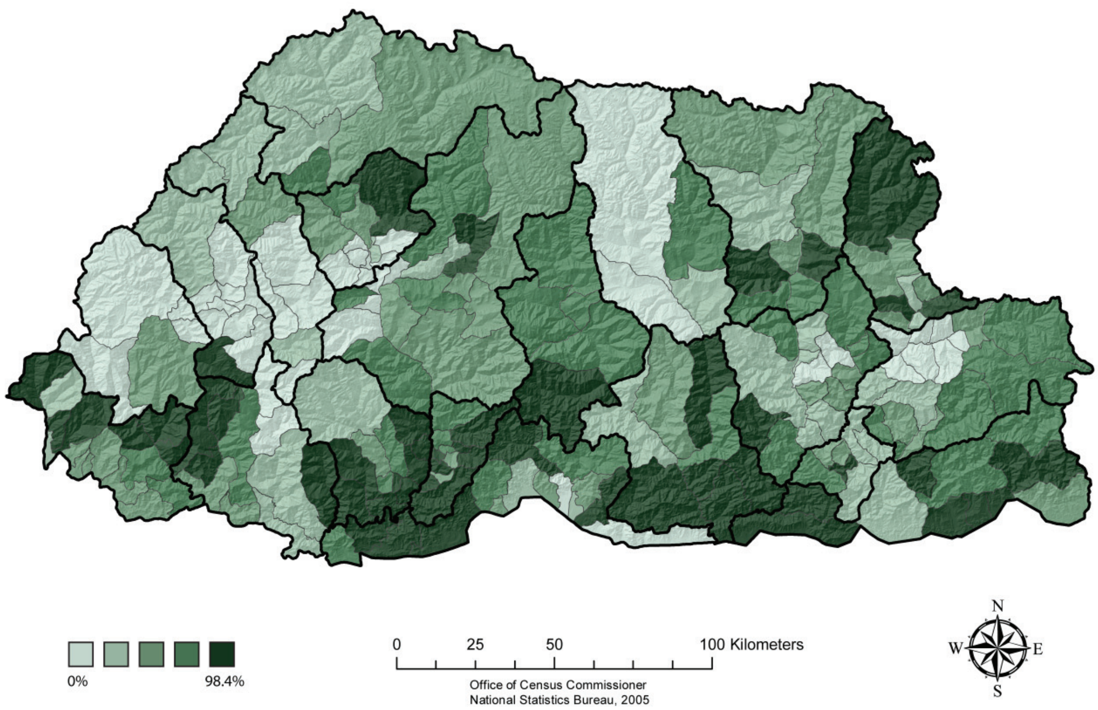

Figure D.12: The use of kerosene for lighting is more widespread than firewood across Bhutan.

Percent of Households Using Firewood as Cooking Fuel

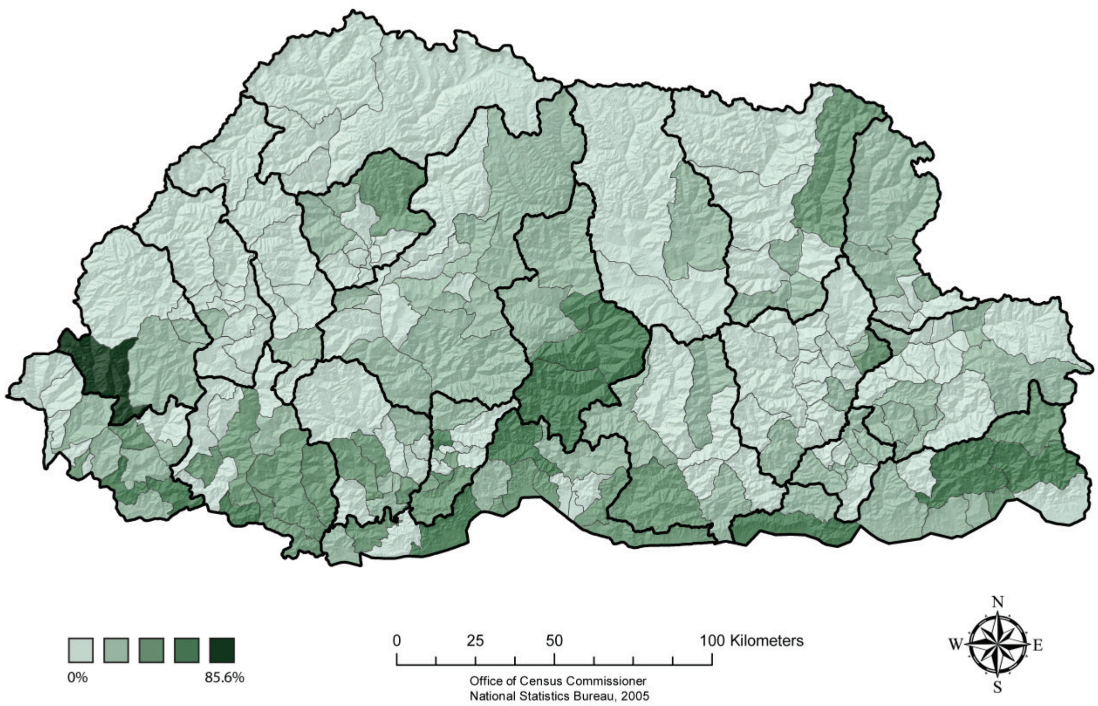

Figure D.13: There is not a widespread use of firewood as cooking fuel; however, Sombaykha geog in Haa has the highest concentration of its use.

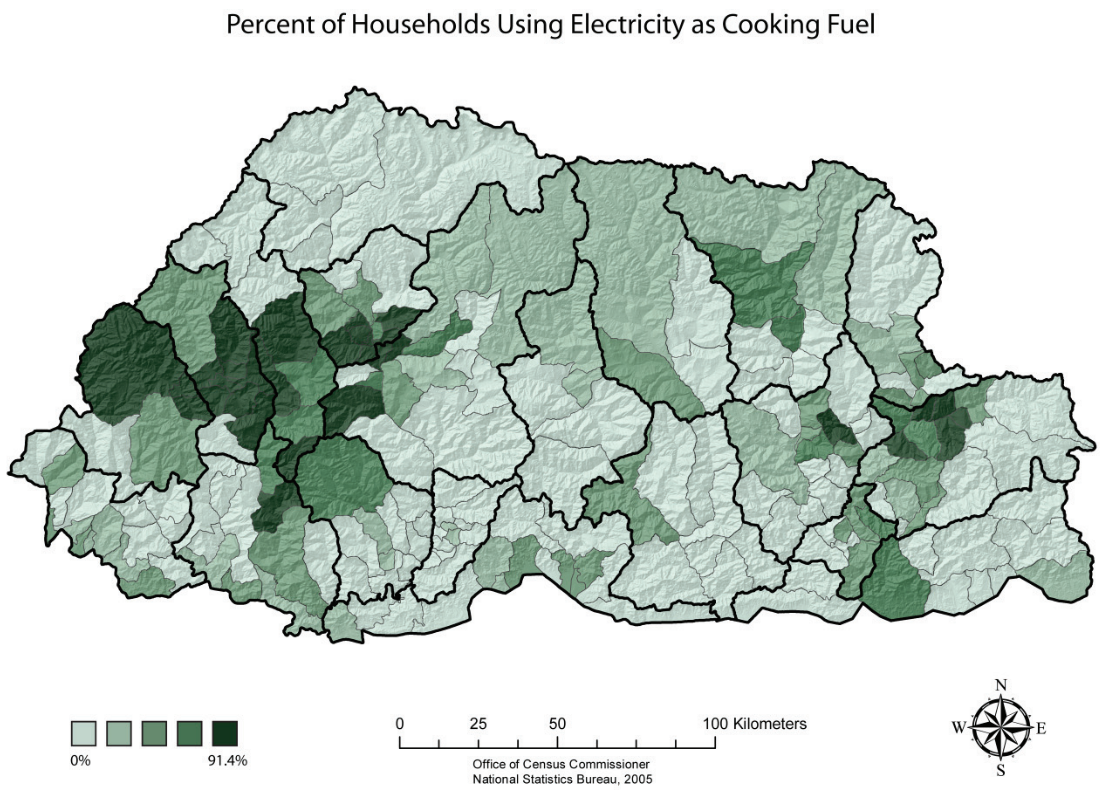

Figure D.14: The majority of households in western Bhutan, especially in the populated areas, use electricity as cooking fuel.