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THE INFLUENCE OF LAND COVER/ LAND USE
CHARACTERISTICS ON
SHUTTLE RADAR TOPOGRAPHY MISSION (SRTM) ELEVATION
ERROR: CASE STUDIES FROM LOUISIANA AND THAILAND

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THE INFLUENCE OF LAND COVER/ LAND USE CHARACTERISTICS ON SHUTTLE RADAR TOPOGRAPHY MISSION (SRTM) ELEVATION ERROR: CASE STUDIES FROM LOUISIANA AND THAILAND

By

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ABSTRACT

THE INFLUENCE OF LAND COVER/ LAND USE CHARACTERISTICS ON SHUTTLE RADAR TOPOGRAPHY MISSION (SRTM) ELEVATION ERROR: CASE STUDIES FROM LOUISIANA AND THAILAND

By

Tara Louise LaLonde

The Shuttle Radar Topography Mission (SRTM) DEM has near-global coverage with its 3 arc second resolution (~ 90 m). This research explores the relationships between the SRTM DEM and other DEMs both in the United States and elsewhere. This thesis investigates the magnitude and variance of SRTM DEM error using online reference data Light Detection and Ranging (LiDAR) data for two Louisiana study areas and SRTM X-band (~25 m resolution) for a portion of Nang Rong, Thailand. The correlations of slope values and elevation values among LiDAR, National Elevation Dataset (NED), and SRTM DEMs were determined. The average SRTM DEM error was found to be positive for all study areas, which indicates an elevation bias of the SRTM. In comparison to land cover/land use characteristics from the National Land Cover Dataset (NLCD) 2001, forested categories had greater average SRTM DEM error. MODIS tree cover indicated significant differences between a high ($\geq$ 50 %) and low percent ($<$ 50 %) tree cover for the Louisiana areas; however, relationships between MODIS tree cover and SRTM error were insignificant for the Nang Rong area. A land use application developed from criteria of flat topography and low topographic position indicated agreement between LiDAR 90 m and NED 90 m DEMs; however, different results were found for the SRTM data. This research contributes to understanding the characteristics of the SRTM DEM, which will improve upon its use as it is adopted in applications.

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and fellow graduate students; along with time spent in the classroom and in the computer lab created my graduate school experience, which I will take with me into the future.

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LIST OF ACRONYMS

CGIAR-CSI: Consortium for Spatial Information

DEM: Digital Elevation Model

DLR: Deutsches Zentrum fur Luft- und Raumfahrt (German Aerospace Center)

DTED: Digital Terrain Elevation Data

DTM: Digital Terrain Model

GIS: Geographic Information Systems

GIScience: Geographic Information Science

GLCF: Global Land Cover Facility

GPS: Global Positioning System

GTOPO30: Global 30 Arc-Second Elevation Data set

JPL: Jet Propulsion Laboratory

LiDAR: Light Detection and Ranging

MODIS: Moderate Resolution Imaging Spectroradiometer Sensor

NAD83: North American Datum of 1983

NASA: National Aeronautics and Space Administration

NAVD88: North American Vertical Datum of 1983

NED: National Elevation Dataset

NGA: National Geospatial-Intelligence Agency

RMSE: Root Mean Square Error

SAR: Synthetic Aperture Radar

SIR-C: Spaceborne Imaging Radar-C

SRTM: Shuttle Radar Topography Mission

USGS: United States Geological Survey

X-SAR: X-Synthetic Aperture Radar

1. Introduction

Digital elevation models (DEMs) are digital representations of the earth's surface and vital spatial data sources for understanding many environmental, social, and geographic issues around the world. An understanding of differences of spatial resolution and production method is important to end users and model selection in application use. The focus of this thesis is on the differences of the Shuttle Radar Topography Mission (SRTM) C-band 90 m DEM in relation to higher quality DEMs through case studies in the United States. This investigation of DEM error sheds light on its relationship with land cover characteristics. A land use model is explored to examine the differences of selected DEMs.

An important part of geographical study is terrain analysis because of its ability to capture characteristics and spatial patterns of the Earth's surface. A digital elevation model (DEM) has been defined as "set of measurements that record the elevation of the surface of the Earth, such that the spatial proximity of, and spatial relationships between, those measurements can be determined either implicitly or explicitly" (Fisher and Tate 2006: 468). The error of the DEM is analyzed by comparison to a more accurate elevation model, termed the reference model (Fisher and Tate 2006). DEM error refers to how closely the values of the model correspond to true elevation values in reality (or what is termed "reference data"). DEM error literature has used this approach to measure vertical differences at individual locations and to summarize overall error through global metrics. In the DEM error literature, accuracy refers to how closely the elevations under investigation match true values.

DEMs included in this research are the National Elevation Dataset (NED) from the United States Geological Survey (USGS), elevation models derived from Light Detection and Ranging (LiDAR) from ATLAS GIS in Louisiana (Atlas 2007), and finished Shuttle Radar Topography Mission (SRTM) from the Earth Resource Observation and Science (EROS) Data Center of the U.S. Geological Survey (USGS 2007). These DEMs comprise a range of spatial resolutions: 30 m, 5 m, and 90 m respectively. Of particular interest is the near-global SRTM DEM, which could be used in many international contexts. Elaborating on the error characteristics of the SRTM using US data would benefit analysis in locations without higher resolution data. Publicly available LiDAR-derived DEMs from ATLAS, The Louisiana Statewide GIS, were obtained as reference data to determine the error of the SRTM model.

This research focuses on investigating the relationships between SRTM error and terrain characteristics to aid users in the proper employment of SRTM data in environmental applications. This thesis research incorporates international data for Nang Rong, Thailand and parts of Louisiana (USA) to gain greater insight into the details of these diverse datasets. The Shuttle Radar Topography Mission (SRTM) 90 m resolution elevation products have become available for locations +/- 60 degrees N/S for public use (Gesch, Muller, and Farr 2006). The SRTM DEM as a seamless radar elevation product is a standard product across multiple scales of analysis from the local, regional, and global level. This highlights an advantage of the SRTM: its consistency across national borders and availability in inhospitable areas, such as steep mountain ranges and dense tropical forests. Thus, this examination of SRTM error in relation to terrain characteristics, such as slope, will aid the public, academics, and professionals in assessing the fitness of SRTM data for specific applications interpreting the results of SRTM environmental applications that apply it. A greater understanding of the applications of SRTM is important to geography research because of the global interest in the earth's characteristics.

Geography consists of understanding thematic relationships across spatial scales of analysis. Geography is the study of what is where and why. Thus, this applies to both environmental characteristics and social demographics. Digital terrain analysis can be used to understand many dynamics in geography. In relation to digital terrain analysis, the availability of data also reflects different scales possible with each product. Scale is defined as the "relative distance on the image to the corresponding distance on the ground" (Bolstad 2005: 191). In large-scale maps, objects and landscape features appear larger and with more detail than on small-scale maps (Bolstad 2005). Figure 1.1 illustrates the DEMs used in this thesis with their coverage extents and general resolution characteristics. Extent refers to the area covered by a particular image (Bolstad 2005). The quality of data used in geographic applications could impact the results of the application. This research explores an agricultural suitability model related to rice production in two different geographic areas of the world to examine the implications of differences in DEMs in application use. An agricultural application was selected because of the similar agricultural conditions and flat topography of both Nang Rong and southwest Louisiana.

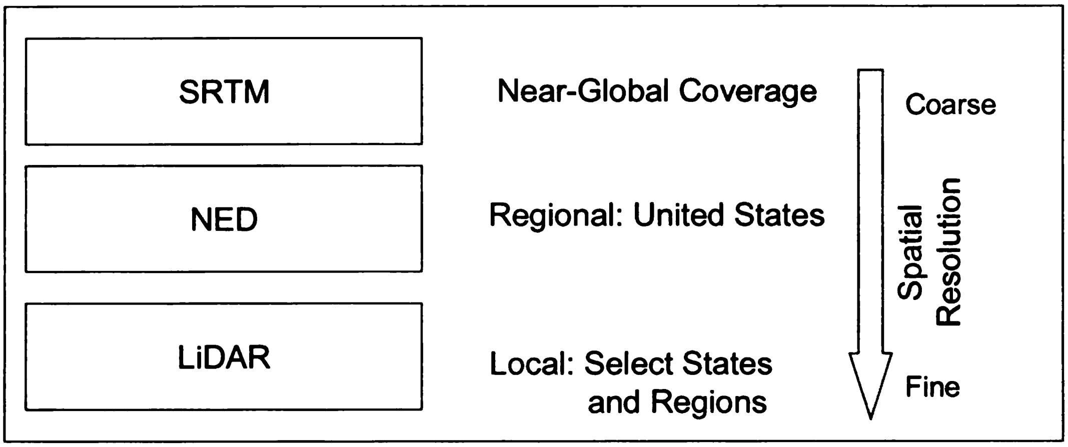

Figure 1.1. Comparisons of Digital Elevation Models

1.1. Motivation

A motivation of this research is to expand understanding of important characteristics of the SRTM DEM to improve its use in the public, private, and governmental settings. Environmental and social issues related to environmental change and earth monitoring faced can be addressed by using SRTM data (Wood 2004). However, understanding the appropriate use of available digital terrain data is still needed to have effective implementation of decisions made from its results. Thus, greater understanding of SRTM gained from applications in data rich areas, such as the United States, will strengthen the appropriate use of the SRTM model in applications internationally.

This comparative study of locations in the United States and elsewhere illustrates how research in an area with very rich spatial data resources, including high resolution raster data, accurate vector datasets, and effective means of public dissemination, can be used to aid research without these resources. The Nang Rong district of Thailand was chosen as one location for this thesis work in conjunction with other research at Michigan State University. Its flat topography and agricultural characteristics were used to identify possible study areas in the United States. Based on these characteristics and the availability of a high resolution reference DEM, two study areas in Louisiana were selected: an area in southewestern Louisiana including mainly Acadia Parish, and an area in northern Louisiana including parts of the Webster and Boosier Parishes. The Acadia study area represents an agricultural area, while the Webster study area represents a forested area. Thus, these study areas: the Acadia, Webster, and Nang Rong study areas, enable research into the characteristics of the SRTM C-band 90 m DEM in relation to land cover/ land use properties.

1.2. Research Questions

This research proposes to answer the following research questions (1-6):

1. What are the relationships among elevations of NED, LiDAR, and SRTM DEMs?

A comparison of the elevations values of the NED, LiDAR, and SRTM DEMs is important to complete in order to determine how much the values are similar or different from one another. Since, the NED, LiDAR, and SRTM DEMs are available for the Louisiana study areas, it is important to determine how the selection of one of these DEMs could portray topographic characteristics similar or different from the others. The elevations of the DEM products are expected to be similar for similar production methods: LiDAR, NED, and SRTM.

2. What are the relationships among NED, LIDAR, and SRTM slopes?

Similar to the elevation comparison, the slopes of the NED, LiDAR, and SRTM DEMs will be compared to determine similarities and differences. These similarities and differences can be important to application use and pertinent to the type of landscape the

DEM is used in. The slopes of the NED, LIDAR, and SRTM DEMs are expected to be correlated for the original and resampled versions from each production method.

3. Is the average SRTM DEM error greater than zero?

The average error is an indicator of whether the DEM is systematically higher or lower than the reference DEM. The average error indicates bias of the DEM. It is expected that the average SRTM DEM error will be different from zero for different land uses. A SRTM error of zero would indicate no difference between the SRTM DEM and the reference DEM.

4. What is the relationship of SRTM error in terms of different land cover/land use classes (i.e. developed, forested, agriculture, water)?

Researchers (Shortridge 2006, Bhang, Schwartz, and Braun 2007, Carabajal and Harding 2006), have recognized that the SRTM DEM has issues with tree canopy. The SRTM DEM has been found to overestimate elevation in locations of dense tree canopy (Shortridge 2006). My thesis research is focused on broad land cover/ land use classes (i.e. developed, forested, agriculture, water, shrub) to determine whether these classes also have certain characteristics with SRTM DEM Error. Distinction is made between non-forested and forested classes for comparative purposes.

5. Is the average SRTM DEM error greater for vegetated or non-vegetated areas?

As seen above in the explanation of the land cover/ land use relationships research question, interest is in the differences between the vegetated and non-vegetated areas. Non-vegetated here is in reference to areas without tree canopy. The vegetated areas are expected to have a larger average SRTM DEM error variance and magnitude. The SRTM error for a vegetated surface is expected to be positive due to an elevation error bias.

6. How will the LiDAR, NED, and SRTM DEMs perform in a land use application?

The application of the SRTM compared to the LiDAR is expected to have a lower overall accuracy. The application of the SRTM compared to the NED is expected to have a lower overall accuracy. Since DEMs are used in geographical research and public setting, it is important to understand how the use of one DEM differs from another. This research question is aimed at identifying the different results of a DEM when used in an application setting. This is valuable information to other researchers in terms of their selection of a specific DEM to employ in their research. It is likely that the given the coarser resolution 90 m of the SRTM DEM used in the application, it would not perform the same as the LiDAR and NED DEMs.

The above research questions are aimed at expanding the knowledge of SRTM elevation models. This examination is focused on the differences between the SRTM model and other available elevation models including LiDAR-derived DEMs and NED data. The limitations of the SRTM can be explored through analysis with higher quality data (i.e. LiDAR and NED) in the United States context and SRTM X-band in the international context. This research is aimed at assessing these error structures in relation to landscape characteristics, such as land cover/land use. Given the nature of the actual slopes of the selected study areas, the slopes of the NED, LIDAR, and SRTM DEMs are investigated in a comparative sense; however, the relationships between their slope properties and SRTM error is not a focus of this research. This research is valid both in the United States and elsewhere where DEMs are employed in government use, research, and environmental modeling.

1.3. Significance

Diverse landscapes and spatial analysis of large regions is possible with digital terrain analysis, an important research topic in geography. This research supplements existing error studies of SRTM data, which used diverse reference data, such as satellite altimetry, Global Positioning Systems (GPS) point data, and National Elevation Dataset DEMs (Berry, Garlick, and Smith 2007; Falorni et al. 2005; Guth 2006). Trends in the characteristics of a model in relation to slope and landscape characteristics can aid in understanding its fitness of use. This research acknowledges that multiple data sources are available to the user from various sources, and explores how variations among these products are important in application use. Since the SRTM DEM has near-global coverage, this research is significant to the international research community where the SRTM model is the best available DEM.

1.4. Overview of Thesis

Chapter 1 provides an introduction to the key questions, and significance. This chapter introduces the topic of elevation models in terms of various resolutions, production methods, and error relationships. Images in this thesis are presented in color.

Chapter 2 presents background information on the digital elevation data sources investigated to address the research questions stated in Chapter 1. Further information is provided on data quality. A review is provided of elevation model sources employed in this thesis: National Elevation Dataset (NED), Light Detection and Ranging (LiDAR), and Shuttle Radar Topography Mission (SRTM) data. The characteristics, production methods, and literature of the SRTM DEM are more extensively reviewed. A review of the literature on SRTM error is presented to provide context for this thesis research in relation to other known relationships between SRTM error and terrain characteristics. Further discussion is provided on the conceptualization of error and resampling techniques in error analysis.

Chapter 3 describes the methodology of site selection of study areas. The characteristics of chosen study areas of Nang Rong, Thailand and portions of Louisiana are examined in relation to geographical and environmental characteristics. This section provides a framework for an agricultural application in both areas.

Chapter 4 outlines a detailed methodological narrative on the processing procedures necessary for this research. The sources of the DEMs and resampling techniques are outlined. Error analysis methodology and application implementation are indicated in relation to study areas.

Chapter 5 discusses the results of the analysis of DEMs for the Acadia and Webster study areas in the United States and Nang Rong in Thailand. Results of SRTM error by land cover/land use characteristics are summarized. General trends and patterns of error characteristics are identified per study area. In addition, a geospatial application related to rice production is presented to illustrate how the use of different DEMs can present different outcomes.

Chapter 6 summarizes the main conclusions of this research in terms of each case study and makes inferences to other areas. Directions of research are discussed to indicate future paths of SRTM error research.

2. Background

The United States' well-structured system of dissemination and coordination of geospatial information enables researchers to access data for anywhere in the U.S. This research utilizes publicly available elevation data to determine the error characteristics of DEMs. This section will focus on discussion of the characteristics of elevation models used in this research, including National Elevation Dataset (NED), Shuttle Radar Topography Mission (SRTM), and Light Detection and Ranging (LiDAR) DEMs. Issues related to the SRTM production will be closely reviewed, along with research directed at understanding the SRTM C-band 90 m DEM's relationship to error and applications. Following discussion of the sources of elevation data, key concepts related to DEM analysis are explained.

2.1. Digital Elevation Background

DEMs are used to address hydrological, ecological, natural resource management, and land use planning issues (Moore, Grayson, and Ladson 1991). Current uses of digital elevation models include watershed delineation, automatic delineation of sub-watersheds, watershed linkages, drainage networks, and overland paths (Jenson and Domingue 1998). More recently, land cover/land use investigations, urban studies, and medical geographers have incorporated terrain variables into analysis (Wilson and Gallant 2000). While elevation itself is important, terrain derivative parameters such as slope, aspect, plan and profile curvature, wetness index, and solar radiation, may be even more valuable for environmental analysis (Carlisle 2005; Wilson and Gallant 2000). Table 2.1 indicates descriptions of key terrain derivatives. These terrain derivatives are obtained from DEMs produced from various sources, including digitized topographic contour maps, scanned aerial imagery, manual profiling techniques, as well as radar technology, such as Synthetic Aperture Radar (SAR) data. The generation of DEMs is useful in understanding landscape properties, visualizations, and applications (Figure 2.1). Visualization techniques for DEMs include contour mapping, hypsometric shading, hillshading, and creating Triangular Irregular Networks (TIN).

Table 2.1. Key Terrain Parameters.

Attribute	Description
Slope	Gradient, Rise over Run (degree and percent); 1st Derivative
Aspect	Direction of steepest slope
Curvature	Plan curvature, Profile Curvature. Curvature indicates the convexity and concavity of the surface. 2nd Derivative

This table defines main terrain attributes of DEMs. Modified from Moore, Grayson, and Ladson (1991).

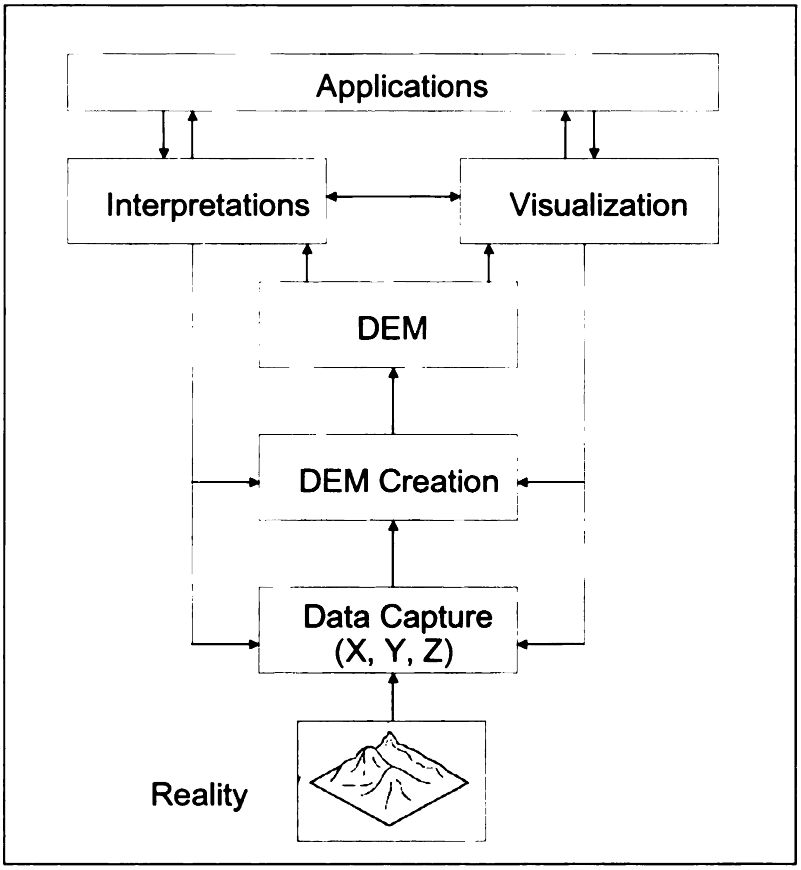

Figure 2.1. Process of Digital Terrain Modeling. This schematic illustrates how once elevation and coordinate information are acquired, they are used to generate DEMs and used in applications. Modified from Hutchinson and Gallant (2005).

Digital elevation models are continuous field models that are able to characterize many natural and anthropogenic features of the earth's surface, ranging from small ditches to vast mountain ranges. The interpolation of X, Y, Z point elevation data to a continuous field model enables the DEM to be incorporated into many GIS applications. However, the interpolation of elevation models can be done in many ways, which can result in models of various resolutions with different properties (ESRI 2006b). The cell size of elevation models can be more or less appropriate for certain details of analysis. Given the significance of resolution and production method of digital elevation models, the following section provides a review of elevation model sources.

2.2. Elevation Model Sources

This section summarizes the elevation model sources for both the United States and internationally used in this research. A review of the characteristics of the NED, SRTM, and LiDAR data are the focus of this section. These elevation models differ in terms of production method and resolution, which will be further explored in this thesis. Recognition of the differences of these models is significant to understanding their fitness for use in applications in a variety of settings

2.2.1. National Elevation Dataset (NED)

The United States Geological Survey (USGS) seamless distribution server provides access to the seamless National Elevation Dataset (NED) elevation models at 1/9th arc second (~3 m), 1/3rd arc second (~10 m), and 1 arc second (~30 m) for the United States (USGS 2007). The NED 1 arc second data are available for the entire United States, while the 1/9th arc second data are created from LiDAR data for select locations. The USGS elevation products correspond to 7.5 minute quadrangle extents

(Moore, Grayson, and Ladson 1991). However, the NED DEM product is not restricted to the extents of the 7.5 minute quadrangles. Each raster cell of the NED DEM represents one elevation posting from the source elevation information. Throughout the examination of the USGS seamless web viewer for this research, consideration was given to its user-friendliness and ease of accessibility (USGS 2007). An increase in the availability of the products to the public, modifications made to public repositories to make them more user-friendly, and the progress of web applications aided broader dissemination of spatial data. The availability of elevation models and spatial data have greatly expanded, which warranted the creation of advanced dissemination methods to the public.

2.2.1.1. NED Production Methods

Advances in geospatial technology have led to the creation of more sophisticated DEMs. NED data were created from manual profiling methods and more recently from incorporated higher resolution LiDAR data (USGS 2007). Artifacts from the production methods of a DEM can be seen by hillshading a DEM. This is valuable information regarding possible production errors observed in the DEMs, such as striping. Striping is seen as linear features in the DEM, which are not part of the actual landscape. Striping is the identification of parallel lines in USGS DEMs from the manual profiling method of production (Fisher and Tate 2006). The NED metadata indicates the production method of the DEM. Metadata refers to the information regarding source, production methods, and originator of these data. Table 2.2 shows the production methods of NED DEMs corresponding to the value indicated in the metadata. The table indicates the names of specialized DEM processing software by names such as (ANUDEM). NED represents elevation models for the United States, while other digital elevation models from radar technology, such as SRTM, have been created over a larger area of the earth. The SRTM model will be discussed in subsequent sections to highlight its main characteristics, relevant research, and application use.

Table 2.2. Production methods of the NED DEMs

Production Method	Meaning
0	Unknown
1	Electronic Image Correlation (specifically Gestalt Photo Mapper II (GPM II))
2	Manual Profiling
3	DLG2DEM: (Digital Line Graph)2DEM
4	DCASS: Digital Cartographic Software System (USGS Software)
5	LT4X: Either LT4X or LTPlus software
6	Complex polynomial interpolation, such as ANUDEM
7	LiDAR or other active remote sensing
8	Photogrammetric mass points and breaklines

The USGS uses specialized software to create DEMs. From Oimen (2002).

2.2.2 Shuttle Radar Topography Mission (SRTM)

On February 11, 2000, the Shuttle Radar Topography Mission was flown on the Space Shuttle Endeavor for 11 days and acquired 12 terabytes of radar data for 60°N to 60°S latitude, which is 80% of the Earth's land surface (Grohman et al. 2006; Korbick 2006). Figure 2.2. indicates the SRTM coverage of the world. The SRTM project was a joint project of the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The SRTM data were used to create an elevation model of the earth representative of the top of the earth's surface (Guth 2006). The vertical absolute height accuracy of the SRTM DEM is less than 16 m (NASA 2002).

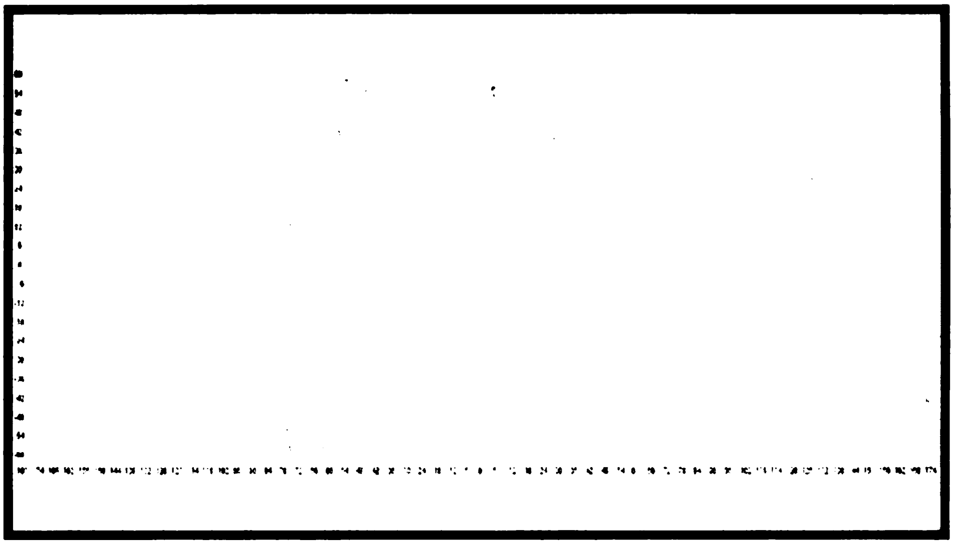

Figure 2.2. Shuttle Radar Topography Mission Coverage. From Landserf (2005).

The Space Shuttle Endeavor that acquired the radar data for the creation of SRTM elevation products entailed sophisticated mechanisms and engineering components. Figure 2.3. illustrates the Space Shuttle Endeavor, which was flown with a single-pass, dual antenna, including a C-band interferometric synthetic aperature radar system and X-band antenna (Slater et al. 2006). The SRTM hardware included a 60 m mast with C-band and X-band antennas and advanced tracking devices (JPL 2005d). Other products obtained from the SRTM included ascending and descending orthorectified image mosaic (AOIM, DOIM), Terrain Height Error Data (THED), Seam Hole Composite Map (SHCM) (Slater et al. 2006). The U.S. Geological Survey disseminates the SRTM version 1 (90 m), and SRTM version 2 (30 m) for only the United States (Slater et al. 2006). For clarification purposes, the SRTM C-band DEM used primarily in this research differs from the SRTM DTED data produced and released prior to the release of the finished SRTM data. The SRTM data used in this research was the finished product from the USGS (EROS) obtained in July of 2007. The completion of the processing of the SRTM C-band data was 2 years (JPL 2005a). The C-band data were processed by the Jet

Propulsion Laboratory, and Deutsches Zentrum fur Luft-und Raumfahrt (DLR), (the German Aerospace Center) processed the X-band data at 25 m resolution, a finer resolution compared to the C-band.

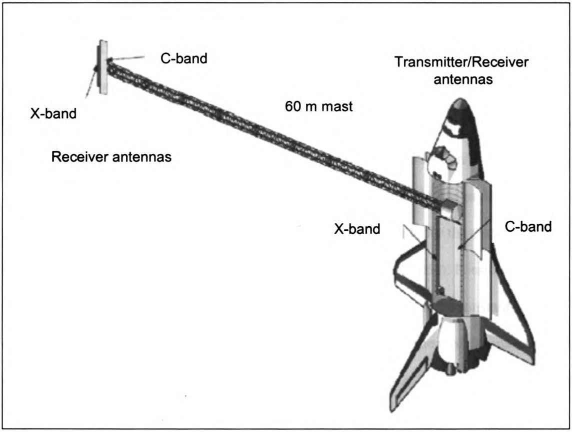

Figure 2.3. Space Shuttle Endeavor. The Space Shuttle Endeavor carried the hardware and software used to acquire the radar topographic information. Modified from Yastiki, Kocak, and Buyuksalin (2006).

Consideration of how the SRTM data were created enables the user to better determine whether a certain use will be appropriate. The SRTM data distributed by the USGS EROS service used the subsampling method to resample the SRTM 30 m DEM to the 90 m resolution, while data distributed from the Land Processes Distributed Active Archive Center (LP DAAC) used an averaging method (NASA 2005). The subsampling used the center cell of the 90 m area, while the averaging method took the average value of the neighborhood of cells. This method decreases the noise in the initial radar data. In addition to understanding the production method of the SRTM DEM, the nomenclature of the various models from the SRTM mission warrants clarification because several versions of the SRTM DEM were released during processing.

SRTM DEMs were created using radar interferometry. Radar interferometry entails obtaining two radar images at different locations and using the differences between the images to determine the elevation (JPL 2005e). The radar technology is able to penetrate clouds, which makes it an advantageous imagery collection method (JPL 1999). These two images are taken by one radar antenna in the shuttle payload bay and another one on the 60m mast (JPL 2005a). A calculation is made for the earth's surface elevation based on the differences of these radar images (JPL 2005a). Possible errors in the interferometric calculations relate to static errors, which are errors constant for the entire dataset and time-varying errors, which are from the movement of the mast and electronic beam steering (Rodriguez, Morris, and Belz 2006).

The C-band and X-band SRTM DEMs have slightly different characteristics, which indicate slight variation in surface response to landscape properties. The C-band radar antenna is able to transmit and receive 5.6 cm wavelengths (JPL 2005c). The 225 km swath width of the C-band radar antenna enabled its 80% coverage of the earth, which is 119.56 M km^2 (JPL 2005c; JPL 2005f). The X-band swath width was 50 km (JPL 2005c). The X-band was able to receive and transmit data at a 3 cm wavelength (JPL 2005c). The different wavelengths of the SRTM DEMs are discussed in subsequent paragraphs as they relate to the radar's response to surface characteristics.

The wavelength of the radar determines how well it is able to penetrate the atmosphere (Lillesand, Kiefer, and Chipman 2004). The radar of the SRTM mission did not penetrate vegetation; rather the radar collects data from the top of the canopy cover (JPL 2005b). However, if the vegetation is less dense, the radar may be able to detect ground conditions (JPL 2005b). The small size of the wavelengths of the SRTM C-band and X-band do not enable deep penetration into vegetation, like the wavelengths of 10 cm to 30 cm (Lillesand, Kiefer, and Chipman 2004). Typically, radar at shorter wavelengths from 2 cm to 6 cm, such as the SRTM C-band and X-band, are better for detecting crop surfaces (Lillesand, Kiefer, and Chipman 2004). It is difficult to decipher differences between the SRTM C-band and SRTM X-band regarding vegetation canopy. If the wavelength they transmitted at was more dissimilar, possibly more of a distinction could be made among vegetated surfaces. Also in comparison, the X-band scatters radar from the top of tree canopies; while the P-band (another radar band that receives and transmits at 74 cm) is able to penetrate vegetation (Andersen, Reutebuch, McGaughey 2006).

A study was found that examined the SRTM C-band and SRTM X-band DEM in an area of Norway in terms of major land cover characteristics (Weydahl et al. 2007). Weydahl et al. 2007 indicated the difference between the SRTM C-band and SRTM X-band for agricultural and forest cover in an area of Norway. The RMSE of the SRTM X-band DEM was 3.4 m for agricultural fields and 9.8 m for dense coniferous forest, where the reference DEM was one created from digital vector data at a cell spacing of 5 m (Weydahl et al. 2007). While the SRTM C-band 90 m had a RMSE of 4.6m in agricultural fields and 9.1 m in deciduous coniferous forest (Weydahl et al. 2007). A main finding of Weydahl et al. 2007 was that the SRTM C-band seemed to penetrate slightly deeper than the SRTM X-band; however, as these researchers noted this slight difference may be insignificant in actual use of the DEMs. Thus, despite slight differences in the penetration of the SRTM C-band and SRTM X-band DEMs, they may still be used effectively by researchers.

Recently the use of X-band SRTM data are appearing in scientific literature (Hoffmann and Walter 2006, Weydahl et al. 2007, Kiel, Alsdorf, and LeFavour 2006) The SRTM X-band Data was obtained for 40% of the land covered by the SRTM C-band (DLR 2008). Table 2.3 indicates the characteristics of the X-band DEM. In comparison to the C-band data, the absolute vertical accuracy is comparable; however, the relative vertical accuracy is better. In addition to differences in accuracies, the two products were processed in reference to slightly different vertical datums, which will be further discussed in later sections. The SRTM X-band DEM was created by using the elevation value of a 25 m by 25 m extent (Wagner 2007).

The most complete article investigating the differences between SRTM-X and SRTM-C band data was Hoffmann and Walter (2006). Hoffmann and Walter (2006) take a global scale approach to investigate the root mean square error (RMSE) differences between data products. In comparison of the SRTM C-band and SRTM X-band to a ground reference, Hoffmann and Walter (2006) found the SRTM C-band to be more accurate than the X-band for water areas in the Amazon and Ohio. In relation to studies that incorporate the X-band data, such as an error assessment in the Norwegian forest area using X-band and C-band SRTM data (Weydahl et al. 2007). In this comparison, a difference of 15-17 m was seen between the SRTM elevations (SRTM X-band and SRTM C-band and the ground value for forested areas (Weydahl et al. 2007). Another study used the SRTM X-band data for analysis of watersheds in the Amazon; however, the authors did not correct for the differences in geoids between the SRTM X-band and other DEMs because their research was interested in variability of results not absolute accuracy (Kiel, Alsdorf, and LeFavour 2006). These examples indicate that where the SRTM X-band data are available, researchers are beginning to compare its fitness for use to those of other products.

Table 2.3. NED, SRTM, and LiDAR DEM Characteristics

	NED	SRTM C-band 90 m	SRTM C-band 30 m	SRTM X-band	LiDAR 5 m
Horizontal Datum	NAD83	WGS 84	WGS 84	WGS 84	NAD83
Vertical Datum	NAD83	EGM96	EGM96	WGS 84	NAD83
RMSE	7 m	10 m	10 m	6 m	0.15-0.5 m

From Wagner (2007), USGS (1999), NASA (2002), Atlas (2007).

2.2.2.1. SRTM: Production issues

Factors related to the SRTM hardware and operations have been explored in the literature in relation to mechanical operations, data voids, and systematic sources of error in the SRTM model (Rodriguez, Morris, and Belz 2006). Some possible contributors to the SRTM error include baseline roll errors, phase errors, beam differential errors, timing, and position errors that occurred in the initial retrieval of radar information (Rodriguez, Morris, and Belz 2006). Also, errors from the extraction methods, data spacing, and smoothing techniques are present from the model's creation methodology (Grohman et al. 2006). The SRTM elevation data distributed by the USGS had a half pixel shift in comparison to the NED (Guth 2006). However, as of February 6, 2007, the USGS corrected this half pixel shift (USGS 2007).

The SRTM product released contains voids in the data from its collection methodology. Voids (i.e. holes in the data) have been investigated by researchers (Grohman et al. 2006). Methods have been investigated to fill the voids, such as a Fill and Feather method and a Delta Surface method (Grohman, Kroenung, and Strebeck 2006). In the Fill and Feather method, the most accurate elevation model available is used to fill the void value and is "feathered " into the SRTM to obtain a smooth transition in values (Grohman, Kroenung, and Strebeck 2006). The Delta Surface method uses SRTM values near the void to fill the void (Grohman, Kroenung, and Strebeck 2006). The SRTM data the USGS distributes did not implement a filling algorithm. However, the Consultative Group for International Agricultural Research Center (CGIAR-CSI) has implemented a void-filling algorithm and use of other DEMs to fill in the voids in the data (CGIAR-CSI 2004). Other SRTM sources, such as the Global Land Cover Facility, have also enhanced their DEMs by filling the voids in the DEM (GLCF 2008). The process of filling the voids alters the original data; thus, this research is focused on using data that was not altered from its finished form.

Recognized systematic errors of SRTM DEMs include striping and mis-alignment with local datums (Miliaresis and Paraschou 2005). Striping is seen as linear patterns in the error characteristics of the DEM, which are unrelated to the Earth's surface characteristics. Striping has been observed in the SRTM DEM from the swath-like manner of the radar collection. In an investigation of SRTM on the island of Crete, a misalignment of the SRTM DEM was observed that was suggested to be from an inability to align the SRTM DEM with the local datum in this location (Miliaresis and Paraschou 2005). Datum issues of SRTM will be further discussed later in the chapter.

In comparison of SRTM to alternative elevation products, the radar technology has potential advantages. SRTM provides consistent source information across a wide land area, better resolution compared to the GTOPO30 (1 km), and better capabilities to analysis surface characteristics. At a global scale before the SRTM mission, the finest global elevation model, (GTOPO30), was available at 1 km (30 arc seconds) resolution (Korbick 2006). The blunders or stripings from manual profiling present in the NED data are not present in the SRTM. Thus, in areas where NED striping or production issues are prevalent the SRTM C-band 30 m DEM could be a useful alternative. Geographic analysis in locations where very few other spatial datasets are available can benefit from the use of the SRTM DEM. Hence, SRTM data have great implications in international land management. Furthermore, locations with poor reference data can benefit from this thesis research.

2.3. SRTM Elevation Model Error Literature

Studies of error in digital elevation models are well-documented in the scientific literature (Carlisle 2005; Fisher and Tate 2006). Rugged areas have less vertical accuracy because of smoothing effects of elevation models (Grohman, Kroenung, and Strebeck 2006). The type of landscape (i.e. flat or rugged) can have different error characteristics. Hydrological applications have been explored in terms of the elevation differences found between USGS 30 m and ground truth points (Holmes, Chadwick, and Kyriakidis 2000). A standard methodology of exploring DEM quality has been by comparing them to a high quality reference model, which will be the methodology employed in this research.(Guth 2006; Shortridge 2006).

More recently, studies began investigating the characteristics of SRTM DEM error (Rodriquez, Morris, and Belz 2006; Guth 2006). A global assessment of the SRTM model was performed using ground control points from kinematic global positioning systems (Rodriquez, Morris, and Belz 2006). The use of kinematic GPS was limited to roads only and lacked inhospitable locations, such as rough terrain, steep cliffs, and high ridges (Rodriquez, Morris, and Belz 2006). Another disadvantage of the global assessment using kinematic GPS was the omission of areas of high difference between GPS ground truth points and SRTM heights, including bridges and heavily forested areas (Rodriguez, Morris, and Belz 2006). This indicates how selective areas for error analysis may not be fully representative of landscape characteristics. Thus, this demonstrates that a different continuous model could be valuable as a reference model in error analysis.

In the United States, a large scale analysis of SRTM and NED investigated geomorphic parameters at over 500,000 sample areas. Guth (2006) found correlations to be high between elevation and relief, but low for curvature and skewness (Guth 2006). In flat landscapes, for example, on alluvial fans, substantial noise has been found in SRTM data, which increases with average slope (Guth 2006). Noise is the term given to disturbances in digital imagery from issues related to the remote sensing technology (Lillesand, Kiefer, and Chipman 2004). DEM errors are related to the physical characteristics of the earth (Carlisle 2005). This illustrates how areas with different topographic characteristics can have different representation issues with a DEM. Further application analysis is needed with these data to determine if results depend on the selected data, in terms of hydrology, slope processes, and viewsheds (Guth 2006).

In contrast to using massive datasets for reference in locations, smaller scale studies on select areas used GPS data as reference. For the Little Washita River in Oklahoma and the Tolt River in Washington, ground control points and USGS DEMs (30 m) were examined in relation to the SRTM C-band 30 m data (Falorni et al. 2005). An analysis of SRTM and differentially corrected GPS elevation points for a site in the Catskill Mountains of New York and a site in Puket, Thailand, indicated correlations between SRTM error and slopes greater than 10 degrees, overestimated elevations on southeast slopes, and underestimated elevations on northwest slopes (Gorokhovich and Voustianiouk 2006). Reference GPS data provide a limited sample of points for comparison to the SRTM model, which may not be representative of an entire region.

DEMs generated from digitized contour lines have been used in locations without GPS data. An alternative approach used to create DEMs is interpolation from contour lines; however, hillshades of these models can have a terraced appearance. From an analysis of the SRTM DTED level 1 for the island of Crete, higher errors were found on mountain tops when using a reference elevation model generated from digitized contour lines (Miliaresis and Paraschou 2005). The use of a DEM created from digitized contour lines was also used in comparison of catchments in Australia (Hancock et al. 2006). In an examination of SRTM and high-resolution models (25 m) for catchments of in the Tin Creek, Swift Creek, and Jemmys Creek of Australia, the SRTM DEM captured slope and elevation characteristics; however, SRTM derivatives of catchment area, relief, and shape were not as accurate with the SRTM DEM (Hancock et al. 2006). The lack of a correspondence between the Australian catchments could have been from the method of the creation of the reference DEM.

SRTM has been considered in relation to reference data sources, such as satellite radar altimetry (Berry, Garlick, and Smith 2007), Ice, Cloud, and Land elevation Satellite (ICESAT) data (Carabajal and Harding 2006). Berry, Garlick, and Smith (2007) employed a continental analysis of SRTM C-band data using satellite radar altimetry. ICESAT was used in a more select manner in representative landscapes to analyze in relation to SRTM (Carabajal and Harding 2006). The C-band of the SRTM 30 m digital elevation model was compared to data from the Ice, Cloud, and land-elevation satellite (ICESat) laser altimetry for Otter Tail County, Minnesota (Bhang, Schwartz, and Braun 2007). NASA's laser vegetation imaging sensor (LVIS) was used as a reference to SRTM for sites in Maine, Massachusetts, Maryland, New Hampshire, and Costa Rica (Hofton et al. 2006). These studies show the use of satellite sensor information, such as ICESat, could be employed as a possible source of reference information to the SRTM model.

Overall, the literature published on SRTM error characteristics ranges in type of reference data. Table 2.4 provides a summary of select literature reviewed in this section. The SRTM DEM is also indicated since different sources enhance the DEM as indicated earlier in the section. The reference data were often dependent on the scale of analysis ranging from small watersheds to global scale analysis desirable by the researchers.

Table 2.4. Summary of SRTM Accuracy Literature

Reference	**Reference Data**	**Study Areas**	**SRTM Model**
Guth (2006)	USGS NED	500,000 sample areas (USA)	SRTM 90 m C-Band
Berry, Garlick, & Smith (2007)	Satellite Radar Altimetry	By Continent	SRTM 90 m C-band
Carabajal and Harding (2006)	Ice, Cloud, and Land Elevation Satellite (ICESAT) data	Amazon, Tibetan Plateau-Himalayan Mountains, East Africa, western Australia, western USA	SRTM 90 m C-band

Table 2.4. continued.

Gorokhovich & Voustianiouk (2006)	Differential GPS points	Catskill Mountains, New York Phuket, Thailand	CGIAR-CSI SRTM 90 m
Hancock et al. (2006)	High resolution models	Catchments of Tin Camp Creek, Swift Creek, Jemmys Creek (Australia)	SRTM 90 m
Miliaresis & Paraschou (2005)	SRTM DTED level 1/ digitized contour lines	Crete Island	SRTM 90 m
Rodriquez, Morris & Belz (2006)	Kinematic global positioning system	Global assessment	SRTM 90 m
Shortridge (2006)	NED/ GPS Ground truth	Oakland County Michigan	SRTM 90 m
Hofton et al. (2006)	NASA's laser vegetation imaging sensor (LVIS)	Maine, Massachusetts, Maryland, New Hampshire, Costa Rica	SRTM 90 m C-band
Falorni et al. (2005)	Ground Control Points, USGS DEMs	Little Washita River (Oklahoma), Tolt River (Washington)	SRTM 30 m

This summary of select literature of SRTM Accuracy indicates the diversity of the range of reference data used and the range of study sites possible for investigation.

2.4. Implications of Land Cover in SRTM

Researchers have investigated the relationship between SRTM elevation and different land cover classes, with special focus on differences between forest and open land. Land cover is defined as natural cover on the surface of the earth, while land use is related to how land is used, such as for agriculture or urban development (Lambin et al. 2001) In a study of STRM in relation to satellite altimeter echoes from the ERS-1 Geodetic Mission, Berry, Garlick, and Smith (2007) found skewed results between the land cover of the Amazon Basin for open land and forest.) They also observed greater differences above the forest canopy compared to open land (Berry, Garlick, and Smith 2007). Similarly, for North America, the SRTM error histogram distribution was skewed in relation to inland water and vegetation (Berry, Garlick, and Smith 2007). The SRTM model was created by NGA and NASA was based on reflections from the earth's surface, thus vegetation canopy present on the surface would affect wavelength transmission (Lillesand, Kiefer, and Chipman 2004).

Similar studies examined the different characteristics of surfaces in relation to SRTM DEM characteristics (Bhang, Schwartz, and Braun 2007; Hofton et al. 2006). An examination of the SRTM DEM using ICESat laser altimetry as reference found bare ground from a classified Landsat-7 image did not impact the SRTM values, while the forested and agricultural areas impact SRTM and ICESAT in different ways (Bhang, Schwartz, and Braun 2007). The irregular surface created by forests was found to impact the radar used in the creation of the SRTM data for a study area in Minnesota (Bhang, Schwartz, and Braun 2007). Also, an accuracy assessment of SRTM C-band DEMs using NASA's laser vegetation imaging sensor (LVIS) as reference found a positive relationship exists between the elevational difference and height of the canopy (Hofton et al. 2006). Similarly, in the Amazon, the dense canopy increased the height of the DEM and obscured the identification of fine scale topographic patterns on the landscape (Valeriano et al. 2006).

In an analysis using Michigan land cover data, an error assessment of SRTM with NED and ground truth data from Oakland County Michigan indicated that the SRTM DEM were overestimated in forested landscapes (Shortridge 2006). The research literature indicated the possible biases of vegetation and SRTM, which would be important to the applications related to forest cover. An application related to tree inventory was created with the inclusion of SRTM and NED data to aid in the tree inventory of loblolly pine *(Pinus taeda)* (Heo et al. 2006). Some researchers have explored how the differences of SRTM and vegetation can be accounted for in offset calculations (Kellndorfer et al. 2004). Additional analysis of canopy height and SRTM elevation, indicated a minimum mapping unit of approx 1.8 ha (18,000 m^2) to be used in vegetation canopy height mapping from SRTM data for Georgia and California in comparison to locations in Iowa and North Dakota identified as tree-less areas (Kellndorfer et al. 2004). Thus, the reference data employed and the region under analysis can find different SRTM error characteristics.

A worldwide assessment of the SRTM C-Band data of various topographic and vegetative sites in the South American Amazon Basin, Asian Tibetan Plateau-Himalayan Mountains, East Africa, western Australia, and the western United States used the Geoscience Laser Altimeter System (GLAS) instrument data (Carabajal and Harding 2006). This study found similar results for elevation values between the products (Carabajal and Harding 2006). In addition to comparisons of elevation values, Carabajal and Harding (2006) examined the SRTM error based on MODIS Vegetation Continuous Fields (VCF) 500 m resolution data. This study confirmed earlier reports that found SRTM elevation values to be less accurate for areas of higher tree cover.

As indicated in Carabajal and Harding (2006), a global land cover dataset was utilized for comparison across study areas. Often as seen from these studies, satellite imagery such as MODIS data is used to examine broad land cover classes to extrapolate relationships of SRTM error and surface characteristics. A brief review follows of the application domains in which SRTM elevation data have been employed to address environmental issues.

2.5. SRTM Application Use

SRTM data have been employed in applications, such as hydrology in the Amazon (Kiel, Alsdorf, and LeFavour 2006), forest mapping in the Everglades (Simard et al. 2006), and lake level reconstruction in Africa (Leblanc et al. 2006). Environmental studies and land management applications have included SRTM DEM information with the desire to include a reliable topographic variable, where possibly not another DEM exists.

Characteristics of geomorphic elements of the landscape have been identified through the use of SRTM DEMs. SRTM elevation data were used to examine mega dunes distribution to better understand the aeolian processes of their formation (Blumberg 2006). Through the selection of multiple locations in northern Africa and across central Asia, the SRTM C-band was compared to SRTM X-band dune locations (Blumberg 2006). This analysis of dune locations and form illustrated how the SRTM X-band was able to identify small scale geomorphic characteristics, unlike work with the SRTM C-band (Blumberg 2006). SRTM DEMs have also been employed to examine valleys and ridges around the La Pacana Caldera, northern Chile (Bailey et al. 2007) and the Pocos de Caldas Alkaline Massif, a volcanic caldera located in southeastern Brazil (Grohmann, Riccomini, and Alves 2007). The SRTM DEM has been previously used in the study of landforms and processes related to landscape change.

Other hydrologic applications have explored the potential of SRTM. The extent of SRTM application use has included hydrological analysis of the Upper Parana River basin of Bolivia (Brandt and Townsend 2006), watershed analysis of the Asu watershed in Brazilian Amazonia using SRTM 90 m (Valeriano et al. 2006), and flood risk identification in Izmir (11, 810 km^2), western Turkey (Demirkesen, Evrendisek, and Berberglu 2006). The surface water elevations acquired from SRTM were used in a regional groundwater flow model in a study area within the Northern Highland Lakes region of Wisconsin, USA (Fredrick et al. 2007). Hydrologic analysis of the Three Gorges Reservoir, China (Wang et al. 2007) and the Minjiang drainage basin (Zhang et al. 2006) have utilized the SRTM DEM. Most applications have found the SRTM 90 m data to be suitable for analysis. However, Hancock et al. (2006) found the SRTM 90 m DEM, in comparison to a DEM derived from photographic images, portray catchment properties, network patterns, and runoff properties adequately. An additional caution was presented in analysis of watershed hydrology of the Elbe Basin and its sub-basins that spans the Czech Republic and Germany, in terms of the SRTM being less appropriate for analysis of small-scale topographic features (Haase and Frotscher 2005).

The literature related to SRTM applications demonstrates how studies related to aeolian processes and hydrological analyses have incorporated the SRTM DEM into their models (Blumberg 2006). Also, as indicated in the above section on the relation of SRTM to land cover characteristics, studies investigating tree cover have utilized the SRTM DEM. Hence, studies around the world have been utilizing the SRTM DEM as an available source of topographic information in a range of different landscapes.

2.6. LiDAR: Light Detection and Ranging

More recently Light Detection and Ranging (LiDAR) data have been utilized as a source of high resolution topographic data for flood mapping and hydrologic analysis. LiDAR represent the best publicly available high resolution data for certain sections of the United States and is the reference data used in this research. LiDAR collection involves a plane flying over an area with a GPS and laser rangefinder technology on board collecting signals, which are used to determine the elevation for locations based on coordinate information (Figure 2.4). LiDAR is collected by directing laser pulses at the earth's surface and using the time of the pulse return to calculate the distance (Lillesand, Kiefer, and Chipman 2004). The LiDAR methodology collects point data for the surface of the earth at a fine scale difference in spacing of points. An airborne scanning LiDAR system consists of airborne GPS, an inertial measurement unit, a pulsing laser, a clock, and onboard computer support (Lillesand, Kiefer, and Chipman 2004).

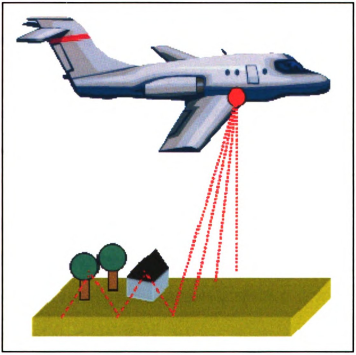

Figure 2.4. Light Detection and Ranging (LiDAR) Data Collection. LiDAR data are acquired through the use of GPS ranging technology onboard a plane flying overhead. Modified from BGMAPS 2008.

A high resolution 5 m DEM can be created as seen in Figure 2.5. with detail not see at a the coarser resolution of 90 m. An advantage of LiDAR data is its ability to collect data on steep topography and inaccessible areas (Lillesand, Kiefer, and Chipman

2004). LiDAR is also able to collect information on surface features at multiple levels above the surface from multiple returns per laser pulse (Lillesand, Kiefer, and Chipman 2004). This distinguishes the first return LiDAR pulses from feature such as tree canopies and buildings, from processing done to obtain bare-earth models (Lillesand, Kiefer, and Chipman 2004). Even though LiDAR can be used to create high-resolution terrain model, some of its limitations also need to be acknowledged, such as canopy and collection issues (Fowler 2007). I will briefly address some issues related to LiDAR, which are acknowledged in the literature; however, the limitations of LiDAR are not a focus of this research.

In previous research, LiDAR has been examined in relation to its resolution implications and production issues implications. Climatic conditions such as rain, mist, fog, or smoke can hinder LiDAR collection (Fowler 2007). Thus, the timing of LiDAR collection is important to consider in data collection. In addition to data collection issues, the resolution of the LiDAR has been investigated. In an investigation of LiDAR derived DEMs (6 m) and 30 m DEMs for the Fishing River Watershed (1,642 km^2) and Neuse River Watershed (1,440 km^2) in North Carolina, high relief areas were found to be similar for hydrologic analysis including watershed delineation, in comparison to low relief areas (Barber and Shortridge 2005). Barber and Shortridge (2005) implemented a resampling methodology to compare the LiDAR-derived data of a small resolution to other datasets at a coarser resolution. Thus, it is necessary for datasets of different resolutions to be aligned through resampling methodology to align with the resolution of other datasets in error analysis.

In terms of the LiDAR-derived data I used for this research from the state of Louisiana, it had already been processed and edited from its raw data version (Atlas 2007). The distributor performed the editing and created the data in raster format. As part of the editing of the LiDAR data before public release, vegetation and obstructions in the data were removed from the dataset (Cunningham, Gisclair, and Craig 2004). Thus, features such as tree canopies and buildings were removed from the dataset prior to its release to the public in raster format. This created a more reliable source of reference elevation data for me use in comparison to the SRTM DEM because it did not contain these surface features.

The state of Louisiana has been acquiring LiDAR data in six phases from 2000 (Cunningham, Gisclair, and Craig 2004). The Louisiana LiDAR project is funded by FEMA and the state of Louisiana (Cunningham, Gisclair, and Craig 2004). This LiDAR project in Louisiana was motivated from high flood loss rated from FEMA, the National Flood Insurance Program (Cunningham, Gisclair, and Craig 2004). The company, 3001, Inc, was in charge of acquiring the LiDAR data, and used the Leica Geosystems ALS40 LiDAR mapping system (Cunningham, Gisclair, and Craig 2004).

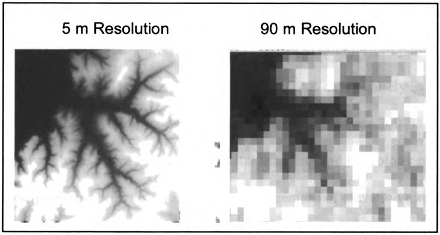

Figure 2.5. Comparison of Fine and Coarse Resolution Data. The 5 m DEM identifies clear features, not present in the 90 m SRTM. Source NASA (2002); Atlas(2007).

Table 2.5. Summary of Publicly Available LiDAR-related online repositories

Source	Description
Kansas Geospatial Community Commons (2007)	LiDAR data are available for the Kansas River Corridor. The elevation datasets available are GPS-Base (ASCII text), LiDAR 2006- All returns (LAS), LiDAR 2006-Bare Earth (ASCII text), LiDAR 2006: DEM (DEM), LiDAR 2006-Intensity (GeoTIF, TIF).
Interactive Numeric & Spatial Information Data Engine (2007)	LiDAR Derived DEMs. The user is able to browse by category: elevation and derived products. This site contains bare earth digital elevation models created from LiDAR data. There is well-documented metadata, which includes source information, accuracy, etc. These files were created by Horizon's Inc. and all canopy and structures were removed.
Atlas: The Louisiana Statewide GIS (2007)	This site enables the user to identify areas by USGS.ID quads. A DEM, contours, edited points, and raw points can be downloaded in feet. The points are 5 m spacing.
Puget Sound LIDAR Consortium (2007)	This site contains LiDAR for parts of Washington State. There is a viewer which enables the user to select designated areas to download. Data are available as LiDAR ASCII points (x,y,z) and DEMs as Bare Earth and Top Surface. This data were surveyed by TerraPoint in feet.
NASA (2006)	This is an index directory to files in tar gunzip format for Darrington, Mt. St. Helens, Rainer, and San Andreas. There is a parent directory, NASA TerraPoint product format information, and a description of TerraPoint systems. Information is also provided on properly citing the data, along with figures of the study areas.
North Carolina: NCFloodsmap.com (2007)	Map Viewer enables the user to download zip files of x,y,z ASCII files. The coordinate system used was NC Stateplane, NAD 83 feet, and elevation values are in feet.
Red River Basin Decision Information Network. North Dakota State University. (2007)	LiDAR data from the Army Corp of Engineers for the Red River Basin. Spot elevations every 2 feet.

This summary of LiDAR data sources indicate their range of formats and select locations of availability. Compiled in April 2007 by author.

A survey of online repositories for LiDAR data was undertaken by the author in the spring of 2007. This investigation identified key sites to obtain from public LiDAR data. Table 2.5 summarizes state-specific sources of LiDAR data publicly available. Online repositories for elevation models are summarized in (Sanders 2007). United States coastal areas have flown LiDAR for coastal mapping and hydrology projects. However, these projects could also be useful for the creation of elevation models for reference to other elevation models, such as SRTM. The USGS Center for LiDAR Information Coordination and Knowledge (CLICK) provides users with access to LiDAR data collected from various locations in the United States in LAS Binary format and American Standard Code for Information Interchange (ASCII) format. The LAS binary format is the standardized binary format for distribution of LiDAR data. Other LiDAR sources include NOAA LiDAR Data Retrieval tool (NOAA 2007), which contains limited amounts of LiDAR for coastal areas. Select states in the United States have had LiDAR flown and made available to the public for free. These include North Carolina, parts of Washington, parts of Louisiana, and a few other areas of certain states as indicated in Table 2.5. Additional information will follow in the methods section related to the LiDAR data sources used in this investigation.

2.7. Error Analysis

2.7.1. Conceptualization

The reviewed literature illustrates how DEMs can be compared to other DEMs through a differencing process (Shortridge 2006). Figure 2.6. illustrates a sample raster subtraction that occurs between DEMs for error analysis. The difference between the reference and the SRTM is termed error. Positive error indicates that DEM1 is higher than the reference DEM2, while negative errors indicate the opposite. Different procedures can be used in the creation of the DEM cell values, such as through points or averages. However, users need to recognize what is represented by the numerical elevation value in a raster cell. In order to determine how the real world is conceptualized in the digital sense, the user needs to have an understanding of projections, scale, and resolution of the data sources to understand fully the meaning of the DEM. Thus, acknowledging the meaning of the 90 m resolution is important to this research. The methodology of the radar-derived SRTM product included averaging to obtain the elevation values of the model. Hence, a resampling method that provides an average value from the input would be appropriate for the comparison of elevation models at the same cell size. A discussion of resampling methods and datums follow to highlight how understanding the meaning of a given elevation value of a DEM is a significant part of DEM error analysis.

5	7	7	7
6	6	7	7
6	6	7	8

6	7	7	9
7	7	9	9
7	7	9	9

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

DEM 1 - DEM2 = DEM Error

Figure 2.6. Procedure for creation of Error Grids. The subtraction of the reference DEM (DEM 2) elevation values from the DEM of interest (DEM 1) results in the DEM error.

2.7.2. Resampling Techniques

High resolution data can be resampled (i.e. 5 m resolution to 90 m resolution) various ways. Table 2.6 represents three various methods of resampling considered in this research. The center cell of a given extent of a larger resolution area can be sampled using the Nearest Neighbor technique (ESRI 2006b). In the Nearest Neighbor method, the output grid is assigned the center cell value of the input grid. Thus, in this research, the nearest neighbor method is used to take the center cell of the reference DEM (i.e. LiDAR 5 m, NED 30 m, and SRTM X-band 25 m) for a 90 m by 90 m area, to assign to a 90 m cell in the output grid. In addition, a weighted average can be taken, which puts more emphasis on the center cells of the 90 m x 90 m resolution area of the higher quality data. A method that includes a larger window to resample from will create a smoother output. Thus, the resampling method of the higher quality data is done to determine the error characteristics of the lower resolution data.

Table 2.6. Differences in Resampling Techniques

Technique	Description
Nearest Neighbor	Center of the input grid cell is computed for the nearest neighbor in the output cell
Bilinear Interpolation	Uses four nearest cells, which provides a weighted average in the output.
Cubic Convolution	Employs sixteen neighboring cells to provide a smoothed output.

Modified from ESRI 2006b.

2.8. Vertical Datums in Terrain Models

Vertical datums are reference surfaces based on the shape of the earth for calculations of elevation values. The reference base height is different with different datums, as seen from Figure 2.7. Figure 2.7 depicts the centered WGS84 datum in comparison to a local datum, which employs different earth models. Understanding the differences of vertical datums is critical because of the comparison of data from multiple sources. The same vertical datum should be used when combining datasets, since the datum represents the baseline of the information. The baseline is the level at which elevation is determined from. Datum transformation was given less attention in the DEM comparison literature. The vertical datum provides a base from which elevation is referenced, while the horizontal datum has significance in terms of positional location. As seen in Table 2.3 of the characteristics of elevation datasets, different datums are used in the reviewed DEMs. Recognition of the differences in datums was found in few articles (Walker et al. 2007), which warranted a greater investigation and is discussed in the methods section. Walker et al. (2007) indicated that the elevation heights needed to be converted to represent heights above the WGS84 (EGM96) geoid. WGS84 refers to the

World Geodetic Datum of 1984. EGM96 stands for Earth Geopotential Model 1996. Datum transformations can be corrected by using the height of the ellipsoid and the geoid undulation (Bhang, Schwartz, and Braun 2007). The issues of datum transformations are further discussed in the Chapter 4.

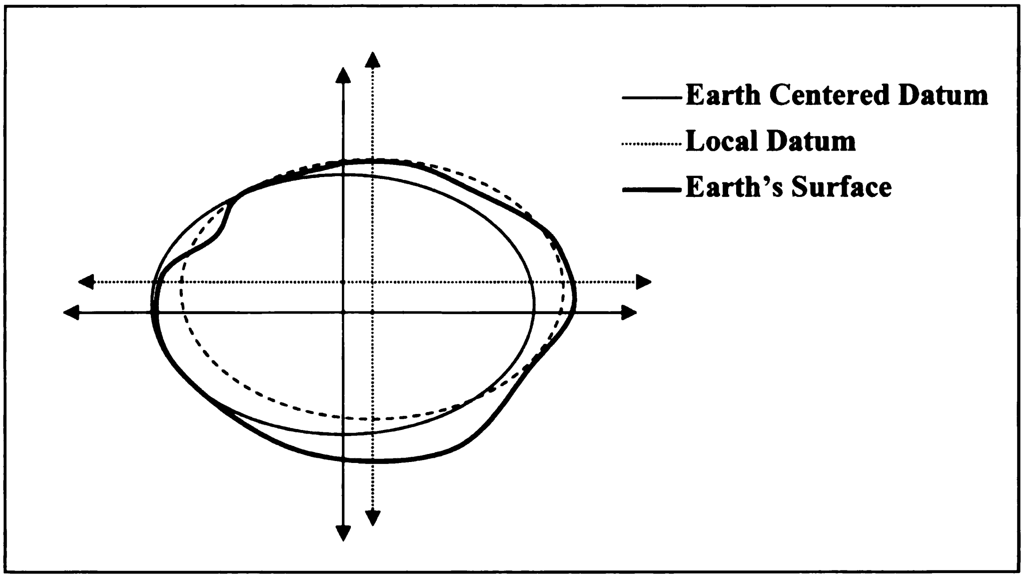

Figure 2.7. Representation of a Datum. The schematic shows the earth centered datum with a different central point compared to the local datum. Modified from Hurvitz (2004).

3. Study Areas

This section provides a background to the study areas of this research and describes the methodology for site selection. International and domestic sites were chosen so that the US study could represent a rich data location where a higher resolution (5 m) DEM could be obtained, and an international location represents an area where only a coarser DEM (90 m, 25 m) is available. This comparative work in important for a number of reasons. First, the Nang Rong study area provides an example of an area, which has the SRTM C-band 90 m and SRTM X-band 25 m available. There is not another publicly available DEM with a finer resolution available for this location. Thus, the locations in the United States where a higher resolution DEM is available can be used to aid the interpretation of the Nang Rong elevation DEM characteristics. The areas in the United States represent two main area with contrasting land cover/ land use characteristics (i.e. one mainly agriculture, one mainly forested). The comparison of the United States areas is important to see the different results between these land cover/land use characteristics. A description of environmental characteristics of selected areas is included related to topographic, environmental, and land cover/land use characteristics. This background provides context for the application developed in this study to compare DEM performance.

3.1. Methodology for Site Selection

A region in northeast Thailand was chosen due to complementary research activities at Michigan State University and the availability of relevant data, such as political boundary extents. Nang Rong a district in Thailand was selected. District data related to its political boundary, hydrology, and classified satellite imagery were acquired from the University of North Carolina, Carolina Population Center (University of North Carolina 2007). The University of North Carolina had compiled a vast spatial dataset related to Nang Rong, including both geographic and socioeconomic variables. The Nang Rong, Thailand site, provides an international location where SRTM data can be easily obtained from the USGS. Following the examination of the topographic and land cover/land use characteristics of Nang Rong, Thailand, comparable locations in the United States were chosen based on similar agriculture and topography characteristics. Key environmental characteristics pertinent to the selection of study areas in the United States are indicated in the next section. Following discussion of these key characteristics, the methodology for site selection in the United States is elaborated on prior to describing these areas.

3.2. Nang Rong, Thailand

The Nang Rong region is located in the Khorat Northeast Plateau region of northeast Thailand, one of six physiographic divisions of Thailand. Figure 3.1 indicates the Nang Rong region in the Buriram province. The major stream networks are illustrated in Figure 3.2.The Nang Rong study area extends from 102° 29' 13'' E, 14°30'45''N in the southwest to 102°54'19''E, 14°49'23'' N. Rice production is observed in flat areas and valleys from a 2003 LandSat image from the University of North Carolina Population Center (2007). The percent of area in capable of rice production was 55.0 % based on reclassification of the imagery.

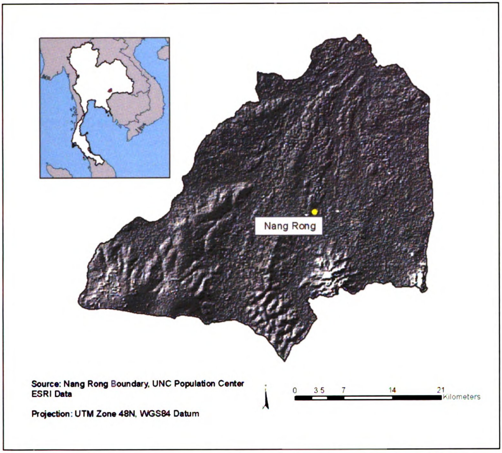

Figure 3.1. Nang Rong, Thailand Elevation and key features

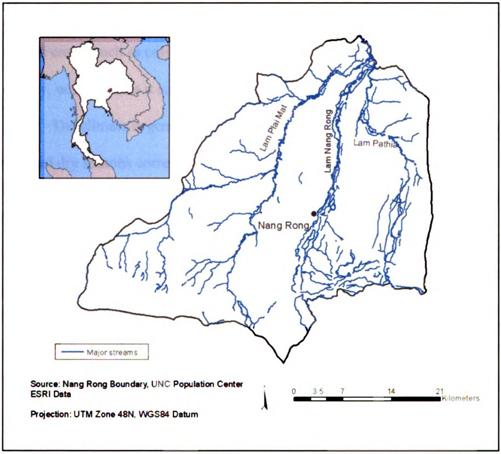

Figure 3.2. Major stream network of the Nang Rong Study Area

Research on the people-environment characteristics of the Nang Rong District have been done by incorporating demographic information and geospatial information (Entwisle et al. 2005). The Nang Rong District is relatively poor with marginal agriculture compared to the rest of Thailand (Entwisle et al. 2005). In the Nang Rong District, crops are grown both for subsistence and export. Cash crops grown on uplands include cassava, corn, and sugar cane, all of which are not consumed locally (Entwisle et al. 2005). Following WWII, the Nang Rong District went through land use/ land cover changes, which altered the patterns on the landscape (Entwisle et al. 2005). The terraces surrounding the alluvial plains were used to grow rice (Entwisle et al. 2005). In addition, cash crops were grown on uplands (Entwisle et al. 2005). Paddy rice located at lower elevations is primarily rainfed, while the higher elevations are covered by forest and upland crops, such as cassava (Entwisle et al 2005). The Nang Rong District has poor soil quality, which makes it suitable for only certain crops (Faust et al. 1999).

The climate is generally hot with a wet and dry season (Faust et al. 1999). These wet and dry seasons correspond to monsoonal season and non-monsoonal season. The monsoonal season provides moisture for agriculture. The typical farming activities in the Northeast area of Thailand include preparation of the field from May to December during the rainy season (Phongphit and Hewison 2001). The rainy season usually begins in May until August and harvests begin in December (Phongphit and Hewison 2001). In February, during the time the radar used for the SRTM was acquired, it is expected that the rice fields would be fallow given the planting from May to July and harvesting season from November to December (IRRI 2007).

Agriculture is a major component of Thailand culture, environment, and lifestyles, so a highly relevant SRTM application issue is related to agricultural uses. As seen from Thai history, connections to the land have played a pivotal role in the development of villages and cultural traditions (Phongphit and Hewison 2001). Other researchers have incorporated social survey data, and satellite imagery to examine the land use/land cover change from deforestation and agricultural activities in Nang Rong (Walsh et al. 2001). It was seen from statistical analysis that elevation changes in the Nang Rong area were slight; however, they could have great implications in land use practices and the suitability of soils (Walsh et al. 2001). Agricultural applications of SRTM data could have worldwide significance because of the value of agricultural products as food and commodities. The supply of food is an important concern of all citizens regardless of locations, thus an application related to food production or land use practices would be significant to research. Thailand, similar to nations around the world, aims to gain the most yields from its resources. Hence, the use of geospatial data, specifically elevation data, could be used to manage land effectively based on the optimal growing conditions of crops. As of 2007, only Gorokhovich and Voustianiouk (2006) have used Thailand SRTM data for comparison to GPS reference data. This research includes an agricultural application, which illustrates the potential differences of DEMs used in the identification of areas on the landscape. Now that the key characteristics of the Nang Rong study area have been described, these will be referred to in the following section on the selection of the United Study areas, as the characteristics of the Nang Rong study area were identified prior to the selection of the United States study areas.

3.3. Selection of United States Sites

Following examination of the characteristics of the Nang Rong region, locations in the United States with rice production were examined for possible comparison to Nang Rong. The main areas of rice production in the United States include locations along the Mississippi River, southeastern Texas, southern Louisiana, and parts of central California (USDA 2005). A map of the areas of rice production from USDA (2005) was examined to determine if these locations would also have high resolution elevation data available. It was evident that climatic, soil, and water properties of only certain locations in the United States area are appropriate for rice production. Although, the type of rice and agriculture techniques of the US differs from the Thailand context, comparison can still be made because the crop characteristics would still be similar on the surface during the time of the SRTM. The main differences in terms of the rice production in Thailand and

Louisiana relate to rice species and irrigation method. The Thailand rice species are mainly rainfed, while the Louisiana species are irrigated (Phongphit and Hewison 2001,

After the areas of rice production were identified and the locations of available reference data (Table 2.5), the state of Louisiana was honed in on to determine possible study areas. The National Land Cover Data (NLCD) 2001 was examined for the state of Louisiana to determine the variability of land cover/ land use characteristics. Similarly, the DEM of the Louisiana was examined for differences in topographic characteristics. Based on these examinations, it was observed that the southwestern part of Louisiana was mainly agriculture and wetland land covers, while the northern part of the state has more forested areas. Following the identification of these characteristics from the NLCD 2001 and DEM of the entire state, the locations indicated in Figure 3.3 were selected. Additional information follows regarding the characteristics of selected study areas. The Webster study area in northern Louisiana extends from 93°37'23.1'' W, 32°37'38.9'' N in the southwest corner to 93°15'12.7''W, 33°0'3.0''N in the northeast corner. The Acadia study area in the southwestern portion of Louisiana extends from 92°37'36.4''W, 30°7'31.4''N in the southwest corner to 92°7'29.3''W, 30°29'54.7"N in the northeast corner.

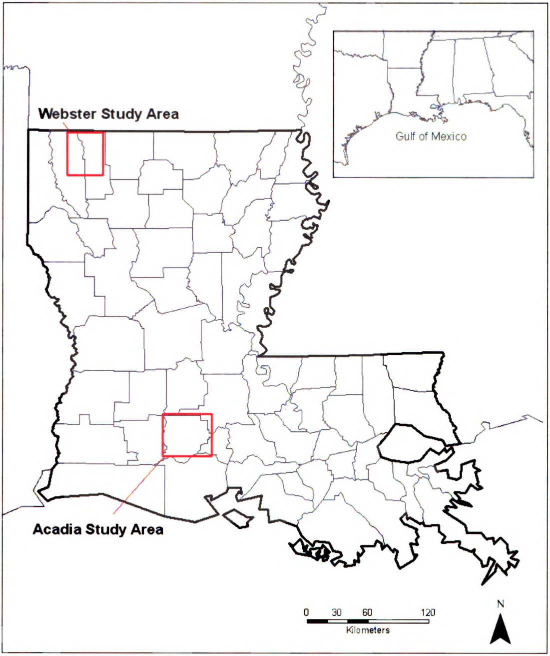

Figure 3.3. Locations of Study areas in Louisiana

3.4. Louisiana Study Areas

Of the possible areas in Louisiana with suitable land cover characteristics and available reference data, two locations were chosen: an area in southwestern Louisiana (Acadia study area) covering parts of Jefferson Davis, Evangeline, St. Landry, Lafayette, Acadia, and Vermillion parishes, was chosen based on its rice production (9.0 %) and an area in northern Louisiana (Webster study area) included parts of Webster and Bossier Parishes with a percent of forest cover (62.2 %) were chosen (USDA 2006) (Table 3.1). At the time of obtaining data for select study areas, some locations around the potential forested areas in northern Louisiana were not available. Hence, the extent 567 mi^2 of the Webster study area is smaller than the Acadia study area 781 mi^2. The southwestern and northern study areas in Louisiana represent two locations with different land cover/ land use properties, which as seen from Chapter 2 may have different error characteristics. In particular the Acadia study area is comparable to the Nang Rong agricultural characteristics, since the Webster study area is mainly forested.

Since the Acadia and the Webster Study area crosses political county borders, a remotely sensed imagery was used to identify the crop-specific characteristics of the study areas. The National Cropland Data Layer-2005 was obtained and the percentage of each class was calculated to create table 3.1. Table 3.1 indicates the percentage of rice in the Acadia study area to be 9.0 % of the total area, which was greater the trace amount in the Webster study area. Other key characteristics obtained from the crop specific data included the percentages of woodland (12.2 % for the Acadia study area and 62.2 % for the Webster study area), percentages of other crops in the study areas such as cotton and grain in Acadia, and pasture percentages.

Table 3.1. Crop-Specific Area Calculated from National Cropland Data (2005)

Code	Description	Cell Counts		Area (m^2)		Percent of area	
		Acadia	Webster	Acadia	Webster	Acadia	Webster
1	Corn, all	19,974	1,178	17,976,600	1,060,200	0.9 %	0.1 %
2	Cotton	54,780	542	49,302,000	487,800	2. %	0 .0 %
3	Rice	202,584	2,760	182,325,600	2,484,000	9.0 %	0 .2 %
4	Sorghum	5,724	2	5,151,600	1,800	0.2 %	0 .0 %
5	Soybeans	39,939	15,464	35,945,100	13,917,600	1.8 %	1.0 %
24	Winter Wheat	191	139	171,900	125,100	0.0 %	0 .0%
25	Other Grains/ Hay	111,935	11,852	100,741,500	10,666,800	5.0 %	0.7 %
45	Sugar Cane	65,799	1	59,219,100	900	2.9 %	0 .0 %
48	Watermelon	0	22	0	19,800	0.0 %	0 .0 %
50	State 560 Other Crops	9,112	0	8,200,800	0	0.4 %	0 .0 %
52	State 562 Other Crops	0	467	0	420,300	0.0 %	0 .0 %
53	State 563 Other Crops	2	0	1,800	0	0.0 %	0 .0 %
56	State 566 Other Crops	9	0	8,100	0	0.0 %	0 .0 %
61	Idle Cropland Fallow	101,039	4,552	90,935,100	4,096,800	4.5 %	0.3 %
62	Pasture, Non-agriculture	821,861	461,177	739,674,900	415,059,300	36.6 %	28.3 %
63	Woodland	275,885	1,016,007	248,296,500	914,406,300	12.2 %	62.2 %
81	Clouds	228,257	49,950	205,431,300	44,955,000	10.1 %	3.1 %
82	Urban	103,024	23,566	92,721,600	21,209,400	4.6 %	1.4 %
83	Water	206,268	26,573	185,641,200	239,157,00	9.2 %	1.6 %
85	Waterway	0	17,860	0	16,074,000	0.0 %	1.1 %
87	Wetland	0	124	0	111,600	0.0 %	0.0 %
92	Aquaculture	0	159	0	143,100	0.0 %	0.0 %

Source: USDA 2006. This crop specific data was originally obtained from satellite imagery from the Landsat 5 Thematic Mapper.

As indicated in Chapter 2, the SRTM X-Band data are not available for the entire earth because of its smaller swath width. Figure 3.4 indicates the X-band coverage of both study areas. The X-band SRTM 25 m resolution data for the Louisiana study areas is not available; however, X-band SRTM data can be obtained for part of the Nang Rong region, and these data were obtained.

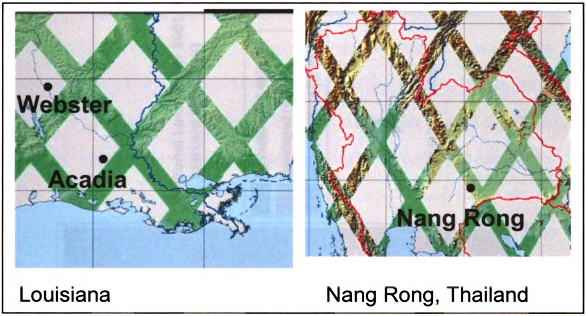

Figure 3.4. Availability of SRTM X-band Coverage in study areas
Modified from (DLR 2007).

The following section provides background information for the Louisiana study sites, focused on its land cover/land use, agricultural production, and environmental characteristics. These geographic and environmental characteristics are especially important in the development of a suitable application where the elevation product would be a significant factor in the analysis. A great deal of publicly available data can be obtained to gain more knowledge about the environmental characteristics of these sites, unlike that available for the Nang Rong site.

3.4.1. Acadia study area

The southwestern study area contains part of Jefferson Davis, Evangeline, St. Landry, Lafayette, Acadia, and Vermillion parishes. This study area will be called the Acadia study area in this research. This southwestern area of Louisiana is mainly rural. The National Land Cover Dataset 2001 of the Acadia study area seen in Figure 3.5 indicates this area to be primarily agricultural and wetlands (USGS 2003). The two major land characteristics of the southwestern Louisiana study area the 1) Gulf Coast Prairie,

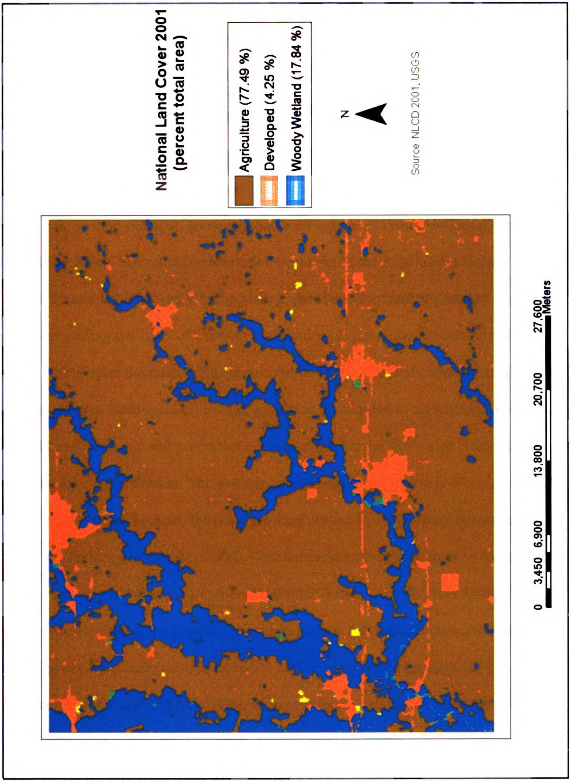

Figure 3.5. Acadia study area: National Land Cover Dataset (2001)

which is characterized by mainly cropland, pastureland, and loamy to clayey soils, that are poorly drained; the 2) Southern Mississippi Valley Silty Uplands characterized by mainly cropland and pastureland, and poorly drained soils (McDaniel, Trahan, and Godfrey 2006). The natural vegetation of the Gulf Coast Prairies contains loblolly pine, water oak, sweetgum, Southern red oak, and magnolia on the better drained soils in higher positions and poorly drained soils in lower positions have water oak, willow oak, overcup oak, swamp chestnut, green ash, and bald cypress present (McDaniel, Trahan, and Godfrey 2006). The main transportation networks of the Acadia area include Interstate 10 and US Highway 90. The main areas of development are located along these corridors including the cities of Crowley and Eunice (Figure 3.6). The stream network in Figure 3.7 illustrates the main drainage patterns in the Acadia study area. Generally, the Acadia study area contains many oil and gas fields, in addition to agricultural land uses.

The climatic and soil properties of parts of the Acadia study area create suitable conditions for rice cultivation. The average annual total precipitation is 60 in. (0.406 m), of which 82 % occurs between the main growing period, from February to November (McDaniel, Trahan, and Godfrey 2006). The temperature ranges from an average of 52 °F in the winter to 81° F in the summer (McDaniel, Trahan, and Godfrey 2006). For southwestern Louisiana, the growing season consists is 280 days (Salassi and Breaux 2006). The average yearly relative humidity in this area in mid-afternoon is 71 % (McDaniel, Trahan, and Godfrey 2006). The main soil map units (91%) in the Acadia parish comprise of soil on level to gently sloping surfaces slopes of 0-3 % with relatively poor drainage, which makes them well-suited for rice cultivation(McDaniel, Trahan, and Godfrey 2006).

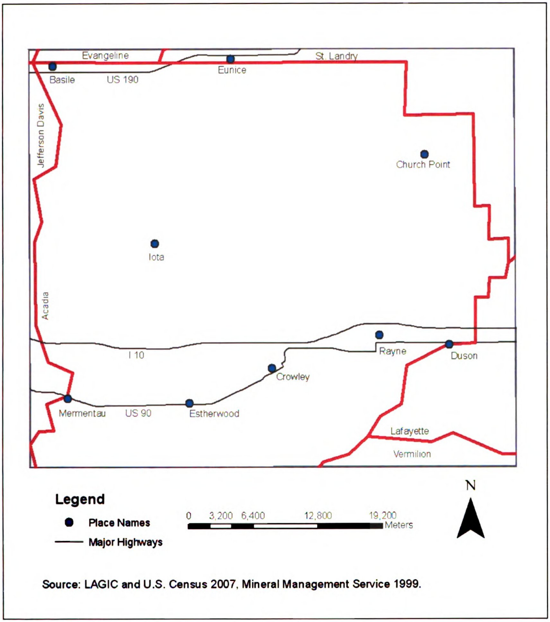

Figure 3.6. Reference Map of the Acadia study area

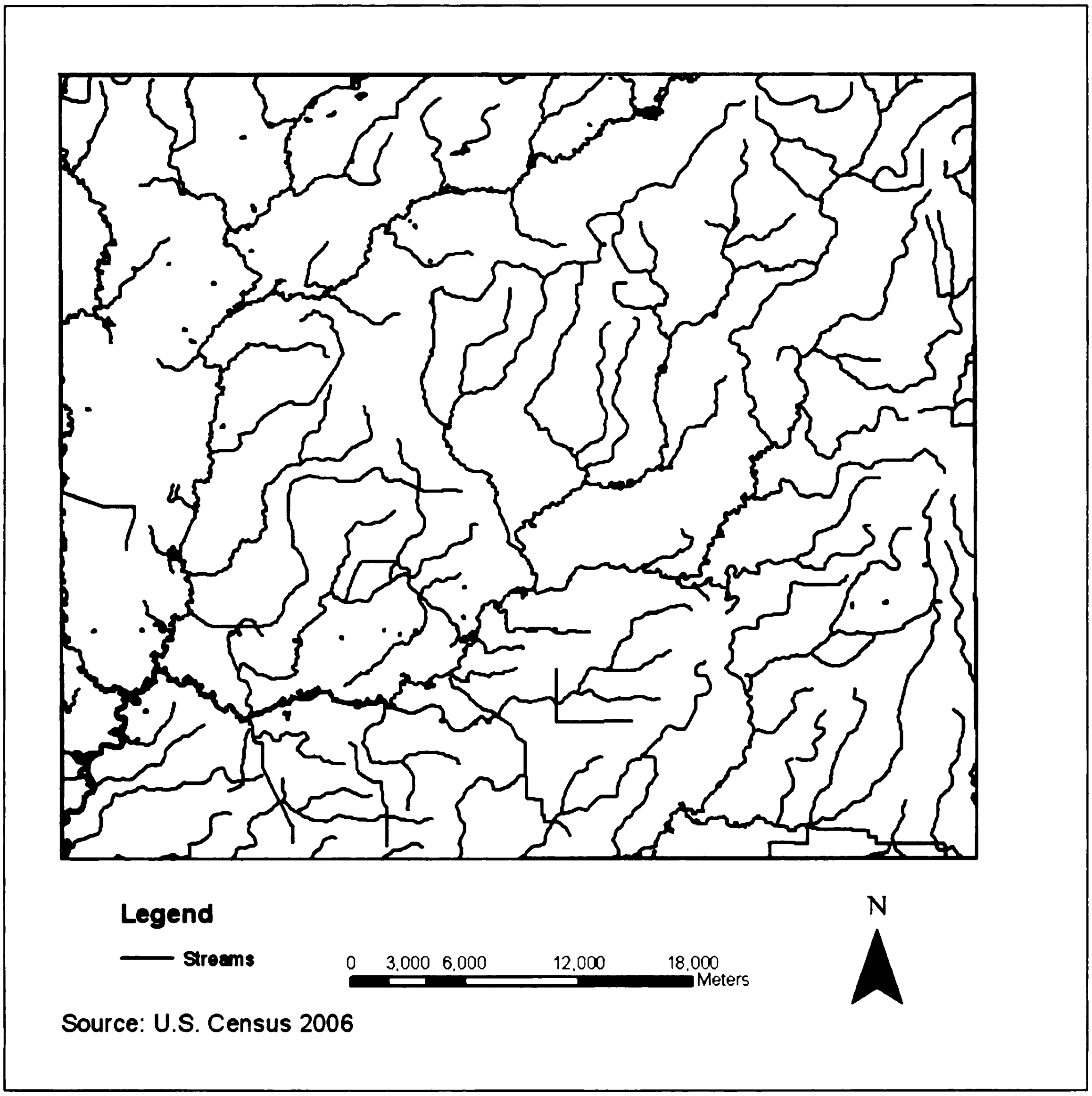

Figure 3.7. Major stream network of the Acadia Study Area

3.4.2. Webster study area

The northern Louisiana study area contains part of Webster and Bossier parishes. This study area is referred to the Webster study area in this research. Webster parish is predominantly rural with many outdoor recreation opportunities related to the rich environmental features such as forests and waterways (Webster Parish 2001). Springhill, Cotton Valley, and Minden developed area are located along US Highway 371, which runs north to south in this study area. Cotton Valley is bordered by the Bodcau State Wildlife Management Area and the Cotton Valley Oil and Gas Fields. The predominant crops in this study area include cotton, grain, sorghum, corn, wheat, hay, and sweet potatoes (Kilpatrick, Godfrey, and Henry 1998).

The Webster study area is predominantly forested (Figure 3.8). The Bodcau Wildlife Management Area in the northwestern portion of this study area and the Kisatchie National Forest is located in the southeastern portion of this study area (Figure 3.9). The rich habitat of this area includes cypress swamps, upland pine, hardwood forests, grassland, and open fields (LWLF 2005). The bottomland forests consist of bald cypress, willow, and cow oaks, while shortleaf and loblolly pine, white, red, and cherrybark oaks, sweetgum and elm trees dominate upland forests (LWLF 2005). Streams run through these forests and upland areas as seen in Figure 3.10.

The Webster study area has climatic conditions similar to the Acadia study area. Average annual temperature is 65°F in Webster Parish (Webster Parish 2001). Climatic characteristics of this area include a summer average of 80°F, and an annual precipitation of 52 inches (Kilpatrick, Godfrey, and Henry 1998). Webster Parish is comprised of level to steep uplands and terraces, with soils that are not conducive to agriculture (Kilpatrick, Godfrey, and Henry 1998). The soils located on uplands are gravelly, loamy, and sandy, with poor drainage (Kilpatrick, Godfrey, and Henry 1998). Thus, the factors of sloping topography, soil wetness, and low fertility in this area limit the growth of crops (Kilpatrick, Godfrey, and Henry 1998).

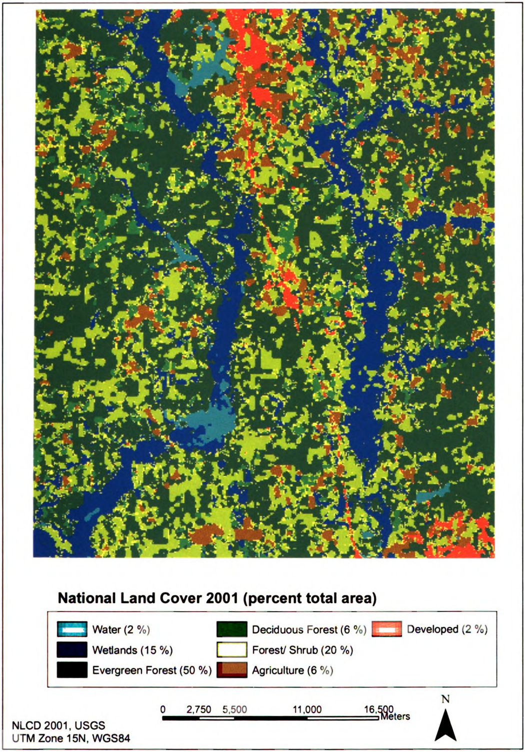

Figure 3.8. Webster study area: National Land Cover Dataset (2001)

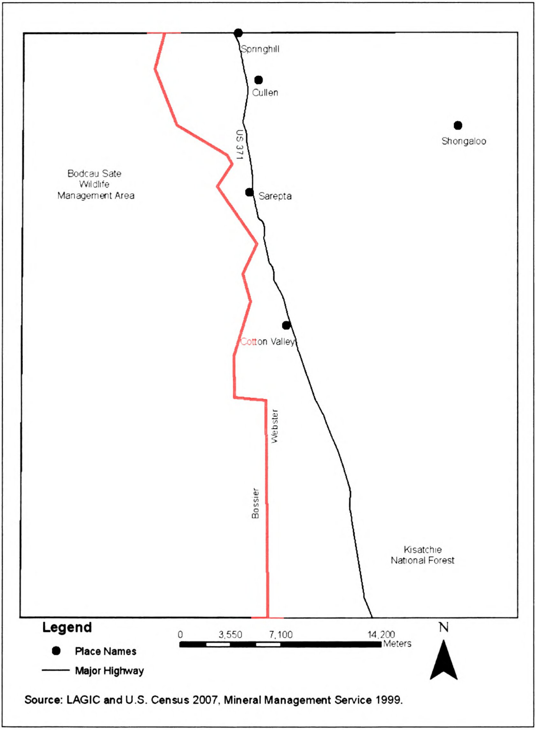

Figure 3.9. Reference Map of Webster Study Area

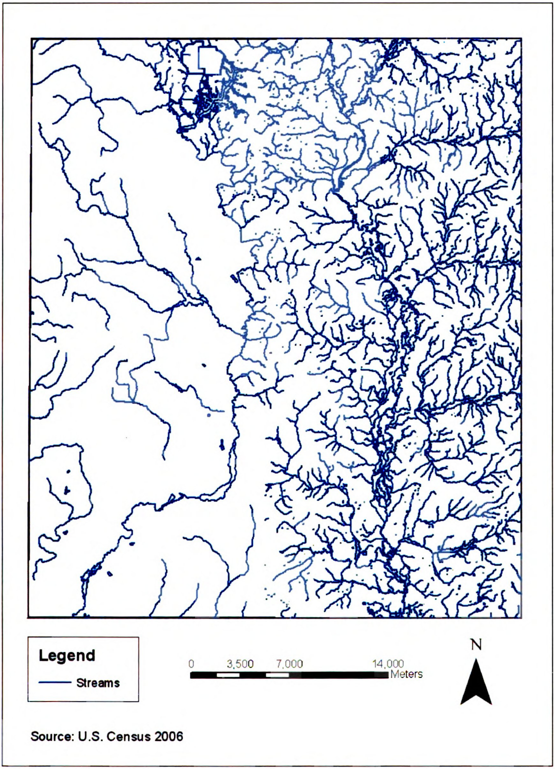

Figure 3.10. Major Stream Network of the Webster Study Area

The examination of the land cover/land use characteristics indicated the potential of an application related to elevation characteristics and land use being pertinent across the Acadia, Webster, and Nang Rong study areas. The following section discusses information related to a land use application that could be relevant in all study areas.

3.5. Land Use Application

Digital terrain models have much utility in diverse geographic application domains, including urban growth models, land use, weather modeling, and vegetation analysis (Wilson and Gallant 2000). An agricultural model was identified as an appropriate application to explore in both the Thailand and Louisiana contexts given their similar surface characteristics. This type of application highlights how the use of terrain models can play a vital role in agricultural models worldwide to better understand land management, food supply dynamics, irrigation methods, and soil management. This section provides a brief review of the approaches to create a GIS model for rice production given the available datasets for both locations and the goal of identifying differences in model use.

Rice production is an important land use in the Acadia study area of Louisiana, in contrast to the more forested land uses in the Webster study area. The availability of water and the soil characteristics of this region create a suitable location for rice production (McDaniel, Trahan, and Godfrey 2006). According to an Extension Rice Specialist and Retired Extension Agronomist of Mississippi State University, rice production is based on the following factors: soils with permeable subsoils, flat area, and a gentle slope (Street and Miller 2004). These criteria for rice production identify the first derivative of the DEM, slope, to be a major factor for rice production, along with drainage characteristics.

Similar to the Louisiana study areas, the low-slope topography is a key suitability factor for rice cultivation in Thailand. In a land suitability study for rice in the Namphong watershed of Northeastern Thailand, slope, water availability, nutrient availability, and salt hazard were variables input into the spatial model (Mongkolsawat, Thirangoon, and Kuptawutinan 1997). Elevation was noted as an important factor for land suitability in the Nang Rong district because of its ties to other land surface characteristics, such as soil moisture (Entwisle et al 2005). The availability of soil moisture can play a role in the cultivation of certain crops in Thailand, such as the growth of rice on the alluvial plain areas versus the growth of cassava on the uplands (Entwisle et al 2005). Thus, not only slope is important, but the relative position on the landscape is important to crop cultivation.

Topographic position is identified as a relevant terrain characteristic by Deng (2007). Low landscape position represents a criterion here for land suitable for agriculture. These areas on the landscapes would have flow accumulation and be appropriate for the production of rice and/or other agriculture in the Nang Rong area. The schematic of a low location indicates the position of an area in relation to surrounding upland areas (Figure 3.11). Through manipulation of an elevation surface, the low topographic positions on the landscape can be incorporated into environmental analysis.

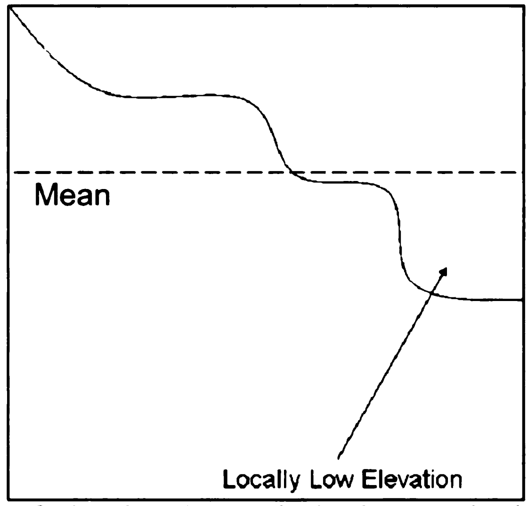

Figure 3.11. Schematic of a low location on the landscape. This low location criterion will be used in the land use application.

In the context of this thesis, the model variables related to the DEM are most relevant. Here a simplified model will be created based on identifying locations on the landscape where potentially rice production or other agriculture can be located based on a low slope and low relative location on the landscape. Analysis of sophisticated crop models with multiple variables is outside the scope and aims of this application. The aims of this application are to assess differences in DEM results.

4. Methods

The methods section indicates the procedures used for Louisiana and Nang Rong, Thailand study areas, and application development. These sections are organized based on data source and processing steps necessary for examining SRTM error properties for each study area. National datasets are used for the United States to enable the possibility of replication in different areas than the ones chosen for this analysis. This methodology enables the examination of SRTM DEM error characteristics in relation to differences between the DEMS (LiDAR and NED) and in relation to land cover/land use characteristics.

4.1. Processing Software

Geographic information systems (GIS) and statistical software were used to investigate the SRTM error characteristics in relationship to landscape parameters. The methodological decisions and techniques employed in this research used ArcGIS 9.1-9.2 in ArcInfo versions, in a Windows platform, and ERDAS Imagine (8.7) software. The statistical software used was SYSTAT (10.0).

4.2. Naming conventions

The following acronyms used in this thesis are indicated with their meanings (Table 4.1). The resolution of the C-band is indicated when necessary, and the X-band SRTM resolution is also indicated to distinguish between the original resolution of 25 m and its resampled version at 90 m.

Table 4.1. Naming Conventions of Data Types with Descriptions

	Description
LIDAR 5 m	Original LiDAR-derived DEM
LIDAR 90 m	Resampled LiDAR-derived DEM
NED 30 m	Original NED DEM from the USGS
NED 90 m	Resampled NED DEM
SRTM 30 m	SRTM 30 m C-band DEM from USGS
SRTM 90 m	SRTM 90 m C-band DEM from USGS
SRTM X-25 m	SRTM X-band from DLR
SRTM X-90 m	Resampled SRTM X-band

4.3. Louisiana study areas

4.3.1. LiDAR Data from Atlas, Louisiana Statewide GIS

The source of the LiDAR data for Louisiana was the Atlas, Louisiana statewide GIS (Atlas 2007). The Atlas, Louisiana Statewide GIS online source of the LiDAR-derived DEM data used as reference was carefully examined to determine whether it would be suitable for analysis in this research (ATLAS 2007). The Louisiana Statewide GIS distributes various raster and vector datasets. Digital topographic quads, LiDAR-derived DEMs, and imagery are obtained though online viewers (ATLAS 2007).

The LiDAR data were identified by their 1: 24,000 Quadrangle USGS name. Appendix A identifies the USGS quads (1: 24,000 scale) in each study area, along with their unique identifiers. The Acadia study area covered 16 quadrangles (781 mi^2, 2,022 km^2) and the Webster study area included 12 quadrangles (567 mi^2, 1,469 km^2). During this process, the decision was made to use LiDAR-derived raster data instead of point LiDAR data. LiDAR point data were seen as less appropriate for this analysis given as it would more processing time, which would not be appropriate for this research. Thus, the LiDAR-derived data for the selected data were obtained in interpolated-raster format. The

LiDAR DEM was downloaded in USGS DEM format, converted to raster, integer format, and mosaiced together to obtain seamless coverage of the desired area.

The Acadia study area data were flown in February/March of 2003 as part of the Louisiana / Federal Emergency Management Agency (FEMA) Project - Phase 3 of Louisiana LIDAR Data Development (Watershed Concepts, 2004a,b,c). The Webster study area data were obtained in February 2006 as part of the Louisiana / Federal Emergency Management Agency (FEMA) Project - Phase 5 of Louisiana LIDAR Data Development: Bossier / Webster Parishes, at 5 m resolution (Watershed Concepts 2006a, b; Watershed Concepts 2005). The processing contractor used the ArcInfo `latticedem` command to create the DEMs from the point-collected LiDAR data (Watershed Concepts 2004a,b,c; Watershed Concepts 2006a,b; Watershed Concepts 2005). The seasonality of the LiDAR acquisition was considered in relation to the timing of the SRTM mission to obtain comparable surface conditions.

The LiDAR DEMs heights were converted from feet to meters by the raster algebra: $DEM_{Meters} = DEM_{Feet} *3.28084$. Following the metric conversion, the DEM was projected and resampled to 90 m by the nearest neighbor method. The nearest neighbor method was chosen to resample the DEMs because it would provide the center cell of the 90 m cell extent of the SRTM resolution. This would represent an elevation value to align with the SRTM 90 m cell extent. Figure 4.1 illustrates these processing steps of the LiDAR DEMs.

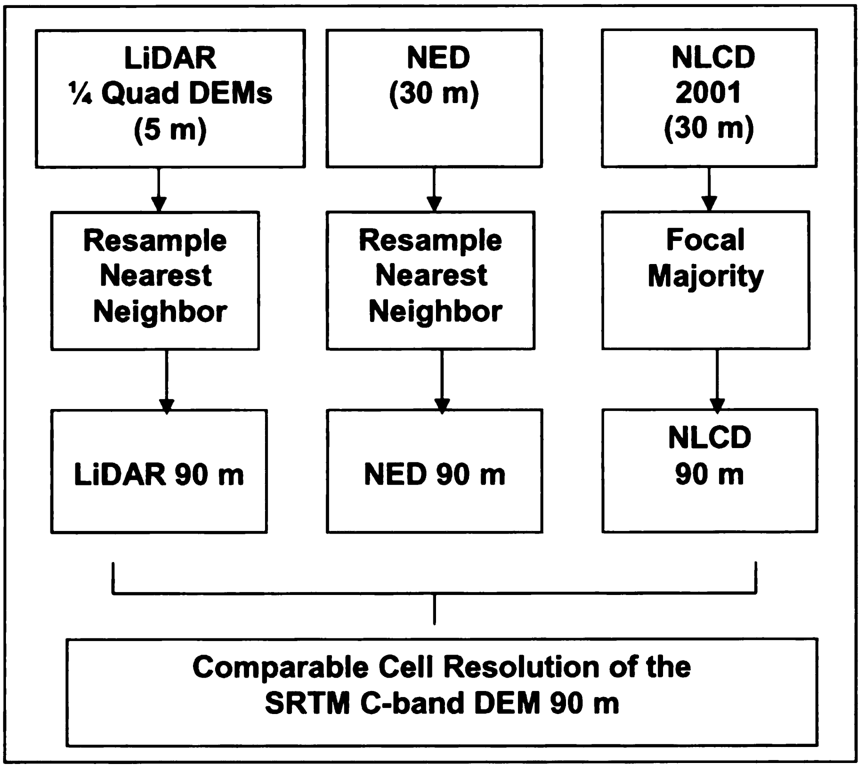

Figure 4.1. Processing Steps for Louisiana Data

The following process was employed in each successive resampled DEM of this research to ensure the alignment of raster cells following resampling. When the DEM was resampled to the resolution of the SRTM C-band data, it was set to 90 m and the raster environment was set to snap to the cells of the SRTM 90 m DEM. This raster cell alignment was necessary for error analysis. The coordinate system used in analysis of the Louisiana DEMs was UTM zone 15N, WGS84 datum (horizontal and vertical) in units of meters. This system ensured that both study areas in Louisiana shared the same zone and that consistency was maintained between the datum of the SRTM C-band data and the other DEMs.

4.3.2. National Elevation Dataset

The National Elevation Dataset (NED) DEM was obtained from the USGS (USGS 2007, USGS 1999). The NED 1 arc second DEM was downloaded for selected Louisiana study areas, projected with a cell size of 30 m, clipped to desired extents, and resampled to 90 m by the nearest neighbor method to match the resolution of the SRTM (Figure 4.1). The Acadia study area NED data were produced by methods 5 (LT4X software) and 3 (Digital Line Graph2DEM) and the data for Webster study area were produced by method 5 (LT4X software) (USGS 1999). The Line Trace 4X (LT4X) software is a specialized software for the creation of DEMs. This information was obtained from the metadata of the NED from the USGS and refers to the production methodology software used in the creation of the NED (USGS 2007). Hence, the LiDAR-derived DEMs have not been incorporated into the NED product as of July 2007; however, have been incorporated into other areas of the state.

4.3.3. Shuttle Radar Topography Mission: C-Band

The finished SRTM 1 arc second and 3 arc second data were obtained from the USGS seamless server for the Acadia and Webster, Louisiana study sites (USGS 2007, NASA 2002). The SRTM data used in this research were downloaded after the USGS corrected the half pixel shift of the SRTM data (USGS 2007). The SRTM 1 arc second and 3 arc second data were projected with a 30 m and 90 m resolution, respectively, and clipped to the desired extents. For the NED, LiDAR, and SRTM data, no filling operation was employed to fill voids in the DEMs. Thus, the DEMs were used without further altering their elevation values to account for sinks or voids in the data because this research is interested in the DEM form obtained by the public or other researchers originally from the USGS and/ or other sites. The methods used to fill sinks or voids in the DEM can differ from one another, and selection of the most appropriate filling parameters or void adjusting method was not part of the research.

4.3.4. Land Cover/Land Use Characteristics

National Land Cover Data (NLCD) 2001 were used to examine the relationship of different land cover/land use classes to SRTM error (USGS 2007, USGS 2003). The specific dataset was the National Land Cover Database Zone 37B, which is the zone covering Louisiana. The NLCD was resampled by using a focal majority (3 x 3) operation to obtain the major land cover code in each cell of the SRTM 90 m C-band DEM (Figure 4.2). The focal majority was chosen to identify the land cover code, which represents the majority of the areal extent in the 90 m area of the 3 by 3 window. As depicted in Figure 4.2 in a 90 m by 90 m neighborhood, the focal majority identifies the code (i.e. 54) with the majority in the new raster. This would be possible with the focal majority neighborhood operation, rather than a focal average operation, which computes an average value of the codes.

The percentage of the land cover/land use codes for the Webster and Acadia study areas were recalculated following the focal operation. The resampled NLCD data were converted to polygons and used to stratify the elevation error samples using Hawth's tools (Beyer 2004).

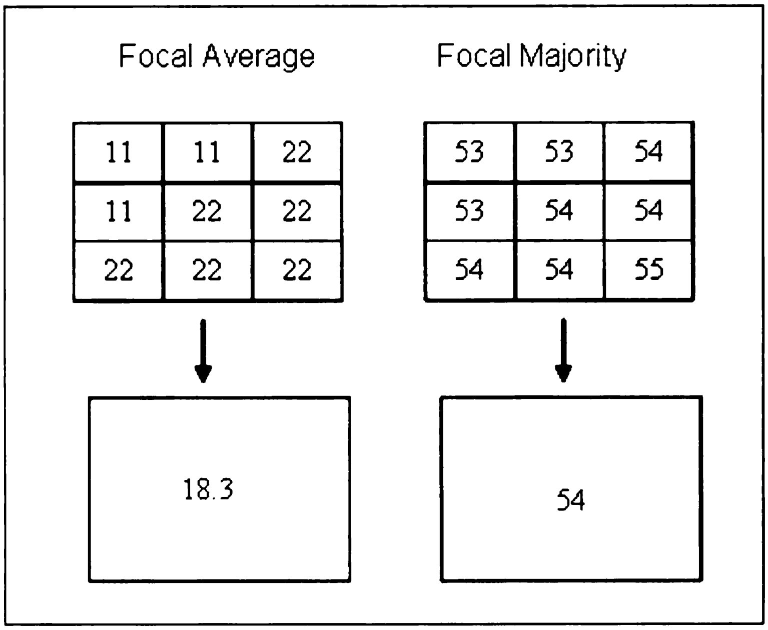

Figure 4.2. Focal Operations

4.4. Nang Rong, Thailand Study Area

4.4.1. C-Band SRTM

The SRTM C-Band 90 m resolution data were downloaded for the Nang Rong region from the USGS Seamless Server (USGS 2007, NASA 2002). This DEM was projected and clipped to the extent of the coverage of the X-band data for the same region. The coordinate system of the Thailand data were UTM Zone 48N, WGS84 datum (horizontal and vertical) in units of meters (Figure 4.3).

4.4.2. X-Band SRTM

The SRTM X-SAR data were obtained in digital terrain elevation data (DTED) format from GAF AG, the German X-band distributor (DLR 2007). The X-Band DEM was projected and clipped to the extent of the overlap with the Nang Rong District boundary (1,564.2 km^2). The X-band SRTM data (25 m) were resampled by the nearest neighbor method to obtain the same cell resolution of the C-band SRTM data (Figure

4.3). The raster environment was set for the resampled 90 m cells to align with the SRTM C-band cells.

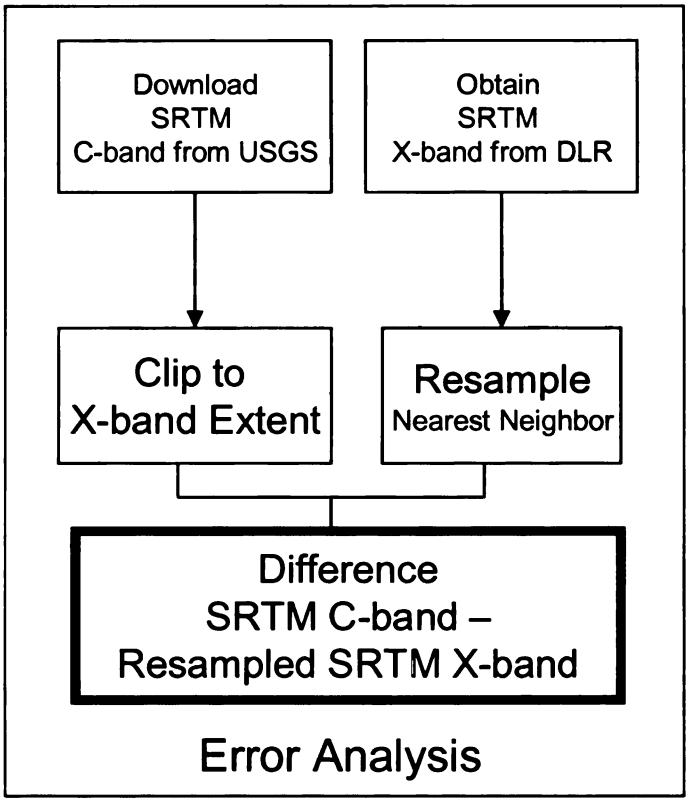

Figure 4.3. Processing Steps for Nang Rong, Thailand study area. The Nang Rong study area used the SRTM X-25 m resampled to 90 m as the reference to the SRTM C-90 m.

4.5. Datum Transformations

The NED, LiDAR, and SRTM DEM employ different vertical datums: NAVD88, NAVD88, and WGS84, respectively. As indicated in the background section, these datums needed to be adjusted to account for the differences in their base elevation reference information. A possible way to account for datum difference is through the use of online converters, such as the NGA EGM96 Geoid calculator (NGA 2006) to determine the geoid heights (m) and the GEOID03 calculator (NGS 2007), which would reflect the NAVD88 vertical datum. However, a different approach was employed in this thesis to adjust for the differences in the vertical datums, which was the use of a graphical representation of datum differences in North America. The average difference between the WGS84 and NADV88 was about 0.6 m for the Louisiana study areas (Roman 2007). This value was added to the NED and LiDAR DEMs, so that their elevations would reflect the WGS84 datum of the SRTM C-band DEM.

To correct for the vertical datum differences of the SRTM C-band and SRTM X-band DEMs, DLR, the distributor of the X-band DEM, suggested the use of ERDAS Imagine. The Recalculate Elevation Values tool was used in ERDAS IMAGINE. The X-band SRTM DEM was recalculated to reflect the elevation values of the SRTM C-band WGS84/ EGM96 Geoid values.

4.6. Terrain Derivatives

The first derivative of elevation, slope (degrees), was generated in ArcGIS 9.2 using the Spatial Analyst extension for each elevation model indicated above. Slope is defined as the rate of change from the steepest neighboring cell, calculated via the Horn algorithm in Arc GIS 9.2 (ESRI 2006a).

4.7. Error Analysis

The LiDAR 90 m was subtracted from the SRTM 90 m to obtain the SRTM-LiDAR error grid. Similarly, the elevations of the NED 90 m DEM were subtracted from the SRTM 90 m DEM (Figure 4.4). The difference of the SRTM and the reference DEM is the DEM error. A similar subtraction method of the X-band and the C-band was employed in the Nang Rong study area (Figure 4.3).

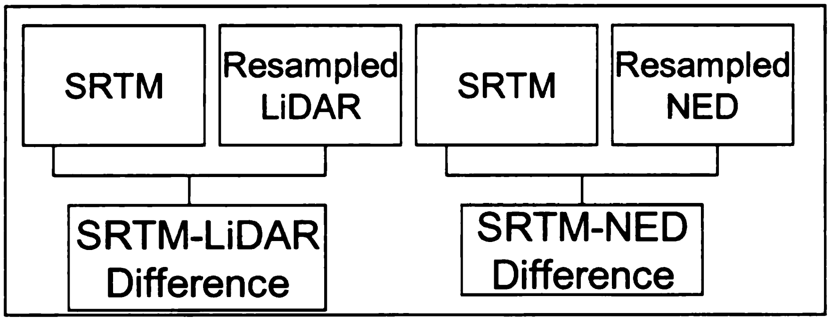

Figure 4.4. Louisiana study area: Error Analysis. For the Acadia and Webster study areas, error analysis of the SRTM C-90 m DEM was done using both the LiDAR-90 m and NED 90 m DEMs.

Each error grid was squared and the average value for each raster was calculated. The square root of the mean squared error is the root mean square error (RMSE), which is:

$$\text{RMSE}=\sqrt{\frac{\sum(Z_{DEM}-Z_{Reference})^2}{n}} \qquad (4.1)$$

The RMSE values are reported in the results section. Additional descriptive statistics for the study areas include minimum, maximum, mean, and standard deviation of the elevation errors (meters), which are presented in Chapter 5.

Error analysis should be developed with independent samples (Shortridge 2006). However, spatial autocorrelation exists in the DEM and error grids; thus, a determination of the distance at which this occurs would be useful in setting the minimum distance between sample points. The ArcGIS Geostatistical Analyst was used to examine the semivariogram of the error grid to measure its spatial autocorrelation. The lag size of the semivariogram was set to 90 m, the cell resolution of the SRTM C-band data. The major range indicates the average minimum distance between uncorrelated cells. This distance was determined to about 650m for the SRTM-LiDAR error grid for the Webster study area. Thus, a distance of 650 m was used as a minimum distance between sample points in a 1500 point sample for the Webster study area. For the Acadia study area, a minimum distance of 800 m was used to create the sample initially with 2000 sample points. Based on the minimum inter-sample distance (i.e. the distance between sample points) and the spatial extent of the areas, there was a limit to how many points could be obtained from the study areas given the minimum distance set in sampling.

Hawth's tool extension for ArcGIS (Beyer 2004) was used to sample the data. This sample is stratified by land cover type of the NLCD focal majority (90 m). This sample was exported for subsequent analysis in SYSTAT 10.0 software, and missing data were removed from the dataset. Statistics are included in the results section. The following subsection indicates the characteristics of the samples taken from the Webster and Acadia study areas, and Nang Rong study area.

4.8. Sampling Procedure

4.8.1. Louisiana study area

The NLCD 2001 Land Cover/Land use data were reclassified into groups to represent different land cover classes, which could be relevant to the characteristics of DEM error. Table 4.2 indicates the NLCD 2001 land cover/land use categories, along with the reclassified class, as justified below.

Table 4.2. Reclassification Scheme of the NLCD (2001)

NLCD 2001 Code	Name	Reclassification Class
11	Open Water	Water
21	Developed, Open space	Developed
22	Developed, Low Intensity	Developed
23	Developed, Medium Intensity	Developed
24	Developed, High Intensity	Developed
31	Barren Land (Rock/Sand/Clay)	Agriculture/Barren
41	Deciduous Forest	Deciduous Forest

Table 4.2. continued

42	Evergreen Forest	Evergreen Forest
43	Mixed Forest	Forest/Shrub
52	Shrub/Scrub	Forest/Shrub
71	Herbaceous/Grassland	Agriculture/Barren
81	Pasture/Hay	Agriculture/Barren
82	Cultivated Crop	Agriculture Barren
90	Woody Wetlands	Wetland
95	Emergent Herbaceous Wetland	Wetland

The NLCD were reclassified in 7 categories based on the understanding that different land cover characteristics may respond differently with the SRTM, which would ultimately lead to different error characteristics. Table 4.3 indicates the cell counts and percentages of the NLCD for each study area. The open water class was left into a group of its own, since the radar technology has been noted to respond to water different than land surfaces. The NLCD 2001 values 21, 22, 23, and 24 representing the developed land uses were grouped together, since they represent built-up surfaces on the landscape. In terms of the natural features on the landscape, the barren land was grouped with the pasture/hay, herbaceous/grassland, and cultivated crop classes because all of these land covers have little vegetation above the earth's surface.

The forest classes evergreen and deciduous were left as distinct classes in the dataset because their tree structure characteristics could potentially have different error pattern in the SRTM DEM data. The coniferous and deciduous trees on the landscape would have different leaf and surface characteristics, which could create different error patterns when the SRTM and reference DEMs are compared. As seen in Walker, Kellndorfer, and Pierce (2007), the SRTM radar does not penetrate trees completely because of its short wavelength and is scattered by branches and leaves. Thus, whether the trees are known to keep their leaves or not could play a role in the scattering potential of the SRTM, and ultimately the SRTM DEM error characteristics. The mixed forest class (NLCD code 43) is identified as a class with deciduous and coniferous tree species, which in this research is identified as a mixed vegetation class. The mixed forest (NLCD code 43) and the shrub/scrub (NLCD code 52) were grouped together as a forest/shrub class in this reclassification. However, for analysis of the sample, the points identified originally as shrub were removed from the sample because the height of the shrubs can not be determined. In both the Webster and the Acadia study areas, the emergent herbaceous wetlands represent very small portions of these areas. Thus, the herbaceous wetland class (NLCD code 95) was grouped with the woody wetlands class (NLCD code 90). The wetlands class was a distinct land cover class because of its predominance in Louisiana.

Following the reclassification of the NLCD 2001 (90 m) data, the percentages of each reclassified class (column 3 of Table 4.2) was calculated. The reclassified NLCD 2001 (90 m) was converted to a vector format for use with the Hawth's tool extension, which requires this format to stratify the sample of the dataset (Beyer 2004). These percentage values were input into the database and used to extract a random stratified sample with the indicated minimum distance (i.e. 650 m and 800 m).

Table 4.3. NLCD Summary Statistics for Louisiana study areas

			Webster		Acadia	
NLCD 2001 Value	**Name**	**Reclassification Category**	**Cell count (90 m)**	**% of entire area**	**Cell count (90 m)**	**% of entire area**
11	**Open Water**	**Water**	2,693	2 %	494	0.2 %
21	**Developed, Open space**	**Developed**	1,540	1 %	698	0.3 %
22	**Developed, Low Intensity**	**Developed**	2,156	1 %	9463	3.8 %
23	**Developed, Medium Intensity**	**Developed**	109	0 %	193	0.1 %

Table 4.3. continued

24	**Developed, High Intensity**	**Developed**	54	0 %	123	0.1 %
31	**Barren Land (Rock/Sand/Clay)**	**Agriculture/Barren**	12	0 %	21	0.0 %
41	**Deciduous Forest**	**Deciduous Forest**	9,702	6 %	14	0.0 %
42	**Evergreen Forest**	**Evergreen Forest**	83,900	50 %	96	0.0 %
43	**Mixed Forest**	**Forest/Shrub**	9,603	6 %	3	0.0 %
52	**Shrub/Scrub**	**Forest/Shrub**	24,268	14 %	415	0.2 %
71	**Herbaceous/Grassland**	**Agriculture/Barren**	0	0 %	901	0.4 %
81	**Pasture/Hay**	**Agriculture/Barren**	9,848	6 %	29,222	11.9 %
82	**Cultivated Crop**	**Agriculture Barren**	156	0 %	160,752	65.3 %
90	**Woody Wetlands**	**Wetland**	24,523	15 %	43,818	17.8 %
95	**Emergent Herbaceous Wetland**	**Wetland**	15	0 %	127	0 %
Total			168,579		246,340	

Table 4.4 Webster study area Reclassified Values

Reclassified Class	# of Cells (90 m NLCD)	Percent of area	Count in Sample (n =1484)
1. Water	2,693	2%	23 (1.5 %)
2. Deciduous Forest	9,702	6%	38 (2.6 %)
3 Evergreen Forest	83,900	50%	740 (49.9 %)
4. Developed	3,859	2%	82 (5.5 %)
5. Forest/Shrub	33871	20%	300 (20.2 %)
6. Agriculture/Barren	10,016	6%	86 (5.8 %)
7. Wetland	24,538	15%	215 (14.5 %)

Table 4.5. Acadia study area Reclassified Values

Reclassified Class	# of Cells (90 m NLCD)	Percent of area	Count in Sample (n =1956)
1. Water	494	0.2 %	
2. Deciduous Forest	14	0.0 %	
3. Evergreen Forest	96	0.0 %	
4. Developed	10,477	4.3 %	92 (4.7 %)
5. Forest/shrub	418	0.2 %	
6. Agriculture/Barren	190,896	77.5 %	1,523 (77.9 %)
7. Wetland	43,945	17.8 %	341 (17.4 %)

Given the proportions of the above samples (Tables 4.4 and 4.5), a minimum threshold of 20 points was set for each class, which eliminated some classes from being represented. This minimum threshold was set so that the sample would be representative of the study areas, for instance with the Acadia study area only 14 cells were deciduous in the entire area, which is less than 1 % of the entire area. For the Webster study area, all classes are represented in the sample; however, with the Acadia study area, the water, deciduous, evergreen classes, and forest/shrub classes did not meet the minimum necessary number of sample points to be represented in the sample (Tables 4.4 and 4.5). The LiDAR 5 m, LiDAR 90 m, NED 30 m, NED 90 m, SRTM 30 m, and SRTM 90 m elevation values and slope values were collected for the sample points. The SRTM-LiDAR and SRTM-NED DEM error values were also collected. The NLCD 2001 and MODIS Percent Tree cover (2000-2001) were also included in the sample. The MODIS Percent Tree cover will be further discussed in a later section. Points with missing data were removed from the sample. A similar methodology of using the semivariogram to determine spatial autocorrelation was employed with the Nang Rong study area.

4.8.2. Nang Rong study area

The semivariogram of the SRTM DEM error grid was examined to determine the minimum distance between sample points for the Nang Rong study area. The cells were spatially autocorrelated up to a distance of 400 m. Thus, a sample of 1537 points with a minimum inter-point distance of 400 m was extracted from the Nang Rong study area covered by both the SRTM-C- and X-band DEMs. The SRTM-90 m, SRTM X-25 m, and SRTM X-90 m elevation and slope values were included in the sample, along with the DEM error difference of the SRTM C-90 m and SRTM X-90 m DEM. The MODIS 2000-2001 data were also included in the sample, which is discussed in the next section.

4.9. Comparative Surface Properties

To compare surface cover characteristics of all study areas to SRTM, a data source needed to be identified that was available in both locations. MODIS data (2000-2001) were determined to be a possible source of data, which would be available for the Louisiana and Thailand case studies. Continuous MODIS vegetation data (500 m) available from the Global Land Cover Facility (GLCF) of the University of Maryland is distributed by continental region in the Goodes Interrupted Homolosine projection (GCLF 2007). North American data on percent tree, percent herbaceous, and percent bare earth were downloaded from the GLCF (Hansen et al. 2003a). Similarly, Euroasian data for percent tree, percent herbaceous, and percent bare earth were downloaded (Hansen et al. 2003b). The projection information for the North America and Euroasian data was defined in ArcInfo using the regional characteristics for the projection (Lethcoe and Klaver 2007). The projected MODIS data were clipped to the extents of the study areas for further analysis.

4.10. Application Development

Based on the discussion of relevant land uses in all study areas in Chapter 3, an application was developed based on slope criteria and topographic position on the landscape to determine how the selection of a certain DEM worked in an application (Figure 4.5). The slope was reclassified for the LiDAR 90 m, NED 90 m, and SRTM 90 m DEMs. To determine the locally low elevations, a circular focal mean of a 900 m radius (10 cells at 90 m resolution) was used in the focal operation. This decision was based on observation of the semivariogram of the SRTM 90 m for Nang Rong, Thailand DEM. For consistency, this distance was applied to all DEMs compared in the application analysis. The actual elevation in each cell was subtracted from the smoothed focal mean elevation. If the difference is positive, the focal mean is greater than the actual, and the cell is a low location in the landscape.

$$\text{Suitable Slope} = \begin{cases} 0 \text{ if Slope} > 1 \\ 1 \text{ if Slope} = 0\text{-}1 \end{cases}$$

$$\text{Suitable Low Position} = \begin{cases} 0 \text{ if Mean Elevation- Actual Elevation} \leq 0 \\ 1 \text{ if Mean Elevation } -\text{Actual Elevation} > 0 \end{cases}$$

Figure. 4.5. Criteria for Land Use Application. This figure indicates the equations for the suitable slope and low position criteria.

This application addresses the second research question related to how differences in DEMs impact the outcomes of applications. Figure 4.6 indicates the cartographic model employed on the LiDAR 90 m DEM, NED 90 m, and SRTM 90 m DEM for the Acadia and Webster study areas. Similarly for the Nang Rong study area, the model will be employed with the SRTM C-90 m, SRTM X-25 m, and SRTM X-90 m to determine how the DEMs perform. The multiplication of the suitable slope locations and the suitable low locations on the landscape indicate the locations where the appropriate criteria were found for both of these variables. The unsuitable and suitable cells for each DEM were recoded with a different value, so that when they were added together, each cell could be 1 of 4 different values. The cell counts were recorded for each combination. An example is provided in Table 4.6 of the possible values from addition. In addition to determining areas found suitable by all DEMs, contingency tables were made using the

LiDAR 90 m as reference in relation to the NED and SRTM application results. These contingency tables indicate the unsuitable and suitable cell counts for the DEMs. For the Nang Rong study area, the SRTM X-90 m was used as reference to the SRTM C-90 m. The Kappa statistics were calculated to determine the agreement of the DEMs in terms of their application results.

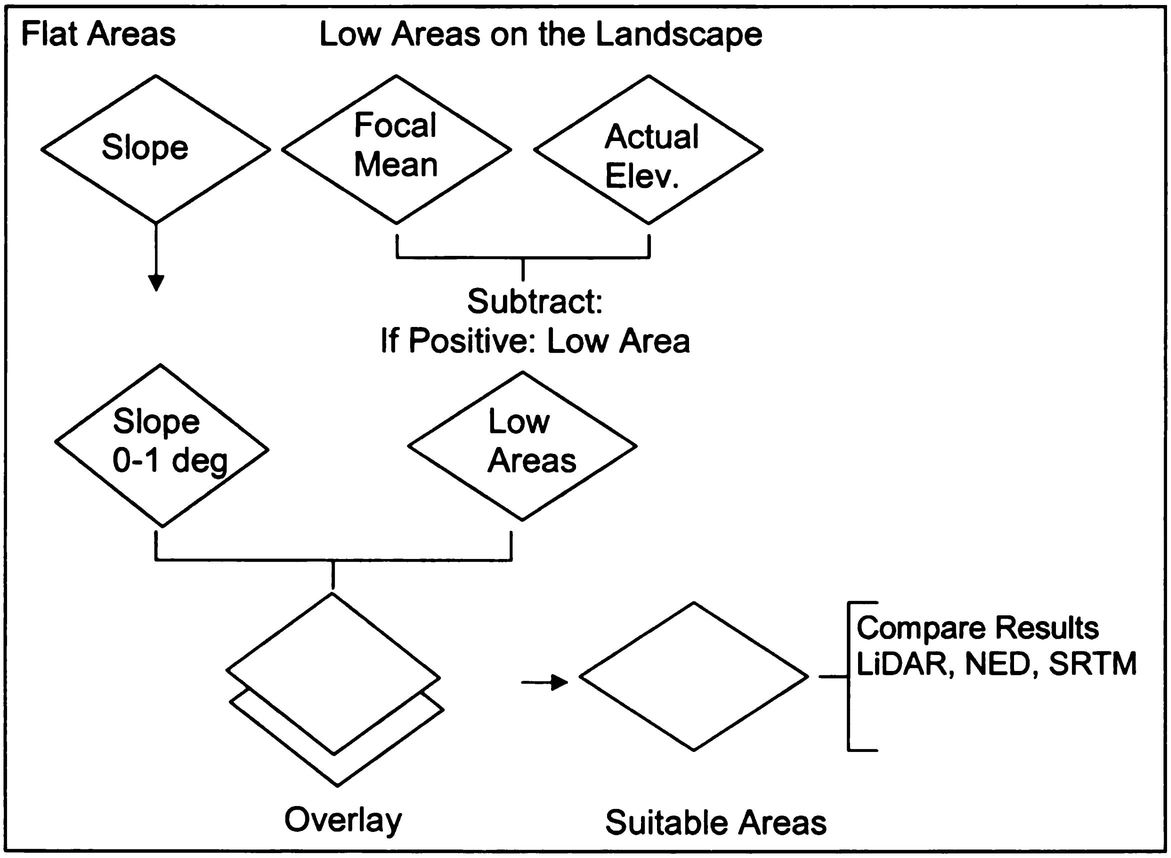

Figure 4.6. Cartographic Model for Land Use Application. This flow chart illustrates the creation of slope and low position variable, along with the overlay process to identify suitable areas for the LiDAR 90 m, NED 90 m, and SRTM 90 m DEMs.

Table 4.6. Addition Process for the Comparison of DEM Application Results

		LiDAR	
SRTM		Unsuitable (10)	Suitable (15)
	Unsuitable (12)	22	27
	Suitable (13)	23	28

This methodology illustrated the process of acquiring data from data repositories, projecting, and processing the DEMs. The process of performing the error analysis was outlined. Furthermore, the description of the land cover/ land use data from the NLCD 2001 was summarized, as the samples of the Louisiana study areas were stratified by the NLCD 2001 codes. The flow chart of the application indicates the process employed on the DEMs to determine how the different DEMS would result in different outcomes. The methodology employed in the study areas in Louisiana and Thailand will aid in identifying characteristics of the SRTM DEM. A better understanding of the properties of the SRTM DEM will benefit future users of the DEM, especially in contexts without another DEM. The following chapter reports the results of these methods and discusses the overall themes across study areas.

5. Results and Discussion

This research is aimed at investigating the characteristics of the SRTM DEM in relation to other available DEMS (i.e. LiDAR, NED, and SRTM X-band 25 m, where available). After the selection of study areas in Thailand and parts of Louisiana (Acadia and Webster study areas), the elevation and slope characteristics of these areas are explored. In addition, the differences across land cover/ land use classes and SRTM error are examined. This chapter contains the results of the DEM resampling, error analysis, and application development. Results are organized by study area: Acadia, Webster, and Nang Rong. The results and discussion of the Acadia and Webster study areas are organized in a similar way. Results from the entire study area opposed to the sample are denoted by the word "entire" in the figure or table title. Following discussion of the error analysis of the SRTM models, the results of the land use application are presented with a focus on comparing different DEM results. The discussion section addresses themes across all study areas.

5.1 Louisiana study areas

5.1.1. Acadia study area

The Acadia study area is a relatively low-slope area in southwestern Louisiana. Figures B.1-B.6 in Appendix B illustrate the elevation and slope characteristics of the Acadia study area for the LiDAR, NED, and SRTM DEMs at their original and resampled resolutions. The color scheme is the same for each map sequence for comparative purposes. The LiDAR elevation model has finer detail of the geomorphic characteristics of the earth, such as the properties of streams, compared to the SRTM 90 m resolution. Agricultural land use patterns and other small-scale topographic features, such as canals, are differentiated from other features on the landscape using LiDAR. The detail observable in the LiDAR DEM is also not seen in the NED DEM. In addition, these landscape details are not preserved in the LiDAR 90 m or the SRTM C-band DEM.

The SRTM DEM 90 m contains striping on the southeastern portion of the study area (Figure 5.1). Similar striations have been noted by Bhang, Schwartz, and Braun (2007) as an artifact from radar collection, and are interpreted as such here. The lower elevation in the streams networks are represented as blocky patches of high and low error in the SRTM C-band. In contrast to the blocky pattern and rectangular form of some trends in the SRTM 90 m, the NED DEM has a comparatively smoothed appearance. The NED DEM also includes the linear feature across the southern portion of the study area; however, this is less prominent than in the LiDAR DEM. This could be attributed possibly to an elevated road because it is higher than the surrounding cells and crosses over a wetland area.

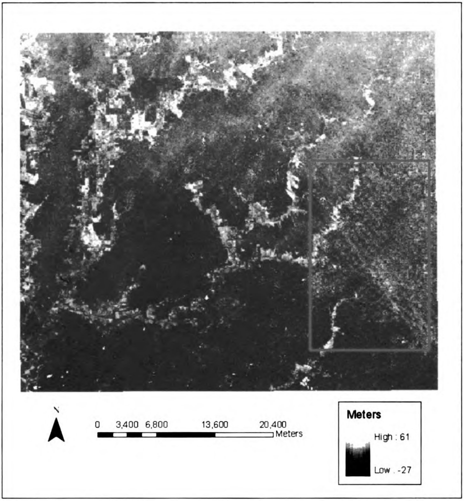

Figure 5.1. Striping in the southeastern portion of the Acadia study area. Striping is an artifact from the SRTM radar collection.

The contrasts in the elevation and slope (degrees) values of the LiDAR, NED, and SRTM models are evident from comparison of the descriptive statistics (Table 5.1). LiDAR and NED models have similar ranges, means, and standard deviations for both their original and resampled resolutions. However, substantial differences are observed between the SRTM DEM and the characteristics of the LiDAR and NED models. The SRTM 30 m and 90 m DEMs contain much higher maximum elevation values (85 m and 61 m) in the study area, along with greater means and standard deviations. The higher maximum values are an indicator of erroneous elevations. In addition, to the comparison of ranges of values, the minimum values of the models are as negative as -32 m and -27 m in the case of the SRTM 30 m and SRTM 90 m DEMs. The negative elevation values are unlikely because the lowest elevation in Louisiana is around 2 m below sea level near New Orleans (MSN Encarta Encyclopedia 2008). A negative value would indicate the elevation was below sea level.

Table 5.1. Entire Acadia study area Characteristics

	Columns x Rows	Min (m)	Max (m)	Mean (m)	Std (m)
LiDAR 5 m	9660 x 8364	-6.1	22.1	8.9	3.9
LiDAR 90 m	537 x 465	-3.3	21.3	9.5	3.9
NED 30 m	1618 x 1404	0.3	20.1	9.1	3.9
NED 90 m	539 x 468	1.1	20.7	9.7	3.9
SRTM 30 m	1617 x 1403	-32	85	11.8	5.1
SRTM 90 m	538 x 468	-27	61	12.3	4.8

In addition to the comparisons of elevation values, the slope (degrees) of the DEMs can illustrate difference in the models (Table 5.2). In comparison of the LiDAR, NED, and SRTM DEMs, a smoothing effect was observed in the resampling of their original resolution to the 90 m resolution. For the LiDAR DEM its maximum slope was 46.3° at 5 m resolution, which was reduced to 4.5° for the LiDAR 90 m DEM. It is likely the maximum of 46.3° was incorrect due to blunders in the LiDAR and was lost in the resampling method. The NED 90 m and the LiDAR 90 m slope range were more comparable than the LiDAR and SRTM ranges. Blunders (aka gross errors) are identified as errors from the equipment used to create the DEM (Fisher and Tate 2006). However, the SRTM 90 m slope range was much smaller than the SRTM 30 m resolution. These observations of the differences in mean slope (i.e. 0.9° for the LiDAR 5 m, 0.3° for the

NED 30 m, and 0.6° for the SRTM 90 m) indicate the difficulty of stating the average elevation of an area, since it can differ based on the model used.

Table 5.2. Slope (degrees) of entire Acadia study area DEMs

	Columns x Rows	Min	Max	Mean	Std
LIDAR 5 m	9660 x 8364	0	46.3	1.0	1.6
LIDAR 90 m	537 x 465	0	4.5	0.2	0.3
NED 30 m	1618 x 1404	0	9.1	0.3	0.5
NED 90 m	539 x 468	0	3.1	0.2	0.3
SRTM 30 m	1617 x 1403	0	39.6	2.1	1.5
SRTM 90 m	538 x 468	0	10.9	0.6	0.7

In addition to reporting the descriptive statistics of the entire study area, the sample descriptive statistics of the Acadia study area are reported in Tables 5.3 and 5.4. From examination of the sample statistics, the SRTM DEMs have greater average elevations (11.7 m for the SRTM 30 m and 12.3 m for the SRTM 90 m) compared to the NED 30 m and 90 m (9.1 m and 9.6 m) and LiDAR 5 m and 90 m DEMs (8.7 m and 9.3 m). The average slope values of the sample are comparable to the entire study area. The standard deviations of the sample statistics are greater(4.0 m to 5.2 m) compared to the standard deviations of the entire study area (3.9 m to 5.1 m) However, the standard deviations of the SRTM 30 m and 90 m slope values are lower compared to the entire area.

Table 5.3. Acadia study area Sample Elevation Characteristics (n = 1956)

	LIDAR 5 m	LiDAR 90 m	NED 30 m	NED 90 m	SRTM 30 m	SRTM 90 m
N of cases	1956	1956	1956	1956	1956	1956
Minimum	0.0	0.0	1.3	1.9	-4	0
Maximum	19.0	19.7	18.9	19.5	32	35
Range	19.0	19.7	18.9	19.5	36	35
Mean	8.7	9.3	9.1	9.6	11.7	12.3
Standard Dev	4.0	4.1	3.9	4.0	5.2	5.0

Table 5.4. Acadia study area Sample Slope (degrees) Characteristics (n = 1956)

	LIDAR 5 m	LIDAR 90 m	NED 30 m	NED 90 m	SRTM 30 m	SRTM 90 m
N of cases	1956	1956	1956	1956	1956	1956
Minimum	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	21.4	2.2	2.3	13.2	4.6	5.6
Range	21.4	2.2	2.3	13.2	4.6	5.6
Mean	0.9	0.2	0.2	2.0	0.6	0.3
Standard Dev	1.6	0.3	0.3	1.4	0.6	0.5

5.1.1.1. Comparison of Elevation Values of LiDAR, NED, and SRTM

The pairwise correlation coefficients (r) of the LiDAR, NED, and SRTM DEMs were investigated in SYSTAT to address research question 1: What are the relationships among elevations of NED, LiDAR, and SRTM DEMs? It is expected that the original and the resampled resolution data will be highly correlated given the nearest neighbor method. The correlation values of the LIDAR, NED, and SRTM DEMs were determined (Table 5.5) A high correlation exists between the NED 30 m and NED 90 m (r = 0.993) and the LiDAR 5 m and LiDAR 90 m (r = 0.989) Also, a high correlation was noted between the SRTM 90 m and the SRTM 30 m DEMs (r =0.936). The SRTM 90 m and the SRTM 30 m showed much lower correlations with the LiDAR 5 m and 90 m (r = 0.633 and 0.625, respectively) and NED 30 m and NED 90 m DEMs (r =0.657 and 0.655).

Table 5.5. Pearson Correlation Matrix of Acadia study area Elevation Data (n =1956)

	LIDAR 5 m	LIDAR 90 m	NED 30 m	NED 90 m	SRTM 30 m	SRTM 90 m
LIDAR 5 m	1.000					
LIDAR 90 m	0.989	1.000				
NED 30 m	0.939	0.929	1.000			
NED 90 m	0.941	0.933	0.993	1.000		
SRTM 30 m	0.619	0.610	0.647	0.644	1.000	
SRTM 90 m	0.633	0.625	0.657	0.655	0.936	1.000

5.1.1.2. Comparison of Slope Values

To determine how correlated the slope values of the datasets were in relation to research question 2 (What are the relationships among NED, LIDAR, and SRTM slopes?), a correlation matrix of the slopes of the original and resampled resolution DEMs was generated (Table 5.6). It is expected that the slopes will not be highly correlated for DEMs of the same production method, given the smoothing effects that occurred during resampling. It is evident that the NED 90 m and NED 30 m have a high correlation (r= 0.776). Medium correlations were found between the LiDAR 90 m and the NED 30 m (r = 0.661) and the LiDAR 90 m and the NED 90 m (r= 0.752). Weak correlations were found between the SRTM 30 m and SRTM 90 m DEMs (r =0.459), along with between the SRTM 90 m and SRTM 30 m DEM and other DEMs. These weak correlations occur because the resampling done to obtain new resolutions smoothed the DEM and decreased the slopes. Generally, the slope values are skewed toward the right. Figure 5.2 shows the histogram of the sample SRTM 90 m slope values.

Table 5.6. Pearson Correlation Matrix for Acadia study area Slope (n =1956)

	LIDAR 5 m	**LIDAR 90 m**	**NED 30 m**	**NED 90 m**	**SRTM 30 m**	**SRTM 90 m**
LIDAR 5 m	1.000					
LIDAR 90 m	0.307	1.000				
NED 30 m	0.332	0.661	1.000			
NED 90 m	0.277	0.752	0.776	1.000		
SRTM 30 m	0.067	0.120	0.124	0.128	1.000	
SRTM 90 m	0.131	0.250	0.213	0.244	0.459	1.000

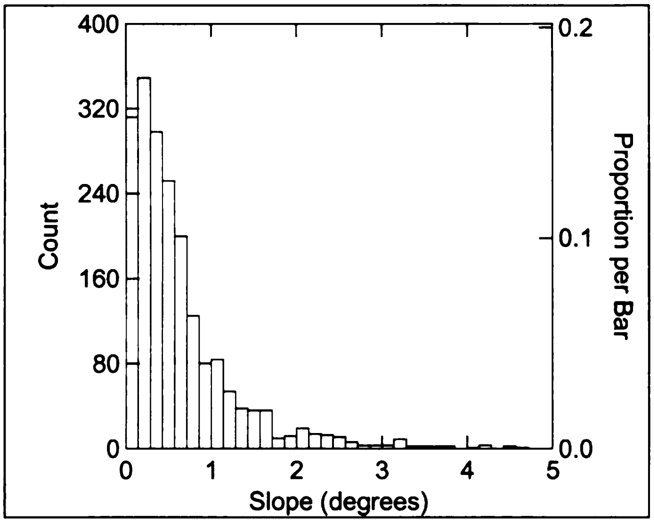

Figure 5.2. Histogram of SRTM 90 m Slope (degrees) (n = 1956)

5.1.1.3. Error Analysis

The SRTM model was analyzed in relation to the LiDAR 90 m and NED 90 m DEM. Table 5.7 summarizes the error descriptive statistics of the Acadia study area. The minimum, maximum, mean, and standard deviation of the SRTM-LiDAR difference grid, and the SRTM-NED difference grid produced very similar results. Table 5.8 indicates the sample SRTM error characteristics of the Acadia study area. The RMSE of the sample characteristics of the SRTM-LiDAR DEM was 4.6 m and the SRTM-NED DEM was 4.6 m , which are comparable to the entire study area RMSE, 4.7 m and 4.6 m, respectively. The main difference between the sample and the entire area is the range of the error values. The range of the entire study area of the SRTM-LIDAR DEM error was -37.1 m to 49.7 m, while the range of the sample was -5.7 m to 21.8 m. The sample range was smaller and contained less extreme values compared to the entire area. Table 5.7 and Table 5.8 display the means of the SRTM DEM error to be greater than zero, which indicates an upward bias of the SRTM. Bias is defined as the over or underestimation of elevation values of the DEM, which can be determined from the mean elevation error being positive or negative (Fisher and Tate 2006). It is expected from findings of the research literature, such as Carabajal and Harding 2006, that similar results will be seen in this research.

Table 5.7. Entire Acadia study area Elevation Error Characteristics

Error grids	Columns x Rows	Min (m)	Max (m)	Mean (m)	Std Dev (m)	RMSE
SRTM- LiDAR	537 x 465	-37.1	49.7	2.8	3.7	4.7
SRTM- NED	537 x 468	-35.8	49.7	2.7	3.7	4.6

Table. 5.8. Acadia study area Sample SRTM Error Characteristics (n = 1956)

	Sample	Min (m)	Max (m)	Mean (m)	Std Dev (m)	RMSE
SRTM- LiDAR	1956	-5.7	21.8	2.8	3.7	4.6
SRTM-NED	1956	-6.7	22.8	2.6	3.8	4.6

To determine whether the SRTM-LiDAR and the SRTM-NED means were significantly different from each other (Figure 4.5), the difference of means t-test was conducted. The null hypothesis is that the mean errors of each sample are equal. The research hypothesis is that the means are not equal. The difference of means test of the SRTM-NED and SRTM-LIDAR (n= 1956) indicated a significant t-value ($t= -4.133$, $p<<0.0001$), thus the null hypothesis is rejected. This indicates that there is a significant difference between the mean values of using the LiDAR as reference to the SRTM versus the NED DEM as reference. In order to see if the mean values of the SRTM-LiDAR DEM error and the SRTM-NED DEM error are significantly greater than zero, a t-test was done with the alternative hypothesis set to the mean greater than 0, and the null hypothesis of a mean equal to zero. As Table 5.9 indicates the SRTM-LiDAR and SRTM-NED average errors were significantly greater than zero ($t=33.007$, $p <<0.0001$;

t= 30.500, p <<0.0001). This supports my initial research hypothesis that the average SRTM DEM error would be positive indicative of an upward bias of the SRTM DEM.

Table 5.9. Acadia study area: One-sided T-test Results

	Mean	**T**	**p-value**
SRTM-LiDAR	2.8	33.007	0.000
SRTM-NED	2.6	30.500	0.000

The correlation coefficient was calculated for the SRTM-NED error and SRTM-LiDAR error. It was anticipated that their error values were highly correlated given the general similarity observed in the error grids spatially. The correlation (r) between the SRTM- LiDAR Error and the SRTM-NED Error was 0.907. This result suggests that using either the NED 90 m or the LiDAR 90 m DEM will yield similar SRTM error characteristics. The histograms of the SRTM-LiDAR Error and the SRTM-NED Error for the Acadia study area indicate a bell-shaped distribution (Figure 5.3), skewed towards the right.

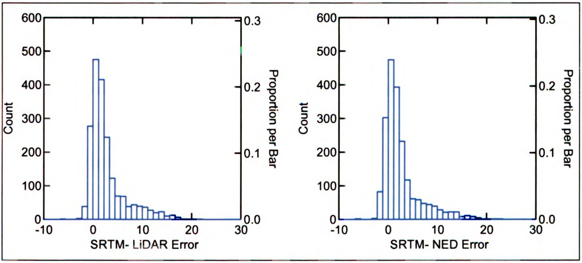

Figure 5.3. Histogram Distribution of SRTM-LiDAR and SRTM-NED Error (n = 1956)

5.1.1.3.1. SRTM-LiDAR DEM Error

The similarity observed in the descriptive statistics of the SRTM-LIDAR DEM error and the SRTM-NED DEM error was also evident from Figures 5.4 and 5.5. The LiDAR has yet to be incorporated in the NED for this area, so data sources are independent. The root mean square error for the SRTM DEM model is 5 m, which indicates the dispersion of error around the mean. The root mean square error (RMSE) represents a global statistic. In the error grids, the very negative error values are associated with voids in the data, which can be seen towards the southeastern area of the Acadia study area.

In terms of the general error characteristics of the SRTM to LiDAR DEM, the patterns of error follow land cover/ land use patterns present on the landscape (Figure 5.4). The symbology of the mean and standard deviations indicate green at locations greater than the average (2.8 m for the SRTM-LIDAR DEM error and 2.7 m for the SRTM-NED DEM error), and purple in locations lower than the average. In addition to the identification of error patterns from the SRTM-LiDAR difference grid, a striated pattern was located in the lower right corner of the region, and is interpreted as was earlier, interpreted by Bhang, Schwartz, and Braun (2007) to be a result of the SAR scanning procedure. Also, Bhang, Schwartz, and Braun (2007) attribute spikes in the SRTM to the radar data used to create the SRTM DEM.

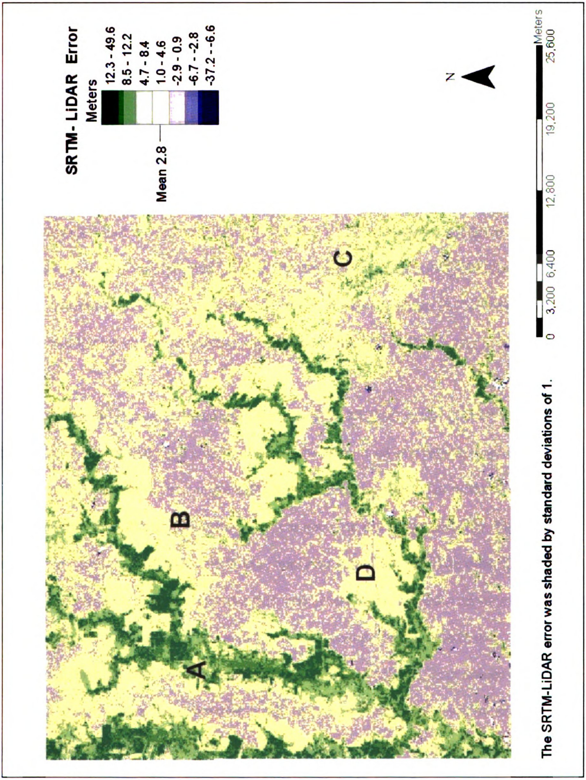

Figure 5.4. Acadia study area SRTM- LiDAR Error

This thesis research indicates that wetlands along the stream networks are areas of high error in the region producing some distinct patterns. These included rectangular level patches, which could possibly correspond to fields or forest patches. The developed urban areas appeared to have low error magnitudes. The negative errors occurred throughout the flatter agricultural lands in the area. More specific discussion of the characteristics of SRTM DEM error and land cover characteristics are in section 5.1.1.4.

5.1.1.3.2. SRTM-NED DEM Error

Examination of the metadata viewer from the USGS indicated some areas of Louisiana have already incorporated LiDAR into the NED product (USGS 2007). However, selected study areas does not have LiDAR incorporated into the NED product, thus this is not the reason for the similar appearance of the SRTM DEM error (Figures 5.4 and 5.5)

Based on the results obtained from the use of the NED 90 m and LiDAR 90 m, both of these products will yield similar error results when used as a reference to the SRTM. This implies that the use of the LiDAR data in this case does not further enhance knowledge of the SRTM error characteristics, compared to the use of the NED. This may be specific to the type of LiDAR data or may apply more broadly based on other LiDAR products. This research thus demonstrates that spatial resolution is a main driver of the representation of the elevation of this area for the different production methods.

Given the high correlation found between the SRTM-LiDAR Error values and the SRTM-NED Error values, the remainder of this chapter will include discussion and figures from the SRTM-LiDAR Error analysis. Any major deviations between the SRTM-LiDAR Error values and the SRTM-NED error results will be noted.

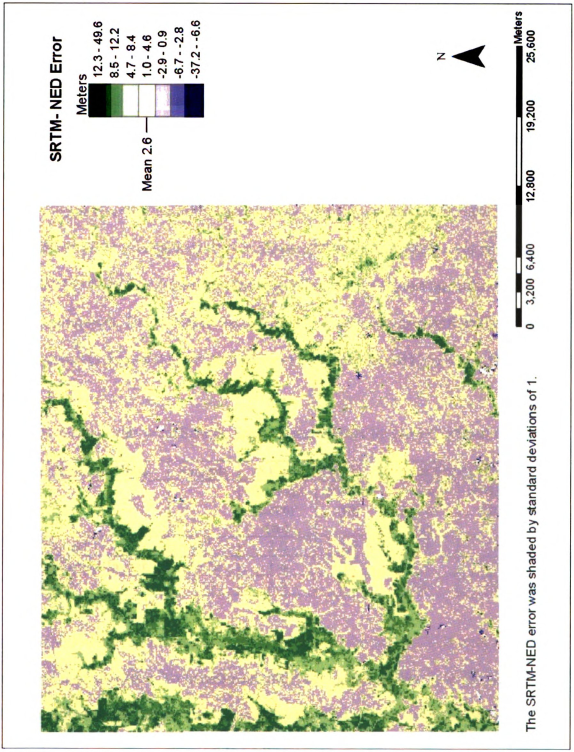

Figure 5.5. Acadia study area SRTM-NED Error

5.1.1.4. Error Relationships to National Land Cover Dataset (NLCD) 2001

The relationships of SRTM DEM error and land cover from the NLCD 2001 were investigated to address research question 4: What is the relationship of SRTM error in terms of different land cover/land use classes? Table 5.10 indicates the average SRTM-LiDAR error and average SRTM-NED error for each reclassed land category: developed, agriculture, and wetland. The RMSE was also calculated for each of these land class. From the average errors of the different land categories it is evident the wetland class has a higher SRTM DEM average error (8.5 m for the SRTM-LiDAR DEM error and 8.6 for the SRTM-NED DEM Error) than the developed (3 m and 2.9 m) and agriculture (1.4 m and 1.2 m) categories. The RMSE of the wetlands (9.5 m) is also greater than the RMSE of the developed (3.9 m) and agriculture classes (2.5 m) for the SRTM-LiDAR DEM error.

Table 5.10. Acadia study area: Sample Error Characteristics by Land Use/Land Cover

Reclassified Class	Sample	SRTM-LIDAR		SRTM-NED	
		Average Error (m)	RMSE (m)	Average Error (m)	RMSE (m)
Developed	92	3.0	3.9	2.9	3.8
Agriculture/Barren	1529	1.4	2.5	1.2	2.3
Wetland	344	8.5	9.5	8.6	9.6

The following section discusses characteristics of the SRTM DEM error in terms of landscape characteristics. To examine the SRTM error characteristics in relation to land cover, errors in the sample were grouped by the reclassed NLCD 2001 categories. The box plot of these groupings of SRTM-LIDAR error illustrates their median values as well as their distributions (Figure 5.6). This indicates the generally higher median error (8 m) for woody wetland locations. The agricultural and urban areas indicated lower elevation errors, 1 m and 3 m respectively. The main contrast seen between the woody wetlands and agricultural lands was further qualitatively confirmed with the vectorization of the NLCD data to a shapefile, which when overlaid on the error grid aligned approximately with the boundary patterns of high and low error.

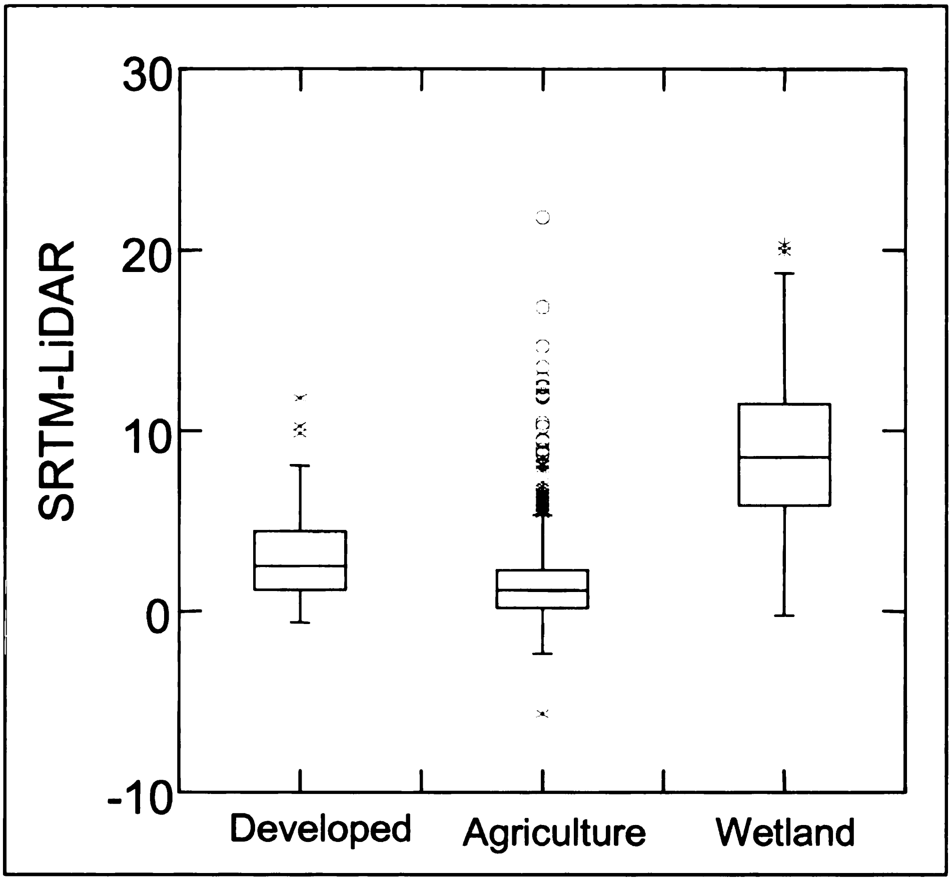

Figure 5.6. Box plot of the SRTM-LiDAR Error and NLCD 2001. The wetland class indicates a higher median error (8 m) compared to the developed (3 m) and agriculture classes (1 m).

In order to investigate research question 5 (Is the average SRTM DEM error greater for vegetated or non-vegetated areas?), a difference of means t-test was conducted. To test the significance of the differences of means between forested wetlands and non-forested landscapes, the sample was coded 0 for non-forest, and 1 for forest. The non-forest class included the developed and agricultural locations, while the forest class included the woody wetlands. The null hypothesis is the difference of means is equal to zero, while the alternative hypothesis is that the means do not equal zero. The mean SRTM-LiDAR error of the non-forested locations was 1.5 m, and the mean SRTM-LiDAR error of the forested locations was 8.5 m, with a t-value of -30.238, which was significant at the 95% confidence level ($p << 0.0001$).

To determine if the average SRTM-LiDAR DEM error of the vegetated class was significantly greater than the SRTM-LiDAR DEM error of the non-vegetated classes, a one-sided t-test was conducted.. This t-test was set up using the SRTM-LiDAR DEM error of the vegetated classes. The mean was set to 1.5 m (the SRTM-LiDAR mean of the non-vegetated classes) and the alternative hypothesis was set up as greater than the 1.5 m. This would indicate whether the average error of the vegetated classes was significantly higher than the mean of the non-vegetated classes. The results indicated a t value of 31.450 ($p <<0.0001$). This result confirms findings indicating a greater SRTM-LiDAR DEM error for the vegetated classes compared to the non-vegetated classes for the Acadia study area.

The variances of the land cover/ land use classes of the NLCD 2001 were also determined to examine differences across the classes (Table 5.11). In the Acadia study area, the variance of wetlands (6.2 m) was greater due to the greater difference between the mean value and the individual values. The wetland class had greater variance because of the changes in canopy height above the surface of the earth contributing to the DEM error. In contrast, the agriculture class had the least variance (1.4 m), since the crop heights would remain relatively constant over an area. These specific land cover/land use classes are investigated more in the next section.

Table 5.11. Acadia Study Area Variances of SRTM-LiDAR error by NLCD 2001 class

	n	Mean	Variance
Developed	92	3.0	6.2
Agriculture	1523	1.4	4.0
Wetlands	341	8.5	17.3
F-ratio	190.702		
p-value	0.000		

5.1.1.5. Select Location Error Comparison

Select areas were identified in the SRTM-LiDAR error grid to examine certain land cover/ land use relationships to DEM error. The letters (A, B, C, D) located on Figure 5.4 identify four locations chosen to represent various locations in the study area with different error characteristics. As discussed above, the highest error values occurred throughout the wetland land cover class, which is represented by Location A. In this wetland area, there are intertwined darker patches with lighter ones, which reflect a range of error values indicative of different heights of plants within the wetland area. The woody wetland land cover class adds height to the earth's surface because of the tree canopy above the surface. The SRTM radar would have been reflected from the tree canopy, which would have biased the elevations in the positive direction. Thus, this likely contributed to the greater difference seen in relation this class and the SRTM DEM. In the predominantly agricultural, non-wetland class (Location B) a relatively consistent lower average error value is depicted. This is likely due to the shorter grasses and/or crops on the landscape, which would not have contributed to the bias within the collection of the SRTM data. Average error was observed in landscapes surrounding the wetland areas, and along the eastern side of the study area where a striping pattern in the

DEM error analysis was present (Location C). The urban land cover class was typically associated with an average error value and had similar characteristics to the agriculture class (Location D). Generalizations about the characteristics of the SRTM DEM error were ascertained by examining these locations in context with the entire study area.

5.1.2. Webster study area

The Webster study area contains slightly higher relief compared to the Acadia study area. Figures B.7-B.12 of Appendix B portray the elevation and slope characteristics of the Webster study area. These figures employ with the same color scheme for comparative purposes. Similar to the Acadia study area, the SRTM 90 m Webster study area elevation surface appeared to have rectangular patterns of similar elevation. Rectangular and raised features are observed in the SRTM DEM towards the middle and western side of the study area, which is likely created from the forest canopy in the area. The eastern portion of the study area contained uplands, which were evident in the SRTM DEM. The curvilinear feature of the Bayou Bodcau Reservoir is observed on the eastern side of the study area in the lower wetland area. The LiDAR 5 m DEM for the Webster study provides a more detailed interpretation of the study area. The LiDAR 5 m DEM clearly indicates two main lower elevation areas, along with branching drainage networks. The uplands on both the western and eastern borders of this study area are identified in the LiDAR DEM. The NED DEM resembles the LIDAR DEM more than the SRTM DEM.

In terms of elevation ranges, the Webster SRTM, LiDAR, and NED DEMs are comparable (Table 5.12). The mean values of the LiDAR and NED values were also very similar, which was also the case for the Acadia study area. Again, the main distinction was between the LiDAR and NED DEMs, and the SRTM DEM for each study location. As with the Acadia study area, slopes decreased with an increase in cell size (Table 5.13). The histogram of the SRTM 90 m slope is skewed to the right, which shows a predominance of low slope values (Figure 5.7).

Table 5.12. Elevation Characteristics of entire Webster study area

	Columns x rows	Min (m)	Max (m)	Mean (m)	Std
LiDAR 5 m	7055 x 8344	44.1	138.1	69.3	12.1
LiDAR 90 m	877 x 585	44.9	135.3	69.9	12.0
NED 30 m	1243 x 1469	43.8	138.3	69.5	12.1
NED 90 m	392 x 464	44.4	135.84	70.1	12.1
SRTM 30 m	1176 x 1391	40	146	77.0	12.4
SRTM 90 m	392 x 464	43	144	77.0	12.4

Table 5.13. Slope (degrees) Characteristics of entire Webster study area

	Columns x rows	Min	Max	Mean	Std
LIDAR 5 m	7055 x 8344	0	47.8	2.3	2.4
LIDAR 90 m	877 x 585	0	10.1	1.0	1.0
NED 30 m	1243 x 1469	0	21.1	1.5	1.7
NED 90 m	392 x 464	0	10.1	1.0	1.0
SRTM 30 m	1176 x 1391	0	27.3	3.1	2.0
SRTM 90 m	392 x 464	0	11.4	1.7	1.1

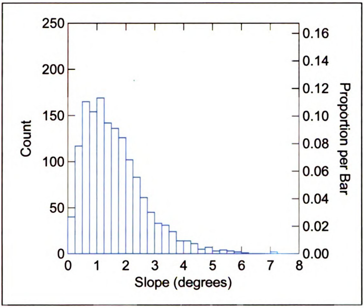

Figure 5.7. Histogram of the SRTM 90 m Slope (n = 1484). The Webster study area slope histogram is skewed to the right and a majority of low-slope areas.

Tables 5.14 and 5.15 indicate the sample elevation and slope characteristics. The means of the SRTM DEMs are higher compared to the LiDAR and NED DEMs, which was also the pattern seen with the Acadia study area. The slope mean values of the DEM were similar for the entire study area. The sample statistics give a more representative picture of the Webster study area, since the sample points are independent of one another.

Table 5.14. Webster study area Sample Elevation Characteristics (n = 1484)

	LiDAR 5 m	LiDAR 90 m	NED 30 m	NED 90 m	SRTM 30 m	SRTM 90 m
N of cases	1484	1484	1484	1484	1484	1484
Minimum (m)	44.7	46.2	45.2	43.9	47.0	49.0
Maximum (m)	130.9	126.1	130.6	128.2	135.0	135.0
Range (m)	130.9	126.1	130.6	128.2	88.0	86.0
Mean (m)	68.4	69.2	68.7	68.7	76.5	76.5
Standard Dev (m)	12.7	11.8	12.4	12.5	12.1	12.1

Table 5.15. Webster study area Sample Slope (degrees) Characteristics (n = 1484)

	LiDAR 5 m	LiDAR 90 m	NED 30 m	NED 90 m	SRTM 30 m	SRTM 90 m
N of cases	1484	1484	1484	1484	1484	1484
Minimum	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	20.3	8.0	12.3	6.9	15.5	7.2
Range	20.3	8.0	12.3	6.9	15.5	7.2
Mean	2.3	0.9	1.1	1.0	3.1	1.6
Standard Dev	2.4	1.0	1.5	1.0	1.9	1.1

5.1.2.1. Comparison of Elevation Values of LiDAR, NED, and SRTM

To determine how closely the elevation values of the LiDAR, NED, and SRTM elevations correspond to each other, the correlation coefficients were calculated between LIDAR, NED, and SRTM DEMs (Table 5.16). This aided in addressing research question 1: What are the relationships among elevations of NED, LiDAR, and SRTM DEMs? It was expected that the original and the resampled resolution data will be highly correlated given the nearest neighbor method of resampling that was chosen to resample the DEM from its original resolution to the resolution of the SRTM 90 m DEM. A high correlation between the NED 30 m and NED 90 m (r =, and the LiDAR 5 m and LiDAR 90 m resolution was observed. However, in this case, the SRTM DEM was also correlated with the other DEMs, which was in contrast to the Acadia study area. Similar to the Acadia study area, the SRTM 30 m and the SRTM 90 m were strongly correlated with an r equal to 0.976.

Table 5.16. Pearson Correlation Matrix for the Webster study area (n = 1484)

	LIDAR 5 m	LIDAR 90 m	NED 30 m	NED 90 m	SRTM 30 m	SRTM 90 m
LiDAR 5 m	1.000					
LiDAR 90 m	0.896	1.000				
NED 30 m	0.961	0.927	1.000			
NED 90 m	0.961	0.927	0.956	1.000		
SRTM 30 m	0.822	0.876	0.851	0.851	1.000	
SRTM 90 m	0.814	0.873	0.846	0.849	0.976	1.000

5.1.2.2. Comparison of Slope Values

To determine how correlated are the slope values of the datasets, the correlation matrix of the slope of the original and resampled resolution DEMs was created to answer research question 2: What are the relationships among NED, LIDAR, and SRTM slopes? (Table 5.17). The correlation coefficients of the slope grids are not highly correlated. This was similar to the Acadia study area, which had low correlation coefficients for slope values. The LiDAR 90 m and NED 90 m were the only slope grids with a correlation above 0.7, which indicates the importance of resolution regardless of the production method. This shows that despite the differences in the original production method of the DEM, when it is coarsen by resampling, the elevation values are comparable.

Table 5.17. Pearson Correlation Matrix for the Webster study area Slope (n = 1484)

	LIDAR 5 m	LIDAR 90 m	NED 30 m	NED 90 m	SRTM 30 m	SRTM 90 m
LiDAR 5 m	1.000					
LiDAR 90 m	0.467	1.000				
NED 30 m	0.025	0.044	1.000			
NED 90 m	0.553	0.711	0.060	1.000		
SRTM 30 m	0.168	0.170	-0.017	0.235	1.000	
SRTM 90 m	0.231	0.277	0.006	0.394	0.464	1.000

5.1.2.3. Error Analysis

The SRTM model was analyzed in relation to the LiDAR 90 m and NED 90 m DEM. Table 5.18 summarizes the error descriptive statistics of the Acadia study area. The minimum, maximum, mean, and standard deviation of the SRTM-LiDAR difference grid, and the SRTM-NED difference grid were very similar. The histograms of the SRTM-LiDAR Error and the SRTM-NED Error for the Webster study area indicate a bell-shaped distribution (Figure 5.8). Table 5.19 indicates the sample SRTM DEM error characteristics, along with the RMSE. These results of the sample are reflective of the RMSE calculated for the entire study area seen in Table 5.18. The minimum (-7.8 m) and maximum (29.7 m) of the SRTM –LiDAR DEM error sample were less extreme compared to the entire area minimum (-18.0 m) and maximum (38.2 m). The sample does not contain as extreme points in the entire study area, which must have been either erroneous points or from other data production issues. As indicated by Table 5.18, the average SRTM DEM error is 7.1 m for the entire SRTM-LiDAR DEM error and 6.9m for the SRTM-NED DEM entire area. These mean values are greater than zero, which suggests my hypothesis regarding research question 3 (Is the average SRTM DEM error greater than zero?) of a positive average error is valid. More statistical analysis follows that supports this hypothesis.

Table 5.18. Error Analysis Results for Webster study area

Error grids	Columns x Rows	Min (m)	Max (m)	Mean (m)	Std Dev (m)	RMSE
SRTM- LiDAR	392 x 464	-18.0	38.2	7.1	5.5	9.0
SRTM- NED	392 x 464	-17.1	29.3	6.9	5.1	8.6

Table 5.19. Webster study area Sample SRTM Error Characteristics (n = 1484)

	Sample	Min (m)	Max (m)	Mean (m)	Std Dev (m)	RMSE
SRTM- LiDAR	1484	-7.8	29.7	7.2	5.6	9.1
SRTM-NED	1484	-6.2	24.1	6.7	5.1	8.6

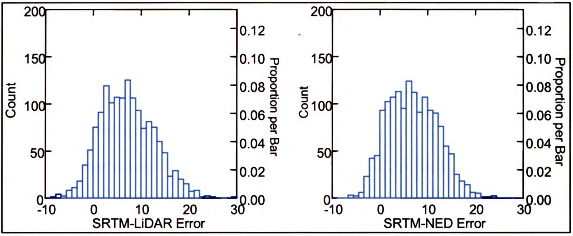

Figure 5.8. Histograms of the Sample Points (n =1484).

5.1.2.3.1. SRTM-LIDAR DEM Error

The Webster study area SRTM-LiDAR DEM error grid contains large positive error values (15.4 m -38.2 m) throughout the western portion of the study area (Figure 5.9). This area of higher DEM error corresponds with the woody wetland land cover on the landscape. Generally, through the middle portion of the study area, there was a patchy pattern of high (9.9 m - 15.4 m) and low error (-1.2 m - 4.3 m) present on the landscape. Towards the eastern side of the study area an alternating pattern of high and low error patterns were present on the upland areas, which is likely due to the high frequency changes in slope directions in this area. However, the uplands also contain groups of high locations (15.4 m- 38.2 m) of error likely from the forests present on the landscape.

For the sample of 1484 cells, the difference of means test of the SRTM-NED and SRTM-LIDAR was done, where the null hypothesis is that the means of each error set was equal given independent samples. The difference of means indicated a significant result ($t = 3.809$, $p << 0.0001$). The Pearson's correlation coefficient was calculated to see how correlated were the SRTM-NED and SRTM-LiDAR values. It was anticipated that their error values were highly correlated given the general spatial similarity observed in the error grid. The correlation (r) between the SRTM- LiDAR Error and the SRTM-NED Error was 0.872 (n= 1484). This indicates there is a strong correlation between the SRTM- LiDAR error and SRTM –NED error for the Webster study area, which was similar to the Acadia study area. However, this correlation is slightly weaker for the Webster study area compared to the Acadia study area.

In order to see if the mean values of the SRTM-LiDAR DEM error and the SRTM-NED DEM error are significantly greater than zero, a t-test was done with the alternative hypothesis set to the mean greater than 0, and the null hypothesis of a mean equal to zero. As Table 5.20 indicates the SRTM-LiDAR and SRTM-NED average errors were significantly greater than zero ($t=49.498$, $p \ll 0.0001$; $t= 51.416$, $p \ll 0.0001$). This supports my initial research hypothesis that the average SRTM DEM error would be positive indicative of an upward bias of the SRTM DEM. Similar results were found with the Acadia study area.

Table 5.20. Webster study area: One-sided T-test Results

	Mean	**T**	**p-value**
SRTM-LiDAR	7.2	49.498	0.000
SRTM-NED	6.7	51.416	0.000

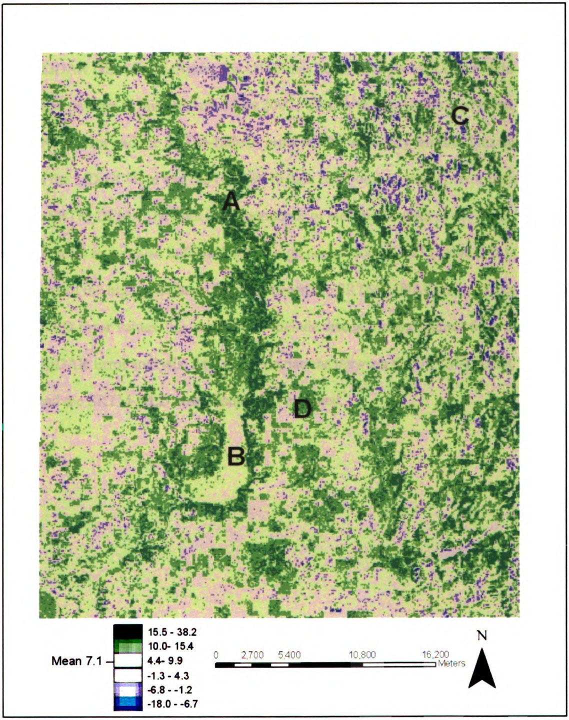

Figure 5.9. Webster study area SRTM –LiDAR Error

5.1.2.3.2. SRTM-NED DEM Error

Figure 5.10 of the SRTM-NED Error illustrates similar characteristics of the SRTM-LiDAR DEM Error. Again, the USGS has yet to incorporate LiDAR data into the NED DEM product in this area as of July 2007. Similar to the Acadia study area, the SRTM-NED error and the SRTM-LiDAR error results were very similar. This again suggests the LiDAR 90 m and the NED 90 m data contribute to similar error patterns with the SRTM DEM. The high correspondence of elevation values of the NED 90 m and LiDAR 90 m was also indicated with a high correlation of 0.93 (Table 5.16).

Given the high correlation found between the SRTM-LiDAR Error values and the SRTM-NED Error values, this section will include discussion and figures from the SRTM-LiDAR Error analysis. Any major deviations between the SRTM-LiDAR Error values and the SRTM-NED error results will be noted.

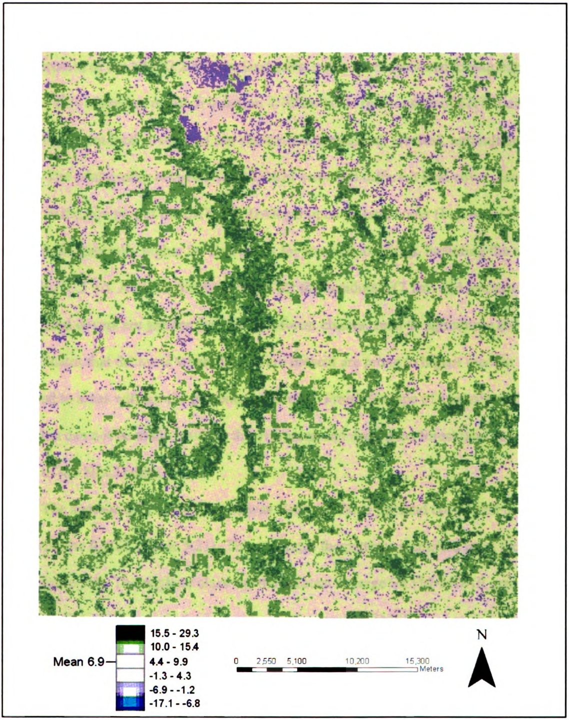

Figure 5.10. Webster study area: SRTM- NED Error

5.1.2.4. Error Relationships to National Land Cover Dataset (NLCD) 2001

To examine the SRTM error characteristics in relation to land cover characteristics of the NLCD 2001, the land cover codes were reclassed to sequential integers. This addresses research question 4: What is the relationship of SRTM error in terms of different land cover/land use classes (i.e. developed, forested, agriculture, water)? The relationship between SRTM DEM error and different land cover classes can be seen in the box plot of the SRTM-LIDAR grouped by land cover (Figure 5.11). This indicates the generally higher median errors for forested locations, including the woody wetlands (10.1 m). Also, the median values for the deciduous (7.1m) and evergreen forest (8.3 m) land covers are greater than the non-forest classes, such as agriculture (0.8 m). This indicates that the areas where forests are present are prone to higher median errors compared to areas without the presence of forests. From this type of analysis, a clear distinction can not be made between the evergreen and deciduous forest land cover with the use of the NLCD data.

The average SRTM DEM error was also calculated per land cover/land use class, along with the RMSE (Table 5.21). This reiterates the patterns identified from the box plots (Figure 5.4). The wetland class has the greatest average SRTM-LiDAR error (10.0 m) and SRTM-NED error (9.8 m), along with the greatest RMSE, 11.1 m and 10.9 m, respectively. The second greatest average SRTM DEM error land cover/land use class was the evergreen forest (8.5 m), then this was followed by the deciduous class (7.9 m). The agriculture/barren class had the lowest SRTM DEM error (1.6 m) and a small RMSE of 4.3 m compared to wetland class. However, the developed class was determined to have the least RMSE value of 1.4 m for the SRTM-LiDAR error and 2.0 m for the SRTM-NED error, which indicates the least spread of error values.

Table 5.21. Webster study area: Sample Error Characteristics by Land Use/Land Cover

Reclassified Class	Sample	SRTM-LIDAR		SRTM-NED	
		Average Error (m)	RMSE (m)	Average Error (m)	RMSE (m)
Water	21	4.4	7.6	4.5	6.8
Developed	38	4.2	1.4	3.4	2.0
Evergreen Forest	922	8.5	10.0	8.2	9.5
Deciduous Forest	76	8.0	9.4	7.6	8.8
Mixed Forest	134	7.2	9.2	7.4	8.9
Agriculture/Barren	79	1.6	4.4	1.7	4.0
Wetland	211	10.0	11.1	9.8	10.9

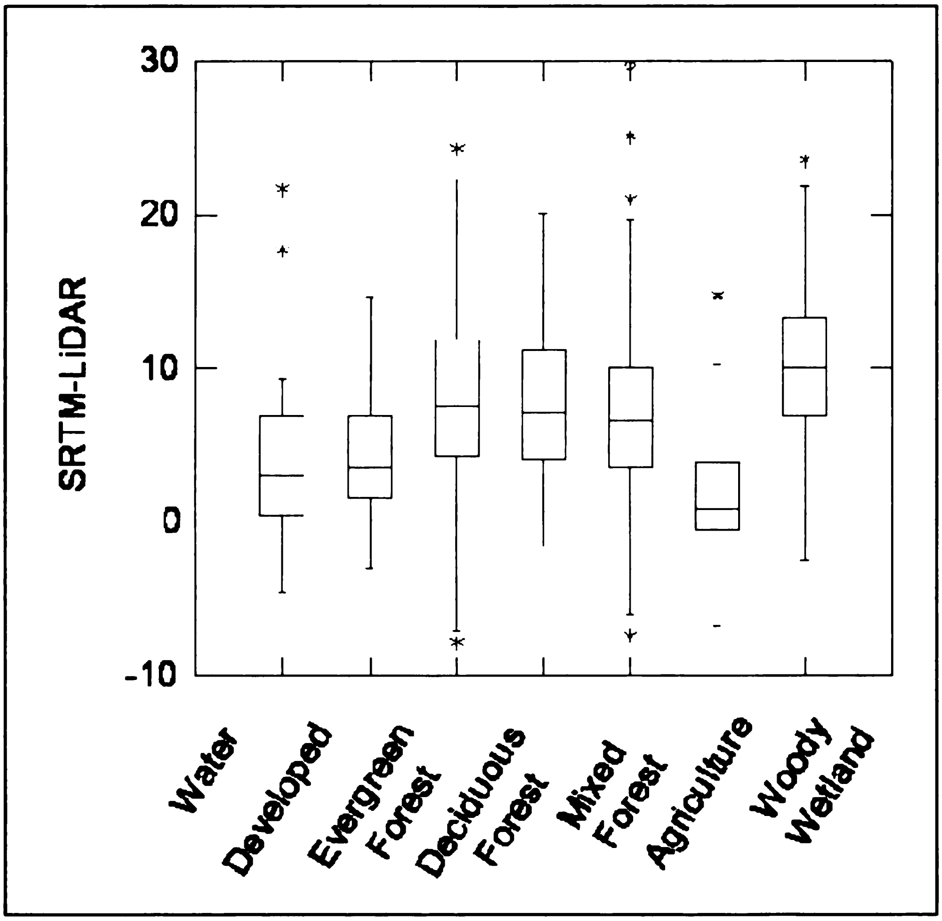

Figure 5.11. Box plot of the SRTM-LiDAR Error and NLCD 2001

A difference of means t-test was performed to investigate research question 5: Is the average SRTM DEM error greater for vegetated or non-vegetated areas? To test the significance of the differences of means between forested and non-forested landscapes, the sample was coded 0 for non-forest, and 1 for forest. The non-forest classes included water, developed, and agriculture/barren. The forested classes were deciduous forest, evergreen forest, mixed forest, and woody wetland. Given that the shrub/scrub class includes vegetation at unknown heights, these sample points were not used in the difference of means for the non-forest and forest classes. It is expected that the non-forest and forested cells will have significantly different SRTM- LiDAR DEM error means. The mean error of the non-forested class was 4.7 m and the mean error of the forested class was 8.2 m, with a t-value of -7.7, which was significant at the 95 % confidence level ($p << 0.0001$). This indicates that the SRTM- LiDAR error is significantly different for non-forest and forest classes. The positive average error indicates the SRTM has positive elevation bias. Also, this result suggests that the forested area had a greater mean SRTM DEM error, which supports my hypothesis regarding the average error of vegetated areas being greater than the average error for non-vegetated areas.

To determine if the average SRTM-LiDAR DEM error of the vegetated class was significantly greater than the SRTM-LiDAR DEM error of the non-vegetated classes, a one-sided t-test was conducted. This t-test was set up using the SRTM-LiDAR DEM error of the vegetated classes. The mean was set to 4.5 m (the SRTM-LiDAR mean of the non-vegetated classes) and the alternative hypothesis was set up as greater than the 4.5. This would indicate whether the average error of the vegetated classes was significantly higher than the mean of the non-vegetated classes. The results indicated a t value of

19.913 (p <<0.0001). This result confirms findings indicating a greater SRTM-LiDAR DEM error for the vegetated classes compared to the non-vegetated classes for the Webster study area. Similar findings were found for the Acadia study area.

The variances of the land cover/ land use classes were also investigated for the Webster study area (Table 5.22). Similar to the Acadia study area, in the Webster study area, the agriculture class had a relatively low variance compared to the other classes. The deciduous class did have a slightly lower variance. The evergreen, forests/shrub, wetland, and deciduous forest classes all had similar variances. These ranged from the wetland variance of 24.2 to the evergreen variance of 27.9. To account for the greater variances in the vegetated classes, I suspect the evergreen class and other forest classes of the NLCD 2001 are at different stages of succession. This would attribute to different heights of the evergreen trees in an area identified as evergreen and have greater SRTM-LiDAR variance for this class. In the Webster study area, the water had the greatest variance. This could be attributed to the SRTM scatter from the water surface. These characteristics will be further investigated in the next section.

Table 5.22. Webster Study Area Variances of SRTM-LiDAR error by NLCD 2001 class

	N	Mean	Variance
Webster			
Water	23	4.1	37.6
Developed	38	4.4	15.4
Evergreen Forest	740	7.9	27.9
Deciduous Forest	82	7.8	24.8
Forest/Shrub	300	5.4	31.7
Agriculture/ Barren	86	1.7	16.3
Wetland	215	9.9	24.2
F-ratio	2.939		
p-value	0.007		

5.1.2.5. Specific Locations Error Comparison

The SRTM-LIDAR error for the Webster study area contains letters that correspond to selected areas representative of the variety of error characteristics (Figure 5.9). Location A is indicative of the forested area, which dominates the study area and is situated toward the center of the study area and corresponds with higher SRTM-LiDAR error. The trees on the landscape add height to the surface of the earth, which is indicated by the higher values in the forested areas. This is evident by the larger error values throughout this section. However, in the bayous in the study area, the SRTM errors are lower than average (Location B). In the eastern uplands, there are alternating patterns of high and low error, which may be attributed more to changes in slope than to characteristics of land cover (Location C). A similar alternating pattern was identified in the Acadia study area. Throughout the uplands in this area, there are patches of high and low error values. There are rectangular patterns of neighboring high and low error situated in the southern, central part of the study area, which indicate that land cover features, such as forests on the landscape, may be playing a role in creating these patterns (Location D).

The Louisiana study areas represented areas in the United States rich with elevation data. These locations were able to further illustrate characteristics of the SRTM DEM given the LiDAR dataset as a reference. However, as seen from the literature, LiDAR data and similar products are not readily available at the international scale. Thus, the Nang Rong study area in Thailand will illustrate how a location with SRTM C-band data was analyzed in relation to the SRTM X-band with a 25 m resolution.

5.2. Nang Rong, Thailand

The elevation ranges and characteristics of the SRTM DEMs of the Nang Rong study area in Thailand indicate similar patterns when shaded with the same color scheme (Figure 5.12). This Nang Rong study area is defined based on the availability of the SRTM X-band data. The SRTM C-90 m and SRTM X-90 m indicate three main stream valleys through the center of the region, flowing from higher elevations in the southern part of the study area northwards. The higher mountain area is also still captured with the X-band data at the 25 m and 90 m resolution. Similarly in the SRTM X-25 m these features are identified in the DEM. This study area contains generally low elevations (mean value 186 m), with a few locations of higher relief. Visually, the SRTM C-90 m, SRTM X-25 m, and the SRTM X-90 m look very similar with only subtle differences. Table 5.23 summarizes the elevation characteristics of the Nang Rong study area.

Table 5.23. Nang Rong study area DEM Characteristics

	SRTM C-90 m	SRTM X-25 m	SRTM X-90 m
Rows x Columns	387 x 499	1374 x 1771	387 x 499
Cell Size	90	25	90
Min (m)	149	29	120
Max (m)	382	387	383
Mean (m)	186.6	185.7	186.0
Std Dev (m)	14.9	15.5	15.3

Table 5.24. Nang Rong Sample Elevation Characteristics (n = 1537)

	SRTM C-90 m	SRTM X-25 m	SRTM X-90 m
N of cases	1451	1451	1451
Minimum (m)	163.0	144.0	163.0
Maximum (m)	353.0	347.0	324.0
Mean (m)	186.6	185.1	185.8
Standard Dev (m)	14.6	17.2	14.6

Table 5.25. Nang Rong study area Slope (degrees) Characteristics

	SRTM C-90 m	SRTM X-25 m	SRTM X-90 m
Rows x Columns	387 x 499	1374 x 1771	387 x 499
Cell Size	90	25	90
Min	0.0	0.0	0.0
Max	21.3	72.4	22.3
Mean	1.0	4.0	1.0
Standard Deviation	0.9	3.1	1.0

Table 5.26. Nang Rong study area Slope Characteristics: Sample (n = 1537)

	SRTM C-90 m	SRTM X-25 m	SRTM X-90 m
N of cases	1451	1451	1451
Minimum	0.0	0.0	0.0
Maximum	9.7	45.8	11.4
Mean	0.9	4.0	0.9
Standard Dev	0.8	2.9	0.9

The Nang Rong slope characteristics indicate the generally level slope topography of this area, with a mean slope of less than 5° for all DEMs (Table 5.24). Figure 5.13 suggests that distinctions can be made between the SRTM C-90 m and SRTM X-25 m slope. The SRTM C-90 m indicates a generally flat study area with slopes less than 2.8°. However, the SRTM X-25 m DEM is characterized by higher slopes (7.0 °-22.3 °) throughout most of the study area. However, these higher slopes are lost with the increase in resolution to the SRTM X-90 m. The summary slope statistics for the SRTM X-90 m generally resembles those of the SRTM C-90 m. However, with the SRTM X-90 m there are a few locations of greater slope in the 7.0 °-22.3 ° range, which could be due to the processing of the DEM or other artifacts of the data. Tables 5.25 and 5.26 indicate the sample characteristics of the Nang Rong study area. These tables indicate the average means are similar to the means found for the DEMs and slope grids of the entire study area.

5.2.1. Comparison of Elevation Values of SRTM C-band and X-band

To determine how correlated the elevation values of the Nang Rong DEMs were to answer research question 1: What are the relationships among elevations of NED, LiDAR, and SRTM DEMs? The correlation coefficients were calculated between the different elevation models (Table 5.27). It is expected the SRTM 25 m and the SRTM X-90 m will be similar given the resampling. It is expected that the original and the resampled resolution data will be highly correlated. The SRTM C-90 m was highly correlated with the SRTM X-90 m (0.977) and the SRTM X-25 m (0.713). The resolution seems to play a greater role than the data product based on the high correlations found between the SRTM C-90 m and SRTM X-90 m DEMs.

Table 5.27. Pearson Correlation Matrix of the Nang Rong study area Elevation values

	SRTM C-90 m	**SRTM X-25 m**	**SRTM X-90 m**
SRTM C-90 m	1.000		
SRTM X-25 m	0.724	1.000	
SRTM X-90 m	0.977	0.713	1.000

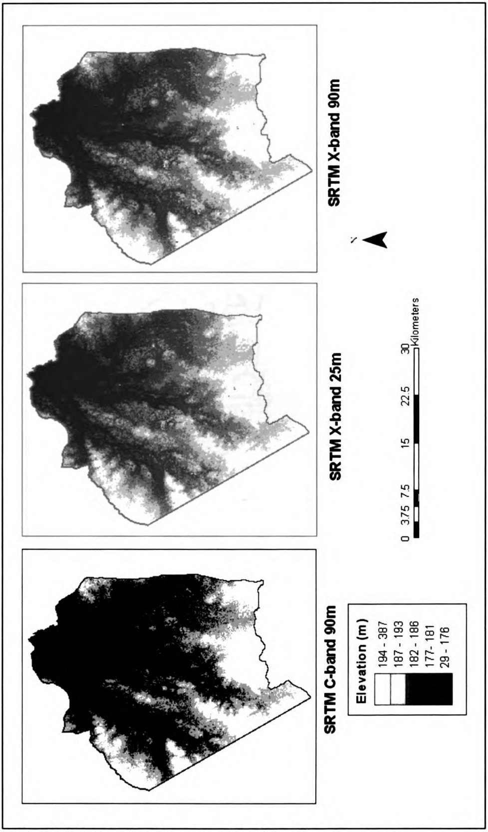

Figure 5.12. Elevation Characteristics of the Nang Rong study area

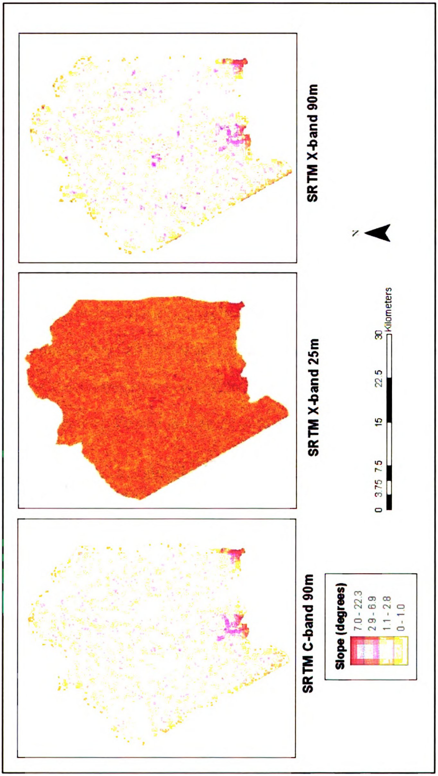

Figure 5.13. Slope (degrees) of the Nang Rong study area

5.2.2. Comparison of Slope Values

To determine how correlated the slope values of the datasets were to address research question 2: What are the relationships among NED, LIDAR, and SRTM slopes? A correlation matrix of the slope of the DEMs was created to answer this question (Table 5.28). From this table it is evident that the SRTM C-90 m and SRTM X-25 m have weak correlations (0.136), although the SRTM X-90 m and SRTM C-90 m are more similar (0.517). This indicates the importance of the spatial resolution rather than the data product. The histogram of slope values indicates the sample points were generally low in slope with slopes less than 10 ° (Figure 5.14). Thus, as in the Louisiana study area, the relationships between SRTM DEM error and slope can not be clearly related because of the lack of much variation in topography.

Table 5.28. Pearson Correlation Matrix of Slope Values of the Nang Rong Site (n =1537)

	SRTM C-90 m	**SRTM X-25 m**	**SRTM X-90 m**
SRTM C-90 m	1.000		
SRTM X-25 m	0.136	1.000	
SRTM X-90 m	0.517	0.276	1.000

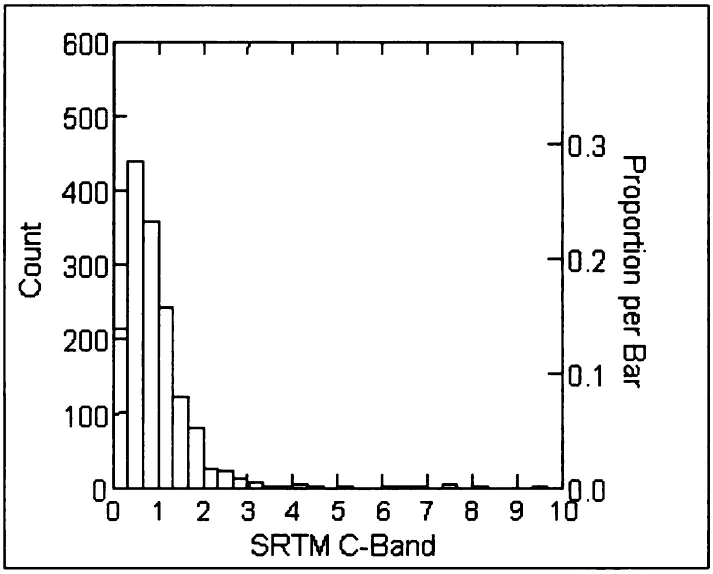

Figure 5.14. Histogram of SRTM C-band Slope Values (n =1537)

5.2.3. Error Analysis: SRTM C-band – SRTM X-band

The error patterns of the SRTM C-band for the Nang Rong study area was investigated through the difference between the SRTM C-90 m and the SRTM X-90 m DEM (Figure 5.15). The range of SRTM error was –79 to 67 m with a mean of 0.7 m (3.2 m standard deviation). The RMSE was 3.3 m. The greater range of the SRTM error is spread over a mainly flat topographic landscape, with some steeper slopes in the southeastern part of the study area. Figure 5.15 indicates the histogram of the sample SRTM error points, which had a generally bell-shaped in distribution. Table 5.29 summarizes the Nang Rong sample characteristics and the RMSE. The RMSE was comparable to the RMSE found for the entire study area. The range of the sample was less compared to the entire Nang Rong area given the sample accounted for spatial autocorrelation. As shown in Table 5.27, the mean was 0.7 m, which indicates the average SRTM DEM error is only slightly greater than zero. Thus, in relation to research

3 regarding the average SRTM DEM error, the differences between the SRTM X-90 m and the SRTM C-90 m are only slightly positive.

Table 5.29. Nang Rong study area Sample DEM Error Characteristics

	Sample	Min (m)	Max (m)	Mean (m)	Std Dev (m)	RMSE
SRTM Error	1537	-23.0	35.0	0.7	3.2	3.2

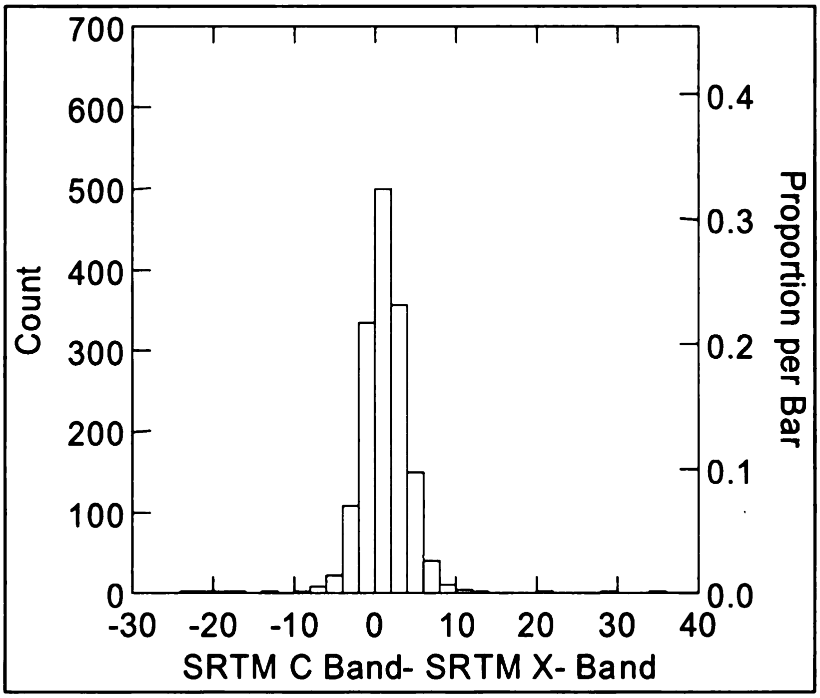

Figure 5.15. Histogram of the SRTM Error

In order to see if the mean value of the SRTM C-90 m –SRTM X-90 m error was significantly greater than zero, a t-test was done with the alternative hypothesis set to the mean greater than 0, and the null hypothesis of a mean equal to zero. As Table 5.30 indicates the SRTM DEM average error was significantly greater than zero (t=9.135, p <<0.0001). This supports my initial research hypothesis that the average SRTM DEM error would be positive indicative of an upward bias of the SRTM DEM. Similar results were found with the Acadia and Webster study areas.

Table 5.30. Nang Rong Study Area: One-sided T-test Results

	Mean	T	p-value
SRTM C-90 m-SRTM X-90 m	0.735	9.135	0.000

5.2.4. Specific Locations Error Comparison

The error characteristics identified from Figure 5.16 indicate that the majority of the Nang Rong study area had low negative error. The letters (A, B, C) identified in Figure 5.16. correspond with specific locations discussed here. There is a slight diagonal pattern of greater DEM error throughout the flatter topographic region (Location A). This is unlikely from land cover/land use characteristics, and may be from production of the DEMs. However, low error values were found throughout this area of flat topography towards the western part of the study area (Location B). Towards the southeastern portion of the study area where the inactive volcanic areas are present, greater positive error (4.1-69.0 m) is identified for this area (Location C). This is likely from the steeper slopes in this area rather than land cover/land use characteristics.

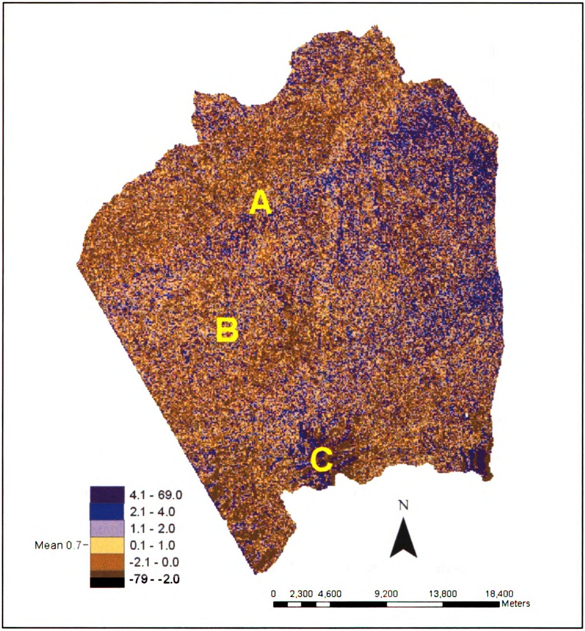

Figure 5.16. SRTM C-band –SRTM X-band Error

5.3. Comparative Analysis: Louisiana study areas and Nang Rong, Thailand

MODIS

Since the SRTM C-90 m DEM is available for 80 % of the earth, an investigation into land cover relationships was done across all study areas in Louisiana and Thailand. This analysis with the MODIS tree cover aids in answering research question 5: Is the average SRTM DEM error greater for vegetated or non-vegetated areas? MODIS data for the land and water were acquired from the Terra and Aqua spacecraft (GLCF 2007). The 500 m resolution of MODIS is a larger spatial resolution compared to the NLCD data used primarily in the United States. However, since the MODIS data were created from satellite imagery, it is available for much larger extents, which will be available for all study areas. Thus, its greater coverage enables its use in wider ranges of study areas. However, it needs to be recognized that the coarser resolution provides a broader understanding of the landscape in contrast to higher resolution land cover products. The ranges of MODIS data varied across study areas, which impacted the categories used per study area (Table 5.31). The lower values for the percent tree cover MODIS data in the Acadia study area correspond with agricultural fields and non-wetland classes. The wetland areas have higher values of percent forest cover in both study regions (Figure 5.17). For the Nang Rong study area, the higher percentages of tree cover correspond with steeper elevation and smaller patches throughout the area.

Table 5.31. Sample Characteristics of MODIS Data

	Acadia	**Webster**	**Nang Rong**
N of cases	1956	1484	1537
Minimum	0.000	0.000	0.000
Maximum	100.00	86.000	45.000
Range	100.00	86.000	45.000
Mean	19.936	53.486	7.962
Standard Dev	20.170	14.877	7.150

The box plots for the Acadia and Webster study areas indicate that areas with MODIS tree cover greater than ≥ 50 %, the median error value was 7.4 % and 7.5 %, which were greater than the median of the areas less then 50 % (1.4 % and 5.6 %) (Figure

5.18). A greater distinction can be made between the more and less forested areas in the Acadia study area compared to the Webster study area. For the Nang Rong study area, the range of percent forest cover from the sample was from 0 to 45 % (mean 8.0 % standard deviation 7.2). Thus, the Nang Rong study area could not be partitioned at 50 %, as were the Louisiana study areas. For the Nang Rong study area, the MODIS tree cover percentages were reclassed at 22.5%. From this classification, no clear relationship can be determined from the relationship between MODIS tree cover and SRTM error relationships. As the box plot in Figure 5.19 indicates, the median error remains near 0 for both classes of MODIS tree cover, 1.0m for the lower than 22.5 % and 0.0 for the greater than 22.5 % class.

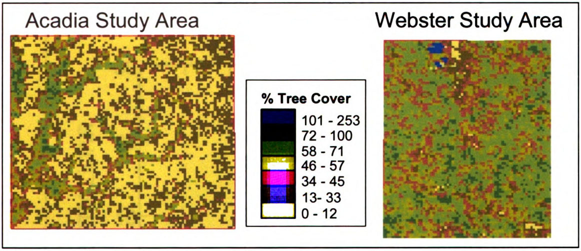

Figure 5.17. MODIS % Tree Cover for Acadia and Webster Study Areas

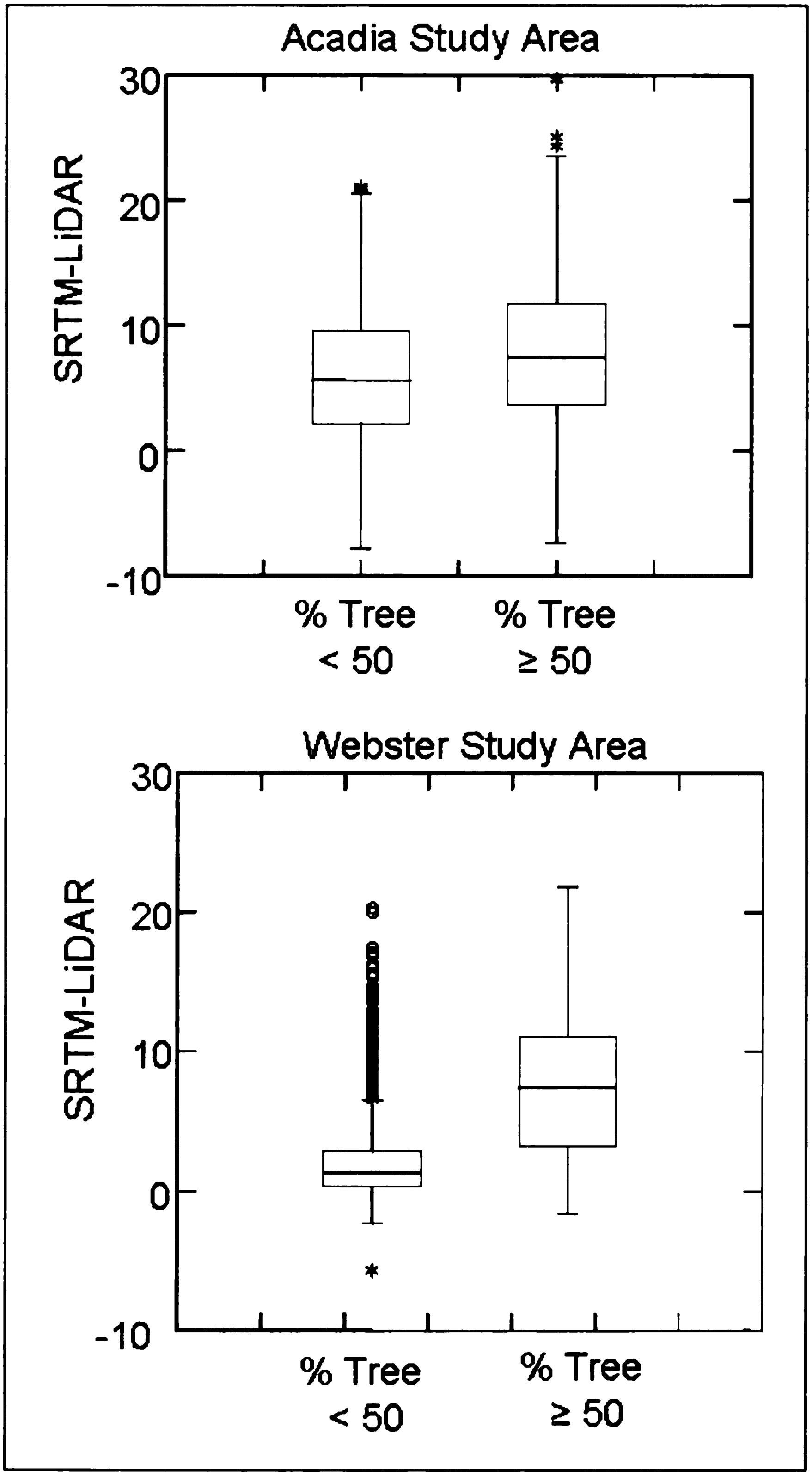

Figure 5.18. Box Plots of the Acadia and Webster Study Area: MODIS % Tree Cover

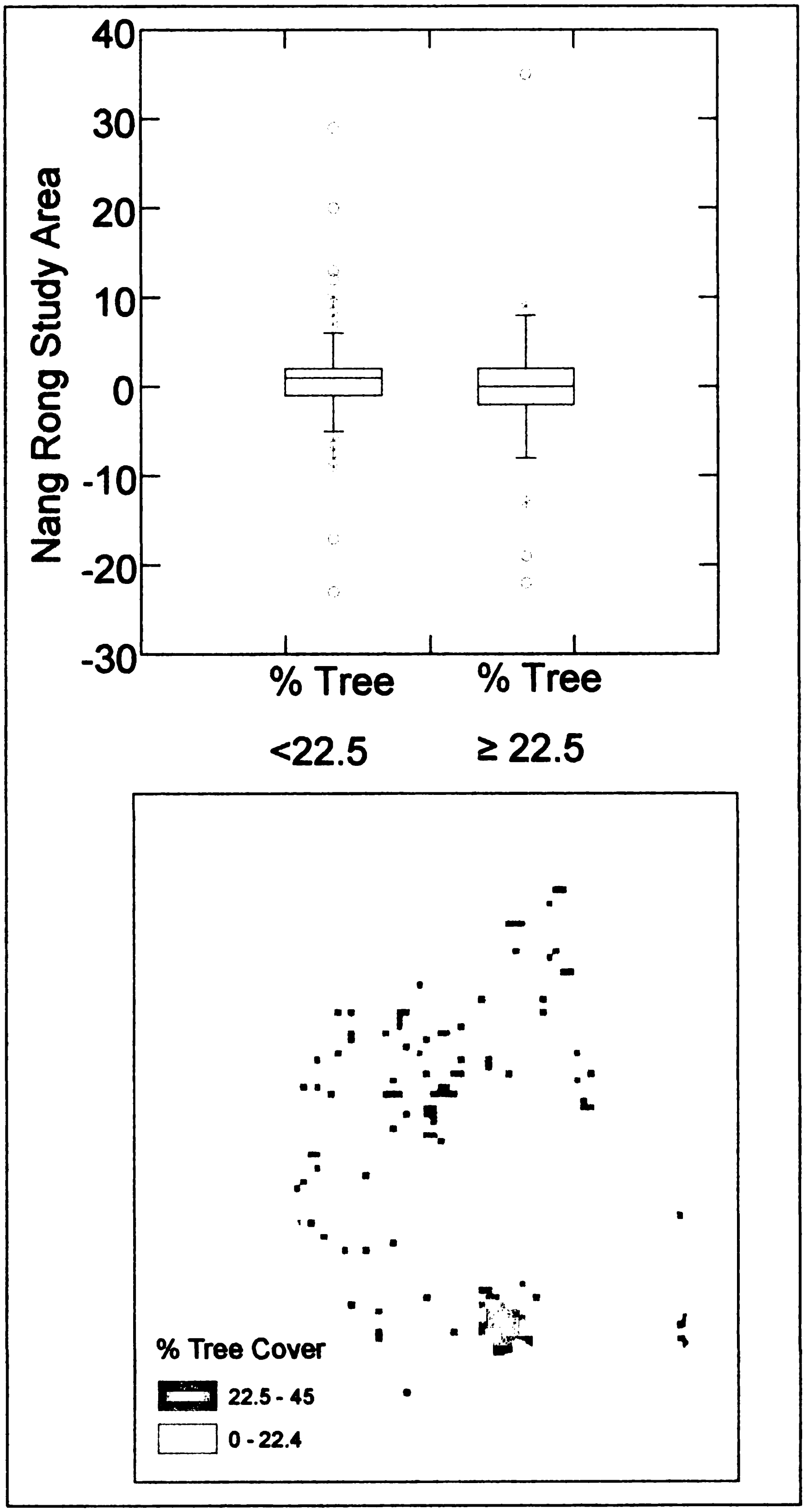

Figure 5.19. Nang Rong study area: MODIS: Percent Tree Cover

The difference of means t-test was also used to test for significant differences between the means of the percent tree cover classes for each study area. The null hypothesis is that the means are equal for both percent tree cover categories. The research hypothesis is that the mean percent tree cover is different from each other. The results for the Louisiana study areas indicate significant differences between the percent tree categories. For the Acadia study area (n = 1956), for the class of percent tree cover < 50 % had a SRTM-LiDAR mean of 2.1 m and a class of ≥ 50 % had a mean of 7.5 m (t= -17.085, p << 0.0001). For the Webster study area, for the class of percent tree cover < 50 % had a SRTM-LiDAR mean of 4.6 m and a class of ≥ 50 % had a mean of 7.5 m (t= -6.897, p<< 0.0001). However, for the Nang Rong study area, the difference of means t-test had insignificant results. The class of percent tree cover < 22.5 % had a SRTM DEM error mean of 0.8 m and the class of ≥ 22.5 % had a mean of –0.4 (t= 1.085, p= 0.283). Thus, the p value of the Nang Rong study area indicates the means of the two percent tree groups are not significantly different from each other.

To determine if the higher MODIS grouping of SRTM-LiDAR DEM error was significantly higher than the lower MODIS grouping, a one-sided t-test was conducted. For the Acadia study area, the mean was set to 2.1, the mean of the SRTM-LiDAR DEM error of the lower (<50 % Tree Cover), and the alternative hypothesis was set to greater than this mean. The results indicated a t value of 17.497 (p <<0.000). This indicates that the mean of the SRTM-DEM LiDAR DEM error of the locations with MODIS % Tree Cover ≥ 50 % was significantly higher than the mean of the locations with MODIS % Tree Cover < 50 %. Similarly for the Webster study area, a one-sided t-test was set up with the mean equal to 4.6 m, and the alternative hypothesis set to be greater than this mean of the MODIS % Tree Cover < 50 % SRTM-LiDAR DEM error. The results of the Webster study area indicated the SRTM-LiDAR error of the MODIS % Tree Cover ≥ 50 % was significantly different (t =17.985, p << 0.0001) from the mean of the locations will less tree cover, < 50 %. However, the findings that the locations with higher percent tree cover in the Acadia and Webster study areas contrasted with the results of the Nang Rong study area. For the Nang Rong study area, the SRTM C-90m –SRTM X-90m DEM error was set to the mean of 0.8 m, the mean of the lower MODIS % Tree Cover class of < 22.5 %, and the alternative hypothesis was set to greater than this mean. Similar to the difference of means results of the MODIS classes, one-sided t-test for the Nang Rong study area indicated insignificant results (t= -1.110, p= 0.864). Thus, the MODIS classes for the Nang Rong study area does not indicate that the areas with greater tree cover have significantly higher DEM error compared to locations with less tree cover.

The variances of the MODIS groupings of the study areas was investigated also to determine whether these differed significantly based on the percent tree cover classes I chose in this research (Table 5.32) For the Acadia study area, the variance between the < 50 % tree cover and ≥ 50 % tree cover was found to be significant (F-ratio = 0.376, p<<0.0001). This shows the variance of areas with more vegetation is significantly different from areas with less vegetation. This could be from the differences in tree heights contributing to a wider range of SRTM DEM error. However, with the Webster study area, the difference of variances across the MODIS groups (% Tree Cover <50 % and % Tree Cover ≥ 50 %) was found to be insignificant (F-ratio =0.991, p= 0.910). I suspect this was found because the Webster study area is heavily forested, a break at 50 % did not make a significant difference in terms of vegetation characteristics and tree height differences on the surface. In the Nang Rong study area, the variances of the MODIS % Tree Cover < 22.5 % and MODIS % Tree Cover ≥ 22.5 % groups were found to be significantly different (F-ratio= 0.130, p <<0.0001). Similar as I noted above with the Acadia study area, the differences in the variances of the MODIS groupings could be attributed to the greater difference seen in the more vegetated class from the various heights of the canopy on the surface. However, with the Nang Rong study area, the SRTM was in reference to the SRTM X-90 m DEM.

Table 5.32. Variances of the SRTM Error by MODIS % Tree Cover Groupings Per Study Area.

	N	Mean	Variance	F-ratio	p-value
Acadia Study Area					
% Tree Cover <50 %	1711	2.1	8.7	0.376	0.000
% Tree Cover ≥ 50 %	245	7.5	23.2		
Webster Study Area					
% Tree Cover <50 %	546	6.0	30.1	0.991	0.910
% Tree Cover ≥ 50 %	938	7.8	30.4		
Nang Rong Study Area					
% Tree Cover < 22.5 %	1490	0.8	8.2	0.130	0.000
% Tree Cover ≥ 22.5 %	51	-0.4	62.8		

For the Acadia and Webster study areas, the SRTM-LiDAR error was used in the above table. The Nang Rong study area used the SRTMC-90 m –SRTM X-90 m DEM error.

The Louisiana study areas and the Nang Rong study area illustrate different outcomes from examination of the MODIS data because of the different land- cover characteristics of these areas (Figure 5.18). The data show the Thailand area with significantly less percent forest cover, which is expected given other knowledge about the agriculture base. In contrast with the Webster study area in Louisiana, where a large portion of the study area is identified in multiple sources as a national forest, this was indicated as forests. The Acadia study area was not predominantly forest, so the percent tree cover was less of an indicator of land cover characteristics for this area. However, this use of the MODIS percent tree data was an example of how a global dataset could be used across study areas on different continents to explore relationships to the SRTM DEM. As significant as using a global dataset to compare properties across study areas, a land use application was created to analyze across study areas.

5.4. Land Use Application

This section summarizes how the LiDAR, NED, and SRTM DEMs perform to address research question 6: How will the LiDAR, NED, and SRTM DEMs perform in a land use application? The suitability model created different outcomes based on the production and resolution of the elevation model. Of the DEMs used in the application, only the Nang Rong study area varied the resolution. The identification of flat areas on the landscape by the reclassification of slope from 0 to 1 degree indicates differences across elevation products (Figure 5.20). For the LiDAR 90 m, the Acadia study area is depicted as being mainly flat, with some steeper slopes (> 1 °) along the wetland areas. Similar representation of the flat topography is illustrated with the NED 90 m. In addition, for the Webster study area, the LiDAR 90 m and NED 90 m are very similar. For the Webster study area, the LiDAR 90 m, NED 90 m, and NED 30 m, depict the general patterns of the valleys in between greater slope upland areas.

For the SRTM elevations, suitable slopes depicted the general patterns of flatter agricultural lands, and some steeper areas along the wetland. However, there are a few locations where there are slopes greater than 1 degree on the landscape. For the Webster study area, the SRTM 90 m slope reclassification illustrated a more regular, rectangular pattern of slope between 0 -1°. This representation is not as smooth as the LiDAR 90 m and NED 90 m representations of the landscape properties. The pattern of the suitable SRTM 90 m slope indicates some grouping where expected in the valley area because of the flat topography and low position.

The other criterion of the land use application was topographic position. Topographic position was highly dependent on the characteristics of the focal mean output for the study areas. The results seen in Figure 5.21 of the focal mean of the Acadia study area indicate a much smoother depiction of the mean elevation characteristics of the study area. The focal mean depicts the lower elevation in the southwest around 3 m compared to the higher elevations around 16 m in the northeast. The focal mean operation produced a surface, which was smoothed in terms of elevation; however, once differenced with the actual elevations the low locations on the surface could be identified.

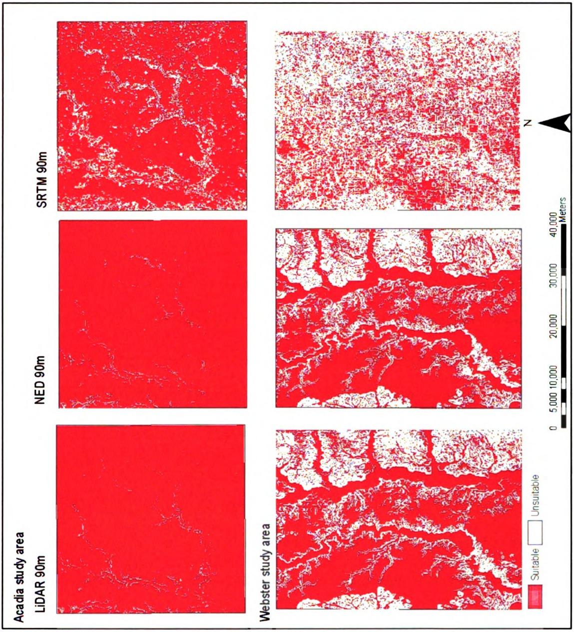

Figure 5.20. Suitable Low Slope Areas: Acadia/ Webster study areas

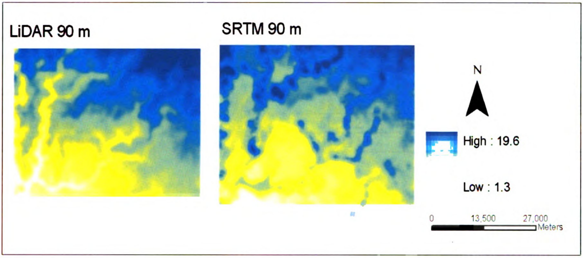

Figure 5.21. Select depictions of the Focal Mean of Acadia study area

The results of the application are summarized by cell count and area (Table 5.33). This table shows that using the LiDAR 90 m and the NED 90 m for the suitability model resulted in overall similar areas. The LiDAR and NED suitability overall cell counts differed by 3 % (Acadia study area) and 1 % (Webster study area). The Webster study area identified less suitable areas with all models, which was expected given the flat topography criterion. Table 5.33 indicates the difference in the total area between the Webster and Acadia study areas. The Webster study area had less flat topography than the Acadia study area. The results were found to be highly dependent on the results of the focal mean operation in relation to the topographic position on the landscape. The subsequent sections discuss the specific application result characteristics for the study areas, along with contingency matrices.

Table 5.33. Suitable Areas from the Land Use Application Output

	Acadia study area		Webster study area		Difference in km^2
	Cell Counts	**Area (km^2)**	**Cell Counts**	**Area (km^2)**	**Webster-Acadia (km^2)**
LiDAR 90 m	110,540	895.4	58,689	475.4	420
NED 90 m	102,917	833.6	56,592	458.4	375
SRTM 90 m	136,684	1,107.1	31,411	254.4	853

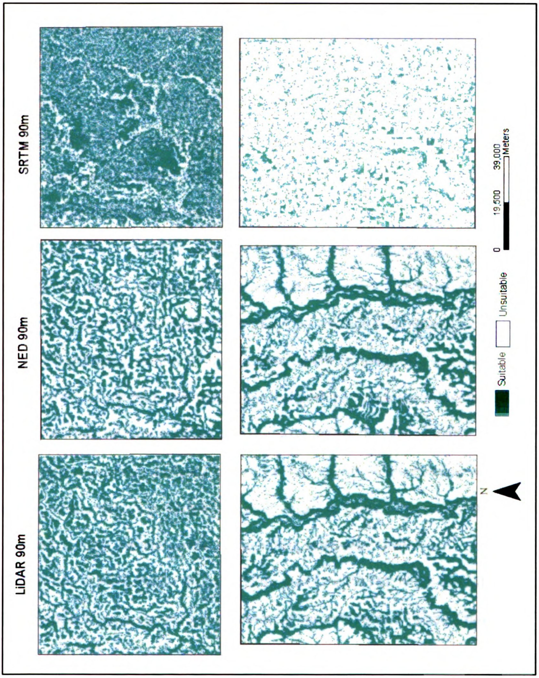

Figure 5.22. Final Application Results: Acadia/ Webster study area

5.4.1. Acadia study area

For the Acadia study area, the LiDAR 90 m and NED 90 m are quite similar based on observations of the suitable areas (Figure 5.22). The wetland area along the southwestern portion of the study area was indicated as suitable in the LiDAR 90 m and the NED 90 m DEMs; however, with the SRTM 90 m this area was seen as unsuitable. This is likely because the SRTM did not identify the wetland as flat given the forests on the landscape give the SRTM a raised appearance in these areas, unlike the LiDAR 90 m and NED 90 m. The LiDAR 90 m and the NED 90 m output contained many linear-like features, which may be a result from the focal mean operation. In contrast, the SRTM 90 m result included the vast majority of the study area excluding the woody wetlands on the landscape. The striping seen in the southeastern part of the study area was also seen as unsuitable here. The striping could have resulted in slope values exceeding the 0-1 degrees, which would have made these areas unsuitable in the final output. Also, in terms of the woody wetlands on the landscape, this would have been identified as not a low location on the landscape and unsuitable in this context. However in reality, the wetlands may be in a depressional area, with a neighboring agriculture field.

From the addition of the suitable results of the SRTM, NED, and LiDAR DEMs, the following contingency matrices were created (Table 5.34 and Table 5.35). The producer's and user's accuracy was calculated to see how the DEMs performed in relation to the LiDAR, used as a reference. The ***user's accuracy*** is calculated by the number of cells correctly classified in each category divided by the number of cells in that category (row total). The user's accuracy represents the probability a category is represented as that category in the reference data (Lillesand, Kiefer, and Chipman 2004).

The ***producer's accuracy*** is the number of cells correctly classified by the reference data divided by the number of cells in that specified category (column total). The producer's accuracy relays how well the reference data of a given category were classified (Lillesand, Kiefer, and Chipman 2004). In terms of the LiDAR and NED comparison, there were relatively high producer and user accuracy.

The ***overall accuracy*** is determined from the correctly classified cell counts of the suitable and unsuitable LiDAR cells divided by the total number of cells. When the LiDAR was compared with the NED, the overall application accuracy of the NED was 74.6 %, which was higher than the SRTM, 51.7 %. The Kappa coefficient is a measure of the degree to which the percent of correctly classified values of the contingency matrix are from true agreements compared to chance agreements (Lillesand, Kiefer, and Chipman 2004). The Kappa coefficient is considered the corrected agreement based on chance. A value closer to 1 indicates perfect agreement, while a value closer to -1 indicates greater disagreement (Lillesand, Kiefer, and Chipman 2004). The ***Kappa coefficient*** was 0.5 for the LiDAR/NED comparison, while the LiDAR/SRTM comparison had a much lower Kappa coefficient of 0.04. These Kappa coefficients indicate greater classification accuracy for the NED-based application than for the SRTM-based application. The SRTM-based application was no better than chance at identifying suitable and unsuitable cells, since its kappa coefficient was 0.04.

Table 5.34. Comparison of LiDAR 90 m and NED 90 m Results: Acadia study area

		LiDAR			
NED		Unsuitable	Suitable	Row Total	User's Accuracy
	Unsuitable	109,155	35,810	144,965	0.7
	Suitable	26,767	74,626	101,393	0.7
	Column Total	135,922	110,436	246,358	
	Producer's Accuracy	0.8	0.7		
	Overall Accuracy	74.6%			
	Kappa Coefficient	0.4			

Table 5.35. Comparison of LiDAR 90 m and SRTM 90 m Results: Acadia study area

		LiDAR			
SRTM		Unsuitable	Suitable	Row Total	User's Accuracy
	Unsuitable	64,173	47,179	111,352	0.6
	Suitable	71,749	63,257	135,006	0.5
	Column Total	135,922	110,436	246,358	
	Producer's Accuracy	0.472	0.573		
	Overall Accuracy	51.7%			
	Kappa Coefficient	0.04			

5.4.2. Webster study area

The locations found suitable for the Webster study area were much more sporadic in comparison to the large areas found suitable in the Acadia study area (Figure 5.20). There was an area in the southwestern portion of the study area along the wetland area, which was found suitable. However, there are some noticeable blocky patterns to the result towards the southwestern portion of the Webster study area. This may have to do with the presence of forests on the landscape neighbored by agriculture or pasture fields, thus the pasture field would have been seen as a low location on the landscape, and suitable in this application output. These rectangular patterns could be created from forests being cut out of the landscape.

The contingency matrices in Table 5.36 and Table 5.37 illustrate the comparisons of the LiDAR to NED application results and the LiDAR to SRTM application results for the Webster study area. The LiDAR/NED comparison had an overall accuracy of 82.0 %, which was greater than the overall accuracy of the LiDAR/SRTM of 66.6 % for the Webster study area. Overall, the Webster study area had greater percentages of correctly classified cells for both the LiDAR/NED comparison (82.0 %) and the LiDAR/SRTM comparison (66.6 %) compared to the Acadia study area. This could be from the different land cover characteristics of these study areas, which are accounted for differently in the models, such as the differences between non-forested and forested areas. As indicated above regarding the more forested landscape of the Webster study area created different suitable patterns compared to the more agricultural Acadia study area. The Kappa coefficient was higher for the LiDAR/NED (0.5) comparison than for the LiDAR/SRTM (0.1) comparison. This indicates there was more agreement between the LiDAR and NED application results compared to the LiDAR and SRTM application results. For the LiDAR/NED comparison, there were relatively high producer's and user's accuracy. However, for the SRTM/LiDAR comparison, the producer's and user's accuracy for the unsuitable category was high compared to the suitable category.

Table 5.36. Comparison of LiDAR 90 m and NED 90 m Results: Webster study area

		LiDAR			
NED		Unsuitable	Suitable	Row Total	User's Accuracy
	Unsuitable	106,998	17,191	124,189	0.9
	Suitable	15,313	41,217	56,530	0.7
	Column Total	122,311	58,408	180,719	
	Producer's Accuracy	0.9	0.7		
	Overall Accuracy	82.0 %			
	Kappa Coefficient	0.6			

Table 5.37. Comparison of LiDAR 90 m and SRTM 90 m Results: Webster study area

		LiDAR			
SRTM		Unsuitable	Suitable	Row Total	User's Accuracy
	Unsuitable	106,048	44,019	150,067	0.7
	Suitable	16,647	14,670	31,317	0.5
	Column Total	122,695	58,689	181,384	
	Producer's Accuracy	0.9	0.3		
	Overall Accuracy	66.6%			
	Kappa Coefficient	0.1			

Figure 5.23 illustrates the different combinations of unsuitable and suitable cells classified per study area for the LiDAR/SRTM and LiDAR/NED comparisons. For both Louisiana study areas, the areas identified as unsuitable areas border the wetlands. Most of the Webster study area was seen as unsuitable, which can be attributed to much of the area not meeting the slope criteria. Fewer areas were identified as unsuitable by the

LiDAR and suitable by the SRTM in the Webster study area compared to the Acadia study area.

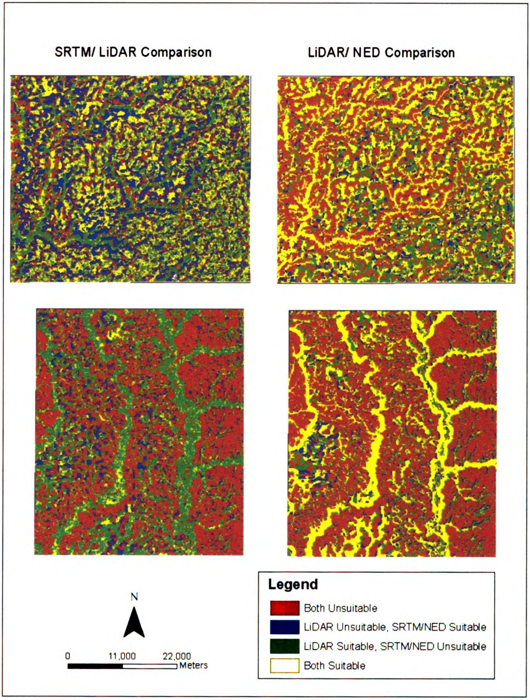

Figure 5.23. Application Result Classified by Possible Categories

These locations of unsuitable by the LiDAR and suitable by the SRTM in the Acadia study area were found surrounding the wetlands. The locations identified as suitable in both the LiDAR and SRTM were found in some water areas in Webster and in patches throughout the Acadia study area. In terms of the LiDAR/NED comparison, locations identified as unsuitable in both study areas were outside the woody wetlands. There were distinct patterns identified as both suitable in the LiDAR and NED. These were identified in valleys and present in agriculture areas in the Acadia study area. Another noticeable pattern in both study areas was the presence of circular borders around suitable areas. This could be attributed to the low topographic position criterion, which used a circular radius in its operation.

The suitable locations were also determined for all the DEMs (i.e. NED, LiDAR, and SRTM suitable) through the multiplication of the grids (Figure 5.24) For the Acadia study area, locations found suitable in all DEMs appear to be clumped throughout the study area. In contrast to the Webster study area, wetland areas are not found to be suitable. The Webster study area indicates some locations to be suitable for all the DEMs. This is likely due to use of the low topographic position criteria in the suitability analysis. The total area found suitable by all the DEMs for the Acadia study area was 331,063,200 m^2 (40,872 cells) (331.1 km^2), and the total area found suitable for the Webster study area was 91335600 m^2 (11, 276 cells) (91.3 km^2). In examination of the areas found suitable in all DEMs, the Acadia study area found a greater area suitable compared to the Webster study area.

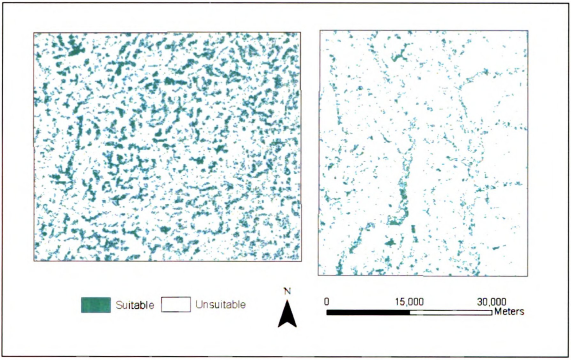

Figure 5.24. Suitable locations found in all DEMs of Application Analysis

5.4.3. Nang Rong study area

The Nang Rong application results were similar for the SRTM C-band and the SRTM X-band 90 m (Figure 5.25). The total area identified as suitable for the Nang Rong DEMs (Table 5.38) indicate the SRTM X-25 m DEM identified much less area than the SRTM C-90 m and SRTM X-90 m resulting in a difference of 311.5 km^2 and 362.3 km^2, respectively. The areas found suitable in the Nang Rong region are generally found throughout the lowland, low slope areas. The higher elevations in the southeastern part of the study area were found to be unsuitable. For the SRTM C-90 m and the SRTM X-90 m, the main valleys were found to be suitable. These areas were identified as low slope and low topographic position. In contrast to the patterns identified with the SRTM C-90 m and the SRTM X-90 m, the SRTM X-25 m DEM indicated generally individual cells as suitable rather than large areas. There is a grouping of cells towards the center of the study area, which likely corresponds with a valley in the study area. This is further identified in the multiplication of the DEMs in Figure 5.26, which identifies all areas (1407 cells ~11.4 km^2) found suitable in the Nang Rong study area DEMs.

Table 5.38. Nang Rong Suitable Areas from the Land Use Application Output

	Suitable Cells	**Suitable Area (km^2)**
SRTM C- 90 m	42,469	344.0
SRTM X-25 m	51,914	32.4
SRTM C-90 m	48,733	394.7

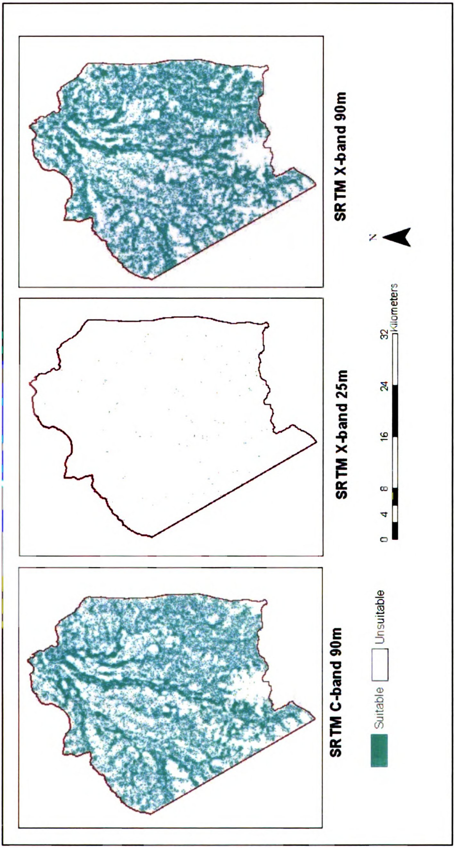

Figure 5.25. Final Application Results: Nang Rong study area

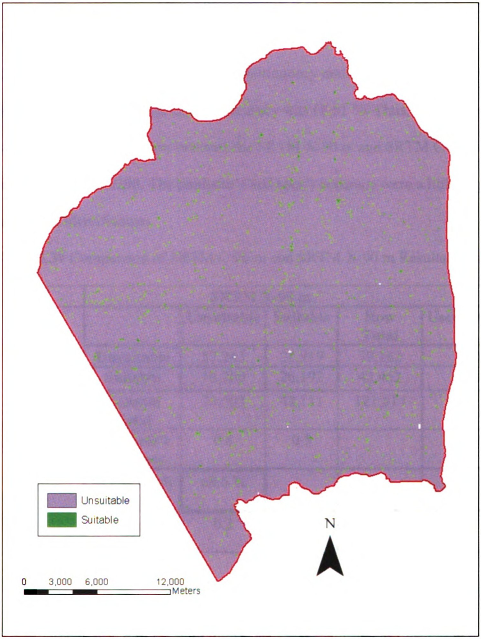

Figure 5.26. Suitable locations found in all DEMs of Application Analysis

The contingency matrix used the SRTM X-90 m as the reference compared to the SRTM C-90 m (Table 5.39). The contingency matrix of the SRTM X-90 m and SRTM C-90 m indicate the overall accuracy was 68.61 %. Thus, this indicates that there was high overall agreement between the SRTM X-90 m and SRTM C-90 m. The Kappa coefficient was 0.3290. The producer's and user's accuracy were a little higher for the unsuitable identification.

Table 5.39 Comparison of SRTM C-90 m and SRTM X-90 m Results: Nang Rong

	SRTM X-90 m				
		Unsuitable	**Suitable**	**Row Total**	**User's Accuracy**
SRTM C-90 m	**Unsuitable**	57,243	21,919	79,162	0.7
	Suitable	16,260	26,192	42,452	0.6
	Column Total	73,503	48,111	121,614	
	Producer's Accuracy	0.8	0.5		
	% Correctly Classified	68.6 %			
	Kappa Coefficient	0.3			

Figure 5.27 illustrates the possibilities of the SRTM X-90 m and SRTM C-90 m comparison. Much of the agricultural area was identified as unsuitable for both the SRTM C-90 m and SRTM X-90 m. There were isolated locations (i.e. single cells) identified as unsuitable for the SRTM X-90 m and suitable by the SRTM C-90 m. A concentration of cells was identified as suitable by the SRTM X-90 and unsuitable by the SRTM C-90 m on the eastern side of the study area. Suitable locations identified by both the SRTM C-90 m and SRTM X-90 m were found in the valleys. Other suitable locations

in the study area had circular edges, which could be attributed to the low topographic position criterion. Thus, the Nang Rong application illustrated how the constraints of flat topography and low topographic position would result in similar areas between the SRTM C-90 m and the SRTM X-90 m. However, when the SRTM X-25 m was employed, the results differed much from the SRTM C-90 m and SRTM X-90 m. This suggests the importance of spatial resolution in this application.

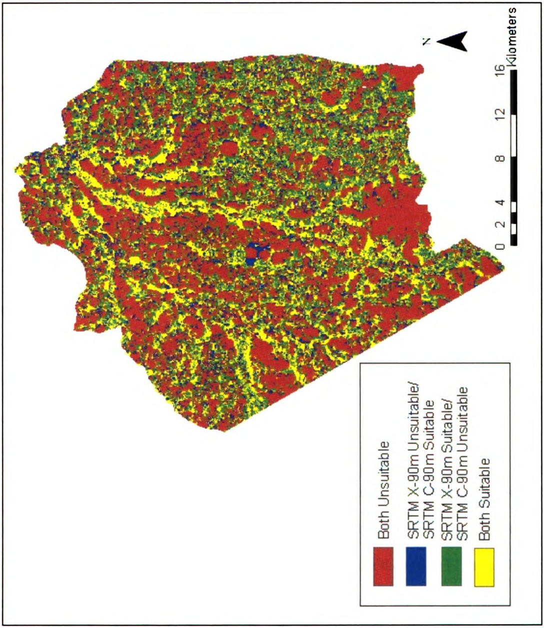

Figure 5.27. Comparison of SRTM X-90 m and SRTM C-90 m

5.5. Discussion: Lessons Learned

This analysis of the SRTM DEM in relation to LiDAR-derived and NED DEMs proved to be useful in identifying pertinent SRTM characteristics. From a geographic perspective, this investigation of the elevation and slope properties of the SRTM DEM showed how similar raster processing and statistical analysis could be employed in different geographical areas. The utility of investigating the properties of different DEMs (LiDAR, NED, and SRTM) was seen in the land use application, which demonstrated how the selection of one DEM could differ from another. This thesis research illustrated some important lessons regarding digital terrain analysis, which are pertinent to geographers and other researchers who incorporate digital elevation models into their research. Themes regarding comparisons of elevation models, error analysis, and land cover/ land use relationships are summarized here.

5.5.1. Louisiana Study Areas

From the analysis of the elevation models in Louisiana, my findings suggest that at the coarser resolution of the LiDAR data, it did not result in significantly different results from the coarsened NED data. This has implications in the utility of the LiDAR in comparison to the NED data. For instance, it may be suitable to use the NED data at a certain coarser resolution and have the same findings as if the LiDAR was used. More research would need to be done regarding resampling the LiDAR data at various resolutions to compare them to the NED DEM at the same resolution.

5.5.1.1. Elevation Characteristics

The elevation characteristics of the LiDAR and NED had similarities; however, had slightly different range and mean elevations (Tables 5.1 and 5.12). Figures B.1-3 and

B.7-9 in the Appendix illustrate a striking difference among the SRTM, LiDAR, and NED DEMs. In the Acadia study area, the woody wetlands are seen as raised in the SRTM DEM in comparison to the surrounding elevations. The NED and LiDAR DEM, on the other hand, depict the wetlands as a low area on the landscape. Also, the striping of the SRTM DEM as is an artifact of the DEM from its radar collection methodology. This is in contrast to the LiDAR and NED DEMs. This pattern in the wetlands of the SRTM is important to consider in terms of using the SRTM DEM in highly vegetated areas, as it could portray inverse relationships between vegetated and non-vegetated areas. Also, the user needs to be aware of the possible erroneous values of the SRTM elevation negative values, as these are not realistic elevation values. As Hancock et al. 2006 warned about the use of the SRTM in hydrology studies because of its coarser resolution, this thesis work cautions the user about working with SRTM in highly vegetated areas.

In order to examine the error characteristics of the SRTM DEM, the reference DEMs needed to be resampled to a comparable resolution. The nearest neighbor resampling technique was used to create DEMs at a coarser resolution. At this coarser 90 m resolution, some key results appeared across the study areas. In terms of the elevation values of the Acadia study area, the LiDAR 90 m and NED 30 m had a correlation of 0.929 and the LiDAR 90 m and NED 90 m had a correlation of 0.933 (Table 5.5). This indicates that the use of the NED 90 m or the LiDAR 90 m would not differ greatly from each other, despite being derived from different source DEMs. Similar results occurred with the Webster study area, which would lead me to believe possibly similar results would occur with the slope characteristics.

5.5.1.2. Slope Characteristics

The slopes of the LiDAR, NED, and SRTM DEMs decreased with an increase in resolution. This is the typical inverse relationship is typical with the coarsening of elevation data. However, despite similarities noted in elevation, smaller slope correlation coefficients were found between the NED 30 m and LiDAR 90 m (0.661) and the NED 90 m and LiDAR 90 m (0.752) (Table 5.6). This suggests that when using a certain DEM, the user needs to be aware of the possible slope/ elevation differences in the underlying data and determine whether these differences are relevant to their use. However, from examination of the slope of the study areas, the user needs to be cautious with interpretation of slope values of the SRTM given the raised areas of vegetated locations seen in the wetlands of the Acadia study area.

5.5.1.3. Error Analysis: Land Cover/ Land Use Relationships

The analysis with the use of the boxplots, difference of means t-tests, comparisons of means, RMSE, and variances were all done to answer my research questions related to the land cover/land use characteristics and relationships of vegetated and non-vegetated characteristics of the SRTM DEM (research questions 3, 4, and 5). As seen with the comparison of elevation values the LiDAR 90 m and NED 90 m were similar, thus, similar results were found from the SRTM error analysis with these products in the Louisiana study areas. This suggests that with the LiDAR DEM coarsened to 90 m, it would be similar to the NED 90 m. However, in consideration of the error results, the Acadia study area had lower average SRTM-LiDAR error (2.8 m) compared to the Webster study area (7.2 m). The error analysis of the Louisiana study areas illustrated the influence of vegetation on the SRTM DEM. From the box plots (Figure 5.6 and 5.11) and significant difference of means of the non-vegetated and vegetated groups for the Acadia and Webster study areas, the vegetated and non-vegetated areas indicated significant differences in SRTM-LiDAR DEM error. The land cover/land use comparisons of the average SRTM DEM errors for the non-forest classes (developed, water, and agriculture) and forest classes (evergreen, deciduous, mixed forest, and woody wetland) show significant differences between non-forest and forest classes.

These positive mean errors of the Acadia and Webster study areas indicate a positive bias of the SRTM DEM compared to the NED and LiDAR DEMs. This positive bias of the SRTM DEM was attributed to the radar scattering from the vegetation cover on the landscape. Significant one-sided t-tests confirmed the positive bias of the SRTM DEM. The relationships between the vegetation cover and the SRTM DEM error were made qualitatively by visual comparison of the error patterns and the NLCD 2001 land cover/ land use and quantitatively from comparisons of the average errors and RMSE values per land cover/land use class. Similar to research findings from (Bhang, Schwartz, and Braun 2007; Carabajal and Harding 2006; Shortridge 2006) regarding the relationships of vegetation and SRTM, this research found higher average errors for forested areas. From examination of the means and variances of the NLCD 2001 classes, it was evident that the wetlands variances (17.3 m for the Acadia study area and 24.2 m for the Webster study area) and other vegetated classes for the Webster study area (evergreen 27.9m, forest/shrub 31.7 m) had high variances compared to the agriculture variance of 16.3 m for the Webster study area and 4.0 m for the Acadia study area (Tables 5.11 and 5.22). This is suggested to be from the various heights of trees in these areas, which would have been recorded at different heights in the radar collection process. Also as seen with the case of the water variance (37.6 m) in the Webster study area, its variance could be from the scattering from the surface. Editing has been done to the SRTM in terms of the boundary of land and water to create a more smooth water surface (NASA 2005).

The variances of the land cover/ land use classes from the NLCD differ because of the manner which the radar used to create the SRTM was collected. The SRTM C-band transmits and receives short wavelengths (5.6 cm), which do not completely penetrate tree canopy. According to Walker, Kellndorfer, and Pierce (2007), the vegetation on the surface including the twigs and branches are able to scatter the radar energy. The SRTM C-band receives and transmits at a wavelength slightly greater than the X-band (3 cm); thus this small difference enables the SRTM C-band to penetrate slightly further into tree canopy (Walker, Kellndorfer, and Pierce 2007). This accounts for the greater variances seen in the vegetated classes in the Acadia and Webster study area. The SRTM C-band and SRTM X-band used to collect data for the SRTM DEM were of short wavelengths, which show less capability to penetrate tree canopy compared to the longer wavelength (74 cm) of the P-band (Andersen, Reutebuch, McGaughey 2006). As longer wavelengths have a greater ability to penetrate tree canopy.

Figure 5.28 illustrates a schematic of the SRTM radar striking tree canopy and a nearby field and the more scattering that would occur from the tree canopy compared to the field. Thus, the agriculture class would have lower SRTM DEM variances as illustrated with my research in the Acadia and Webster study areas. To illustrate how the variance of the SRTM DEM error would differ within a vegetated class, Figure 5.29

shows how the radar striking the surface of a vegetated surface, such as an area identified as deciduous forest, would scatter and record the height differently for locations within that area. These schematics show the tree canopy with leaf on conditions. This would lead to more differences with the same deciduous area in an SRTM DEM error analysis, as my research illustrated greater variances in the vegetated classes.

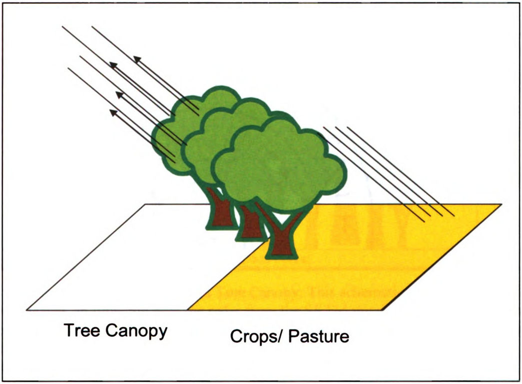

Figure 5.28. Interaction of Landscape Feature with short wavelength radar. This schematic shows the radar used to create the SRTM DEM reflecting off the tree canopy in leaf on conditions, while less scattering is observed with the short grasses or crops in the nearby pasture. Modified from Andersen, Reutebuch, and McGaughey (2006).

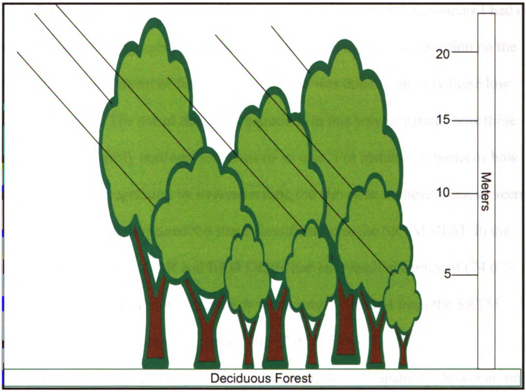

Figure 5.29. Reflectivity of Radar from Tree Canopy. This schematic of a deciduous forest with leaves on illustrate how the radar from the SRTM mission would reflect from the forest canopy at different heights above the surface. These various height differences would be reflective as DEM error in my analysis and result in greater variances for the vegetated classes.

5.5.1.4. Land Use Application

The land use application demonstrated how the choices of the user can impact the results from various DEMs. Specifically, the land use application is important because it highlights the results of the SRTM in comparison to other models. In locations, with only the SRTM DEM as a reliable DEM, there would not be any DEM to compare the results of an application to. However, from this research it can be seen how the characteristics of the SRTM influence an application result. The criteria of the land use application warrants some further discussion. In terms of identifying an agricultural land use practice, slope is a significant factor, given the relationships to soil moisture characteristics (McDaniel, Trahan, and Godfrey 2006). However, given the limited data sources I had on the Thailand area, the topographic position was used to identify relative position on the landscape. By the employment of focal operations, this was done to identify these low areas on the landscape. The use of the focal operations in this way illustrates how these can be combined to identify pertinent locations of an area. For instance in terms of how the SRTM responds to vegetation by overestimating the elevation in these areas, as seen in the wetlands of Acadia, impacted the slope classification in the SRTM DEM. In the end to the results from the LiDAR and NED DEMs had an overall accuracy of (74.6 % and 82.0 %) for the Acadia and Webster study areas, which differed from the SRTM DEM results of 51.7 %, and 66.6 %, respectively (Tables 5.34-37).

LiDAR DEMs show promise in terms of their analytical capability; however, only time will tell about how successful their widespread use will be. As the fine-resolution of the LiDAR DEMs do require more processing time and larger data storage capabilities. So, given that LiDAR is becoming more mainstream on national, state, and local geographic data repositories indicates to me, students and researchers will have to become more aware of this type of data's uses and limitations. However, the United States seems to be advancing at greater speeds in terms of its LiDAR collection compared to other countries, since the literature using airborne LiDAR is mostly with United States study areas from those sources identified from Table 2.5. Internationally, satellite sources of LiDAR have been used as reference to the SRTM DEM and other DEMS (Hoften et al. 2006). Thus, given the SRTM X-band is available for part of the world, this thesis research investigated its utility in elevation analysis compared to the SRTM C-90 m, which is publicly available.

5.5.2. Nang Rong, Thailand

The flat topographic characteristics of the Louisiana and Thailand data illustrate some key findings to the research community. As in the case of the Nang Rong area, the SRTM DEM appeared bumpy in a relatively flat area, which was not realistic of the terrain characteristics. This was further accentuated with the Nang Rong SRTM X-25 m which appeared to have much noise in the DEM. Researchers should consider the utility of the SRTM X-25 m DEM in this context of a mainly flat topographic region given the noise seen in the slope of this DEM. In terms of the Nang Rong study area, when the nearest neighbor method of resampling was used on the SRTM X-band 25 m, the SRTM 90 m was more comparable to the SRTM C-90 m (elevation correlation coefficient of 0.977) and removed the noise seen in the SRTM X-25 m DEM (Table 5.27). Future consideration of the use of a spatial filter or a resampling method to smooth the X-band DEM may be warranted to have a more realistic interpretation of the earth's surface.

The SRTM C-90 m and SRTM X-90 m had a mean error of 0.7 m, which showed little bias of the SRTM C-90 m. It is expected that the SRTM C and SRTM X would have similar responses to land cover/ land use classes on the landscape given their collection methods. However, a global land cover dataset was not incorporated into this research. Even with the examination of the SRTM C-90 m DEM, it appeared bumpy in areas of low relief, thus knowledge of the region of interest and DEM characteristics are needed to interpret these elevation models correctly. From the land use application of the SRTM

X-90 m and SRTM C-90 m, there seemed to be in agreement in the majority of the study area; however, not the southeastern portion of the study area (Figure 5.27). This land use application in the context of the Nang Rong study area illustrated how DEMs of the same resolution but from different original production methods could identify some but not all areas as appropriate for the application of interest.

5.5.3. Comparable Tree Cover Analysis

Similar to Carabajal and Harding (2006) who incorporated a global land cover dataset into their investigation to compare SRTM characteristics across land cover types, this thesis research used MODIS % tree cover to examine vegetation characteristics across study area. From this thesis research, a few significant findings presented itself. As expected, the Webster study area had higher average % tree cover (53.5 %) compared to the Acadia study area (19.9 %). However, the ranges of the Webster and Acadia study areas differed slightly from 86 % for the Webster study area and 100 % for the Acadia study area (Table 5.31). The Nang Rong study area has a smaller range (45 %) compared to the Louisiana study areas. This indicated that mainly forested areas occur at the higher elevations or near villages in the Nang Rong District.

From the Acadia study area, it was learned that the portioning of the MODIS % tree cover at 50 % would show significant differences between mean SRTM-LiDAR error and variances of the groupings. However, the variances of the Webster study area were not significantly different (Table 5.32) Future research could involve the identification of a certain percentage that would yield significantly different results. In terms of the MODIS data for the Nang Rong study area the variances were found to be significantly different between the groups. The MODIS % tree cover gave some pertinent information regarding the vegetation cover. Future research may involve the identification of a land cover dataset, which would have more comparable cell resolution of the SRTM DEM for more specific analysis by land cover class or vegetation species.

5.5.4. Global implications

In geographical research analysis of different types of environments is important to discovering common themes across regions. The SRTM DEM is a near-global dataset created from consistent processing, and overlaps national boundaries. Through this dataset, it is able to be incorporated in local, regional, and national level research. As seen from the applications (Blumberg 2006; Brandt and Townsend 2006; Fredrick et al. 2007) the SRTM DEM is making research possible over broad geomorphic areas, in relevant areas of physical geography, and people/environment interaction research. By learning about the SRTM characteristics from comparisons of the Acadia and Webster study areas in Louisiana with high resolution DEMs, other applications in areas without another DEM can be better informed. Thus, global environmental research that incorporates digital terrain analysis shows much potential through the incorporation of the SRTM DEM, advancement of geospatial technology, and human intuition.

6. Conclusions

The aim of this research was to gain a greater understanding of SRTM elevation error characteristics in terms of its magnitude and its relationships to land cover. The correlations of elevations and slopes were examined to determine the similarities between the data products: NED, SRTM (C-band/X-band), and LiDAR. SRTM C-band data were explored through error analysis using LiDAR DEM data for two locations in Louisiana, including an agricultural area in southwestern Louisiana and a mainly forested area in northern Louisiana. Also, SRTM data (C-band and X-band) were examined in a portion of the Nang Rong region of Thailand. This analysis illustrated differences in the DEM characteristics through comparable analysis with land cover/land use data, NLCD 2001 for two areas in Louisiana, and MODIS (2000-2001) data for the two areas in Louisiana and Nang Rong study area. In addition to differences across land cover characteristics, the land use application illustrated how the selection of a certain DEM can give different results in an analysis. This section summarizes the key findings, limitations, and suggests directions for future research.

6.1. Summary

The survey of available DEMs in the United States indicates that select locations have high-resolution DEMs available (i.e. LiDAR DEMs) for geographical analysis. The predominance of LiDAR availability in coastal areas was due to the concern of coastal changes and hazard management. Greater availability of LiDAR in the United States and elsewhere would enable more fine-scale geographical analysis. Access to high resolution

DEM information in the United States enabled this research into SRTM DEM error characteristics.

The first research question was: **What are the relationships among elevations of NED, LiDAR, and SRTM DEMs?** This was investigated with the creation of correlation matrices. As expected the original and resampled DEMs of the same production method were found to be similar to each other; however, similarities were also noted between the NED and LiDAR production methods. For the Acadia study area, high correlations were observed between the NED 90 m and LiDAR 90 m DEMs (0.933) and between the NED 90 m and LiDAR 5 m (0.941). Similarly, for the Webster study area, a high correlation was observed between the LiDAR 90 m and NED 90 m (0.927). For both study areas, the SRTM 90 m DEMs had lower correlations when compared to the LiDAR 90 m (0.625 for the Acadia study area and 0.873 for the Webster study area) and NED 90 m (0.655 for the Acadia study area and 0.849 for the Webster study area). The similarities between the NED and LiDAR DEMs were visually observed through comparable color schemes. For the Nang Rong study area, the SRTM X-90 m and SRTM C-90 m DEMs were highly correlated (0.977).

Similar to the methods used to address research question 1, a correlation matrix was created to address research question 2: **What are the relationships among the slopes of NED, LIDAR, and SRTM DEMs?** Weaker correlations were observed among the slope grids compared to the correlations observed with the elevation values. For instance, the slope of the NED 30 m and NED 90 m slopes had a correlation of 0.060 for the Webster study area. However, this was expected given the resampling done to obtain the 90 m resolution from the original datasets. For the Webster study area, the LiDAR 90 m and NED 90 m had a correlation coefficient above 0.7. The Nang Rong study area had similar SRTM X-90 m and SRTM C-90 m slope ranges (0-22.3°). However, from examination of the slope distributions from all study areas, the predominance of relatively flat topography limited investigations of SRTM DEM error patterns in terms of slope. The Webster study area contained slightly greater relief (43 m-130 m); however, the gradients were limited to upland areas. Similarly the Nang Rong study region was mainly not a rugged area, since slope values were relatively small (< 10°). However, some distinction could be made between the flatter part and steeper slopes of the volcanic areas. Future research could be directed to investigation of more rugged study areas and SRTM DEM error.

Following the investigation of the similarities of the elevation and slope values across datasets, the differences of the DEMs was taken to consider the SRTM DEM error for the study areas. This was done to address research question 3: **Is the average SRTM DEM error greater than zero?** For the Acadia and Webster study areas, the average SRTM-LiDAR DEM errors of the entire study areas were 2.8 m and 7.1 m, respectively. The average SRTM DEM error was greater for the Webster study area compared to the Acadia study area, which can be attributed to the forested cover on the Webster study area landscape. This research found the SRTM- LiDAR DEM error for the Acadia and Webster study areas, and the SRTM-NED DEM error to illustrate very similar spatial patterns of error. This is due to the similarity of the NED 90 m and LiDAR 90 m DEMs. A positive average elevation error indicates a bias in the SRTM DEM. For the Nang Rong study area, the average SRTM DEM error was 0.66 m, which was only slightly greater than 0. In the Nang Rong site, the general error pattern identified on the landscape was of low error throughout the majority of the flatter, agricultural valleys in the northern part of the site and higher error on the steeper slopes of the volcanic areas in the southeastern part of the area. To determine if the average SRTM DEM error was significantly greater than zero, the t-test was done with the alterative hypothesis that the average SRTM DEM error was greater than zero. For the Acadia and Webster study areas, this t-test was significant indicating the upward bias of the SRTM. However, for the Nang Rong study area, this t-test was insignificant.

Given the vertical accuracy of the SRTM DEM to be less than 16 m, it is noted that some of the higher extremities of the ranges exceeded 16 m. The greatest SRTM-LiDAR DEM error for the Acadia study area was 49.7 m for the entire area and 21.8 m for the sample. For the Webster study area the highest SRTM-LiDAR DEM error was 38.2 m for the entire area and 29.7 m for the sample. The Nang Rong study area also exceeded the 16 m at times, with a range of SRTM error of -79 m to 67 m for the entire area. Thus, this suggests that at certain locations the DEM error exceeds the 16 m accuracy expectations of the SRTM.

Another key error statistic calculated for all study area was the root mean square error (RMSE). The RMSE of the SRTM-LiDAR error analysis for the Acadia study was about 5 m. However, the RMSE of the SRTM-LiDAR error analysis of the Webster study area was about 9 m. These RMSE values are within the accepted error values of the SRTM DEM of 10 m (NASA 2002). The RMSE of the Nang Rong study area was about 3 m. This is more comparable to the RMSE found in the Acadia study area, which had a predominantly flat and agricultural landscape. Despite the differences in the reference model used in both the United States and the Thailand context, this research illustrates how the determination and analysis of DEM error relationships to landscape characteristics can better illustrate the properties of the SRTM model.

This research expands on the options of reference data being used in DEM error work. As seen reference data ranges from kinematic GPS from Rodriguez, Morris, and Belz 2006 to satellite sources, such as Hofton et al. 2006. Based on examination of the large scale error analysis completed with satellite altimeter data the result, there was a 3.60 m global mean difference, with a 3.18m mean difference for North America and a 2.54 m mean difference for Euroasia (Berry, Garlick, and Smith 2007). Other global assessments have reported different statistics to determine height differences for the SRTM DEM and reference DEMs. For instance Rodriguez, Morris, and Belz 2006, indicated for North America there is an absolute height error of 9.0 m and for EuroAsia there is an absolute height error of 6.2 m. Since other researchers have not done error analysis with LiDAR-derived data in my selected Louisiana study areas, I ca not make direct comparisons. However, I can speculate on comparisons regarding overall differences. However, as my results indicate the general trend of the Nang Rong study area in Asia had a lower mean error compared to the United States areas is valid; however, there is a difference in the reference DEMs used.

The fourth research question: **What is the relationship of SRTM error across different land cover/land use classes?** was investigated through the examination of the SRTM error with NLCD 2001 in Louisiana. Generally, the locations of more forested areas compared to agricultural areas were associated with higher SRTM DEM error. The SRTM DEM error was higher and positive, which indicates biases in forested areas. In the Acadia study area, the wetlands had greater average error (8.5 m), while the developed (3.0 m) and agriculture (1.4 m) categories had lower average error and lower RMSEs. For the Webster study area, the wetland class had a mean error of 10.0 m, which was than other classes. Both Louisiana case studies reflected rectangular, regular patterns in relation to agriculture and forest patches evident in the error grid. For the Nang Rong study area, no direct relationship to land cover was made with this research, since a land cover/ land use dataset with broad classes was not incorporated into this analysis.

The variances of the SRTM-LiDAR error of the land cover/ land use classes from the NLCD 2001 were considered for the Acadia and Webster study areas. It was found that the wetland class had greater variance (17.3 m) compared to the agriculture (4.0 m) and developed (6.2 m) classes for the Acadia study area. Similarly, in the Webster study area, the wetland class had a relatively higher variance (24.2 m) , along with the other vegetated classes of evergreen (27.9 m) and forest/shrub (31.7 m). The water class of the Webster study area was also seen to have a high variance (37.6 m). It is thought that the variations in the canopy height of the vegetated areas would contribute to the greater variances of the vegetated classes. The variations in heights of vegetation classes would not be indicated from the satellite data used to create the NLCD 2001. Similarly, the scattering that occurs with the radar collection used in the SRTM DEM would attribute to greater variance in this class (Andersen, Reutebuch, McGaughey 2006).

In subsequent analysis in terms of the SRTM DEM error and the vegetated and non-vegetated areas, a difference of means t-test was conducted to address research question 5: **Is the average SRTM DEM error greater for vegetated or non-vegetated areas?** For both the Acadia and Webster study areas, the difference of means t-test was significant. The one-sided t-test was used to determine if the SRTM DEM error was significantly greater than zero. The results of the one-sided t-test showed that the vegetated classes had significantly greater mean s than the non-vegetated classes for the Acadia and Webster study areas.

The MODIS data with its 500 m resolution did not provide as useful information as expected to investigate the relationships about the percent tree cover and error characteristics. The range of the MODIS percent tree cover data for the Nang Rong study area (0- 45 %) was not as large as the Louisiana study areas' MODIS range (0-100 % for the Acadia study area and 0-86 % for the Webster study area). In addition to the difference of means t-test with data from the NLCD (2001), MODIS data was used to investigate patterns of vegetation by grouping the percent tree cover of less than 50 % together and the percent tree cover ≥ 50 % together for the Acadia and Webster study areas, and ≥ 22 % tree cover and < 22.5 % tree cover for the Nang Rong study area. Significant differences were observed for the Acadia and Webster study areas; however, not for the Nang Rong study area. So for the Nang Rong study area, the relationships between more (≥ 22 % tree cover) or less (< 22.5 % tree cover) forested areas and error could not be made definitely.

The land use application indicated how the selection of a specific DEM for use could identify varied application results. The land use application addresses research question 6: **How will the LiDAR, NED, and SRTM DEMs perform in a land use application?** The criteria of flat slope (0-1°) and a low topographic position on the landscape indicated the LIDAR 90 m, NED 90 m, and SRTM 90 m would identify different suitable areas on the landscape. The LiDAR 90 m and the NED 90 m did result in similar suitable results in terms of application use. The contingency matrices used the

LiDAR 90 m as reference for the Louisiana study areas, and the SRTM X-90 m as reference for the Nang Rong study area to confirm these findings. The overall accuracy of the LiDAR 90 m and NED 90 m was 74.6 % and 82.0 % for the Acadia and Webster study areas. However, in terms of the comparison of the LiDAR 90 m and SRTM 90, the overall accuracy for the Acadia and Webster study areas were 51.7 % and 66.6. %, respectively. Thus, the SRTM had greater differences compared to the LiDAR and NED outcomes. The SRTM C-90 m and the SRTM X-90 m also identified similar areas in the application for the Nang Rong site.

Agricultural models and land use analysis with different DEMs can indicate different outcomes, which may have implications in policies and recommendations for future land use. As seen from the application literature (land cover/ land use, hydrology, geomorphology), the incorporation of the SRTM DEM has been used to understand environmental phenomena better. My research illustrated how a land use application could differ in results based on DEM choice. Hence, understanding the resolution and production methods (i.e. LiDAR, NED, or SRTM) of the input model is necessary for choosing the appropriate DEM for use in analysis. In terms of policy decisions, identification of key biophysical characteristics of the earth including factors related to soil moisture, climatic characteristics, and agricultural growth controls, along with socioeconomic factors are necessary (Bouman et al. 2000). Policy decisions are made following research on past, present, and projected trends in land use dynamics. Thus, land use models and applications incorporating the SRTM DEM are likely to occur in the future.

The research is significant to the global community, academic professionals, and users. This research illustrates the characteristics and potential SRTM has in addressing environmental issues, and also challenges of its use. The consideration of greater use of the SRTM also implies greater access to geographic information. Thus, trends in spatial data and infrastructure to support data sharing, user-friendliness, and analysis methodologies can benefit from the use of topographic datasets. However, caution must be employed with the selection of the DEM for application purposes. Knowledge of production methods and their limitations are important for interpretation of application results. Thus, in regards to applications of SRTM, it is important to consider the properties of the model under investigation to properly interpret its results.

6.2. Limitations

This research uses the standard methodology of error assessment, which involves the alignment of raster cells and differencing of DEMs with consistent projections and vertical datums. However, this process has limitations related to the data sources and auxiliary data used in analysis of the DEM error. LiDAR was chosen as a higher quality DEM in relation to the coarser SRTM DEM. However, LiDAR can come from different sources and be collected and processed in different ways; thus, those factors need to be considered in the replication of this type of analysis in other locations with available LiDAR data. In addition, this research involved the assessment of DEM error in relationship to land cover from remotely sensed land cover information both from LandSat (USGS 2003) at the U.S. sites and MODIS (both in the United States and elsewhere). As seen with other research, Landsat and/or MODIS land cover products have been used to assess error differences in the SRTM (Bhang, Schwartz, and Braun

2007; Carabajal and Harding 2006). These data have accuracy and resolution limitations that were not investigated in this research. Also, the MODIS data used at a 500 m resolution was not downscaled to obtain values at the same resolution of the SRTM model. These limitations are acknowledged as factors that may result in different outcomes if data from other areas are employed in a similar process.

6.3. Future Direction of Research

This research illustrates the potential directions geography research can take in relation to the investigation of DEMs and land use characteristics. Future research can be directed into the following areas to strengthen understanding of the implication of error in spatial data analysis and employment of SRTM data in international case studies as a source of elevation information. This SRTM DEM error research can be advanced in terms of the application chosen to investigate, reference data chosen in analysis, and selection of study areas for investigation. Also, the development of land cover sensitive elevation error models could be used to create more accurate depictions of the earth.

Geomorphic and other types of application domains are utilizing SRTM data in various landscapes. This research could be furthered by the expansion of the application domain to include a geomorphic application, which could have limitations based on resolution of the landscape feature. These geomorphology applications could relate to study of river hydrology changes or alluvial fan development, as these features would be observed with SRTM DEM data. For example, certain small topographic features may be not completely represented with the 90 m resolution of the SRTM. If the SRTM X-band data were available at a greater extent and at no cost, greater use of this product would enable more detailed analysis. The higher spatial resolution data could be employed for different types of applications, which are more appropriate with this level of resolution.

Future research directions could explore the relationships between SRTM and LiDAR in other locations in the United States with different topographic characteristics, for example to coastal ranges of Washington or the Appalachians of North Carolina, to determine if such similarities exist between NED 90 m and LiDAR 90 m elevation grids when used in error assessment. This type of analysis would be utilizing different LiDAR data as a reference; however, the overall methodology employed would be same. Currently, the United States in working on a national LiDAR project, with each state developing projects to obtain lidar for large sections (Stoker et al. 2007). As seen with the LiDAR distributed from the USGS and other repositories this data can be valuable to obtaining high-resolution elevation data (Stoker et al. 2006). However, with the greater extent of coverage of LiDAR other geospatial technology changes would also need to occur for greater public and researcher use of this data. An effective means of dissemination would need to be coordinated among agencies collecting LiDAR data. The USGS along with other state agencies are currently collaborating and addressing the many challenges associated collecting large datasets across large areas (Stoker et al. 2007).

This work with relatively flat topographic areas contributes to understanding the SRTM DEM characteristics in this type of landscape. This is relevant to coastal areas globally, since these areas have been the focus of geographical research, hazard research, and environmental change research. International research has been devoted to analysis of coastal areas given the occurrence of natural disasters such as hurricanes and tsunamis.

Thus, this research shows that if high resolution data is available, it can be used in comparative purposes. In addition, this thesis research shows the global research community how the SRTM can be employed and analyzed in a flat topographic area.

Investigations in more rugged terrains would further illustrate the characteristics between slope and SRTM DEM error. As seen with work by Miliaresis and Paraschou 2005, SRTM has certain characteristics with more rugged terrain. Internationally, investigations of more rugged areas could have implications in mountain geomorphology studies and investigations in inaccessible areas. As geomorphology studies have an international focus concerned about characterizing landforms in all parts of the world. Since, mountains often can not be fully surveyed with the use of traditional GPS technology, the use of the radar collected SRTM data or possibly LiDAR data opens new ways to analyze these rugged environments.

The future of elevation data in the United States is tending towards LiDAR data; however, at the international level, LiDAR data is not being acquired at great speed. As seen in the literature, LiDAR studies are predominantly reported using United States study area opposed to area outside the United States. Thus, satellite-derived data remain the main source of elevation data. The SRTM C-90 m DEM improved upon the resolution of the GTOPO30; however, as seen with this research the SRTM X-25 m did not prove to be more useful in terms of application use or elevation/slope comparisons in the case of Nang Rong. Thus, it may not me useful to obtain this data if the SRTM C-90 m DEM would be sufficient for the application intended by the user. The SRTM X-25 m does have more detail than the SRTM C-90 m DEM; however, their may be noise in the DEM that could obscure results from the use of this DEM.

This research into the characteristics of a near-global model has many implications for global change research. Globalization of the world has made the need to address environmental issues on much larger scales. The International-Geosphere-Biosphere Program: A Study in Global Change was created to focus on global issues and would benefit from the incorporation of a near-global elevation model into studies (Kates 1987). Similarly in land cover/ land use change and environmental change research, the incorporation of a near-global elevation source would complement global land cover analysis. In addition to environmental change and earth monitoring analysis, interests in global sustainability could benefit from the incorporation of a near-global DEM (Wood 2005). Global issues can incorporate geospatial technology, geographic research, and scientific studies to address issues that cross country and regional borders, and that have wide-reaching implications. Hence, future studies about the SRTM model are necessary because of its utility in environmental analysis across multiple scales and application domains. Results obtained in the United States regarding the characteristics of the SRTM DEM could apply elsewhere given similar topographic and landscape characteristics. Future research could be directed into more high resolution comparisons of elevation datasets with near-global land cover/ land use datasets to determine their appropriateness of use.

Appendix A

Table A.1. Louisiana study areas: LiDAR Data

Quad Name	**Number: USGS ID**	**Name**	**ID**
Acadia Parish		**Webster Parish**	
Basile	3009236	Taylor	3309361
Euricesouth	3009237	Walkerville	3309362
Richard	3009238	Shongaloo	3209306
Churchpoint	3009239	Cullen	3209305
Mire	3009247	Carterville	3209304
Branch	3009246	Ivan	3209312
Iota	3009245	Cotton Valley	3209313
Evangeline	3009244	Leton	3209344
Mementau	3009252	Minden North	3209322
Crowley West	3009253	Hortman	3209321
Crowley East	3009254	Brodrau Lake	3209320
Dusch	3009255	Benton	3209319
Gueydan	3009260		
Wright	3009261		
Kaplan	3009262		
Lafayette Parish			
Carencro	3009248		
Breaux Bridge	3009441		
Broussard	3009149		
Lafayette	3009256		
Download Date Atlas 2007	6/27/07		7/1/07

Source: ATLAS (2007).

Appendix B

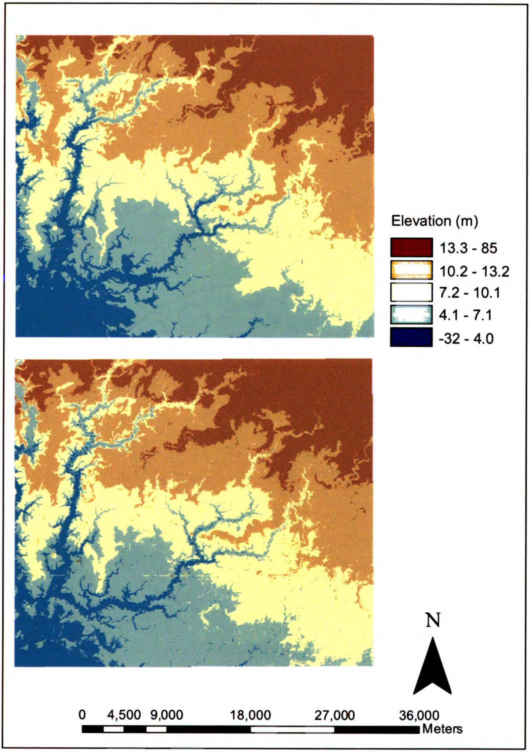

Figure B.1. Acadia Study Area LiDAR 5m and LiDAR 90m DEM (meters)

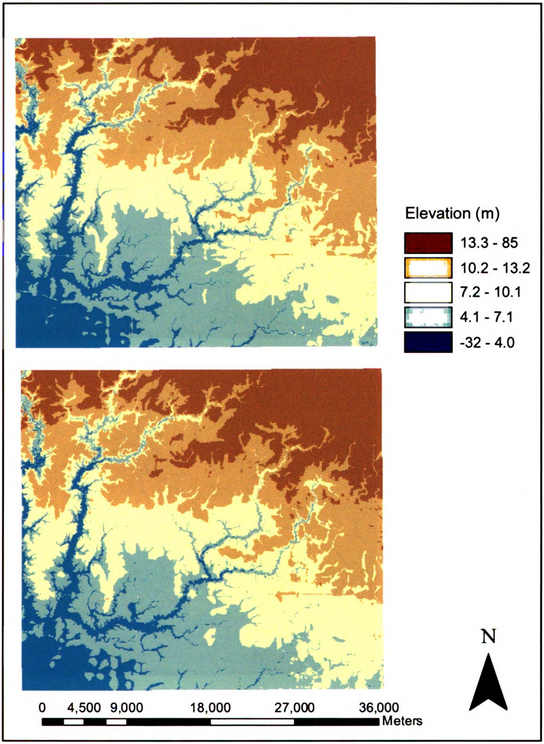

Figure B.2. Acadia Study Area NED 30m and NED 90m DEM (meters)

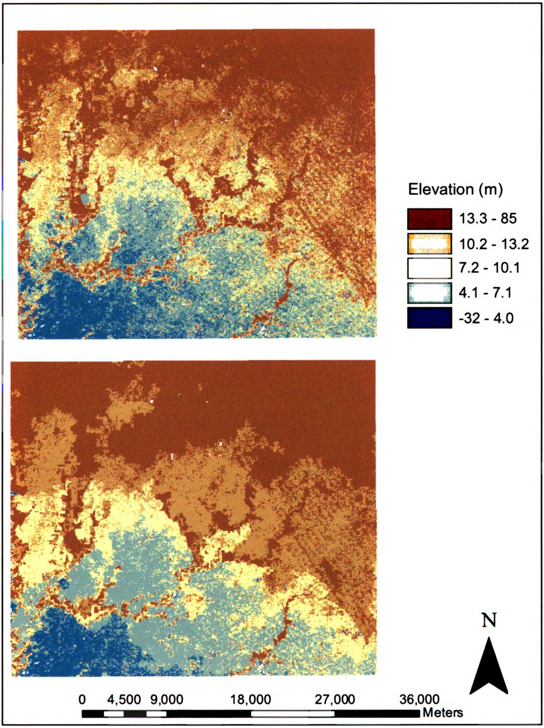

Figure B.3. Acadia Study Area SRTM 30m and SRTM 90m DEM (meters)

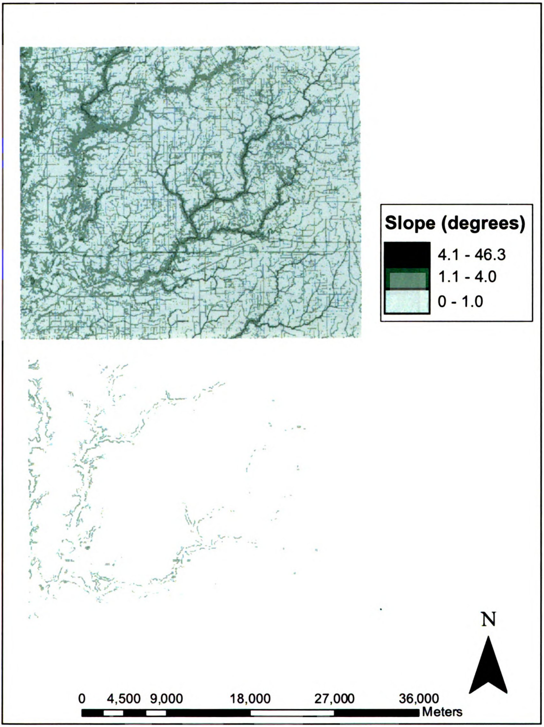

Figure B.4. Slope: Acadia Study Area LiDAR 5m and LiDAR 90m DEM

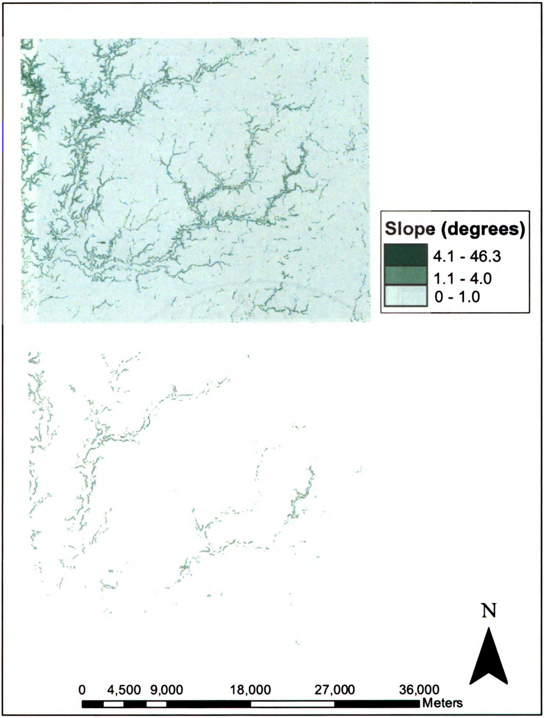

Figure B.5. Slope: Acadia Study Area NED 30m and NED 90m DEM

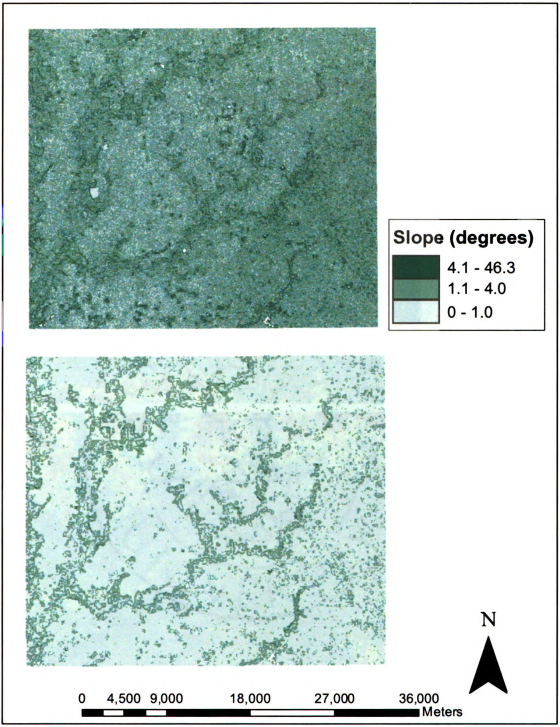

Figure B.6. Slope: Acadia Study Area SRTM 30m and SRTM 90m DEM

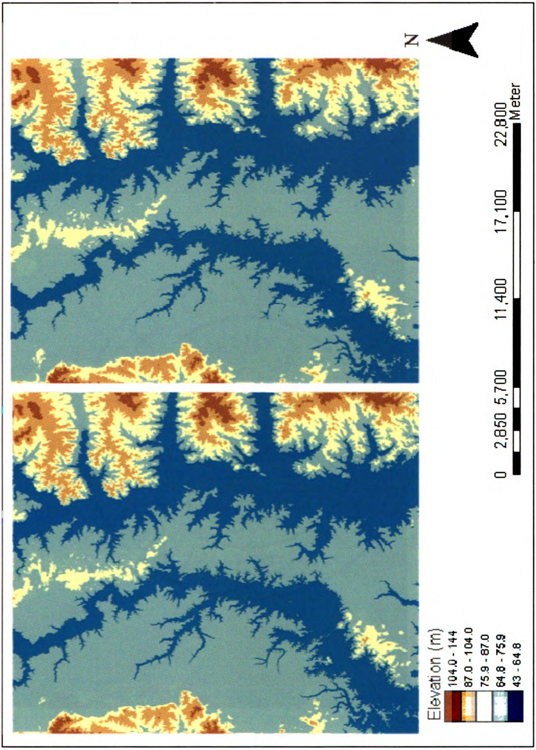

Figure B.7. Webster Study Area LiDAR 5 m and LiDAR 90 m DEM

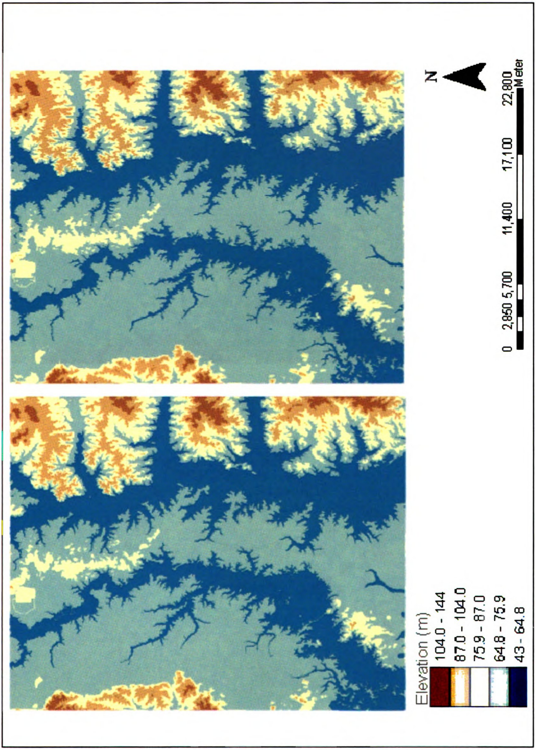

Figure B.8. Webster Study Area NED 30 m and NED 90 m DEM

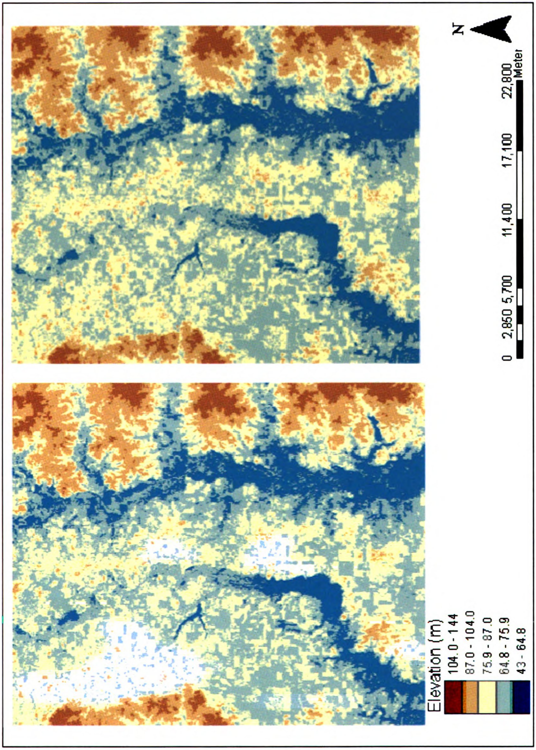

Figure B.9. Webster Study Area SRTM 30 m and SRTM 90 m DEM

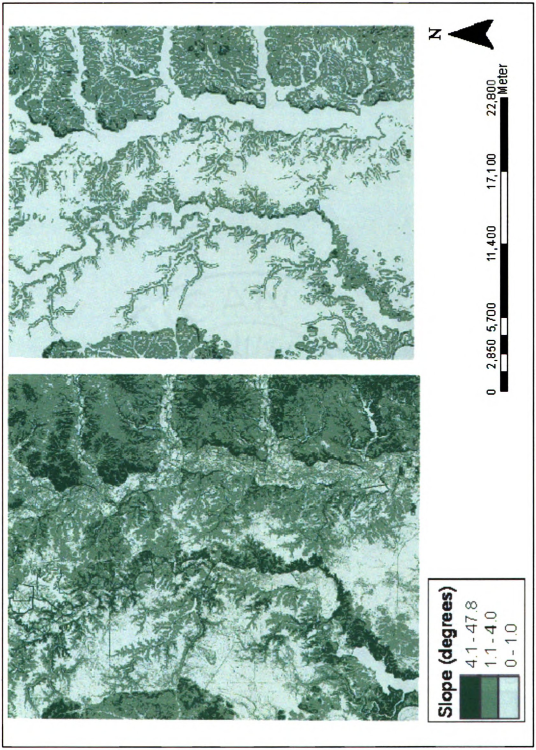

Figure B.10. Slope: Webster Study Area LiDAR 5 m and LiDAR 90 m DEM

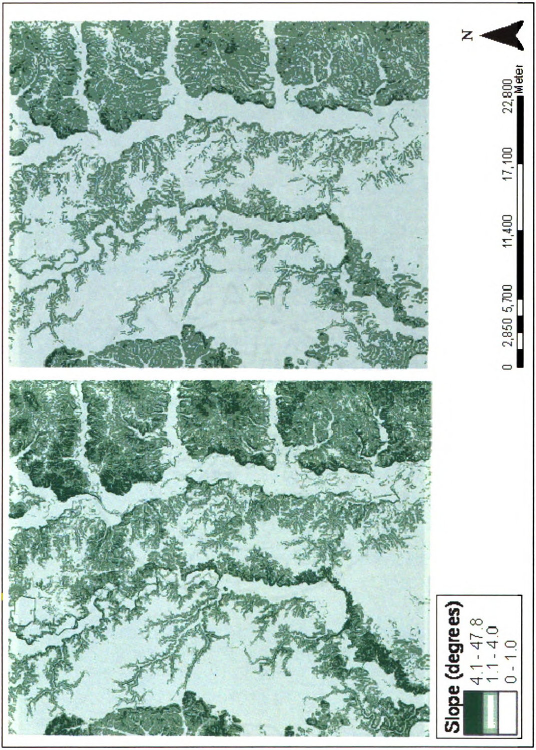

Figure B.11. Slope: Webster Study Area NED 30 m and NED 90 m DEM

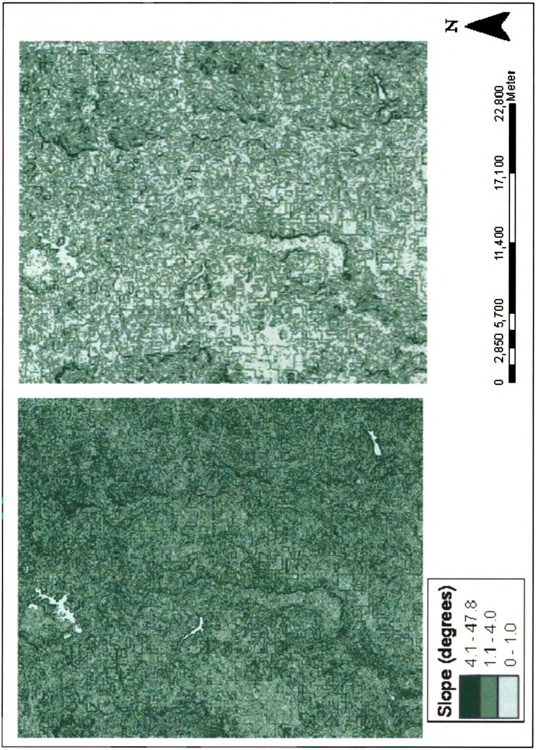

Figure B.12. Slope: Webster Study Area SRTM 30 m and SRTM 90 m DEM

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