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# GIS-based Analysis and Modelling with Empirical and Remotely-Sensed Data on Coastline Advance and Retreat

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GIS-BASED ANALYSIS AND MODELLING WITH EMPIRICAL AND REMOTELY-  
SENSED DATA ON COASTLINE ADVANCE AND RETREAT

by

Sajid Rashid Ahmad

A Dissertation

Submitted to the Faculty of Graduate Studies

through Earth and Environmental Sciences

in Partial Fulfillment of the Requirements for

the Degree of Doctor of Philosophy at the

University of Windsor

Windsor, Ontario, Canada

2010

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GIS-based Analysis and Modelling with Empirical and Remotely-Sensed Data on  
Coastline Advance and Retreat

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## **DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION**

### **I. CO-AUTHORSHIP DECLARATION**

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

This thesis also incorporates the outcome of a research undertaken by me under the supervision of Professor Dr. V. Chris Lakhan. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-author was primarily in the guidance and supervision of field and laboratory work, and in the writing of manuscripts.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis.

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### **II. DECLARATION OF PREVIOUS PUBLICATION**

This thesis includes four (4) original papers that have been previously published / accepted for publication in peer reviewed journals, as follows:

<b>Thesis Chapter</b>	<b>Publication title/full citation</b>	<b>Publication status</b>
Chapter 3	Framework for a spatio-temporal information-based system (STIBS) for decision-making.	Published
Chapter 4	GIS-based analysis and modeling of coastline positional changes.	Published
Chapter 5	GIS-based analysis and modeling of coastline advance and retreat.	Accepted in Marine Geodesy
Chapter 6	Time series modeling of data on coastline advance and retreat.	Accepted in Journal of Coastal Research (JCR)

I certify that the above material describes work completed during my registration as graduate student at the University of Windsor.

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## ABSTRACT

With the understanding that far more research remains to be done on the development and use of innovative and functional geospatial techniques and procedures to investigate coastline changes this thesis focussed on the integration of remote sensing, geographical information systems (GIS) and modelling techniques to provide meaningful insights on the spatial and temporal dynamics of coastline changes. One of the unique strengths of this research was the parameterization of the GIS with long-term empirical and remote sensing data. Annual empirical data from 1941–2007 were analyzed by the GIS, and then modelled with statistical techniques. Data were also extracted from Landsat TM and ETM+ images. The band ratio method was used to extract the coastlines. Topographic maps were also used to extract digital map data. All data incorporated into ArcGIS 9.2 were analyzed with various modules, including Spatial Analyst, 3D Analyst, and Triangulated Irregular Networks. The Digital Shoreline Analysis System was used to analyze and predict rates of coastline change. GIS results showed the spatial locations along the coast that will either advance or retreat over time. The linear regression results highlighted temporal changes which are likely to occur along the coastline.

Box-Jenkins modelling procedures were utilized to determine statistical models which best described the time series (1941–2007) of coastline change data. After several iterations and goodness-of-fit tests, second-order spatial cyclic autoregressive models, first-order autoregressive models and autoregressive moving average models were identified as being appropriate for describing the deterministic and random processes operating in Guyana's coastal system. The models highlighted not only cyclical patterns in advance and retreat of the coastline, but also the existence of short and long-term

memory processes. Long-term memory processes could be associated with mudshoal propagation and stabilization while short-term memory processes were indicative of transitory hydrodynamic and other processes.

An innovative framework for a spatio-temporal information-based system (STIBS) was developed. STIBS incorporated diverse datasets within a GIS, dynamic computer-based simulation models, and a spatial information query and graphical subsystem. Tests of the STIBS proved that it could be used to simulate and visualize temporal variability in shifting morphological states of the coastline.



## **DEDICATION**

This thesis is dedicated to my beloved wife Mona for being a light in dark times and children (Aamna, Muhammad, Momna and Murtaza) who have always stood by me and dealt with all of my absence from many family occasions with a smile. Their efforts and sacrifices have made my dream of having this degree a reality.

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My appreciation also goes to my family especially my brother Rashad Jamal for their efforts and suggestions towards my progress in life. To my mother, who has been a source of encouragement and inspiration to me throughout my life, a very special thank to

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# CHAPTER 1

## INTRODUCTION

### 1.1 Introduction

Coastlines, at all spatial scales, either advance (synonymous with accretion) or retreat (synonymous with erosion) in response to the effects of either anthropic factors or a diverse range of natural processes, including winds, waves, currents, sediment supply, and changing water levels. The cumulative effects of the various forces acting on coastlines are, however, not easily recognizable because the change from one state to another state is governed by complex nonlinear feedback loops (Lakhan, 2003).

According to Shore Protection Manual (Coast Engineering Research Center (CERC) 1984), shoreline is defined as the line contacting between the mean high water line and the shore. In contrast to the shoreline, coastline is easier to identify based on a clear morphological shift between the shore and the coast. Essentially, the coastline is described as the line that technically forms the boundary between the coast and the shore, i.e. the foot of the cliff or the foot of the dunes (Sverdrup et al. 2006). The atlas of Natural Resources Canada states that coastline is not measured as precisely as shoreline. Shoreline is the perimeter of the land along the water's edge, measured to the closest exactness possible.

At any given time, one or more processes act as forcing functions, and could influence changes to the morphological states of the coastal system. For instance, an extreme storm event, associated with erosive waves, could cause significant positional shifts of the coastline (Augustinus, 2004). Moreover, short-term stochastic processes

occurring over several seasons could cause the coast to advance or retreat in various locations (Lakhan, 2005). One portion of the coast could be retreating while a short distance away advancing conditions could prevail.

In addition to the effects of multidimensional temporal processes, coastlines are affected by global sea level rise (SLR). If, as is predicted, a worldwide SLR will intensify the positional shifts of coastlines. According to Stive et al. (2009, p. 1023), an accelerated SLR will result in much faster coastline retreat with particularly severe impacts on low lying areas. Even a gradual increase in SLR will have adverse impacts on coastal populations, ecosystems and socioeconomic systems for nearly two hundred low-lying coastal areas (Jelgersma et al., 1993; Bird, 2005). Guyana, the area of focus of research in this thesis, is a prime example of a vulnerable, low lying coastal area which will suffer disastrous consequences with SLR because more than 90% of the country's population live on the coast which is below sea level (Ahmad, et al. 2006). According to DHV Environment and Infrastructure (1992), life in the entire coastal zone of Guyana will be disrupted because there will be aggravating problems of coastal erosion, salt water intrusion, and flooding. Given the vulnerability of low-lying areas to the cumulative effects of coastal processes it, therefore, becomes necessary to obtain additional insights on the dynamics of coastline changes.

While progress has been made in isolating and understanding individual processes influencing coastal change substantial research, nevertheless, remains to be done on understanding the advance and retreat dynamics of coastlines in the spatial and temporal domains. Given the compelling demand to develop efficient, integrative, and innovative approaches to investigate coastline changes, this thesis focussed on the development of

geographical information systems (GIS)-based approach to analyze, model, and predict spatial locations along the Guyana coast that will either advance or retreat. The unique strength of this approach is that it incorporates empirical and remotely-sensed derived data into a GIS to analyze, model, predict, and visualize coastline changes. The empirical data represent one of the longest time series (1941–2007) of Guyana’s coastline change data, and the remotely-sensed data are from a total of eight Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) images.

In addition to analyzing and predicting coastline changes the time series of coastline change data were also modelled with Box-Jenkins time series modelling techniques (Box and Jenkins, 1976; Box et al., 1994; Harvey, 1993; Hipel and Mcleod 1994). The data were fitted to various types of autoregressive models in order to identify models which best described the nature of the localized stochastic processes operating in Guyana’s coastal system. Doing this facilitated an in-depth understanding of the transitory and periodic processes influencing temporal changes in Guyana’s coastal system.

## **1.2 Objectives of the Research**

According to Sutherland et al.(2004); Lakhan (2010), substantial research remains to be done on analyzing and modelling coastline change data in order to obtain better insights on the multidimensional processes influencing changes along coastlines at different spatial and temporal scales. It was claimed that even basic questions cannot be clearly answered as, for example: When will changes occur along the coastline? or Where will changes occur along the coastline? With the understanding that uncertainties still exist in understanding the dynamics of coastline change, this research has objectives to:

1.2.1 Utilize a GIS to analyze, model, and predict the spatial and temporal accretional (i.e., advance) and erosional (i.e., retreat) changes that have and will occur along the coast of Guyana.

1.2.2 Identify statistical time series models that best describe the processes generating the coastline change data from Guyana's coast.

1.2.3 Formulate the framework for an innovative spatio-temporal information-based system to identify, simulate, and query changes in the coastal environment.

### **1.3 Hypotheses**

The objectives of this research facilitate testing of the following hypotheses.

1.3.1 Advance and retreat of the coastline could be predicted with data incorporated into geographical information systems.

1.3.2 Coastline change empirical data, at some time intervals, could be fitted to second-order spatial, cyclic autoregressive models thereby suggesting the presence of cyclical processes in the coastal system.

1.3.3 Coastline change empirical data, at some time intervals, could be fitted to space-time autoregressive moving average models, thereby indicating short-term transitory stochastic processes in the coastal system.

### **1.4 The Study Area**

The study area is a portion of the northeast coast of the South American continent known as the Guiana coast, and stretches some 1600 km between the mouths of the Orinoco and Amazon Rivers (see Figure 1.1). It forms the coastline of French Guiana,

Suriname, Guyana, and parts of the Brazilian and Venezuelan coasts. Emphasis is on the Guyana coast which has a length of about 435 km. The coastal plain is bordered by sandy rolling lands in the east and the Pre-Cambrian lowlands in the west. The coastal plain is Guyana's smallest physiographic region, and has a width that varies from 16 km in the west to 64 km in the east. Much of the lower coastal plain is below sea level at high tides, and is therefore vulnerable to flooding and erosion (Lakhan, 1994).



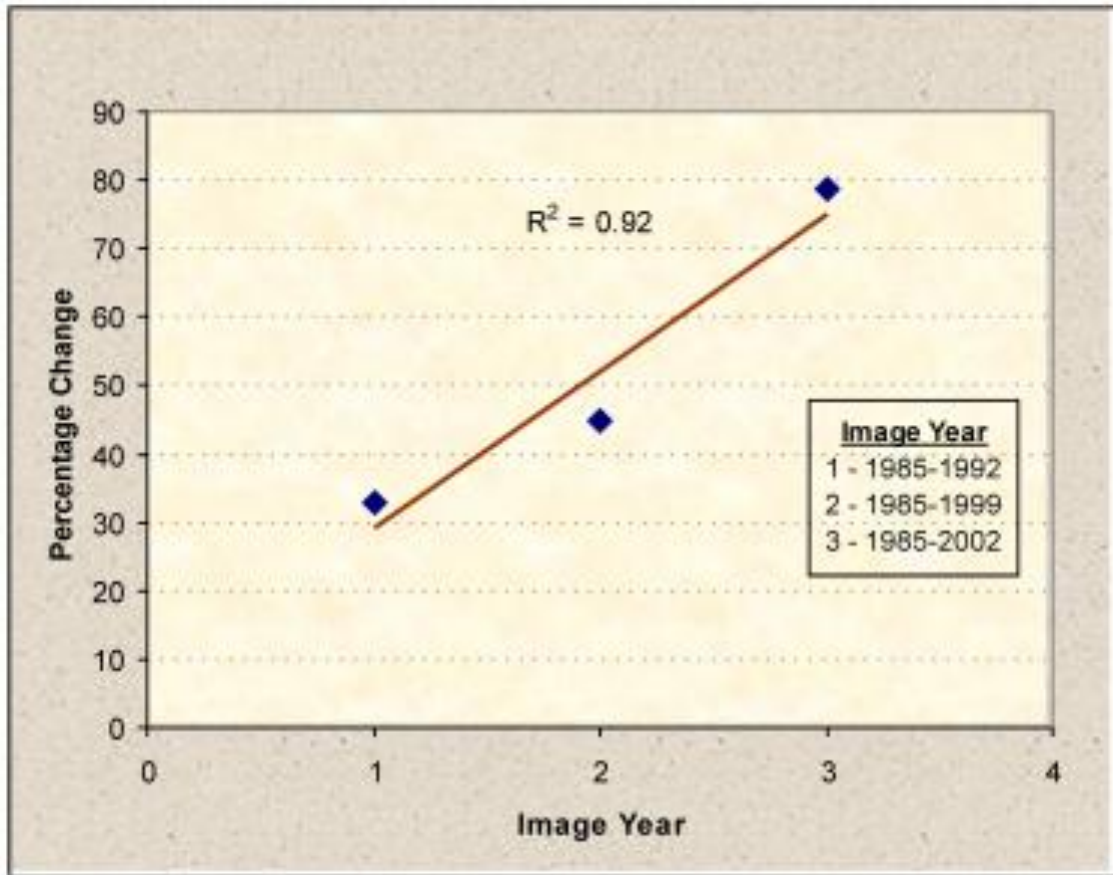
Figure 1.1: Setting of the Guyana Coast (modified from Augustinus, 2004).



Guyana is a prime example of a vulnerable low-lying coastal area which will suffer disastrous consequences with projected sea level rises (Lakhan, 2005). Coastal residents, comprising more than 80% of Guyana's population, are faced with recurring problems of salt water intrusion, inundation, flooding and erosion. It was estimated by Singhroy (1996) that flooding could destroy almost US\$1 billion of economic activity in the coastal areas if steps are not taken to maintain proper coastal protection structures. In addition to flooding, Guyana's coast is affected by episodes of accretion and erosion, associated with variable nearshore hydrodynamic and sedimentological processes (Lakhan and Pepper, 1997).

The coast is under the influence of massive loads of sediments discharged at the mouth of the Amazon River (Allersma, 1971). The bulk of the sediments are transported from the Amazon in a north-westerly direction by the Equatorial Current, and subsequently by the Guiana Current which flows along the continental shelf. The volumes of sediment transported along the Guyana coast varied seasonally with the highest concentrations occurring in April and May (Nedeco, 1972). With the use of data acquired by remote sensing satellites, Ahmad et al. (2006) demonstrated that there was a linear increase in the concentration of sediments in the near and offshore areas of the Guyana coast for the period 1985–2002 (see Figure 1.2). The results of their finding demonstrated that the amount of sediments along the coast of Guyana increased by more than 60%. Grain size distributions of coastal sediments have been analyzed by Lakhan et al. (2002). The very fine silts and clays which are transported tend to flocculate, and when the concentrations exceed 450 kg per cu m it forms a coherent mass of viscous

mud, and eventually settle to form mudbanks (also referred to as mudshoals) (Allersma, 1971).



**Figure 1.2: Linear increase in the concentration of sediments in the near and offshore areas of the Guyana coast for the period 1985–2002 (from Ahmad et al., 2006).**

Mudbank morphological states are characterized by the formation of mudflats which could be considered the emerged parts of mudbanks. Twenty-one mudbanks were recorded along the coast between the Waini River, northwest Guyana and Cayenne in French Guiana (Delft Hydraulics Laboratory, 1962). In a computer simulation study by Lakhan (1991) on the interactions on nearshore water levels and coastal morphology it

was found that along the Guyana coast severe erosional cycles will occur every eleventh and twenty-fourth year. The erosional sequences were associated with the disappearance of shore-parallel mudshoals. The mudflats and associated mudbanks affect nearshore hydrodynamics, sedimentology and morphological states along the coast (Eisma and Van Der Marel, 1971; Barreto et al., 1975). Soft mud accumulates in the nearshore areas experiencing sedimentation. The soft mud deposits dampen the effects of propagating waves. The reductions in wave energy initiate depositional conditions (Winterwerp et al., 2007). With dampening of wave energy, the process of siltation begins to occur. Hence, coastal areas directly opposite a stationary mud shoal experience episodes of accretion. Conversely, the coastal areas between the troughs of two mud shoals are exposed to erosive waves. The study by Augustinus (2004) claimed that the influence of northeast trade winds, and associated wind-generated wave action influence the migration and displacement of mudbanks along the coast of the Guiana's. One consequence of the immobilization and eventual migration of mudbanks is a shift in the coastline.

With displacement of a mudbank erosion occurred in those coastal sections that were protected by the mudbank along the coast of Guyana, especially if the mudbank was once attached to the coast. Instead of the mudbank attenuating the impacts of shoreward propagating waves, the coast became exposed to the effects of concentrated erosive wave energies. Hence, the movement of mudbanks along the coast of Guyana was accompanied by a pattern of erosion and accretion of the adjacent coast. This situation was also observed along the neighbouring coasts of Suriname (Augustinus, 1987), and French Guiana (Froidefond et al., 1988). Erosion along the Guyana coast is also exacerbated by anthropogenic disturbances of the natural accretion processes, resulting in

serious erosion in certain coastal sections (Winterwerp et al., 2007). Efforts to alleviate problems of erosion along the coast have not met with much success because coastal management plans to date have not incorporated any scientific knowledge on the spatial and temporal shifts in the morphological states of the coastline. Flooding and erosional problems still persist in the coastal zone because of unscientific and ill-conceived planning and development strategies (Lakhan, 1994; Lakhan et al., 1995), and a lack of scientific understanding on the spatio-temporal dynamics of coastline changes.

## **1.5 Organization of Thesis**

The objectives of the research are discussed in various chapters of this thesis. The main Chapters (3–6) are manuscripts published in conference proceedings or being accepted by international journals (Journal of Coastal Research and Marine Geodesy) with reported impact factors. Chapter 3 is titled, “Framework for a spatio-temporal information-based system (STIBS) for decision-making.” Chapter 4 is titled, “GIS-based analysis and modelling of coastline positional changes.” Chapter 5 is based on, “GIS-based analysis and modelling of coastline advance and retreat.” Chapter 6 is on, “Time series modelling of data on coastline advance and retreat.” Chapter 7 presents “General discussions and conclusions” and relates the material presented in Chapters 3 to 6 to each other.

## **1.6 Significance of the Research Contribution**

The research presented in this thesis represents a considerable advancement over previous investigations on coastline changes because it combines geospatial techniques with computer-based models to assess and predict coastal changes in both the spatial and

temporal domains. Here it is worthwhile to emphasize that Lakhan (2010, p. 186) made it quite clear that, “coastal accretion and erosion and associated coastline positional changes, unpredictable in magnitude and duration, cannot be satisfactorily studied with small-scale experimental studies and time-limited empirical investigations.” In this research an advanced geospatial framework is presented whereby the coastline could be studied, modelled, and predicted at various scales.

The GIS-based modelling approach has the capabilities of being able to incorporate data from multiple sources in order to assess not only historical coastline changes but also to predict future advance and retreat states of the coastline. This is particularly important from coastal planning and development purposes because coastal managers could examine areas along the coast with different magnitudes of erosion and accretion. Erosional “hotspots” could be identified and visualized in order to implement effective coastal protection strategies. With the incorporation of coastlines extracted from remotely-sensed images, the GIS could be updated on a timely basis. This would be beneficial to countries like Guyana which have limited financial resources to regularly collect field data on coastline advance and retreat.

The significance of the research is further enhanced by fitting collected data to statistical models. This will permit the identification of temporal stochastic processes operating in the coastal system at different spatial scales. Understanding the stochastic processes in the coastal system will certainly lead to an improvement of knowledge on coastal behaviour. Since all models have to be validated, it is expected that this research will promote the development and testing of new hypotheses on the behaviour of coastal changes, not only in Guyana but also in other coastal locations. With the research

utilizing both data and models, it will also promote the development of spatial information systems. The framework for the spatio-temporal information-based system proposed here could serve as a practical and useful tool for the management of vulnerable coastlines.

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## CHAPTER 2

### BACKGROUND OF RESEARCH

#### 2.1 Literature Review

As far as could be ascertained there is no study has been done along the coast of Guyana which has used geospatial and geostatistical techniques to analyze, predict and model coastline changes. Many researchers around the world have, however, conducted investigations in the coastal environment with the use of remote sensing and GIS techniques. A selection of recent studies in the literature reveals the use of GIS and remote sensing techniques to study coastal changes in Brazil (Alves et al., 2003; Noernberg and Marone, 2003; Grigio et al., 2005), Cambodia and Vietnam (Sakamoto et al., 2007), China (Chen et al., 2004), Egypt (White and El Asmar, 1999; Dewidar and Frihy, 2010), French Guiana (Fromard et al., 2004), Iran (Alesheikh et al., 2004; 2007; Ghanavati et al. 2008; Ahadnejad and Maruyama, 2010), Ireland and the United Kingdom (Bagli and Soille, 2004), India (Maiti and Bhattacharya, 2009; Prabakaran et al., 2010; Kumar et al. 2010), Kenya (Ouma and Tateishi, 2006), Korea (Ryu et al., 2002), Malaysia (Li et al., 1998; Zakariya et al., 2006), Mauritania (Wu, 2007), Pakistan (Siddiqui and Maajid, 2004), Turkey (Ekercin, 2007; Sesli 2010; Kuleli, 2010), and the United States (Scott et al., 2003; Schupp et al., 2005).

Alves et al. (2003) utilized Landsat 5 TM imagery for monitoring and evaluating coastal morphodynamic changes along the northeast coast of Brazil. Images for 1989 and 1998 were used to identify changes in erosional and depositional states marked by changes in coastal geometry. In analyzing the images emphasis was placed on simple contrast stretched false colour composites which revealed good reflectance contrast

between clear and turbid water areas. The authors were successful in evaluating different morphodynamic areas along the coast, including beaches and dune fields. Erosion was found to be predominant over the ten-year imaging period.

Noernberg and Marone (2003) extracted shoreline positions by employing the Normalized Difference Water Index (NDWI) algorithm along the Brazilian coast. The combination of Landsat imagery and the NDWI enhanced the differences in pixel resolution between land and water. Reflectance of water was maximized at the visible end of the electromagnetic spectrum, and minimized within the near-infrared spectrum. Soil and vegetation land cover generated the highest reflectance in the near-infrared portion of the spectrum.

Changes along the Guamare coastline, Rio Grande do Norte State, Brazil were studied by Grigio et al. (2005) with remote sensing and geographic information systems techniques. Images from Landsat 5 TM and Landsat 7 ETM+ were utilized, and the NDWI was computed. The authors found that the use of the NDWI index method in Band 3 produced a large enhancement in the submerged and emerged areas, providing a better definition of water bodies and tidal channels. The resulting NDWI image compositions for the years 1989, 1998, 2000 and 2001 provided the required delimitation of the coastline. The results indicated that in the time period 1998–2001 the accretion and erosion processes of the coastline were more intense when compared with those of the earlier 1989–1998 period. In 2000–2001 erosion prevailed, contributing 78.1% of the total alteration of the coastline. GIS and remote sensing were found to be useful to evaluate evolution of the coastline.

Sakamoto et al. (2007) detected temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta (VMD) with MODIS time series imagery. Temporal changes in the extent of the inundated region in Cambodia and the VMD were assessed at a resolution of 500 m from 2000 to 2004. Water surface pixels were identified when the NDWI was greater than or equal to 0.8. The “not water-surface” pixels were identified when the NDWI was less than 0.8. Although the inundated area had a margin of error associated with the low resolution of the sensor, the estimates showed a strong correlation with the inundated areas and the images from the Landsat satellite.

Spatial patterns of the coast and water quality were determined by Chen et al. (2004) whereby a Landsat TM image was integrated with 58 *in situ* water quality datasets, and 30 samples from two concentrations maps of water quality from the Pearl River estuary and the adjacent coastal waters of Hong Kong. The NDWI was extracted from a December 22, 1998 Landsat image. The authors claimed that the NDWI was processed to enhance the water message and separate water pixels from land and shadows in the raw TM image. The land/water interface was identified by a value of 0.175 in the NDWI image.

Landsat TM imagery was used by White and El Asmar (1999) to delineate shoreline positions along the Nile Delta, Egypt. A segmentation algorithm permitted the identification of known pixels of open water, referred to as “seeds” to determine a common spectral reflectance class for water. The segmentation technique merged similar neighbouring pixels into a water classification, and proceeded to expand in a homogenous grouping in all directions until dissimilar pixels were detected. Results from the

segmentation approach demonstrated differences in land and water areas along the Delta. Shoreline positions were then mapped.

Dewidar and Frihy (2010) used Landsat images (MSS, TM and ETM+) between 1972 and 2007 along the northeastern coastline of Nile Delta in Egypt. They analyzed these images to quantify erosion and accretion patterns. Rates of shoreline changes were calculated by using a Digital Shoreline Analysis System (DSAS). After the comparison of the shoreline changes from the satellite data and empirical data, they claimed that the methodology applied is reasonably accurate, with a correlation coefficient of 0.76.

A combination of field surveys, aerial photographs, and SPOT satellite images were used by Fromard et al. (2004) to study coastal changes along the coast of French Guiana for the period 1951-1999. SPOT 3 images for 1991, 1993 and 1997 and a SPOT 4 image for 1999 were geometrically corrected and exported into a geographical information systems. Synthetic digital maps were then produced by combining the data from the various sources in the GIS. Net accretion was observed for the period 1951–1966. Between 1966 and 1991 erosion occurred, and this was then followed by an accretion phase. The integrated approach followed by the authors allowed them to state that the French Guiana coastline was unstable and continuously changing.

Alesheikh et al. (2004) utilized Landsat TM and ETM+ data for the years 1989, 1998 and 2001 to extract Urmia Lake coastlines in Iran. The authors utilized histogram thresholding and band ratioing together in order to achieve a higher degree of accuracy in separating land from water areas. By combining the two ratios they obtained an accuracy of 1.3 pixels for the extracted coastlines. The results permitted the conclusion that the extracted coastlines matched those from ground truth observations. The utilization of the

combined ratio technique permitted recognition of changes in the coastline between 1998 and 2001 because the water levels of Urmia Lake dropped by three metres.

Ghanavati et al. (2008) used Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data in order to monitor geomorphologic changes of Hendijan River Delta, southwestern Iran. They used Image- to -Map rectification scheme and an adequate number of Ground Control Points (GCPs) to give Root Mean Square Error (RMSE) of 0.34 pixel to rectify the ETM+ image. The techniques of bands subtraction, principal component analysis (PCA) and fuzzy logic were used to identify regions that have undergone land cover changes. The results of this study showed that the Hendijan River channel migrated several times over the last 48 years.

Remote sensing and GIS techniques was used by Mousavi et al. (2007) to determine the morphological changes of Sefidrud delta, Iran over the last three decades (1975–2005). LANDSAT MSS, TM and ETM+ and IRS data for the period of 1975 to 2005 was processed. The data were georeferenced with respect to 1:25,000 topographic maps. All the required datasets were registered to the IRS-Pan image. The data were then imported into GIS environment for analyzing and possible change detection. The updated features were digitized on screen and overlaid with the previous data. The obtained results demonstrated that the land area eroded at an average rate of 215.6 m/yr. The Caspian Sea level raised 2.6 m from 1975–2005, affecting the coast of Sefidrud delta promontory. It was observed that its promontory moved to eastward about 2 km as a maximum shoreline change over the last three decades. They emphasized the use of geospatial information for coastline change detection.

Ahadnejad and Maruyama (2010) used 18 multi-temporal satellite images (MSS, TM, MODIS) for fluctuations assessment in Uremia Lake in 1976–2009. The NDWI was used for separation and detection water from other phenomena. The near and middle infrared bands in the TM and ETM sensors, green and near infrared bands in MSS sensor, and the middle infrared and short wave bands in MODIS sensor were utilized. The Cellular Automata and Markov Chain methods were then used for the prediction of lake change areas. Based on the analysis, they claimed that lake area in 2019 will be reduced to about 2000 sq. km.

Bagli and Soille (2004) utilized Landsat 7 ETM+ images to extract coastlines and lake boundaries. Morphological image segmentation techniques were used to combine spectral and spatial information for the various images. A geographical information platform was then used to evaluate the performance of several embedded morphological segmentation algorithms. After extracting coastlines and lake boundaries for Ireland and the United Kingdom the authors concluded that morphological segmentation could be applied to Landsat 7 ETM+ data in order to extract and map coastlines for the entire European continent.

Maiti and Bhattacharya (2009) claimed that combined use of satellite imagery and statistical methods can be a reliable method for shoreline studies. Multi-resolution Landsat MSS, Landsat TM, Landsat ETM+ and ASTER images of different dates (1973 to 2003) were used on 113.5 km long coastal stretch on the east coast of India and West Bengal States. The linear regression method was used to calculate the past shoreline change rates. The estimated past shoreline positions were cross-validated using the RMSE technique. Predictions of short (13 year) and long (30 year) term intervals

shoreline positions were carried out. Results indicated that 39% of transects have uncertainties in the estimation of shoreline.

Remote sensing and GIS were also applied by Prabakaran et al. (2010) on 1076 km length of the Tamilnadu coast of the India to determine coastline change. Digital topographic maps dated 1970 (scale 1:50,000), Landsat TM, IRS – P6 LISS III and Cartosat1 satellite data were used to generate land use map for 1998, 2003, and 2008. Obtained results demonstrated that there was a drastic reduction of coastal land use types of the Vedaranniyam coast due to reclamation, dredging, tipping and other anthropogenic activities along the coast.

Kumar et al. (2010) used the topographic maps and multi-spectral satellite images to differentiate the positions of shoreline and spits during different periods (1910 to 2005) along the Karnataka coast, western India. The rate of change in shoreline position was calculated by using the statistical linear regression method and cross-validated with regression coefficient and RMSE methods. Past and future shoreline positions were demarcated and future positions of shoreline were estimated for time periods of 10- and 24-years.

Ouma and Tateishi (2006) developed the Water Index (WI) for the rapid mapping of shorelines. The WI was based on a combination of the Tasseled Cap Wetness (TCW) index and the NDWI. The WI was applied to quantify changes in five saline and non-saline Rift Valley lakes in Kenya using Landsat TM and ETM+ data. The WI detected the shorelines with an accuracy of 98.4%, which was 22.3% higher than the TCW, and 43.2% more accurate than the NDWI. The authors made the claim that the WI was



suitable for not only enhancing the desired lake water body, but also for accurate mapping of the shoreline.

Another study which employed remote sensing imagery was that done by Ryu et al. (2002) who evaluated data from Landsat TM, the Earth Observing System-Terra satellite, and the Advanced Spaceborne Thermal Emission and Radiometer. The tidal flat area of Gomso Bay, Korea was investigated and water lines were extracted. The near-infrared, short wavelength infrared, and thermal infrared were found to be reliable in extracting water lines at the flood tide positions. Among the three spectral bands, the thermal infrared was found to be the most effective in discriminating exposed tidal flat surfaces from sea water. The authors cautioned against using a single spectral band for delineating the various features of the tidal flat environment.

Li et al. (1998) used GIS application to study shoreline changes along the coast in the state of Pinnang, Malaysia. The erosion conditions were mapped and monitored by aerial mapping techniques, as well as a coastal geographic information systems was developed to support modernized shoreline monitoring and management. It consists of three components, shoreline erosion monitoring, coastal engineering management and coastal inventory. The data involved was spatial data, time series data, social and economic data and aerial photographs. The results showed that integration of spatial and time series data proved a successful technique to monitor and manage the coastline. They claimed that experiences gained from this study are beneficial for similar application in other geographic areas of the world.

Another study done in Malaysia was by Zakariya et al. (2006) who used Landsat 5 (1996) and Landsat 7 (2002) images to detect shoreline areas, and the Terengganu River

mouth, Malaysia. Both images were geometrically corrected and transformed and then connected to the same spatial location and projection. The Iterative Self-Organizing Data Analysis Technique (ISODATA) was then used to delineate the inter-tidal zone and land and water areas. Unsupervised classification on hue, intensity and saturation imagery with ISODATA produced different ranges of values for the different coastal features. Spatial analysis of the changes within a GIS permitted the detection of erosion and accretion at different scales. Between 1996 and 2002 there was more accretion than erosion in the study area.

Wu (2007) monitored coastline evolution of Nouakchott region, Mauritania, northwestern Africa and its potential change estimation by remote sensing techniques with multi-temporal, SPOT images. Markov chain analysis was used in the assessment process. The results showed that the north beach of the harbour extended by 0.92 km<sup>2</sup> (92 ha) from 1989 to 2001 and the accretion will probably reach its maximum limit in about 13 years  $\pm$ 6 months (in 2014–2015).

Siddiqui and Maajid (2004) used principal component analysis (PCA) on Landsat MSS and TM data to evaluate coastal changes between 1973 and 1998 in Pakistan. The multi-temporal PCA analysis results were integrated with each other in a GIS environment. The multi-temporal Landsat data used in this study were found to be useful for monitoring and mapping the coastal land accretion and erosion processes. The study provided the most recent database of the coastal environment along the coastal belt of Karachi.

Ekercin (2007) examined the coastline changes at the Aegean Sea by using satellite data from Landsat MSS, TM, and ETM for the period between 1975 and 2001. In

this study ISODATA classification and temporal image ratioing techniques were used for coastline change assessment. Significant coastline movements (in some parts more than 200 m) were detected for a 26-year period.

Kuleli (2010) used multi-temporal Landsat images (MSS dated 1972, TM dated 1987, and ETM dated 2002) to monitor the evolution of the coastline, and estimation of its potential changes along the Cukurova Delta at the southeast coasts of the Mediterranean Sea in Turkey. He used the ISODATA procedure, mosaicing, band ratioing (B5/B2), edge detection, and overlay techniques to extract coastlines. The rate of coastline changes (erosion/accretion) was calculated over a 30 year period with the Digital Shoreline Analysis System (DSAS).

Twelve Landsat 7 ETM+ scenes from Louisiana and Delaware were acquired by Scott et al. (2003). The scenes were then mosaicked together to form a continuous scene, and then processed with ERDAS IMAGINE. The Tasseled Cap Transformation (TCT) was then used to extract shorelines. The TCT was chosen over other methods because it was efficient and consistent in classifying pixels. The TCT recombined spectral information of six ETM+ bands into three principal view components. Of the three principle view components (i.e., brightness, greenness, and wetness) the wetness component was exploited to differentiate land from water. The results demonstrated that shoreline data could be defined by increasing the temporal resolution of image data sources, even if the spatial resolution was decreased. The claim was made that it was possible to accurately relate extracted shoreline data to elevation values obtained from coastal tide observation stations.

Historical coastline changes along the Massachusetts coast were mapped and analyzed with a GIS by Schupp et al. (2005). Shorelines were extracted from a variety of map and aerial photograph sources. The Digital Shoreline Analysis System was then used to calculate rates of shoreline change for different transects along the coast. The linear regression results indicated that 68% of the transects eroded and 30% of the transects accreted over time. Only 2% of the transects indicated no net change. Based on the maps and digital information that were produced the authors were able to claim that historical rate of change shoreline data are not only important for development planning but also allow for an evaluation of past coastline management efforts.

Chalabi et al (2006) used IKONOS data from 2004 and aerial photographs of 1966, 1975, 1983 and 1994 from the Kuala Terengganu area in Malaysia to determine the pattern of shoreline changes. The pixel based segmentation technique was applied on the IKONOS image and aerial photographs to extract the shoreline. Differential Global Positioning System (DGPS) was used to obtain thirty ground control points. The root mean square error (RMS) was less than half pixel (1 m). The results of time series data were combined and compared to each other showing spatial changes in the shoreline. Erosion and accretion revealed the geomorphological changes that occurred over the 38 years period (1966-2004). From these results, the values of erosion and sedimentation were not stable, with changes influenced by tides, waves and human activities.

Shu et al. (2010) proposed a new semi-automated method for shoreline extraction along the Canadian Pacific coast from RADARSAT-2 intensity imagery based on narrow band level set segmentation. Pre-processing techniques consisting of Gaussian filtering and histogram adjusting were first applied to improve the contrast of the SAR images.

Thresholding technique was then combined with morphological filtering to generate the preliminary segmentation of SAR image into land and sea. The narrow band level set segmentation method was implemented to refine the segmentation result. In the fourth step, morphological filters were used to remove any remaining false segments. Boundaries between the land and the sea were delineated into shoreline based on the segmentation result. The results indicated that the average error was less than one pixel. 3.08% of average commission and 0.48% of average omission errors were determined. Visual inspection indicated that the proposed method worked well. It also indicated that the initial contours of level set, and the narrow band method for propagating level set, largely reduced the computational burden and improved extraction efficiency. The authors indicated that to get a good preliminary segmentation result during the experiment, only the values of intensity threshold and the number of iterations required to be adjusted. They also claimed that the proposed method might be applied to shoreline mapping and updating by using interferometry, polarimetric, or multipolarization SAR images.

In addition to the use of GIS and remote sensing techniques to monitor and analyze coastal changes in specific countries, several authors have addressed the use of geospatial techniques to provide reliable and timely information on coastline changes. The development and benefits of GIS-based approaches for coastal investigations were emphasized by Bartlett (1999), and Bartlett and Smith (2005). Essentially, a GIS can be used to incorporate all aspects of coastal process and attribute data. The data can then be used to simulate various coastline change scenarios. Green and King (2003) also stressed the use of GIS as a formidable tool for monitoring and visualizing processes in the coastal

system. In addition, a GIS could serve as a up-to-date database with the incorporation of remotely-sensed images. The importance of remote sensing to monitor coastline changes accurately and efficiently has been stressed Ramsey (2005) who claimed that remote sensing is the only tool that can economically measure coastal morphodynamic features and processes over large areas at appropriate resolutions.

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## CHAPTER 3

# FRAMEWORK FOR A SPATIO-TEMPORAL INFORMATION-BASED SYSTEM (STIBS) FOR DECISION-MAKING<sup>1</sup>

### 3.1 Introduction

Information systems parameterized with diverse geospatial datasets were now emerging as powerful tools for decision makers who have to address contemporary spatio-temporal issues and problems occurring in vulnerable environments. While there is a compelling demand for the protection of vulnerable coastal environments within a framework of informed decision-making, yet current approaches are not providing reliable and timely solutions to escalating spatio-temporal problems including flooding, inundation, saltwater intrusion, and erosion. If, as is predicted, a worldwide sea level rise develops and accelerates as a consequence of global climatic warming there will be adverse impacts on coastal populations, ecosystems and socioeconomic systems for nearly 200 low-lying coastal areas (Jelgersma et al., 1993).

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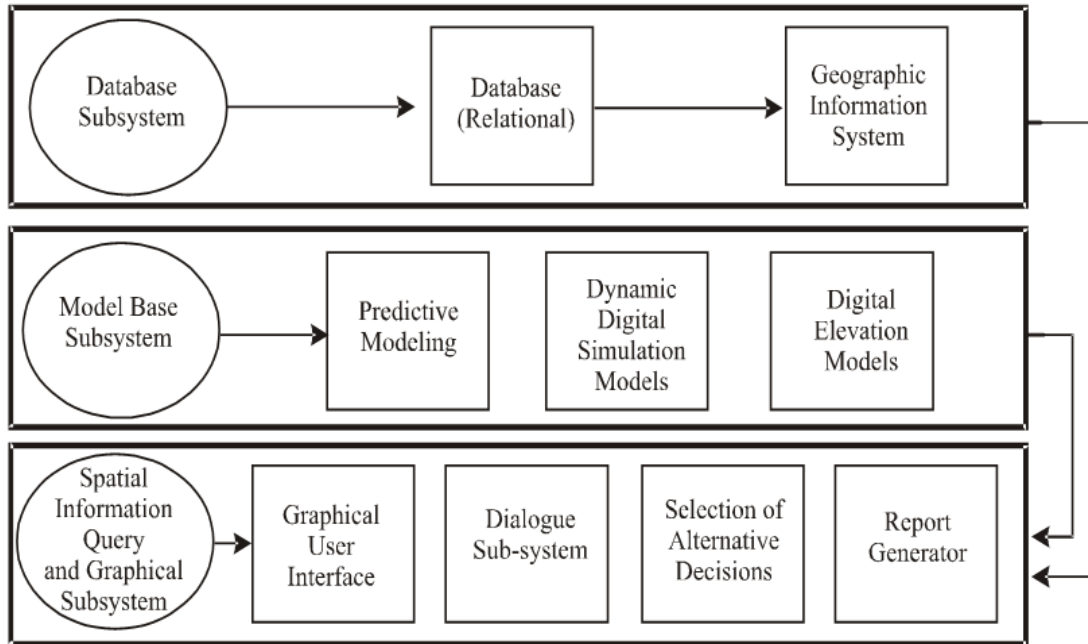
<sup>1</sup>A version of this Chapter was published in the *Proceedings. The International Multi-Conference on Engineering and Technological Innovation* as:

Ahmad, S.R., and Lakhan, V.C., 2009. Framework for a Spatio-Temporal Information-Based System (STIBS) for Decision-Making. In: Callaos, N., Chu, H-W., Savoie, M., and Zinn, C.D. (eds.), *The International Multi-Conference on Engineering and Technological Innovation*. Orlando, FL: International Institute of Informatics and Systemics, pp. 103-107.

Since a more effective and efficient approach must be utilized to deal with current and expected future problems confronting vulnerable coastal environments this paper presents the framework for a Spatio-Temporal Information-Based System (STIBS) which is applicable for not only interactive decision-making, but also beneficial for vulnerability assessments and problem-solving in the coastal environment. The STIBS presented here employs a methodological approach which integrates interacting subsystems to handle data and databases, dynamic computer-based simulation models, information flows, queries, and graphical displays.

### **3.2 General Framework of STIBS**

The unique strength of the STIBS framework lies with the fact that it combines practical geospatial technologies and information-gathering systems with a diverse array of datasets and dynamic computer-based simulation models to form components of a scalable, adaptive, and interactive decision-making system. After Lakhan (2005) considered the architectural design of spatial decision support systems (Armstrong et al., 1986; Densham, 1991), SOLAP technology (Rivest et al., 2005), IPODLAS software architecture (Isenegger et al., 2005) and other methods of spatio-temporal data integration and visualization, this research formulated a STIBS to include three subsystems, each with interconnected modules (see Figure 3.1).



**Figure 3.1: Framework of a spatio-temporal information-based system. Source: Lakhan, 2005**

While space limitations prevent a full discussion of the aforementioned illustrated schematic framework some brief remarks are, nevertheless, provided on the utilization of the three subsystems namely, (a) database subsystem, (b) model-based subsystem, and (c) spatial information query and graphical subsystem.

### ***3.2.1 The database subsystem***

Embedded in this subsystem is the relational database management system (RDBMS) and the geographical information systems (GIS). The RDBMS utilized by the STIBS is Microsoft Office Access (Microsoft Corp. Inc., 2007), formerly Microsoft Access. This versatile RDBMS system offers the capabilities of asking complex queries and analyses across large datasets. One of the advantages of using this RDBMS is that it

can be linked to the GIS software via the Open Database Connectivity (ODBC). The ODBC allows the movement of data back and forth between various compliant applications.

The GIS facilitates the manipulation, analysis, modelling and visualization of both non-spatial and spatially-referenced data (Lakhan, 1996). Applications of GIS in the coastal environment by Lakhan, (2005; 2008) demonstrate that a GIS can be parameterized with data from several sources, including:

- (a) topographic and thematic maps - maps for coastlines land use, soils, geology, hydrology, vegetation, transportation, anthropogenic infrastructure, and other characteristics can be digitized and stored in layers for analysis, interpretation and manipulation.
- (b) archival sources, especially national and municipal censuses which provide demographic, economic, social, income, educational, industrial, household, etc. data. The data permit the creation of attribute files for use by the GIS.
- (c) field measurements on an ongoing basis are vital for the acquisition of current hydro-meteorological, sedimentological, geochemical, environmental, water level, water currents, and drainage etc. data.
- (d) biotic and ecological data, especially on plants, animals and ecosystems, etc.
- (e) global positioning system data for the creation of geometrically accurate databases.

- (f) aerial photographs for various time periods could be scanned to obtain spatial and attribute information on coastline positions, industrial and agriculture activities, biophysical characteristics, etc.
- (g) remotely sensed data especially from multiple satellites can be used to supplement data acquired from aerial photographs. The acquisition and processing of remotely sensed data will permit an understanding of ongoing spatial and temporal changes. In addition, remotely sensed data will be invaluable for regular updates of thematic and other layers in the GIS.

With the knowledge that a GIS has the functionality to assess changes over a broad spatial area it will also be beneficial to acquire data which will facilitate how coastal processes shape the configuration, morphology and landform characteristics in the coastal environment.

### ***3.2.2 The model-based subsystem***

Since a GIS cannot perform dynamic simulations, state-of-the-art models (numerical, and simulation) are coupled within the GIS. As shown by Gilman et al. (2001) and Vance et al. (2007), the integration of a GIS with coastal and decision support models permits not only enhanced analyses and queries but also geovisualization of spatial results.

Given the need to understand and predict the impacts of various coastal processes on morphological states, settlements and infrastructural works along the coastline it is necessary to utilize a range of numerical and dynamic simulation models. Essentially the models must be capable of predicting impacts in both the spatial and temporal domains.



Several relevant coastal models can be found in recent edited books by Lakhan (2003) and Lakhan (2004). The coast could be studied with commercially available models such as TELEMAC (SOGREAH Consultants, 2009), MIKE 11 (Danish Hydraulic Institute, 2004), and DHI Marine Data Model (Danish Hydraulic Institute, 2007). In addition, inexpensive models can be employed for certain applications. For the coastal environment OCEANOGRAPHIC ANALYST (Hooge and Hooge, 2000) is used to provide 3-D analysis and display of volumetric and time series oceanographic data because it has an extension to the ArcView GIS. GUYSIM (Lakhan, 2002) is applicable for simulating the impacts of propagating waves and changing nearshore water levels on coastal morphology. Factors influencing coastal erosion and accretion could be assessed. In addition, inundation impacts from rising sea levels can be simulated with various scenarios of global mean sea level rise. The Digital Analysis Shoreline System (DSAS), version 3.2 (Thieler et al., 2005) is a software extension to ArcGIS version 9.0 and is therefore ideal for calculating shoreline rate of change statistics from multiple historic shoreline positions. DSAS can be used to simulate future coastline positions and associated erosional and accretional changes at different spatial scales and durations.

### ***3.2.3 Spatial information query and graphical subsystem***

With the functional applications to model, map, and query a diverse array of spatial datasets, the decision-maker could use the GIS to visualize various results and make multiple queries depending on specific objectives. For instance, with a realistically parameterized STIBS, the decision-maker could make queries pertaining to the occurrences of floods and erosion through time and over space. Here it is worthwhile to note that the GIS provides the environment for data and model integration, and results

visualization. GUYSIM (Lakhan, 2002) and other models provide simulation results on coastal processes, flooding, inundation and erosion/accretion occurrences under various wave and water level scenarios.

With the GIS serving like a central hub between the RDBMS and the simulation model runs, the formulated STIBS can provide the decision-maker with multidimensional information sets which can subsequently be queried for specific solutions and answers. For instance, modelling results on the spatial extent of flooding and inundation could be visualized in the GIS environment, and then queries could be made on which communities will be most affected by flooding/inundation occurrences. In addition, another query could yield information and maps on the spatial extent of a flood or erosion episode. Moreover, with the integrated RDBMS, temporal information could be obtained on the durations of various flooding/inundation and accretion/erosion episodes.

### **3.3 Methodology**

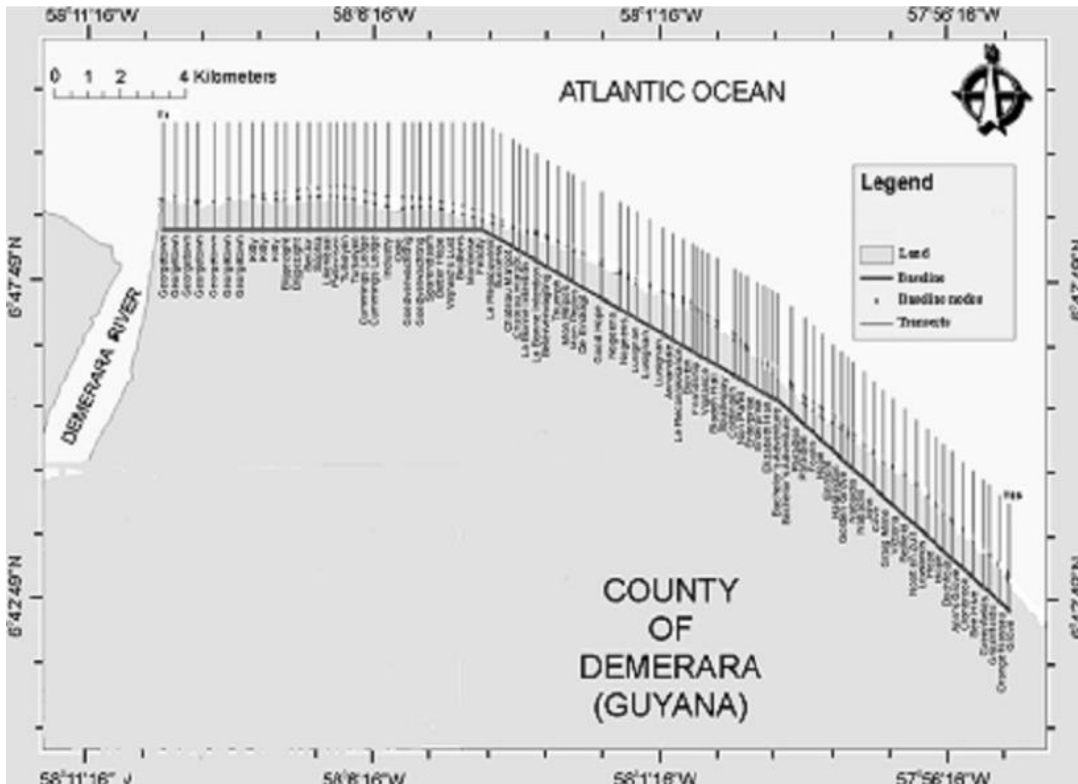
The detailed methods are followed as:

#### **3.3.1 Data sources**

To fulfill the objectives of this research, data on Guyana were obtained from several sources. Data were collected from archival sources, field measurements, topographic maps, remotely-sensed satellite images, and a global positioning system (GPS).

### 3.3.2 Data from archival sources

The Ministry of Works and Hydraulics, Lands and Surveys Division, Government of Guyana collects and maintains data collected from the coast of Guyana. After examination of the various datasets, permission was obtained to use the coastline change data collected for the period 1941–1987. This data set represents a complete set of coastal records pertaining to annual foreshore 45 feet + GD (Georgetown Datum) and 50 feet + GD contour elevation measurements along the settled portion of the coast of Guyana. The data set used in this thesis were measurements obtained from 86 transect profiles measured approximately 300 m apart along the Demerara coast. These transect profiles along with the name of the communities are shown in Figure 3.2.



**Figure 3.2: Transit profiles (1-86) showing communities name along the Demerara coast, Guyana.**

The 45 feet + GD (hereafter referred to as 45 GD) contour corresponds with the approximate Chart Datum or mean low water level while the 50 feet + GD (hereafter referred to as 50 GD) contour is the datum which is 0.5 feet (0.3 m) below mean sea level. The foreshore elevation for 45 GD is 13.7 m, and for the 50 GD is 15.24 m.

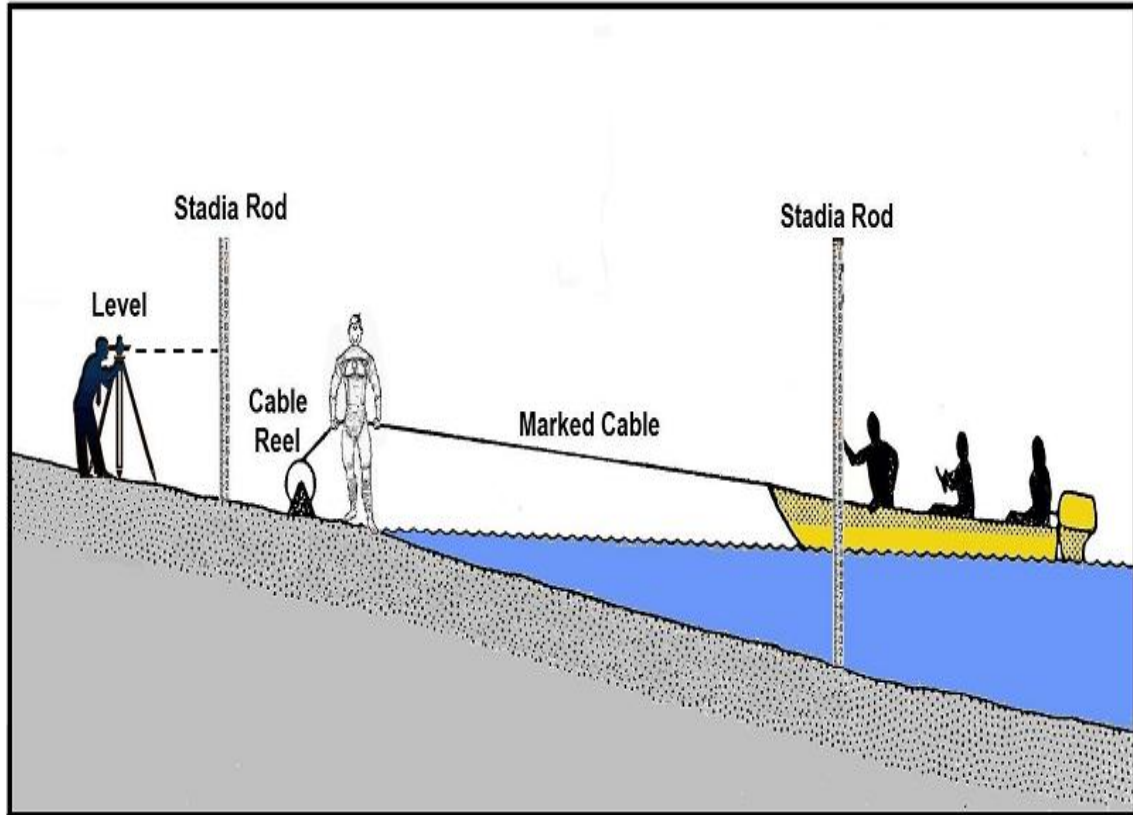
### ***3.3.3 Field measurements***

Since budgetary constraints prompted the Government of Guyana to suspend the coastal field data collection program in 1987, a program was initiated by Dr. V.C. Lakhan in 1988 to continue data collection along each of the 86 transect profiles established by the Lands and Surveys Department. Researchers in Guyana and various graduate students, including myself, have collected data from each of the 86 transect profiles. From 2005 to 2007 I participated in the collection of coastline change data and data relating to processes (wave heights, wave periods, current velocities, suspended sediments, water levels, etc.) in Guyana's coastal system. A transit level, a Magellan GPS, a Lufkin surveyor's chain, a stadia rod, and a Topcon GTS-230W electronic total station (Figure 3.3) were used in the data acquisition process.



**Figure 3.3: Topcon GTS-230W electronic total station**

The total station has an accuracy of  $\pm 5$  mm. Field data collection was done as illustrated in Figure 3.4.



**Figure 3.4: Illustration of field data collection.**

Prior to data collection, the original transect profile established by the Department of Lands and Surveys was identified and resurveyed using a Sokkisha B2 automatic level. For the sake of safety, and accuracy measurements were taken at low tides.

By extending the transect profile lines data were also collected for at least 100 m seaward. This was done using a boat, a stadia rod, and a Lufkin surveyor's chain. Care was taken to align the boat with two markers on the coast in order to keep the transect profile as nearly perpendicular to the baseline as is possible. Changes in elevation of the nearshore slope were recorded at 50 m intervals.

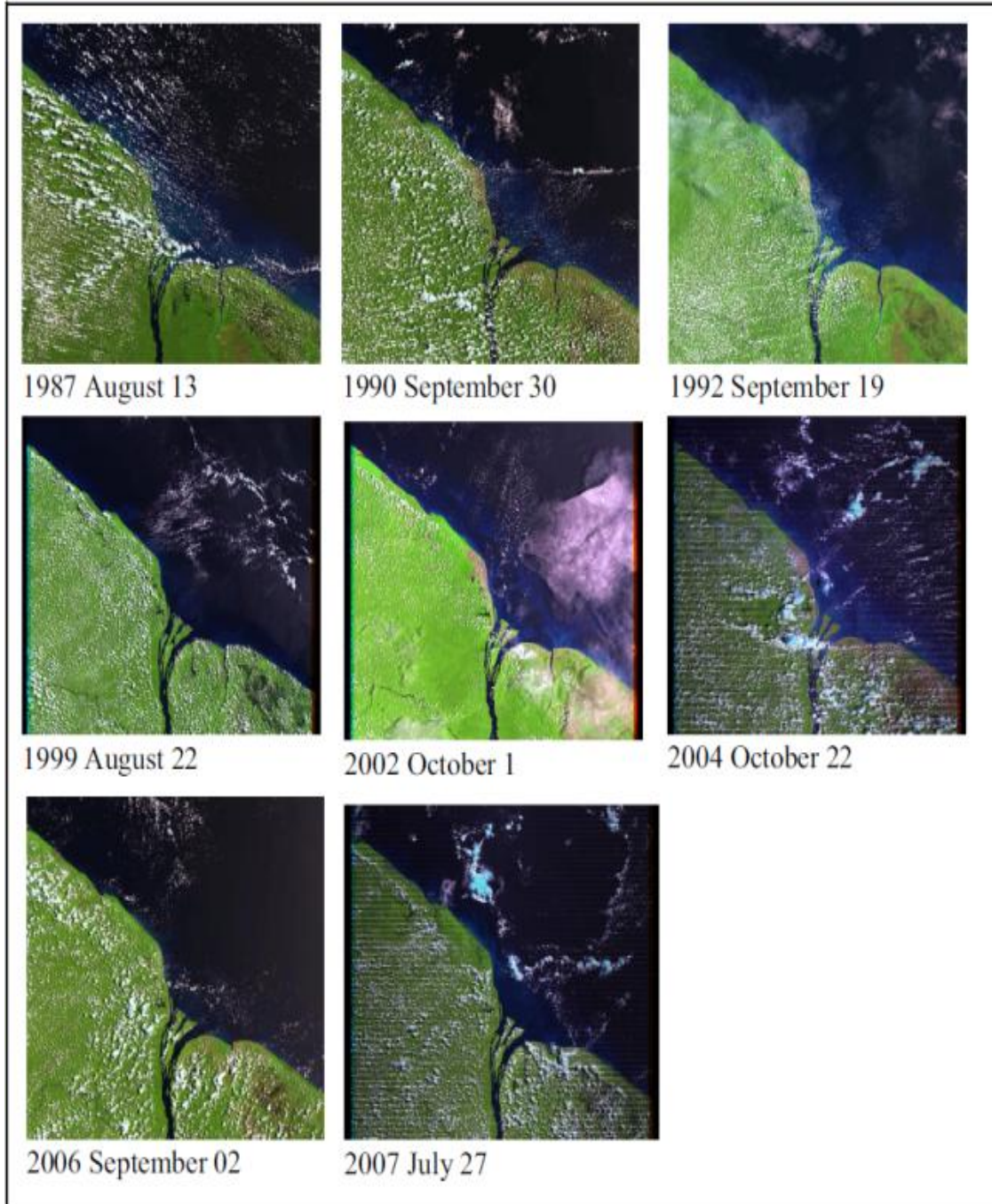
### ***3.3.4 Topographic map data***

Guyana topographic UTM Grid maps (scale 1:50,000) for the years 1964 and 1986 were used to obtain digital data for input into the GIS. The quadrangles 20NW and 21SE, representing the study area along the Guyana coast, were digitized according to the procedures outlined by Lakhan (2003). The coastlines were digitized as line features with a Calcomp digitizer. Each map was digitized until the Root Mean Square Error (RMSE) was below 0.002. This error is below the acceptable limit mentioned by Lin (1999). The completed coastline vectors were converted to a UTM projection with the map units in meters.

### ***3.3.5 Remotely-sensed satellite images***

Landsat images of the Guyana coast were also used to extract coastlines for various time periods. Coastlines were extracted from Landsat Thematic Mapper (TM) images for the time periods August 1987, September 1990, and September 1992. Enhanced Thematic Mapper Plus (ETM+) images were acquired for the time periods August 1999, October 2002, October 2004, September 2006, and July 2007. Figure 3.5 provides a preview of each of the eight images.

All images were acquired at low tides in order to maximize the discrimination of the seaward edge of the coastline. Each of the six reflectance bands of the eight images has a spectral resolution of 30 m.



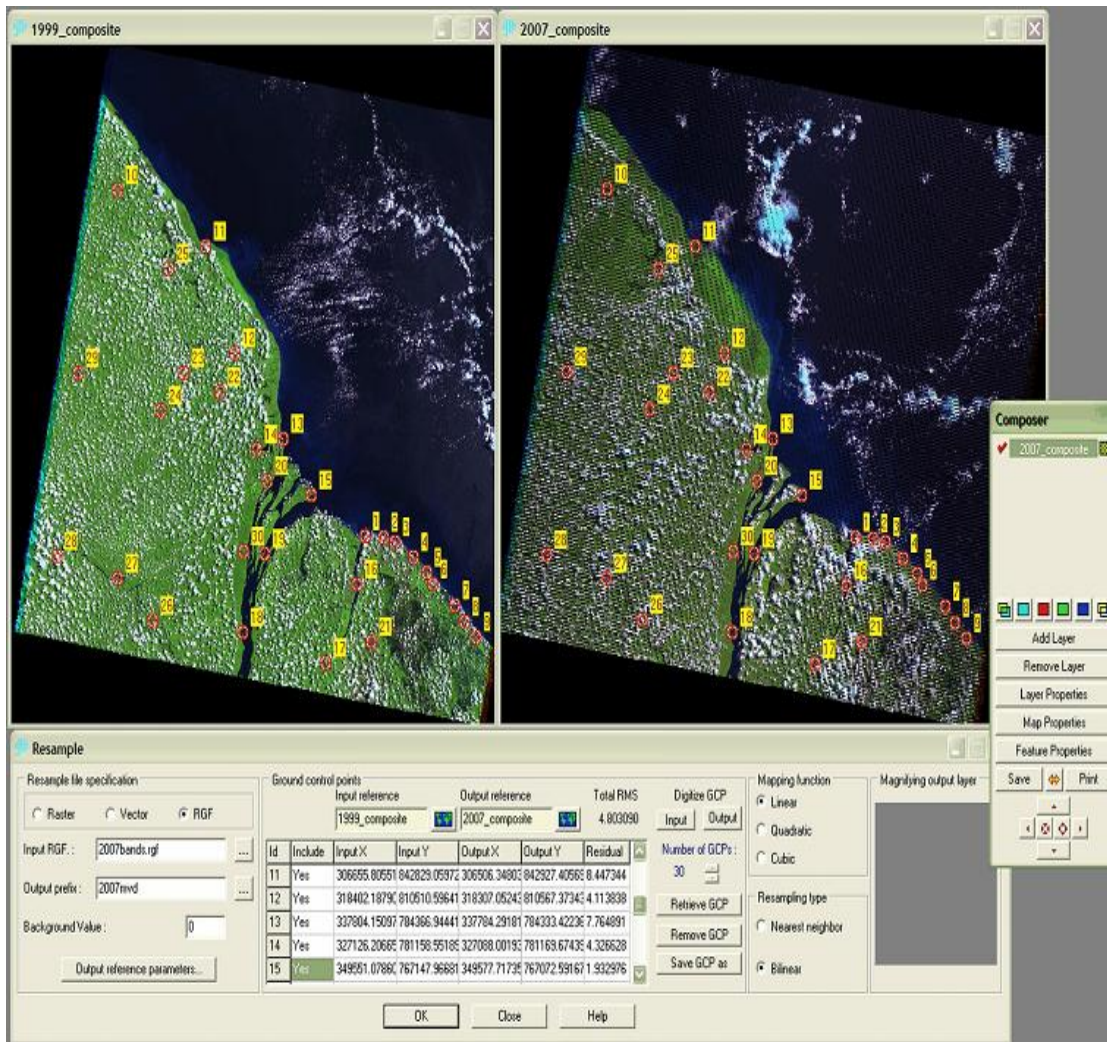
**Figure 3.5: Preview of eight Landsat images of the study area along the coast of Guyana.**



### 3.3.5.1 Image processing

Geoprocessing techniques in Idrisi Kilimanjaro, version 14.02 (Clark Labs, 2003) were used to process each of the images. Each of the images had to be radiometrically corrected and geometrically rectified. Relative radiometric correction was performed in order to normalize the multiple satellite scenes to each other. To do this Eckhardt's et al. (1990) recommendations were considered and pseudo-invariant features (PIF) were selected. Each of the PIF had fairly constant reflectance values during the time period that the images were acquired. Based on field work along the Guyana coast, the PIFs that were selected included beaches, asphalt roadways, concrete drainage sluices, and cricket playgrounds.

Each of the images was also geometrically rectified with topographic maps and GPS ground control points (GCPs). A total of 42 GCPs were used, with 12 obtained with a Magellan Mobile Mapper GPS. Thirty ground control points were obtained from 1:25,000 topographic maps. With the use of the Idrisi software the accuracy of the georeferenced images was maintained by minimizing the RMSE to 0.16 pixels. Figure 3.6 shows that the RMS value is 4.8 m (0.16 pixels). Although the specified coordinate system was UTM Zone 21N for each of the eight images, the Idrisi Project module was, nevertheless, used on all image bands to remove anomalies or distortions.



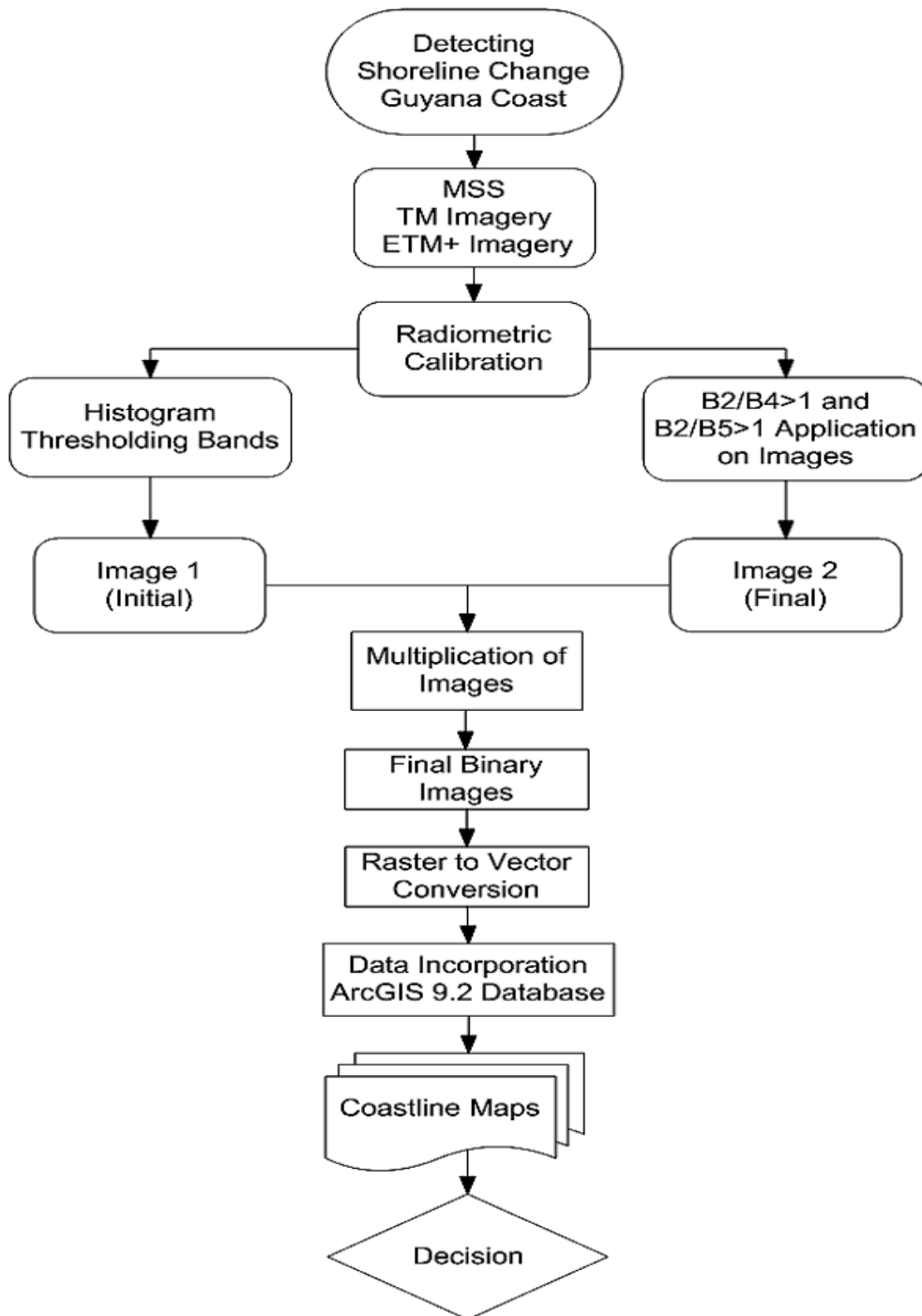
**Figure 3.6: Ground control points used with Total RMS value.**

### 3.3.5.2 Extraction of coastlines

The method that was selected to extract the coastlines from the Landsat TM and ETM+ images was selected on after reviewing several coastline extraction and change detection techniques, among them the Normalized Difference Water Index (NDWI) (McFeeters, 1996; Grigio et al., 2005), threshold level slicing (Braud and Feng, 1998), density slicing (Frazier and Page, 2000), Tasseled Cap Transformation (Scott et al., 2003), morphological segmentation algorithms (Bagli and Soille, 2004), band ratioing

(Alesheikh et al., 2004; Guariglia et al., 2006), and Iterative Self-Organizing Data Analysis Technique (Yuksel et al., 2008; Kuleli, 2009). The decision was made to use the band ratio method because it has the advantage of considering all the multispectral data present in the various spectral bands. The findings of Lakhan and Chan (2007) were substantiated whereby it was found that the ratio images were very useful in exploiting the information present in the near-infrared and short wave infrared bands. A high percentage of the wavelengths of these bands are absorbed by water, and as a consequence surface water appears black on imagery. Moreover, as reported by Braud and Feng (1998) and Fraizer and Page (2000) the near-infrared and short wave infrared bands exhibit higher reflectance characteristics from soil and healthy vegetation and as such provide a clear distinction of the land/water interface. Given the efficiency, and results of the band ratio technique it was, therefore, used to extract the coastlines from the eight images. The procedures of the band ratioing method were outlined by Alesheikh et al. (2004). The use of the band ratio method follows the outline presented in Figure 3.7. Each of the eight images was subjected to histogram thresholding, band ratioing (Band 2/Band 4 > 1 and Band 2/Band 5 > 1), image multiplication, and raster to vector conversions. The eight binary images which were produced were exported from Idrisi to ArcGIS 9.2 (ESRI, 2007) as Geotiff files. The ArcScan extension of ArcGIS was used to

convert the raster images to vector files.



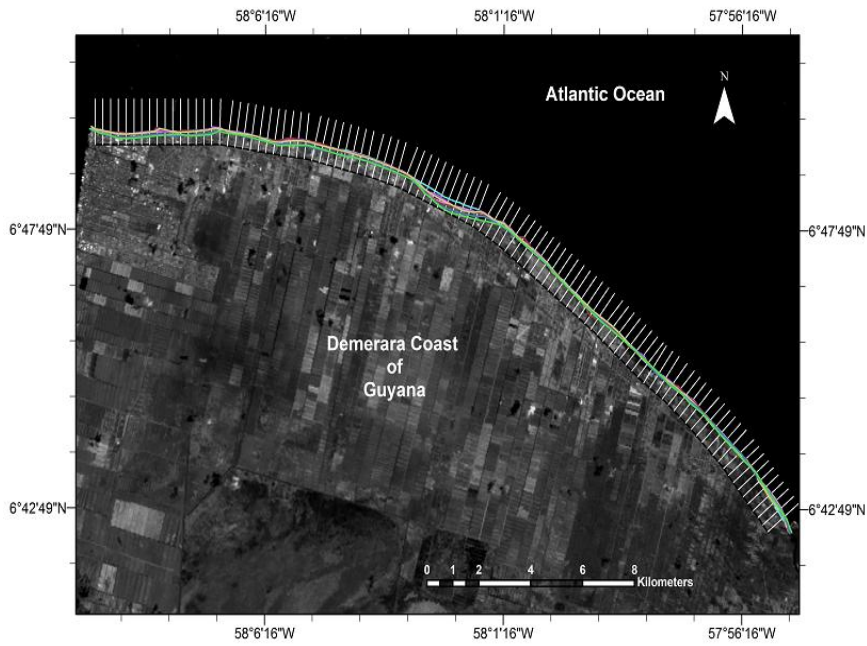
**Figure 3.7: Flowchart outlining the band ratio and thresholding method (from Alesheikh et al., 2004).**

### **3.3.5.3 Coastline prediction**

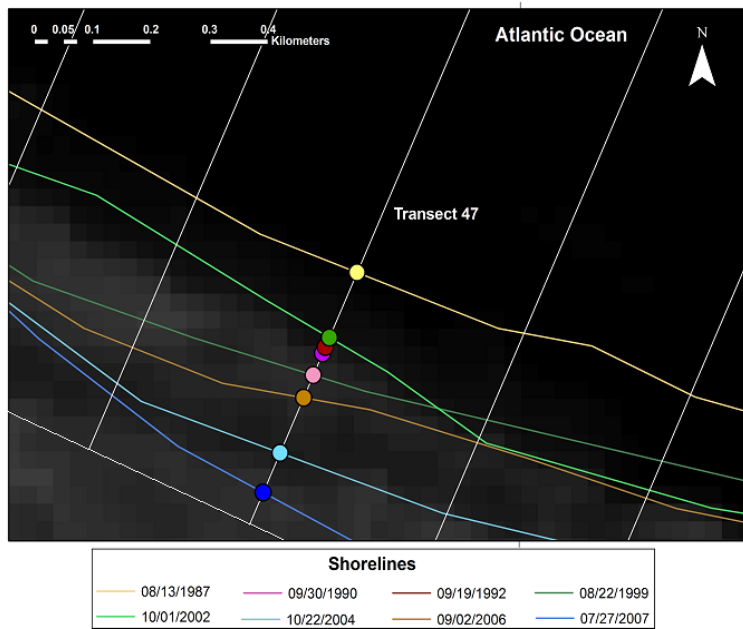
The Digital Shoreline Analysis System (version 4, Thieler et al., 2009), hereafter referred to as DSAS, was used to predict coastlines extracted from the remotely-sensed images. In brief, DSAS is an ArcGIS extension that is used to calculate coastline (referred to as ‘shoreline’ by DSAS) rates of change and net coastline movements from multiple historic coastline positions (Thieler et al., 2005).

Following the requirements and procedures required by the DSAS software a baseline was established. DSAS then generated transects that were cast perpendicular to the baseline at a user-specified spacing. In experimenting with the transect spacing it was found that the DSAS was capable of generating transects at every 30 m, thereby matching the size of a pixel from the Landsat TM and ETM+ images. The average advance and retreat rates were, however, computed for every 300 m. This 300 m spacing represented here (see Figure 3.8) was used to match the 300 m spacing interval that was established by the Lands and Surveys Department, Government of Guyana.

With the use of the GIS and DSAS the amount of material lost or gained from each of the eight extracted coastlines (see Figure 3.9) was calculated. DSAS permitted the calculation of advance or retreat rates from each of the 86 transect lines.



**Figure 3.8: Transects cast by the DSAS software at 300 m intervals**



**Figure 3.9: Eight extracted coastlines from 1987 to 2007 along the Guyana coast.**

### ***3.3.6 Statistical modelling procedures***

With the assumption that data are generated by the governing processes in the coastal system, this research employed statistical modelling procedures to identify the various types of statistical models which could best fit the acquired data. According to Lakhan (2005), time series models are essential for understanding not only the operating processes but also to gain insights on the spatial and temporal behaviour of the coastal system. In this respect, Box-Jenkins time series modelling procedures were fitted to the data. Several types of time series models can be obtained from any time series of coastal data. The autoregressive moving average (ARMA) models have been described by Box and Jenkins (1970; 1976) while the autoregressive integrated moving average (ARIMA) models have been generalized by Cressie (1993) to incorporate spatial locations. Whatever type of time series model that is to be fitted to any given data set it is worthwhile to follow the identification, estimation, diagnostic, and construction stages recommended by Box and Jenkins (1976). The iterative approach of the various stages of model fitting used in this thesis is presented in Figure 3.10.

In order to identify and fit the most appropriate model to the time series of coastal data it was also necessary to follow a number of steps of model identifications and parameter estimations. In the selection of the best fit model the flowchart presented in Figure 3.11.

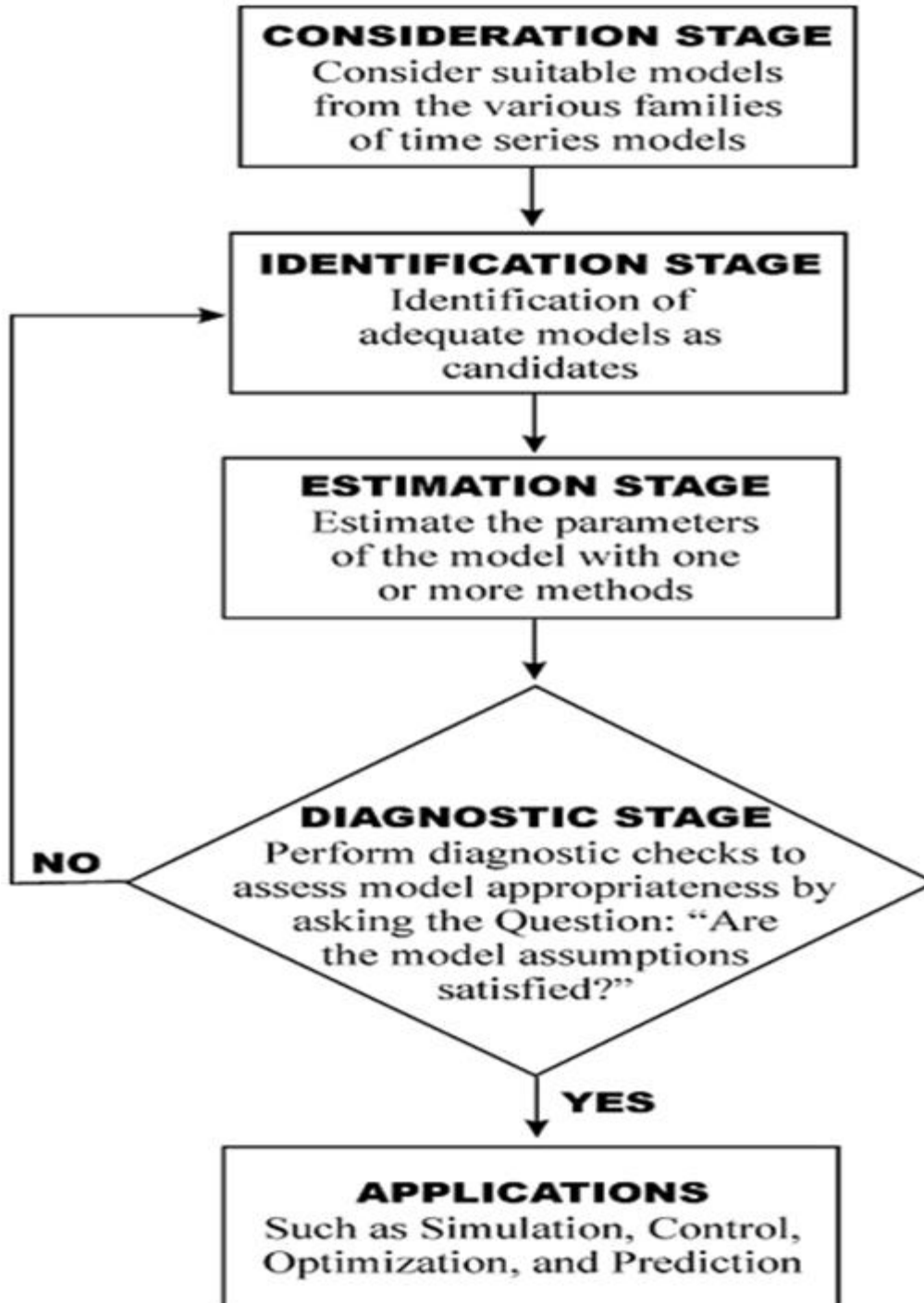


Figure 3.10: Stages in the iterative approach to model construction steps in model selection. Source: Lakhan, 2005.



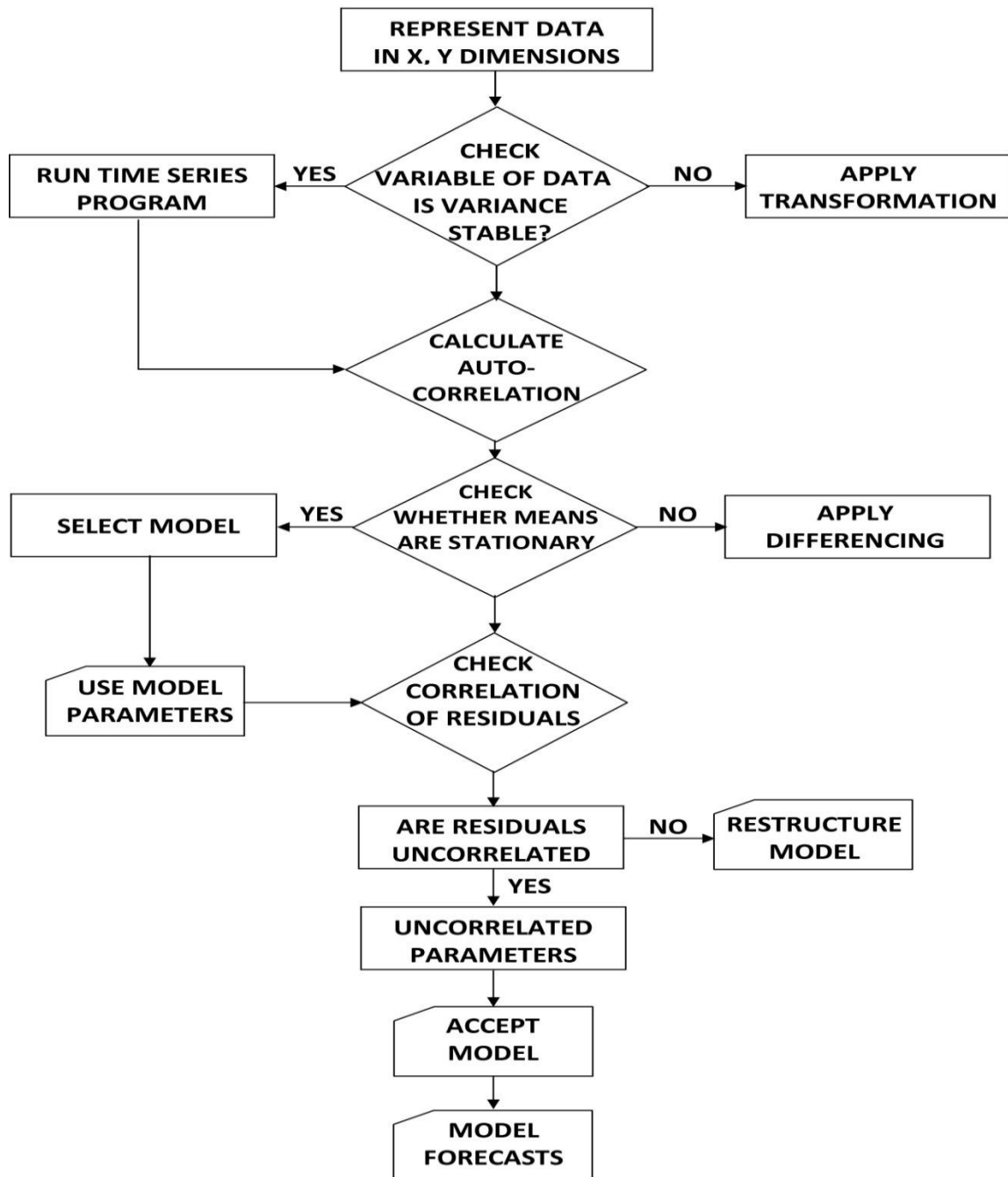
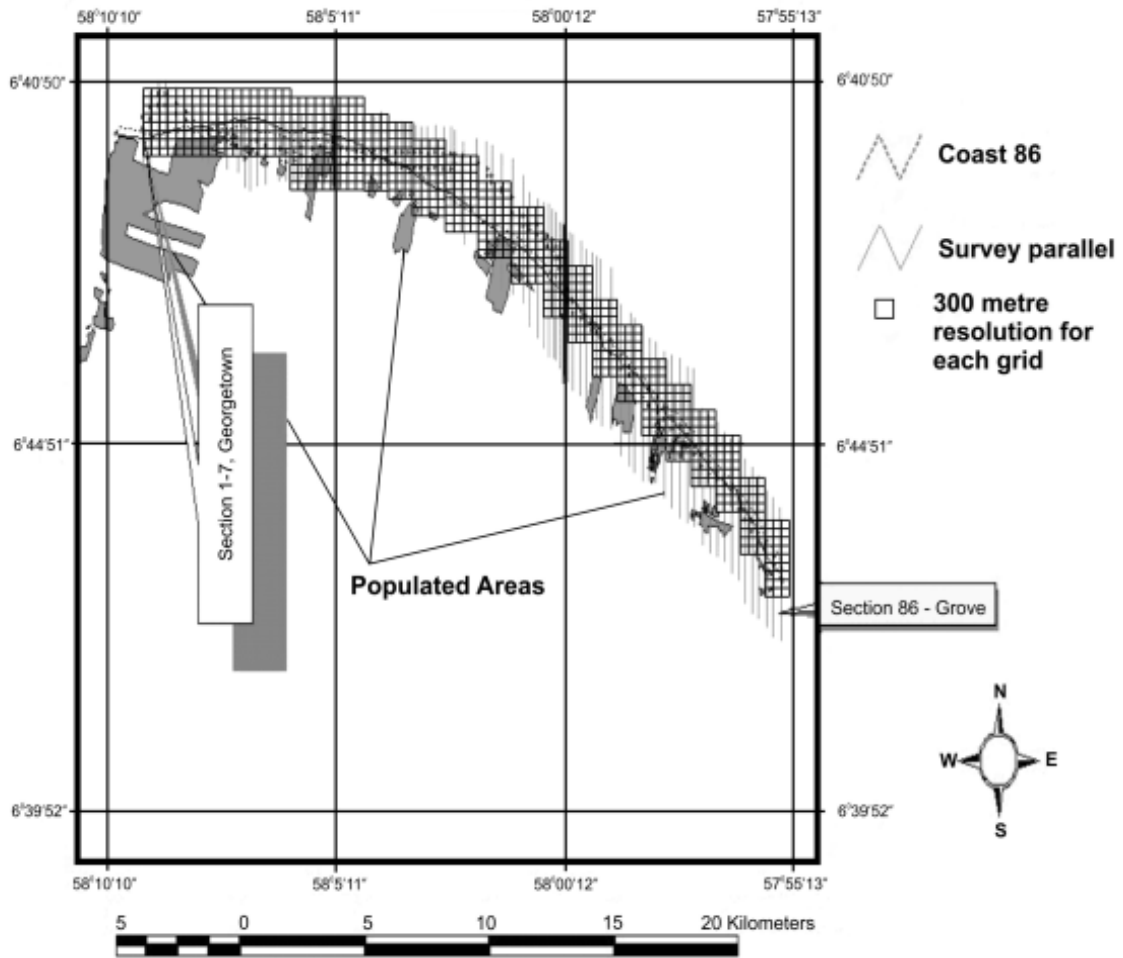


Figure 3.11: Box-Jenkins procedures used to select the best fit model. Source: Lakhan, 2008.

Essentially, before a model is selected and fitted to a given time series it is necessary to determine that there should be: a) no systematic change or trend in the mean, b) no systematic change in the variance, c) no deterministic periodic variations, and d) the autocorrelation function must be dependent on the lag interval, and not the starting point of the series (Chatfield, 1984). If the parameters of the series are uncorrelated, then the most appropriate model is accepted. To determine with certainty that the most appropriate models have been selected this research also examined correlogram plots which depict lag intervals plotted against partial autocorrelation coefficients.

### **3.4 Application of STIBS – A case study**

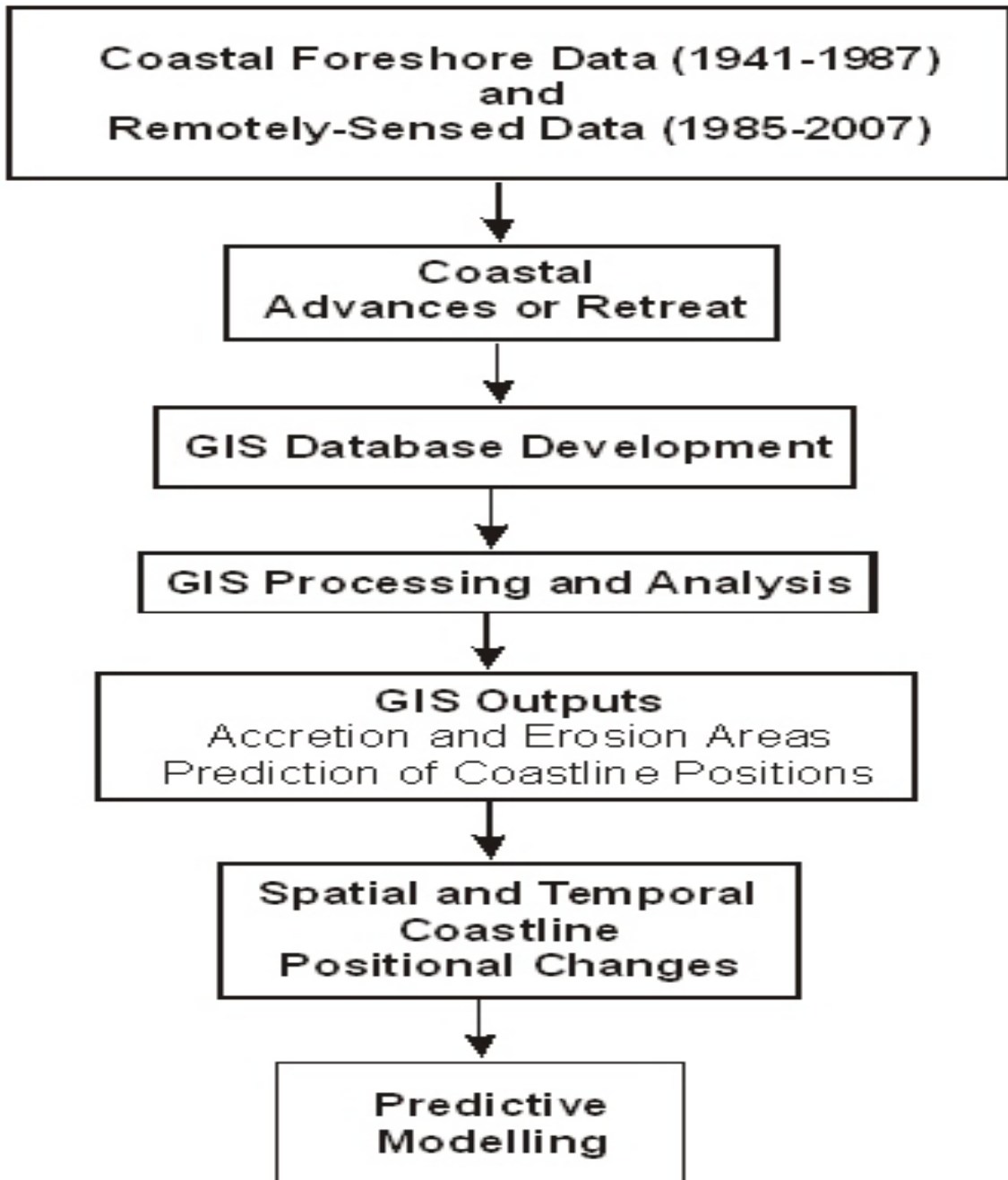
The STIBS system was applied to the Guyana coast because it is a prime example of a vulnerable low-lying coastal area which will suffer disastrous consequences with projected sea level rises. Based on the findings of the Intergovernmental Panel of Climate Change (2007), this study assumes a sea level rise of 18 cm to 59 cm by 2095, plus an additional 10 to 20 cm to allow for a potential response of global warming to an eventual total range of 18 to 79 cm by 2095. To investigate the spatial locations that will experience flooding, inundation and erosional occurrences at different periods through time the STIBS was initialized with a representative section of the Guyana coast. Topographic maps and bathymetric contour maps were then digitized. A GRID structure was then generated at a 300 m resolution to cover the entire coastal area of interest (see Figure 3.12). To realistically represent the coast and study the temporal impacts of various processes grids extended both landward and seaward of the coastline.



**Figure 3.12: Generated grid structure for research study area. Source: Lakhan, 2008.**

The STIBS was then parameterized with erosion and accretion data collected along the coast for the period 1941 to 1987. To supplement the empirical data, remotely-sensed images from the Landsat TM and the Landsat ETM+ satellite systems were also acquired for eight time periods (1985, 1987, 1990, 1992, 2004, 2006 and 2007). The data were processed with the Idrisi software (Clark Labs, 2004), and coastlines were extracted for each of the time periods. The empirical data on coastline advance and retreat were

then used together with the remotely-sensed data to predict spatial and temporal positional changes. The procedure followed is outlined in Figure 3.13.



**Figure 3.13: Graphical representation of coastline prediction procedures. Source: Ahmad et al., 2005.**

The advance and retreat rates data for 86 survey locations, representing a 30-km section of the Guyana shoreline, were then stored in a dBASE (dataBased Intelligence, Inc., 2006) file. The data file with the  $x$  and  $y$  values were then used in ArcGIS 9.0 (ESRI, 2004) to create point and line layers. Long-term rates of shoreline change were then generated in ArcGIS 9.0 with the Digital Shoreline Analysis System (DSAS), version 3.2 (Thieler et al., 2005). The DSAS facilitated calculation of the shoreline change process, providing both rate of change information and the statistical data necessary to establish the reliability of the calculated results. With the DSAS extension, the distance between two coastlines (1964–1986) was derived. Long-term rates of shoreline change were then computed with the linear regression method. Historical coastlines (1979 and 1994) and future coastlines (2016 and 2031(see figure 3.14)) were then predicted. The predicted coastlines were then graphically displayed.



**Figure 3.14: Predicted future coastlines (2016 and 2031) along the coast of Guyana.**

### **3.5 Discussion and conclusion**

When the predicted historical coastlines were compared with the actual coastlines of 1979 and 1994 an extremely close similarity was found between the observed and predicted coastlines. Since the results demonstrate that coastline configurations could be predicted, it is possible to make the claim that the historical rate of coastline change is a good indicator for predicting future coastline changes. Examination of the historical coastline movements and future coastline positions clearly highlight noticeable erosional and accretional trends along the coast of Guyana. When the historical coastline positional data are processed in a GIS and then used for predicting future coastlines with the DSAS it becomes evident that the coastline, through time, will exhibit positional changes in width and configuration. The temporal phase shifts in sections of the coast emphasize the occurrences of spatial positional changes in relation to advance and retreat of the coast. Whenever the coast advances or retreats coastal communities are confronted with problems associated with seawater intrusion, or inundation, or flooding. Problems are further exacerbated with rising water levels which provide the medium for higher and steeper waves. As previously reported by Lakhan, (1991), the combined effects of waves, currents, and water levels will remove the conditions necessary for morphological stability. As a consequence, not only mangals will disappear from the coastal environment but there will also be inundation and destruction of crops and displacement of settlements.

The STIBS information system is, therefore, practically useful for identifying several spatio-temporal coastal risk factors, among them: (a) spatial extents of flood and erosion affected areas along the coast, (b) the scale and impacts of flooding and erosion,

(c) the demographics, socioeconomic characteristics, and ecology of the coastal communities that will be affected by flooding and erosion, and (d) evaluating and predicting temporal durations of flooding, inundation, erosion and accretion events. From the 2016 and 2031 predicted coastlines decision-makers and policy planners can decide on the most effective strategy on how to mitigate and prevent ongoing and future flood and erosional occurrences. For instance, decisions could be made on whether people should be moved away from areas which are likely to be affected by floods or whether flood protection and erosional control structures should be strengthened.

The parameterization of STIBS with reliable data and tightly coupled models could produce timely and meaningful results to facilitate a proactive rather than a responsive management to problems confronting vulnerable coastal communities. With modifications, a STIBS could herald a new area of risk management and environmental decision-making, especially for vulnerable coastal environments which experience recurring spatio-temporal flooding and erosion problems. Without doubt, a STIBS could facilitate effective decision-making not only by policy planners, but also by all concerned members of the general public.

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**CHAPTER 4**  
**GIS-BASED ANALYSIS AND MODELLING OF COASTLINE**  
**POSITIONAL CHANGES<sup>2</sup>**

**4.1 Introduction**

Coastal systems throughout the world are governed by temporal stochastic processes which influence positional changes (i.e., advance and retreat) of the coast at different spatial scales (Lakhan, 2003). To better protect and sustainably develop all coasts which are affected by nonlinear processes which drive changes in unpredictable directions researchers are now focussing on the use of GIS-based analysis and modelling approaches. Several studies (for example, Green and King, 2003; Hennecke et al., 2004; Snow and Snow, 2005; Wheeler et al., 2008; Pais-Barbosa et al., 2010) have emphasized the application of GIS-based analysis and modelling approaches which permit better insights on the dynamics of the coastal environment. Since a GIS can serve as a platform for designing and testing models of various scenarios, and can be used to simulate complex situations at various temporal and spatial scales (Bartlett, 1999), this research focused on the utilization of a GIS to analyze and model coastline positional changes along the vulnerable coastline of Guyana. The low-lying flood-prone coast of Guyana is a

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<sup>2</sup>A version of this Chapter was published in *Papers of the Applied Geography Conferences* as:

Ahmad, S.R., and Lakhan, V.C., 2010. GIS-based analysis and modeling of coastline positional changes. *Papers of the Applied Geography Conferences (2010)* 33: 147–156

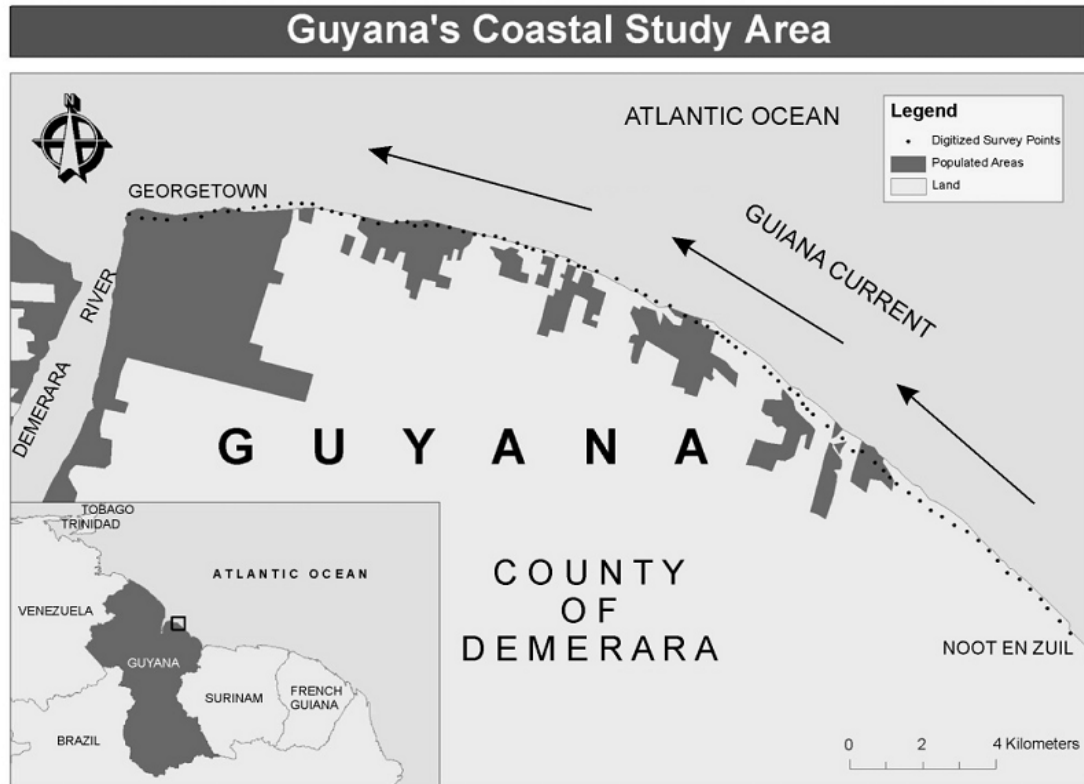
prime example of a vulnerable coastline, and GIS-based applications would be useful to coastal resource managers, especially when timely proactive measures must be taken for coastal protection and management. In addition to using the GIS for identifying and targeting erosional and flood-prone areas, the GIS could also be used for the selection of the appropriate sites which require the emplacement of sea defense infrastructure.

#### **4.2 Study Area and GIS-Based Approach**

The study area is a portion of the northeast coast of the South American continent known as the Guiana Coast, and stretches some 1600 km between the mouths of the Orinoco and Amazon Rivers. It forms the coastline of French Guiana, Surinam, Guyana, and parts of the Brazilian and Venezuelan coasts. Emphasis was placed on the Guyana coast which has a length of approximately 435 km. Nearly 90 percent of the population of Guyana live along the coast, with the majority in the County of Demerara (see Figure 4.1). A comprehensive account on the development of Guyana's coast was presented by Lakhan (1994).

The Demerara and other sections of Guyana's coastline are influenced by a broad spectrum of ocean processes including waves, tides, currents, and massive loads of sediments. The very fine silts and clays which are transported in a northwesterly direction by the Equatorial and Guiana Currents tend to settle to form mudbanks (also referred to as mudshoals) (Allersma, 1971). The mudshoals have a significant influence on positional shifts of the coastline. Investigations on the dynamics of the mudshoals by various researchers (for example, Eisma and Van Der Marel, 1971; Augustinus, 1987) revealed that the mudshoals migrate in a westerly direction along the coast. At times the

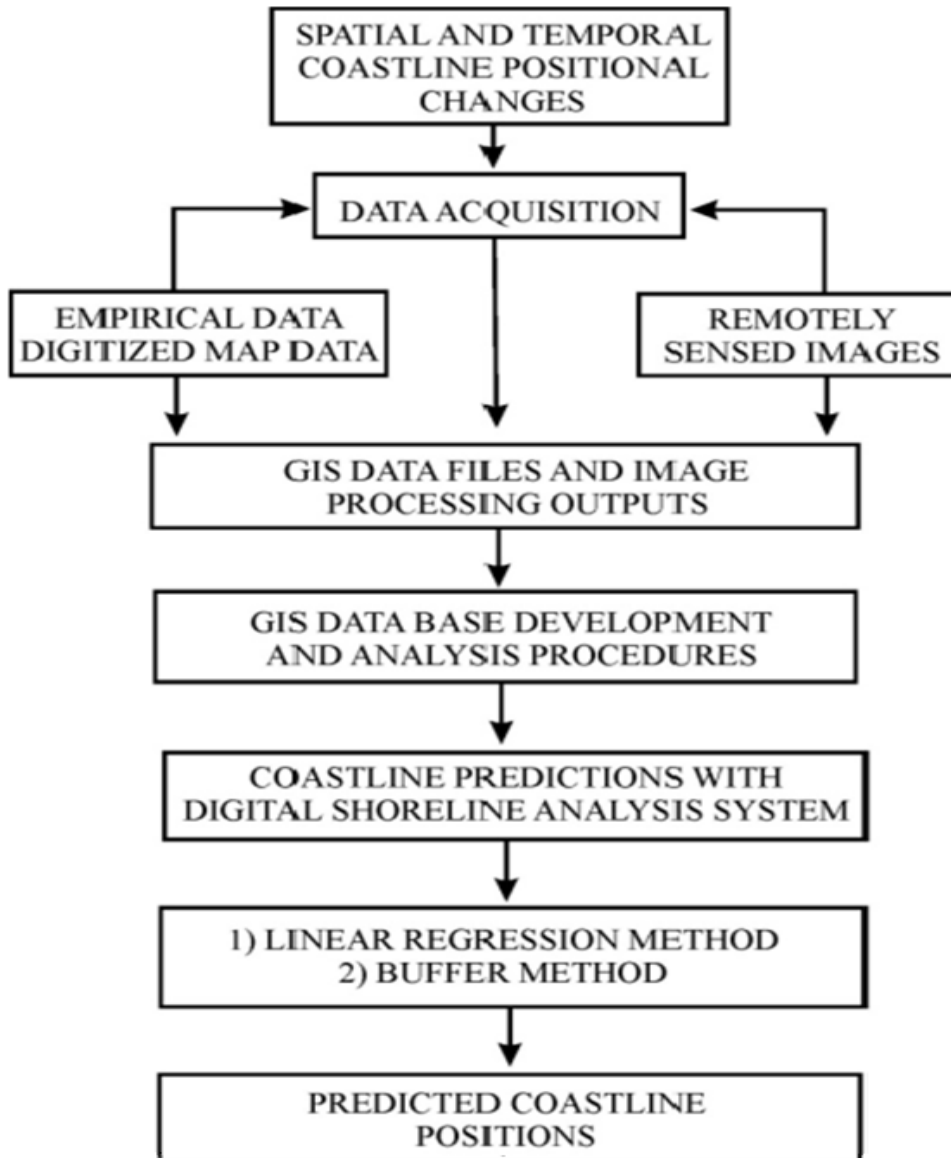
mudshoals also remain stationary. Coastline configuration is, therefore, affected by the location of the mudshoals along the coast.



**Figure 4.1: Portion of the Demerara Coast, Guyana.**

Accretion takes place on the coast directly opposite the mudshoals, while erosion occurs along the coast opposite the troughs situated between two mudshoals. When the mudshoals remain stationary opposite the coast the section of the coast that is protected by the mudshoals experiences accretion (Daniel, 1988; Lakhan and Pepper, 1997). In a simulation study done by Lakhan (1991) it was found that there were oscillating cyclical patterns in the erosional and depositional states along the coastline. The width and position of the coastline change with either episodes of advances or retreats of the coast.

Given the positional shifts of different temporal durations and spatial scales it was decided to utilize a geographical information system (GIS) to analyze and model positional changes along the coast of Guyana. Figure 4.2 provides the schematic framework used in this paper to analyze historical coastline changes and predict future coastline changes.



**Figure 4.2: Geographic Information Systems-based analysis and coastline prediction procedures (from Lakhan, 2009).**



### **4.3 Data acquisition**

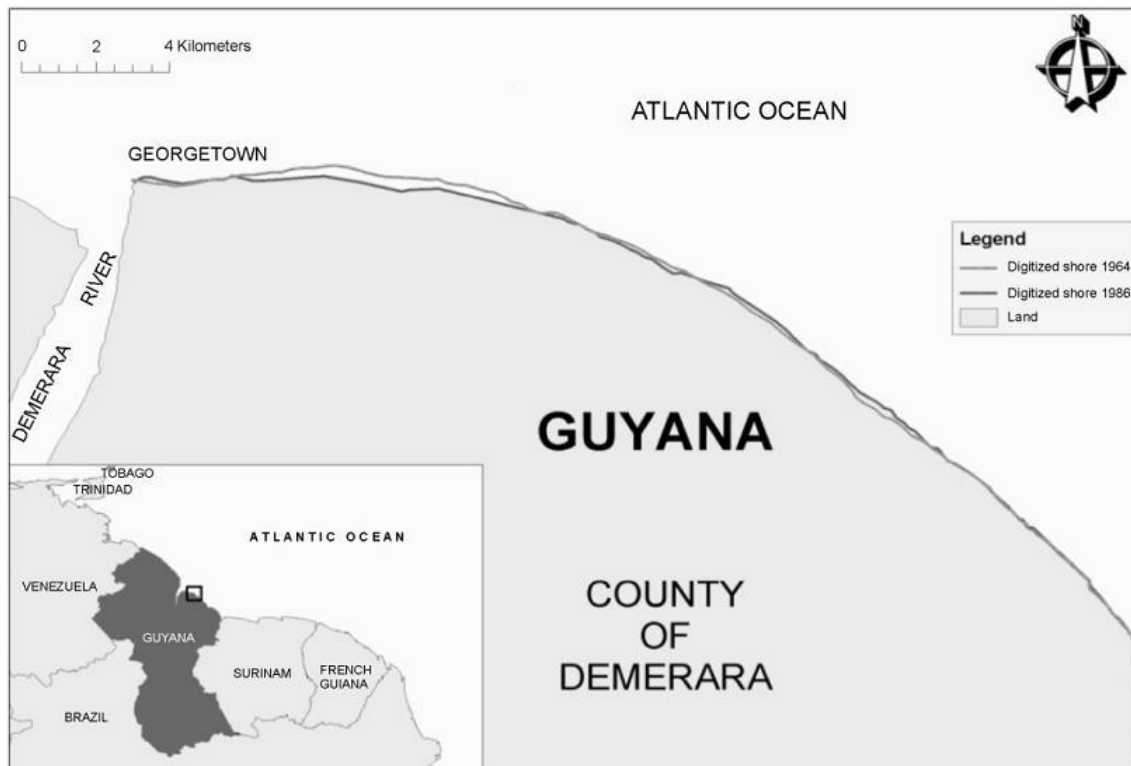
The data along the coast of Guyana were acquired as below:

#### **4.3.1 Empirical data**

The empirical data represented annual foreshore 45 feet + GD (Georgetown Datum) and 50 feet + GD contour-elevation measurements collected by the Lands and Surveys Department, Government of Guyana. The 45 feet + GD (hereafter referred to as 45 GD) contour corresponded with the approximate Chart Datum or mean low water level while the 50 feet + GD (hereafter referred to as 50 GD) contour was the datum which was 0.5 feet (0.3 m) below mean sea level. The foreshore elevation for 45 GD was 13.7 m, and for the 50 GD was 15.24 m (DHV Environment and Infrastructure, 1992). The most complete dataset was for the period 1941–1987, and represented measurements collected from 86 transect profiles along the Demerara coast. Here it should be emphasized that the dataset also included the elevation levels for the 45 GD and 50 GD contour positions.

#### **4.3.2 Digitized map data**

Digital data were also obtained from topographic UTM grid maps (scale 1:50,000) for the years 1964 and 1986. The quadrangles 20NW and 21SE, representing the study area along the Guyana coast, were digitized. The coastlines were digitized as line themes (see Figure 4.3). Each map was digitized until the Root Mean Square (RMS) Error was below 0.002. Completed coastline vectors were converted to a UTM projection with map units in metres.



**Figure 4.3: Digitized coastlines from 1964 and 1986 topographic maps.**

### **4.3.3 Data from remotely-sensed images**

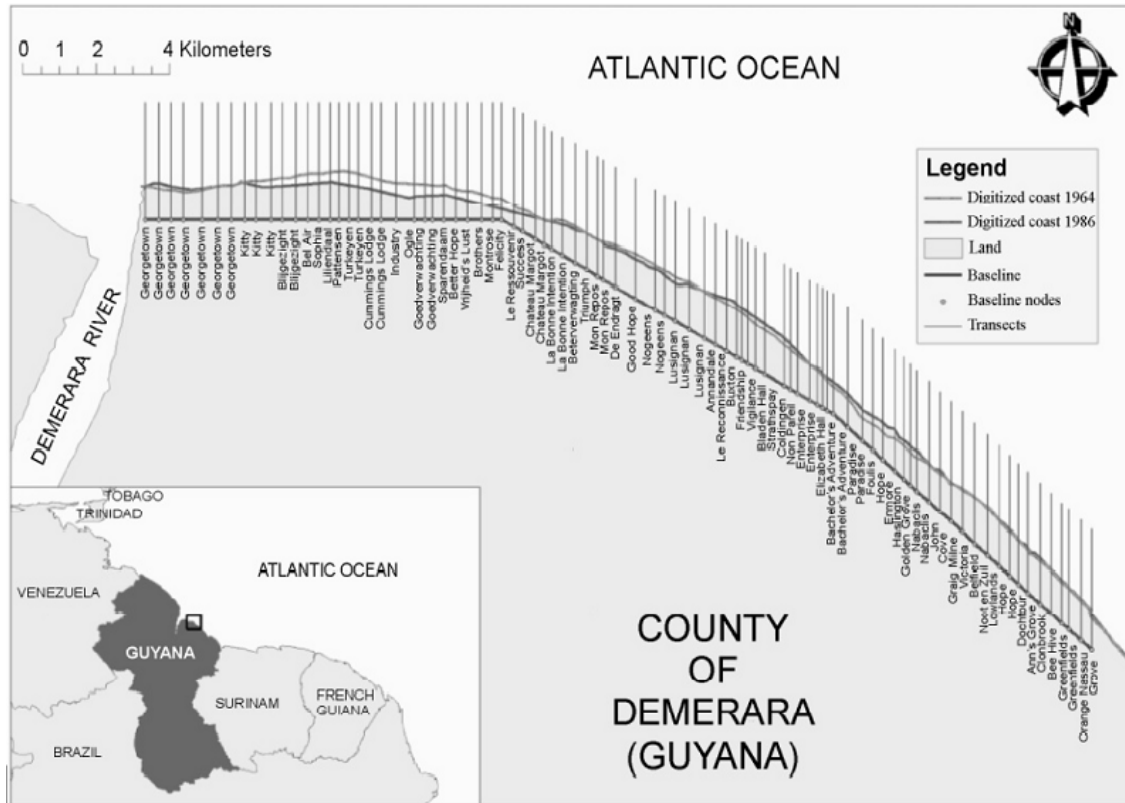
With the knowledge that remotely-sensed satellite data are both accurate and reliable for monitoring changes in width and configuration of coastlines this study also utilized Landsat satellite images of the Guyana coast. Coastlines were extracted from a 1992 Thematic Mapper (TM) image and a 2002 Enhanced Thematic Mapper Plus (ETM+) image. Each of the six reflectance bands of both the TM and ETM+ images has a spatial resolution of 30 m. The technique for extracting the coastlines from the various bands could be found below.

#### 4.4 GIS data files and image processing outputs

It was necessary to create data files with the  $x$ ,  $y$ ,  $z$  and  $t$  values for use by the GIS. In this study, the  $x$  and  $y$  values represented the locational coordinates while  $z$  represented the altitude or elevation values. The time dimension was given as  $t$ . Along the Guyana coast the transect profiles have permanent  $x$  values or longitudinal coordinates. These were expressed in decimal degrees in the dataset. The latitudinal coordinates or  $y$  values were the contour positions. The input data that were recorded were from the centre line of defense or the total distance from the centre line of defense to the position of the contour. The coordinate values for 86 transect profiles were prepared so that they could be stored as dbase files. Two sets of  $z$  values ( $z_1$  and  $z_2$ ) were included in the GIS. The first set of  $z_1$  values was used to represent rates of advance and retreat (i.e., AOR rates) of the coast. The AOR rates could be related to positional change between the two GD contours. The  $z_2$  values constituted the contour elevation data because each contour was associated with a specific elevation.

Geoprocessing techniques in Idrisi Kilimanjaro, version 14.002 (Clark Labs, 2003) were used to produce radiometrically corrected and geometrically rectified images for 1992 and 2002. Even though the specified coordinate system was UTM Zone 21N for both the 1992 and 2002 image files, the Project module was used on all image bands to remove any potential anomalies or distortions. To extract, on a simple basis, the coastlines for 1992 and 2002 the algorithm presented by Alesheikh et al. (2004) was used. In the extraction process each of the two images was subjected to band ratioing (Band 2/Band 4 and Band 2/Band 5), histogram thresholding (Band 5), image multiplication, and raster to vector conversions. Since the objective was to delineate areas

along the coastline which were advancing and retreating. Spatial Analyst was used to subtract the 1992 image from the 2002 image. An attribute table was then produced for the difference image to indicate polygons along the coast which were either retreating or advancing or showing no change. Positional shifts were delineated and recorded for each of the 86 transect profiles (Figure 4.4).

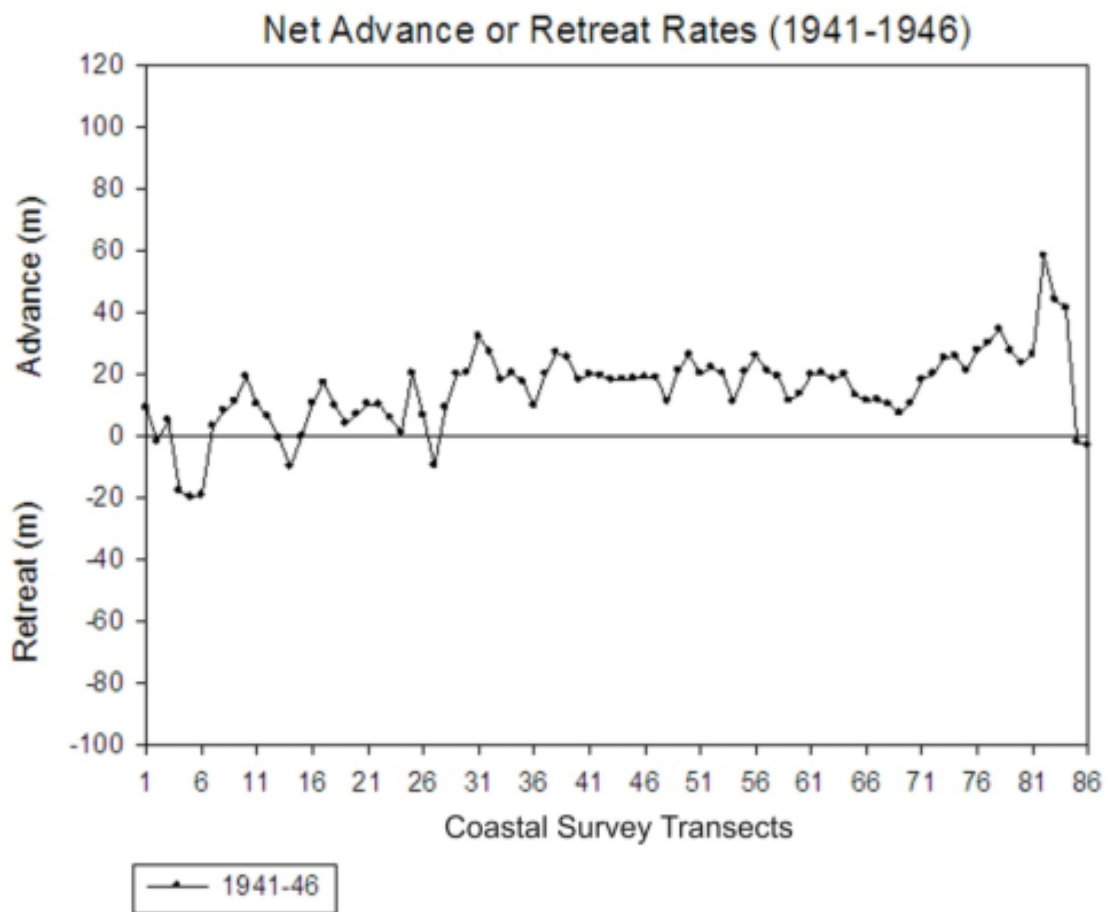


**Figure 4.4: Transect profiles used by DSAS to compute coastline change statistics.**

#### **4.5 GIS database development and analysis procedures**

The database was developed to integrate, manipulate and process empirical data, digital map data, and data extracted from remotely-sensed images. To assess and predict coastline positional changes it was necessary to create the geodatabase with the necessary locational and attribute data. This permitted analysis and outputs within the framework of

a GIS environment. For instance, one of the tasks was to compute and plot the AOR rates for different time periods to determine when and where there were positional shifts of the coast. Hence, for each of the 86 transect profiles the AOR rates were calculated by dividing the total distance of coastline contour movement by the time elapsed between the earliest and latest coastline positions. Graphical plots of the AOR rates were then made to highlight changes in accretion (i.e., advance) and erosion (i.e., retreat) along the coast. Figure 4.5 provides an example of those transect profiles along the coast which have either advanced or retreated for the five-year time period 1941–46.



**Figure 4.5: Net advance or retreat rates (1941–1946) along the investigated sections of Guyana Coast.**

It could be seen from Figure 4.5 that over time the coast retreated along spatial locations represented by transect profiles 5, 6, 7, 15, 16, 48, 85 and 86. The other transect profiles demonstrated areas where the coast advanced. ArcMap was used to visualize the results of the AOR rates.

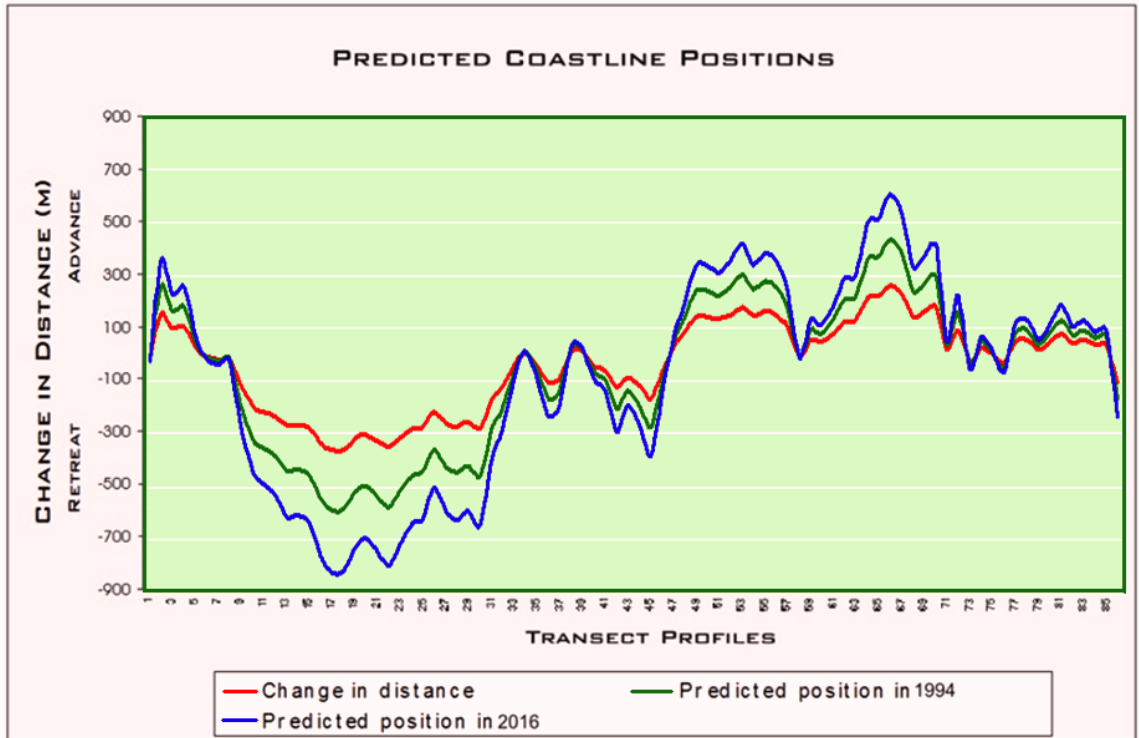
To further facilitate the identification, analysis and mapping of positional shifts along the coastline several ArcGIS 9.2 (ESRI, 2007) extensions and functions were utilized, among them the BUFFER function and Spatial Analyst. Moreover, long term rates of coastline change were generated in ArcGIS 9.2 with the Digital Shoreline Analysis System (DSAS, version 4) extension.

#### **4.6 Coastline predictions with the Digital Shoreline Analysis System**

DSAS permitted the calculation of coastline rate of change statistics from a time series of multiple coastline (DSAS uses the word “shoreline”) positions. The two components required by DSAS were the baseline and the transect feature class. The DSAS transects created in DSAS version 3.2 (Thieler et al., 2005) for ArcView 3.3 were imported for use in DSAS version 4.0 (Thieler et al., 2009). The baseline was constructed adjacent to the digitized and extracted coastlines. Transects were then cast perpendicular to the baseline at 300 m intervals. After the transects feature class was created the data were used to compute net coastline movement and coastline change statistics. The rate of change statistics incorporated in the DSAS included the endpoint rate, linear regression, weighted linear regression, and supplemental statistics for least squares and weighted regression. The linear regression method was selected because in an evaluation of different algorithms (endpoint rate, minimum description length, linear regression, etc.) for coastal management purposes Crowell et al. (1997) mentioned that the linear

regression method was typically equal or better than the other techniques. Moreover, Morton et al. (2004) emphasized that the linear regression method was the most statistically robust quantitative method that could be applied for expressing rates of change.

The linear regression was used to calculate rate of change at each of the 86 transects. A linear model was used to account for the trend in extrapolating historical and future coastline positions. The linear trend was determined by fitting a regression line to the coastline positional data. Coastline positions for 1994 and 2016 were then estimated. This required use of the expression:  $Y = mX + B$ , where  $Y$  denotes the coastline position,  $m$  is the rate of coastline movement,  $X$  is the date, and  $B$  is the intercept. The 1964 coastline was initialized as the first base year and an intercept value of 3.8 was chosen. This intercept value was obtained after fitting a linear trend to the data for the 86 survey sections. Based on the parameterization of the DSAS, coastlines were predicted for 1994 using the 1964 base year, and 2016 using the 1986 coastline. Prediction was also done with the coastlines extracted from the 1992 and 2002 remotely-sensed images. The predicted coastlines from the 1964 and 1986 data (see Figure 4.6) clearly indicate locations along the 86 transects which are likely to advance or retreat. When the 1992 and 2002 extracted coastlines were included in the prediction additional erosional areas along the coast were recognized. These results were then mapped to highlight which areas along the coast will erode in the future. ArcMap was used to map the spatial locations along the coast which will retreat in the future.

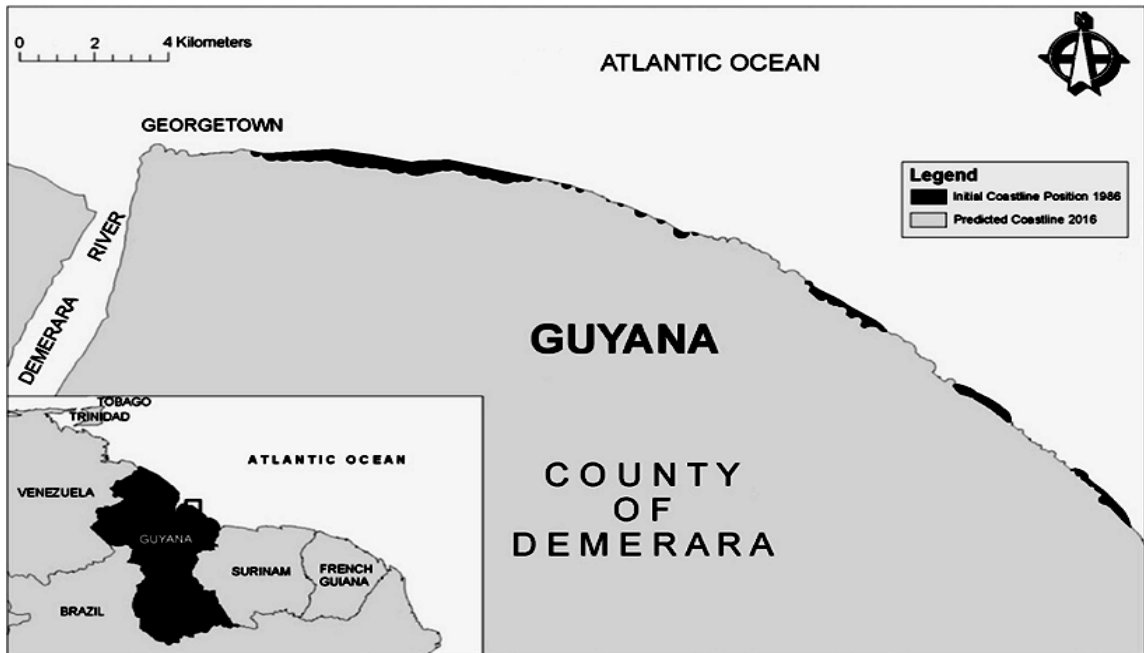


**Figure 4.6: Predicted coastline positions (1994 and 2016) from 1964 and 1986 data.**

#### **4.7 Buffering predicted coastlines**

In ArcMap GIS a Buffer function was employed to spatially map the coastline positions based on the magnitude of coastline change values. The buffering procedure for each predicted coastline was completed for each profile section. New positions were connected with line segments along the edges of the buffered zones. This resulted in mapping of the predicted coastlines for 2016. A spatial representation of the 2016 coastline position is plotted (see Figure 4.7) to highlight areas that are likely to retreat.





**Figure 4.7: Predicted coastline position for 2016. Dark areas represent portions where the coastline will likely retreat.**

#### **4.8 Discussion and conclusion**

This research substantiated previous observations by Lakhan et al. (2006) that the coastline of Guyana is a morphologically dynamic feature which shifts positions through space and over time. The results highlighted that at different times and at various locations the coast will move either landward or seaward. The GIS analysis of the historical coastline change data demonstrated that some locations along the coast experienced somewhat persistent erosional trends whereas in other areas depositional occurrences were more dominant. A comparison of the predicted 1994 coastline positions with that of the actual 1994 coastal data on advance and retreat of the coast revealed almost similar erosional patterns along transect profiles 9–48. From this finding the claim could be made that the DSAS was reasonably effective in predicting historical coastline

positions. Although several investigators (for example, Thieler and Danforth, 1994; Crowell et al., 1997; Moore, 2000) mentioned that the calculated rates of change provided by DSAS are subject to uncertainties it should, nevertheless, be stressed that this research kept measurement and sampling errors to the lowest level of tolerances.

By taking into consideration the 1994 predicted coastline, it is possible to make inferences about the accuracy of the predicted 2016 coastline. Caution must be taken when evaluating the results because the linear regression technique assumes a uniform trend. Most coastlines are, however, governed by nonlinear processes which influence positional shifts which are not easily predictable (Lakhan, 1989). Hence, it is imperative to use, as done in this study, a dataset of a long temporal duration to account for aspects of the dominant nonlinear processes operating in the Guyana coastal environment. While the true position of the 2016 coastline cannot be ascertained at this time the results, nevertheless, permit visualization of those areas along the coast which are likely to experience positional shifts. Coastal resource managers and policy planners in Guyana and elsewhere can now use contemporary technologies like a GIS to spatially visualize the dynamic nature of the coast. Vulnerable erosional areas could be examined and visualized at various scales. With a GIS that is parameterized with appropriate data, different modelling scenarios could be examined, and the most appropriate proactive management strategies could be considered to protect and sustainably manage the coast.

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**CHAPTER 5**  
**GIS-BASED ANALYSIS AND MODELLING OF COASTLINE**  
**ADVANCE AND RETREAT<sup>1</sup>**

**5.1 Introduction**

It is increasingly being recognized that, “shoreline mapping and shoreline change detection are critical for safe navigation, coastal resource management, coastal environmental protection, and sustainable coastal development and planning” (Di et al., 2003, p. 1). Hence, to better understand the dynamics of coastline changes researchers are now focussing on the use of a wide range of models and techniques (Lakhan, 2003), including the application of geospatial approaches. Several worthwhile studies (Li et al., 1998; Cracknell, 1999; Kevin and El Asmar, 1999; Green and King, 2003; Hennecke et al., 2004; Liu and Jezek, 2004; Schupp et al., 2005; Srivastava et al., 2005; Guariglia et al., 2006; Vanderstraete et al., 2006; Ekercin, 2007; Sesli et al., 2008; Addo, 2009; Pais-Barbosa et al., 2010) have applied GIS-based approaches to obtain better insights on both the short and long-term changes occurring in coastal and marine environments.

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<sup>1</sup> A version of this Chapter has been accepted to the *Journal of Coastal Research* as:  
Sajid Rashid Ahmad and V. Chris Lakhan, August, 2010. Time series modeling of data on coastline advance and retreat.

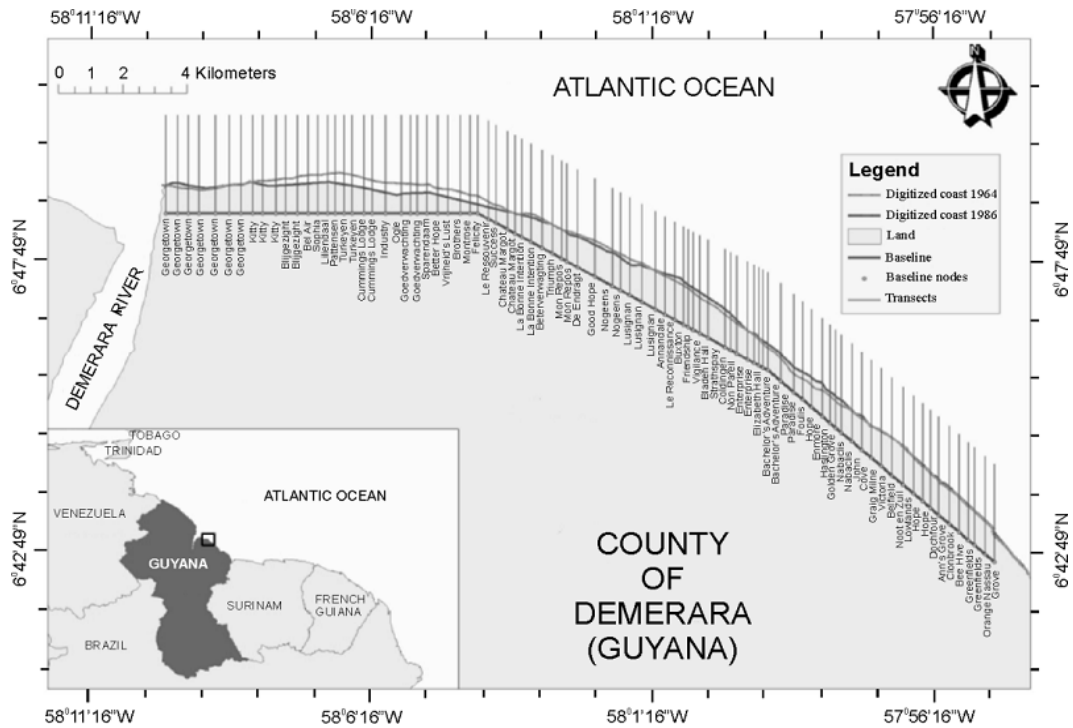
Since a GIS is useful for not only testing models to simulate coastline scenarios at various temporal and spatial scales, but also valuable for providing visual information on coastline change detection (Bartlett, 1999), this research incorporated empirical and remotely-sensed data into a GIS to analyze and model coastline advance (synonymous with accretion) and retreat (synonymous with erosion) along the coast of Guyana.

The low-lying, vulnerable flood-prone coast of Guyana is studied because there is a paucity of meaningful research on the recurring problems of coastline advance and retreat.

## **5.2 Study area**

The Guyana coast forms part of the northeast coastline of the South American continent shared by Brazil, French Guiana, Surinam, and Venezuela. Approximately 90 percent of the country's population live on the coast which is approximately 435 km in length, with a width of between 77 km in the west and 26 km in the east. The coast is approximately 2.4 m below mean sea level. As a consequence recurring episodes of flooding and erosion affect the nearly 90% of the country's population who live in the coastal environment (Lakhan, 1994). The majority of the people live in the various communities in the County of Demerara (see Figure 5.1).





**Figure 5.1: The study area, Demerara Coast, Guyana.**

Other than the influence of waves, tides and currents the coast is also affected by the continuous presence of massive loads of sediments. These sediments are transported from the mouth of the Amazon River in a northwesterly direction by the Equatorial Current, and subsequently by the Guiana Current. The very fine silts and clays which are transported tend to flocculate, and eventually settle to form mudbanks (also referred to as mudshoals). Investigations into the dynamics of mudbanks revealed that they migrate in a westerly direction (Allersma, 1971; Augustinus, 1987). Accretion takes place on the coast directly opposite the mudbank whereas erosion occurs along the coast opposite the troughs situated between two adjacent mudbanks. At times when the mudbanks remain stationary opposite the coast, broad mudflats begin to develop on the landward edge of the coast (Eisma and Van Der Marel, 1971; Lakhan and Pepper, 1997). Field

investigations by Lakhan et al. (2002) found that homeless residents normally erect shelters on the landward edge of accreting mudflats. When the mudbanks migrate away from coastal areas being protected erosion occurs, thereby resulting in losses of settlements and associated infrastructure.

### **5.3 Data acquisition and preprocessing**

The following data acquired and preprocessed for use in a GIS-based environment were from the following:

#### ***5.3.1 Empirical Field Measurements***

The data from empirical field measurements represented annual foreshore 45 feet + GD (Georgetown Datum) and 50 feet + GD contour-elevation measurements collected by the Lands and Surveys Department, Government of Guyana, and by the authors and graduate students. The 45 feet + GD (hereafter referred to as 45 GD) contour corresponded with the approximate Chart Datum or mean low water level while the 50 feet + GD (hereafter referred to as 50 GD) contour was the datum which was 0.5 feet (0.3 m) below mean sea level. The foreshore elevation for 45 GD was 13.7 m, and for the 50 GD was 15.24 m (DHV Environment and Infrastructure, 1992). Each survey transect was approximately 300 m apart. The most complete archival dataset was for the period 1941–1987, and represented measurements collected from 86 transect profiles along the Demerara coast (see Figure 5.1). Here it should be emphasized that the dataset also included the elevation levels for the 45 GD and 50 GD contour positions. To supplement archival data the second author and various graduate students collected data from each of the 86 transect profiles on an annual basis from 1988–2007.

Microsoft Excel spreadsheet was used to prepare the data for processing by the GIS. The advance or retreat (AOR) method was utilized to determine the amount of material gained or lost by the coastline. The AOR was computed for the 86 transect profiles by comparing the initial and finishing positions of the 45 GD and the 50 GD contours. The Excel spreadsheet was used to calculate the AOR rates on an annual basis, and for every 5 years. For example, in the calculation of rates for the 1941–1946 period, positions for the two contours (45 GD and 50 GD) in 1941 were used as a starting point, and the 1946 contour positions were then subtracted from them. The differences were then divided by ten because data for two contours over a five-year period were used. Graphical plots of the AOR rates were then made to reveal the advance and retreat of the coast along the 86 survey transect profiles.

### ***5.3.2 Data from Remotely-Sensed Images***

With the knowledge that remotely-sensed satellite data are reliable for monitoring changes in width and configuration of coastlines (Liu and Jezek, 2004; Ekercin, 2007) this study utilized Landsat satellite images of the Guyana coast. Coastlines were extracted from a September 19, 1992 Thematic Mapper (TM) image, and from Enhanced Thematic Mapper Plus (ETM+) images for August 22, 1999, October 1, 2002 and September 2, 2006. Each of the six reflectance bands of both the TM and ETM+ images has a spectral resolution of 30 m. All images were acquired at low tides in order to maximize the discrimination of the seaward edge of the coastline. Before coastlines were extracted geoprocessing techniques in the Idrisi Kilimanjaro software, version 14.02 (Clark Labs, 2003) were used to produce radiometrically corrected and geometrically rectified images.

Relative radiometric correction was performed in order to normalize the multiple satellite scenes to each other. This involved the selection of ground targets (for example, beaches, asphalt roadways, and concrete drainage sluices) with reflectance values fairly constant over time. In the selection of these pseudo-invariant features the recommendations of Eckhardt et al. (1990) were considered. All four images were also geometrically corrected with the selection of 42 ground control points. Accuracy of the georeferenced images was maintained by minimizing the RMS error to 0.16 pixels. Although the specified coordinate system was UTM Zone 21N for each of the four image files, the Idrisi Project module was, nevertheless, used on all image bands to remove any potential anomalies or distortions.

Before the coastlines were extracted from the Landsat TM and ETM+ images, this study reviewed several coastline extraction and change detection techniques, among them the Normalized Difference Water Index (NDWI) (McFeeters, 1996; Grigio et al., 2005), threshold level slicing (Braud and Feng, 1998), density slicing (Frazier and Page, 2000), Tasseled Cap Transformation (Scott et al., 2003), morphological segmentation algorithms (Bagli and Soille, 2004), band ratioing (Alesheikh et al., 2004; Guariglia et al., 2006), and Iterative Self-Organizing Data Analysis Technique (Yuksel et al., 2008; Kuleli, 2009). Based on the findings reported by the aforementioned authors and tests by Lakhan and Chan (2007), the decision was made to use the band ratio method because it has the advantage of considering all the multispectral data present in the various spectral bands. Hence, in the coastline extraction process the band ratio algorithm presented by Alesheikh et al. (2004) was used. Each of the four images was subjected to histogram thresholding, band ratioing (Band 2/Band 4 > 1 and Band 2/Band 5 > 1), image

multiplication, and raster to vector conversions. The four binary images which were produced were exported from Idrisi to ArcGIS 9.2 (ESRI, 2007) as Geotiff files. The ArcScan extension of ArcGIS was used to convert the raster images to vector files.

#### **5.4 GIS database development and analysis procedures**

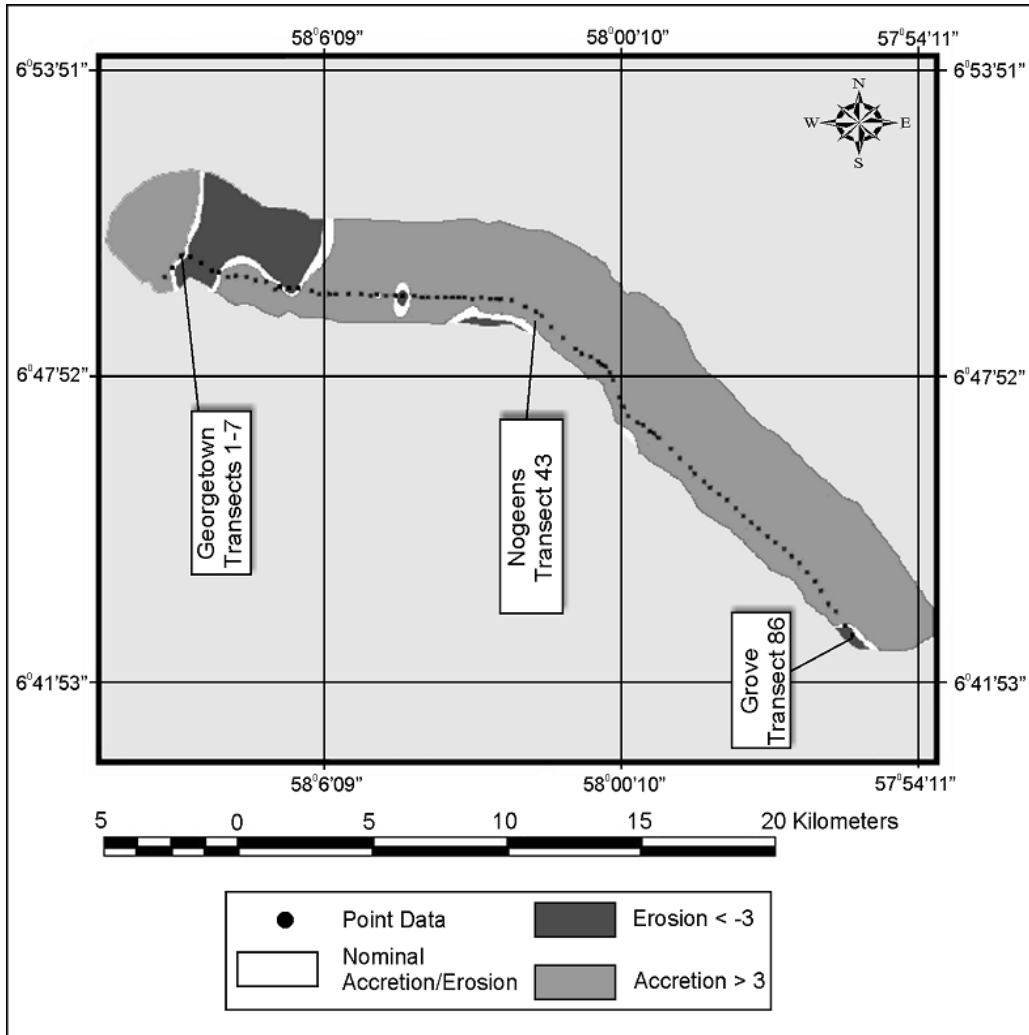
In the development of the GIS database it was necessary to create data files with the  $x$ ,  $y$ ,  $z$  and  $t$  values. The  $x$  and  $y$  values represented the locational coordinates while  $z$  represented the altitude or elevation values. The time dimension was given as  $t$ . Along the Guyana coast the transect profiles have permanent  $x$  values or longitudinal coordinates. These were expressed in decimal degrees in the dataset. The latitudinal coordinates or  $y$  values were the contour positions. The input data that were recorded were from the centre line of defense to the position of the contour. The coordinate values for the 86 transect profiles were prepared so that they could be stored as dbase files. Two sets of  $z$  values ( $z_1$  and  $z_2$ ) were included in the GIS. The first set of  $z_1$  values was used to represent rates of advance and retreat (i.e., AOR rates) of the coast. The AOR rates could be related to positional change between the two GD contours. The  $z_2$  values constituted the contour elevation data because each contour was associated with a specific elevation.

In order to identify, analyze and visualize advance and retreat areas along the coast it was also necessary to utilize the Spatial Analyst and 3D Analyst extensions of ArcGIS 9.2. The locational information were represented as points. The point layers provided the basis for creating grids with the AOR rates, and for developing Triangulated Irregular Networks (TINs). The Buffer tool was applied on the specified point features. The buffer at the southern (i.e., landward) boundary was set at 500 m while the northern

boundary (i.e., ocean) had a 3000 m buffered zone. The established boundary extents permitted analysis with the Spatial Analysis extension.

Spatial Analyst was used to convert the polygon feature classes to a raster format. By using the AOR rate values as a  $z$  dimension, interpolation was then done with the Interpolate to Raster function. For analytical purposes, the AOR rates were divided into nine time periods (1941–46, 1946–51, 1951–56, 1956–61, 1961–67, 1967–72, 1972–77, 1977–82, 1982–87). Interpolation was then done for each of the nine time periods with the Regularized Spline method to create a smooth surface. The cells for each of the nine time periods were classified with Reclassify. Cells with values of greater than 3 were denoted as areas of coastal advance while cells with values less than 3 were indicative of coastal areas experiencing retreat. The spatial extent that fell between 3 to 3 constituted nominal advance and retreat. These three ranges were then mapped for each of the nine time periods. An examination of the advance and retreat areas for all nine time periods revealed that the coastline advanced and retreated at various locations over time. For example, Figure 5.2 highlights that for the 1941–46 period an extensive section of coast advanced seaward, while from 1946–51 a long stretch of the coast retreated (Figure 5.3).

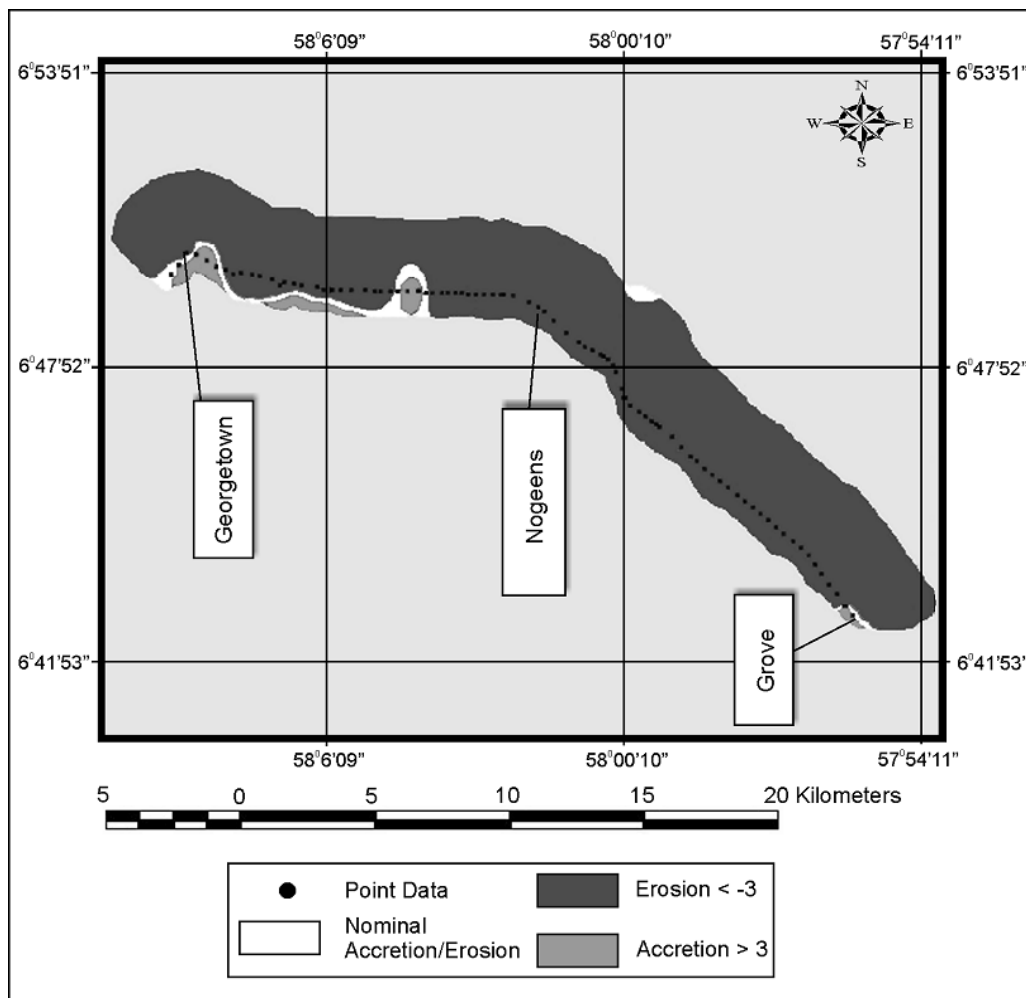
A distinctive advancing trend recurred between 1977–82, while pronounced retreat was noticeable between 1982–87, and thereafter. Moreover, the GIS results also indicated that during some time periods only some sections of the coast retreated and advanced. Figure 5.4 highlights both advancing and retreating patterns along the coast during the 1967–72 period.



**Figure 5.2: Coastline advance (1941–1946) along the coast of Guyana.**

To understand the impacts of advance and retreat on the coastal sediment budget, Spatial Analyst and 3D Analyst were used. Volumetric statistics were calculated with the  $z_2$  values (i.e, elevation data) of the 45 GD and 50 GD contours. This necessitated the creation of TINs. Net differences in sediment volumes were then computed. Figure 5.5 provides the percentage changes in sediment volume over time. It is clearly evident that the losses of sediments in the two time periods (1946–51 and 1971–76) corresponded

very closely to the same periods of coastal retreat. Moreover, the gains in sediment could be associated with the time periods when the coast was advancing.

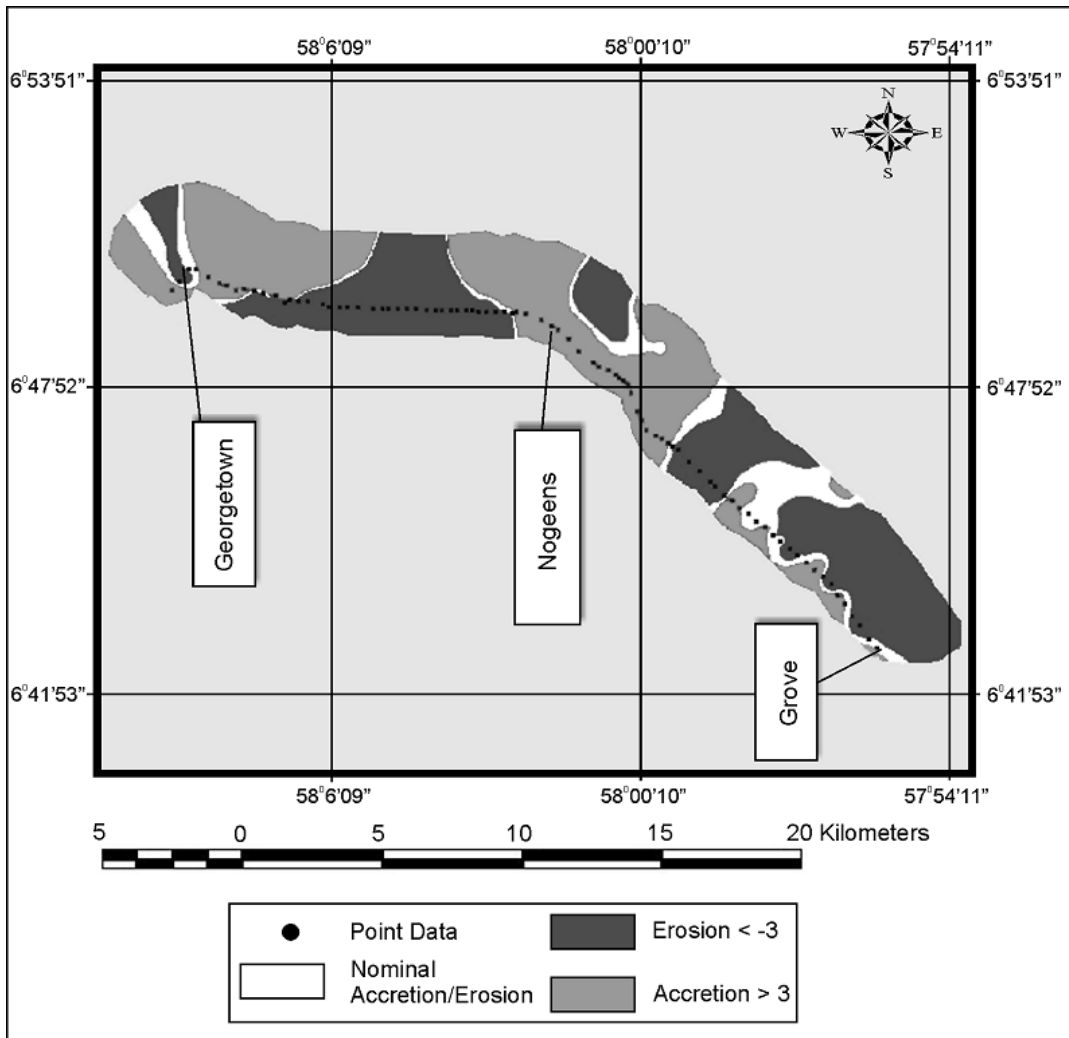


**Figure 5.3: Coastline retreat (1946–1951) along the coast of Guyana.**

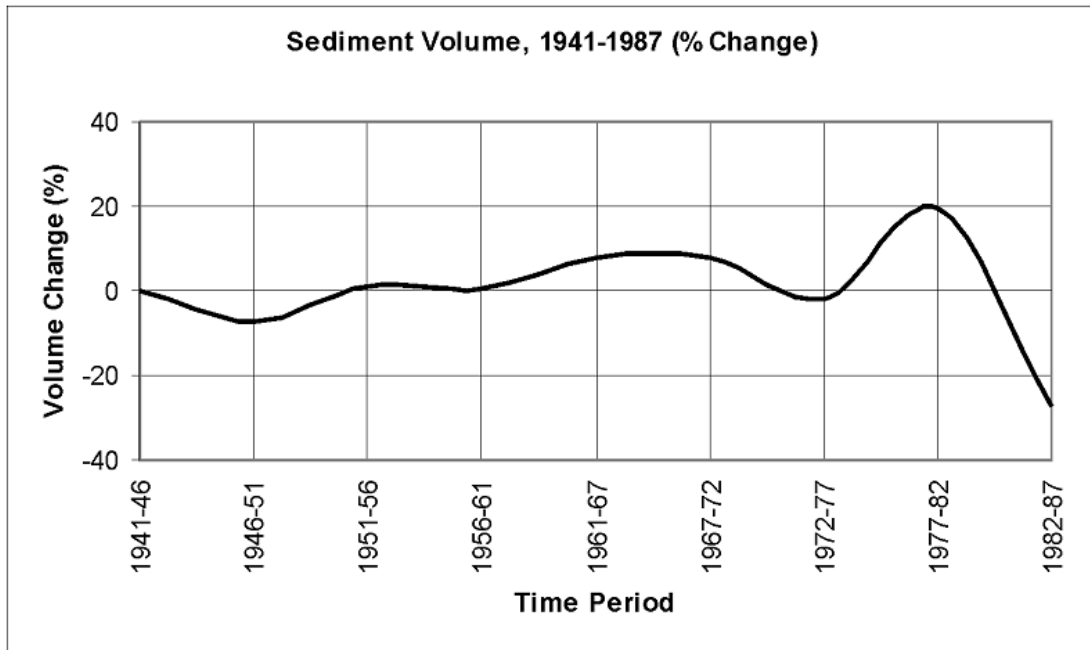
With the GIS results demonstrating that the coastline advanced and retreated at various spatial locations and for different temporal durations, further GIS-based analysis was done to understand the trend of coastline advance and retreat. Following the findings of Fenster et al. (1993) it was assumed that the historical rates of coastline change were a good indicator for predicting future coastline positions. The Digital Shoreline Analysis System (version 4, Thieler et al., 2009), hereafter referred to as DSAS, was used to



predict coastlines extracted from the remotely-sensed images. In brief, DSAS is an ArcGIS extension that is used to calculate coastline (referred to as ‘shoreline’ by DSAS) rates of change and net coastline movements from multiple historic coastline positions (Thieler et al., 2005).



**Figure 5.4: Patterns of Guyana’s coastline advance and retreat (1967–1972).**

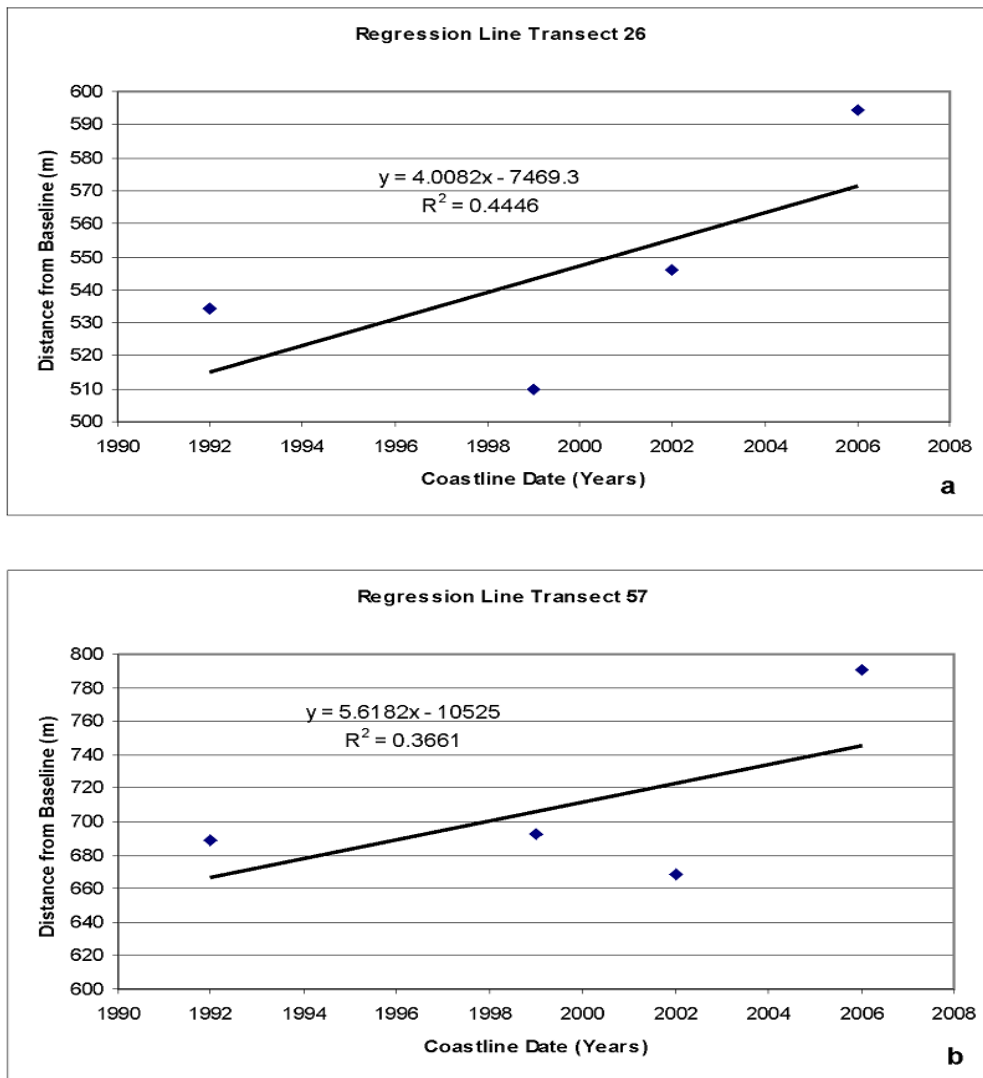


**Figure 5.5: Percentage change in sediment volume (1941–1987) of Guyana’s coast.**

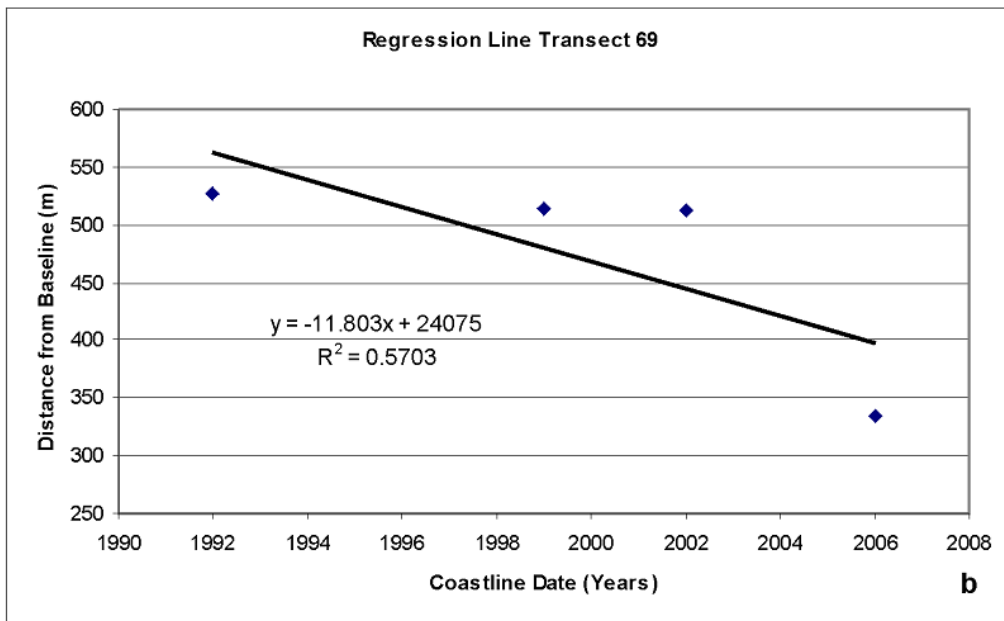
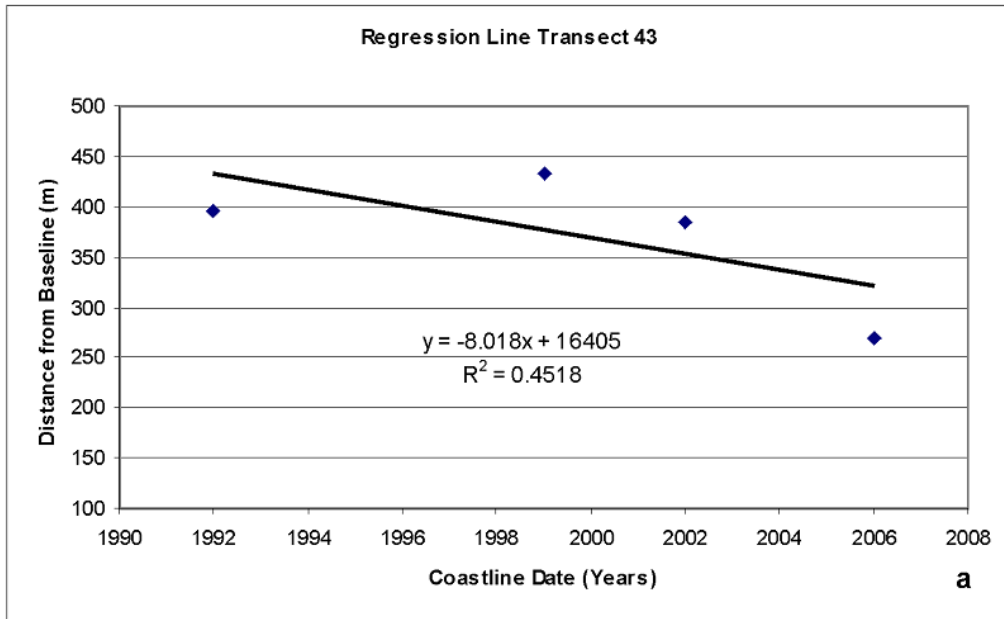
### **5.5 Predicting Coastline advance and retreat**

Following the requirements and procedures required by the DSAS software a baseline was established. DSAS then generated transects that were cast perpendicular to the baseline at the user-specified spacing of every 300 m. The 300 m spacing interval was selected to match the spacing of the coastal transect profiles established by the Lands and Surveys Department, Government of Guyana. DSAS was then used to calculate linear regression rates of change statistics by fitting a least squares regression to all coastline points for each of the 86 transects. A trendline was fitted with the expression,  $y = mX + b$ , where  $m$  is the rate of coastline movement,  $X$  is the date, and  $b$  is the intercept. The slope of the trendline gives the linear regression rate of change of the coastline in meters per year. Accreting (i.e., advancing) areas have positive values, and eroding (i.e.,

retreating) areas have negative values. The standard error of the slope and the  $R^2$  values are calculated at the 95% confidence level interval. Regression results from DSAS for the 86 transects demonstrate which of the transects for the time period 1992–2006 are advancing or retreating. Transects 26 and 57 (Figures 5.6a and 5.6b) are examples of coastal advance because the  $b$  values for Transect 26 and 57 indicate that the coast is advancing by 4.008 m and 5.618 m respectively.

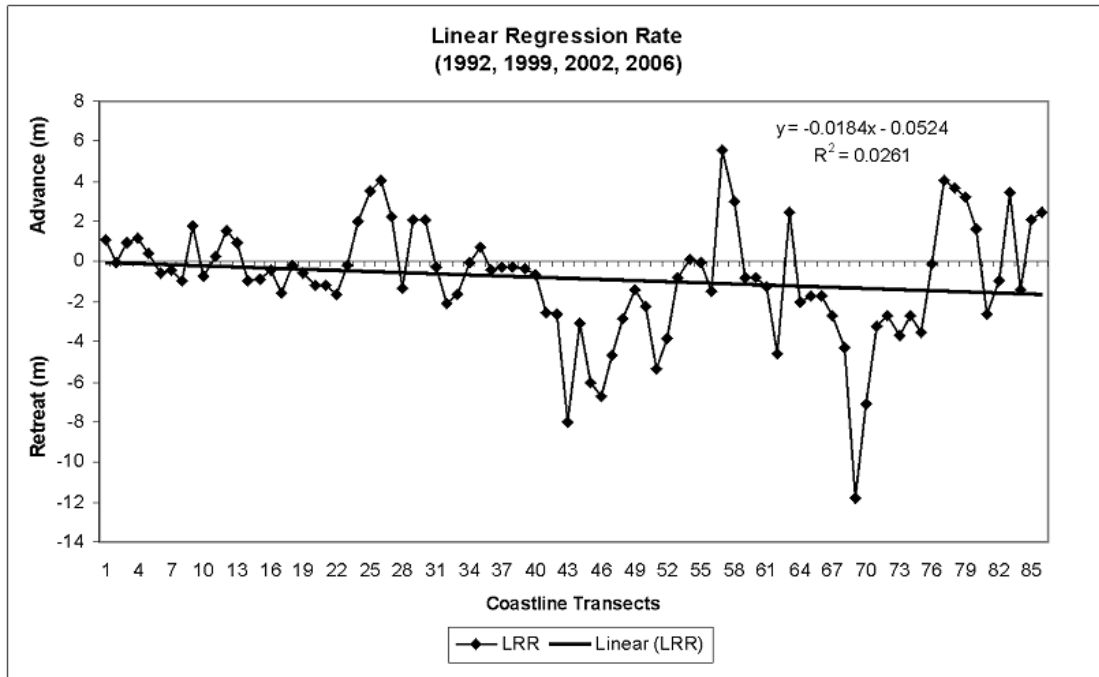


**Figure 5.6: Transects 26 and 57 along the coast of Guyana showing the advancement of coastline .**



**Figure 5.7: Transects 43 and 69 along the coast of Guyana showing the retreation of coastline .**

Several areas along the coast are also retreating, with Transects 43 and 69 (Figures 5.7a and 5.7b) highlighting that the coast is retreating by 8.018 m and 11.803 m respectively. When the results for all 86 transects are plotted (Figure 5.8), a retreating trend for the coast is observed. The relatively low  $R^2$  value of 0.0261 is indicative of a high degree of variability in the rate of change along the length of the coastline.



**Figure 5.8: Linear regression showing advance and retreat of the Demerara Coast, Guyana**

## 5.6 Discussion

The GIS-based approach, when used to analyze a time series (1941–1987) of coastline AOR data, permitted the recognition of temporal episodes of coastal advance and retreat. The coastline shifted landwards or seawards at various spatial scales, and for different durations. For example, a landward sequence was initiated, beginning in 1941

and ending in 1946 (see Figure 5.2). Thereafter, the coast retreated, with a distinct erosional sequence from 1946–51 (see Figure 5.3). These episodes of advance and retreat recurred, with noticeable landward movement from 1977–82, and retreat from 1982–87. Moreover, the coast for different spatial extents retreated and advanced for different temporal durations (see Figure 5.4). These transitory morphological states which are portrayed by the GIS analysis could be attributed to the presence of temporal stochastic processes operating at different spatial scales in the coastal system.

In addition to the influences of the various hydrodynamic processes (waves, near and longshore currents, water velocities, etc.), the Guyana coast is also influenced by migrating mudbanks. Investigations along the coast of Guyana (for example, Allersma, 1971; Eisma and Van der Marel, 1971; Augustinus, 1987), and along the neighbouring coast of Surinam (Wells and Coleman, 1981) and French Guiana (Froidefond et al., 1988) reported that mudbanks have significant impacts on the northern South American coastal system. Various sections along the coast respond to the presence or absence of mudbanks. Aggradation and coastal advance occurs along those sections of the coast that are protected by stationary mudbanks. In effect, the mudbank dampens the erosive effects of wave and currents. As the mudbanks move through space and over time, unprotected sections of the coast become eroded, and therefore retreat. The mudbanks are associated with cyclical behavior, with NEDECO (1972) postulating that a 30-year cycle of erosion and accretion exists along the Guyana coast. GIS analysis of the Guyana coast AOR data revealed the existence of this 30-year cycle of erosion and accretion that also includes shorter periods of coastal advance and retreat. Figure 5.5 highlights that the two periods of major sediment losses are about 30 years apart.

The GIS findings on episodes of coastal advance and retreat are reinforced with the results of coastlines extracted from the remotely-sensed images. The DSAS outputs provide evidences that over time there are positional shifts at each of the 86 transect profiles. Figure 5.8 clearly highlights those sections of the coast that either advanced or retreated. Aggradation was very high at Better Hope (Transect 26), and at Enterprise (Transect 57). Very high retreat rates were observed at Nogeens (Transect 43) and Nabaclis (Transect 69). Field measurements by the authors substantiate the DSAS results. Retreat occurred at all the transect profiles predicted by DSAS. An assessment of the linear regression rate of change values demonstrated that 58 of the 86 transect profiles retreated. This finding, supported by field observations, permit the observation that the Guyana coast is experiencing an erosional trend. In addition to the effects of migrating mudbanks, erosion along the coast is further exacerbated by rising sea levels and extreme wave events. Studies by Khan and Sturm (1995) and Dalrymple and Pulwarty (2006) reported that the Guyana coast is becoming more vulnerable due to ongoing sea level rise. Even with a very low projected 2 mm per year increase in sea level, it is expected that there will be increased flooding and greater erosion along the coastline of Guyana. Without doubt, increases in water levels are contributing to greater erosive power of nearshore currents and waves. The occurrence of extreme wave events are also contributing to the retreat of several coastal areas. For example, the extreme wave event of October 2005 resulted in massive flooding and erosion along the Essequibo and Demerara coast (Van Ledden et al., 2009). This flooding resulted in the temporary displacement of nearly 50% of the coastal residents (International Strategy for Disaster Reduction, 2005).

## 5.7 Conclusion

This paper demonstrates that a GIS-based approach is invaluable for not only analyzing and visualizing the past positions of a coastline, but also for providing useful insights on the advance and retreat patterns along the Guyana coastline. The Demerara coastline is a morphological dynamic landform that exhibits changes in width, position, and configuration. An understanding of the duration, magnitude, and spatial scale of these changes could be obtained from ongoing field measurements and the application of geospatial technologies. Hence, an underdeveloped country like Guyana without research budgets for coastal investigations could make use of low cost Landsat and other remote sensing images to monitor the coast on a timely basis. By combining remotely-sensed images in a ArcGIS-based environment, which allows the use of predictive models like DSAS, it is possible to identify likely locations where the coast will either advance or retreat. While the predictive models may not be able to account for the various factors contributing to coastal advance and retreat they could, nevertheless, assist end users, especially coastal residents living in erosion areas, to make effective decisions on property protection, community planning, and resettlement (Agrawal et al., 2008). Moreover, policy planners and coastal managers could use the GIS-based approach to identify and target erosional “hot spots” for protection from problems related to flooding, inundation, salinization and erosion. Without doubt, the approach presented here could be used to facilitate the implementation of functional strategies to protect and sustain the coast for current and future generations.



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**CHAPTER 6**  
**TIME SERIES MODELLING OF DATA ON COASTLINE ADVANCE**  
**AND RETREAT<sup>3</sup>**

**6.1 Introduction**

The coastal system, at all spatial scales, is governed by a number of independent and interacting stochastic processes (for example, waves, winds, currents, velocity flows, etc.). Over time the coastal system, therefore, exhibits complex variability patterns of advance and retreat at a wide range of spatial scales. To better understand and predict the spatio-temporal behaviour of the coastal system researchers are now focussing their efforts on various modelling approaches because “models facilitate considerable more enlightenment on the relationships between process scales and scales of coastal behaviour” (Lakhan, 2004, p. 658). A comprehensive review of relevant and applicable coastal models can be found in Lakhan (2003) and Hearn (2008). From the literature it is evident that different types of coastal models (for example, mathematical, stochastic, physical, and computer-simulation) can be used to study the various characteristics and processes governing the coastal system. In this paper time series models, based on stochastic properties, were employed to understand the spatial-temporal behavior of the

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<sup>3</sup> A version of this Chapter has been accepted to the *Journal of Coastal Research* as:

Sajid Rashid Ahmad and V. Chris Lakhan, August, 2010. Time series modeling of data on coastline advance and retreat.



coastal system. Empirical data on coastline advance (i.e., synonymous with accretion) and retreat (i.e., synonymous with erosion) were fitted to time series models.

## **6.2 Research Rationale**

This research is premised on the understanding that, “the fundamental assumption in data-base modeling is that the sample sufficiently well reflect the essential properties of the process under study in time and space” (Larson *et al.*, 2003, p. 761). In an extensive review of papers Finkl (2002) emphasized the necessity of using appropriate datasets to understand long-term trends in beach and shoreline changes. While the changes occurring along the coast must be understood in both the spatial and temporal domains, most of the coastal research being done focuses on either the spatial or the temporal aspects of coastal change. This research, therefore, has the rationale of analyzing and modeling long-term coastline change data with combined spatial-temporal techniques. By following this approach both serial and spatial autocorrelation effects could be assessed thereby being more beneficial than regression analysis where the regression coefficients estimating the rate of change could be biased by serial autocorrelation effects. As a consequence, invaluable insights could be obtained on the occurrences of both erosional and accretional changes of various durations and spatial scales in the coastal system.

## **6.3 The Study Area**

The 435-km long Guyana coastline forms part of the northeast coastline of the South American continent that stretches some 1600 km between the mouths of the Amazon and Orinoco Rivers. Comprehensive accounts of the Guyana coast have been provided with reference to its evolution and morphology (Eisma and Van Der Marel,

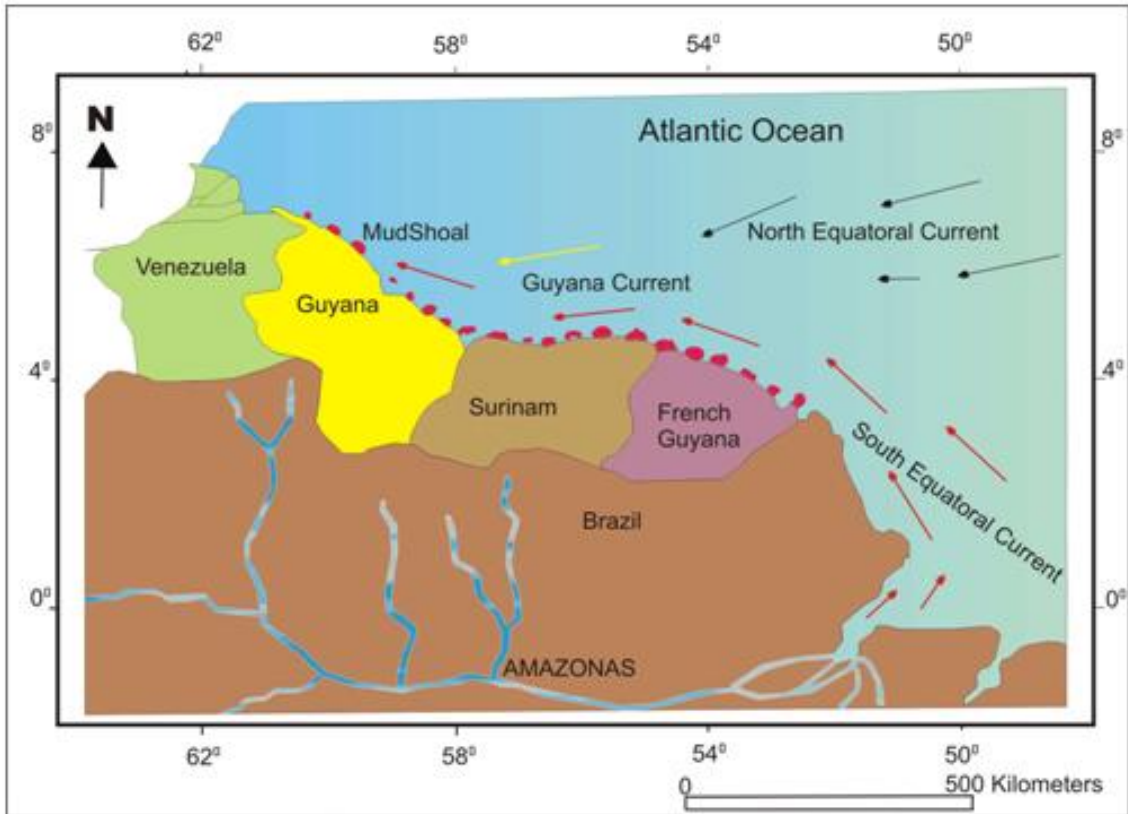
1971; Augustinus, 1987), environmental characteristics (Lakhan et al., 2000; Lakhan et al., 2002), and development (Lakhan, 1994). More than 90% of the country's population lives along the coast, with the majority of the people living in the various communities in the County of Demerara.

Along the Demerara coast there are sections which can be classified as a recessed coast or an oceanic coast. The oceanic portion of the coastline is exposed to a broad spectrum of oceanic processes including waves, tides, currents, and migrating mudshoals (also referred to as mudbanks). Froidefond et al. (1988) cited a report from the Delft Hydraulics Laboratory which reported twenty-one mudshoals along the lengths of the French Guiana, Surinam and the Guyana coasts (Figure 6.1). The mudshoals move westward at a rate of about 1.5 km per year from the Amazon estuary. The propagation and stabilization of the mudshoals are accompanied by a pattern of erosion (i.e., retreat) and accretion (i.e., advance) of the adjacent coast (Allersma, 1971). To monitor changes along the coast, data on the advance and retreat of the coastline have been collected since 1941 by the Government of Guyana and others.

#### **6.4 Analyzed Data**

The data that were acquired, analyzed and modelled were from empirical field measurements along the coast of Guyana. The data represent annual foreshore 45 feet + GD (Georgetown Datum) and 50 feet + GD contour-elevation measurements collected by the Lands and Surveys Department, Government of Guyana, the authors and graduate students. The 45 feet + GD (hereafter referred to as 45 GD) contour corresponds with the approximate Chart Datum or mean low water level while the 50 feet + GD (hereafter

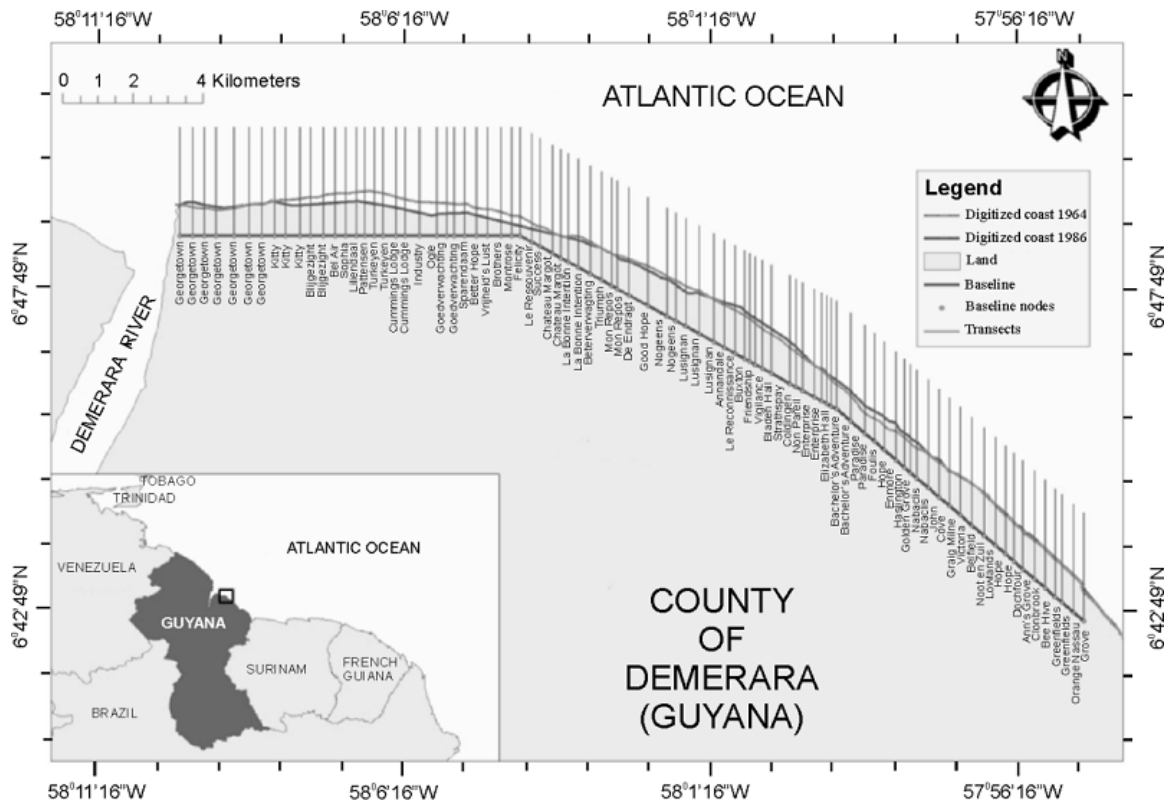
referred to as 50 GD) contour is the datum which is 0.5 feet (0.3 m) below mean sea level.



Source: Delft Hydraulics Laboratory, 1962 (digitized by Author)

**Figure 6.1: Regional setting of study area showing mudshoals movements along the northeast coast of South America.**

The foreshore elevation for 45 GD is 13.7 m, and for the 50 GD is 15.24 m (DHV Environment and Infrastructure, 1992). Each survey transect is approximately 300 m apart. The most complete archival data set is for the period 1941–1987, and represents measurements collected from 86 transect profiles along the Demerara coast (see Figure 6.2). Here it should be emphasized that the data set also includes the elevation levels for the 45 GD and 50 GD contour positions.



**Figure 6.2: The study area along the Demerara coast and associated transect profiles.**

To supplement archival data the second author, various graduate students, and participating researchers in Guyana initiated a program in 1988 to continue data collection along each of the 86 transect profiles established by the Government of Guyana. Since the first author participated in data collection until the end of 2007, this paper will use the data set for the time period 1941–2007. Equipment and materials which have and are being used to obtain data from each of the 86 transect profiles include a Sokkisha B2 Automatic Level, a Magellan Field Global Positioning System, a Lufkin Survey Chain, a Stadia Rod, and a motorized boat.

Mircosoft office Excel program is used to prepare the data for processing. The advance or retreat (AOR) method is utilized to determine the amount of material gained or lost by the coastline. The AOR is computed for the 86 transect profiles by comparing the initial and finishing positions of the 45 GD and the 50 GD contours. The Excel spreadsheet is used to calculate the AOR rates on an annual basis, and for every five years. For example, in the calculation of rates for the 1941–1946 period, positions for the two contours (45 GD and 50 GD) in 1941 were used as a starting point, and the 1946 contour positions were then subtracted from them. The differences are then divided by ten because data for two contours over a five-year period were used. Graphical plots of the AOR rates were produced to visualize the advance and retreat of the coast along the 86 survey transect profiles.

## **6.5 Data Analysis and Time Series Modelling**

Before statistically valid models were fitted to the data, it is necessary to ascertain that the data should have (a) no systematic change or trend in the mean, (b) no systematic change in the variance, (c) no deterministic periodic variations (Chatfield, 1996). The STATISTICA software (StatSoft, Inc., 2004) is used to examine the mean and variance present in the entire time series (1941–2007). Mean and variance values were also obtained for subseries of five-year time periods (1941–46, 1946–51, 1951–56, 1956–61, 1961–67, 1967–72, 1972–77, 1977–82, 1982–87, 1987–92, 1992–97, 1997–2002, 2002–2007). Five-year time intervals were used because it is assumed that data less than a five-year temporal span would not adequately capture the advance and retreat of the coastline. Here it should be noted that data were not collected in 1966 because of political instabilities in the country, and as such the 1961–67 subseries is for six years.

After fulfilling the mean and variance requirements the data were then detrended by generating standardized values for all of the 86 profiles for each of the years. A plot (see Figure 6.3) of the AOR data for each of the five-year time periods for the entire time series (1941–2007) clearly demonstrates no deterministic periodic variations within the data set. There were clear evidences of wide variability in the spatial patterns of coastal advance and retreat over time. To advance an explanation for the joint spatial-temporal variations in the AOR data time series modelling procedures were utilized. The time series of AOR data (1941–2007) were divided into 13 subseries or time periods and were represented as ZT1 (1941–46), ZT2 (1946–51), ZT3 (1951–56), ZT4 (1956–61), ZT5 (1961–67), ZT6 (1967–72), ZT7 (1972–77), ZT8 (1977–82), ZT9 (1982–87), ZT10 (1987–92), ZT11 (1992–97), ZT12 (1997–2002) and ZT13 (2002–2007).

Before time series models were fitted to the data, an Excel spreadsheet is used to represent the data as:

T<sub>1</sub> (1941): P1, P2, P3, P4,..... P86

T<sub>2</sub> (1942): P1, P2, P3, P4,..... P86

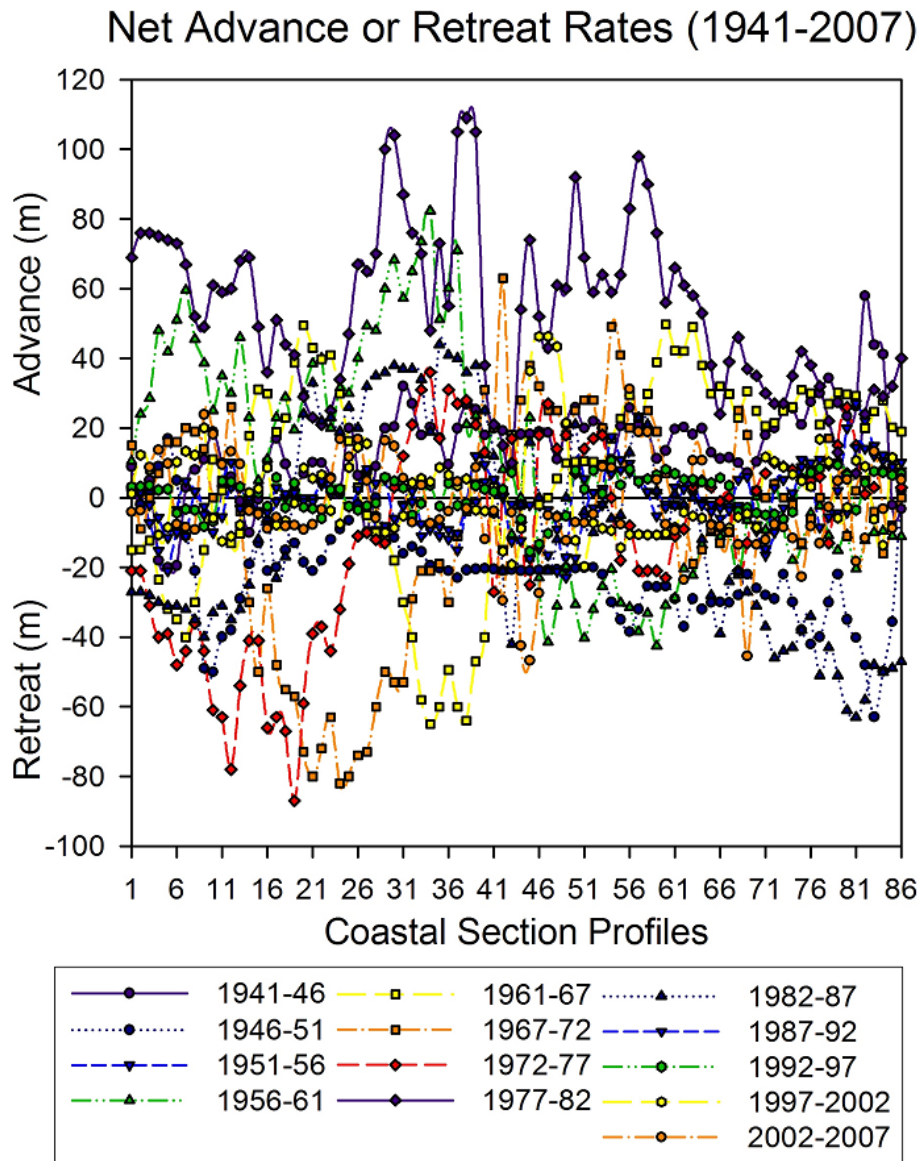
|

|

T<sub>67</sub> (2007): P1, P2, P3, P4,..... P86

Where T<sub>1</sub> is the first time period at 1941 and T<sub>67</sub> is the last time period at 2007. For each time period the data are from 86 profiles (P), stretching from P1 to P86. While the time series data are divided into sub-series it should be noted here that the 86 profiles being studied are not split into different spatial sections. This is because preliminary analysis of the data indicates the presence of spatial autocorrelation. This suggests small-scale spatial

dependence due to the interdependence of neighbouring sites. Cressie (1993) emphasized that small-scale spatial dependence is generally stochastic in origin, and therefore difficult to predict. As such, this research assumes that the amount of accretion or erosion at a specific site will be stochastically related to that observed at the adjacent updrift site.



**Figure 6.3: Line graph of coastal advance and retreat for 13 subseries from 1941-2007**

## 6.6 Types and Selection of Time Series Models

Lakhan (2005) provides a comprehensive overview on the application of time series models for coastal investigations, and emphasizes that time series models are essential for obtaining insights on the temporal processes operating in the coastal system. While the details of time series modelling are not presented here it is, nevertheless, worthwhile to state that several types of time series models can be obtained from any time series of coastal data. Models include the autoregressive (AR), the integrated (I), the moving average (MA), and mixed autoregressive moving average (ARMA) models. There are also extensions of the ARMA models by Box and Jenkins (1970, 1976) to include the autoregressive integrated moving average (ARIMA) and the seasonal autoregressive integrated moving average (SARIMA) processes. Granger and Joyeux (1980) introduced the autoregressive fractionally integrated moving average (ARFIMA) model while the threshold autoregressive model is presented by Lai and Wong (2006). Based on the applications and meaningful results obtained by previous investigators (LaValle et al., 2001; Southgate, 2008; Guillas et al., 2009) who used autoregressive models to investigate the temporal variations in the coastal system, this study places emphasis on the use of Box-Jenkins modelling procedures because the ARIMA models have been generalized by Cressie (1993) to incorporate spatial location. Models with a spatial component include the spatial autoregressive (SAR) models, spatial cyclic autoregressive (CAR) models, space-time autoregressive (STAR) models, and the space-time autoregressive moving average (STARMA) models. The space-time autoregressive component can be represented as:

$$Y_{s,t} = \psi_{s-1,t} Y_{s-1,t} \pm \psi_{s,t-1} Y_{s,t-1} \pm \psi_{s-1,t-1} Y_{s-1,t-1} \pm \varepsilon \dots\dots\dots(1)$$



where the  $P$  terms represent the estimated autoregressive parameters,  $\varepsilon$  indicates the error or residual term,  $s$  is the spatial location, and  $t$  is time.

The STARMA model takes the form (Cressie, 1993, p. 449):

$$Z(t) = \sum_{k=0}^p \sum_{j=0}^{\lambda_k} \xi_{kj} W_{kj} Z(t-k) - \sum_{l=0}^q \sum_{j=0}^{\mu_l} \phi_{lj} V_{lj} \varepsilon(t-1) + \varepsilon(t) \quad \dots\dots(2)$$

where  $W_{ij}$  and  $V_{ij}$  are given weight matrices,  $\delta_k$  is the extent of spatial lagging on the autoregressive component,  $\mu_l$  is the extent of spatial lagging on the moving average component, the residuals are given by,  $\varepsilon(t) \sim N(0, \sigma^2)$  and  $\xi_{kj}$  is the autoregressive parameter to be estimated while  $N_{lj}$  is the moving average parameter to be estimated. From Equation 2 it can be seen that the STARMA model uses an observation  $Z(s_i, t)$  taken at spatial location  $s_i$  and time  $t$  and defines  $Z(t) = [Z(s_1, t), \dots, Z(s_n, t)]^T$ .

## 6.7 Steps in Model Selection

The Box-Jenkins modelling construction procedures of identification, estimation, and diagnostic checking, outlined by Lakhan (2005), were followed in order to fit statistically valid models to the data for each of the 13 subseries or time periods. At the identification stage various model structures (AR, MA, ARMA, SAR, CAR, STARMA) and model orders (first-order, second-order, etc.) were considered. In the identification process an automated iterative procedure is used to fit models of various structures and orders. Best fit models were obtained with the STATISTICA software (StatSoft, Inc., 2004). Time Series modules through a process that involves examination of a number of tentative model identifications and parameter estimations. One of the steps that is followed is an analysis of the graphical plots of autocorrelation function (ACF) and

partial autocorrelation function (PACF).

In addition to an examination of the ACFs and PACFs, several statistical parameters were evaluated, including the r-values, the autocorrelation coefficients, the T-ratios, and the approximate probability values at the 0.05 significance level. Before the models were finally selected diagnostic checking is performed. In checking each of the models care is taken to ensure that the residuals are random, and that the estimated parameters are statistically significant. The goodness-of-fit of each model is determined with the Box-Ljung Q statistics. If a model is chosen as acceptable, then the probabilities associated with the Box-Ljung Q values must be greater than 0.05.

## **6.8 Results**

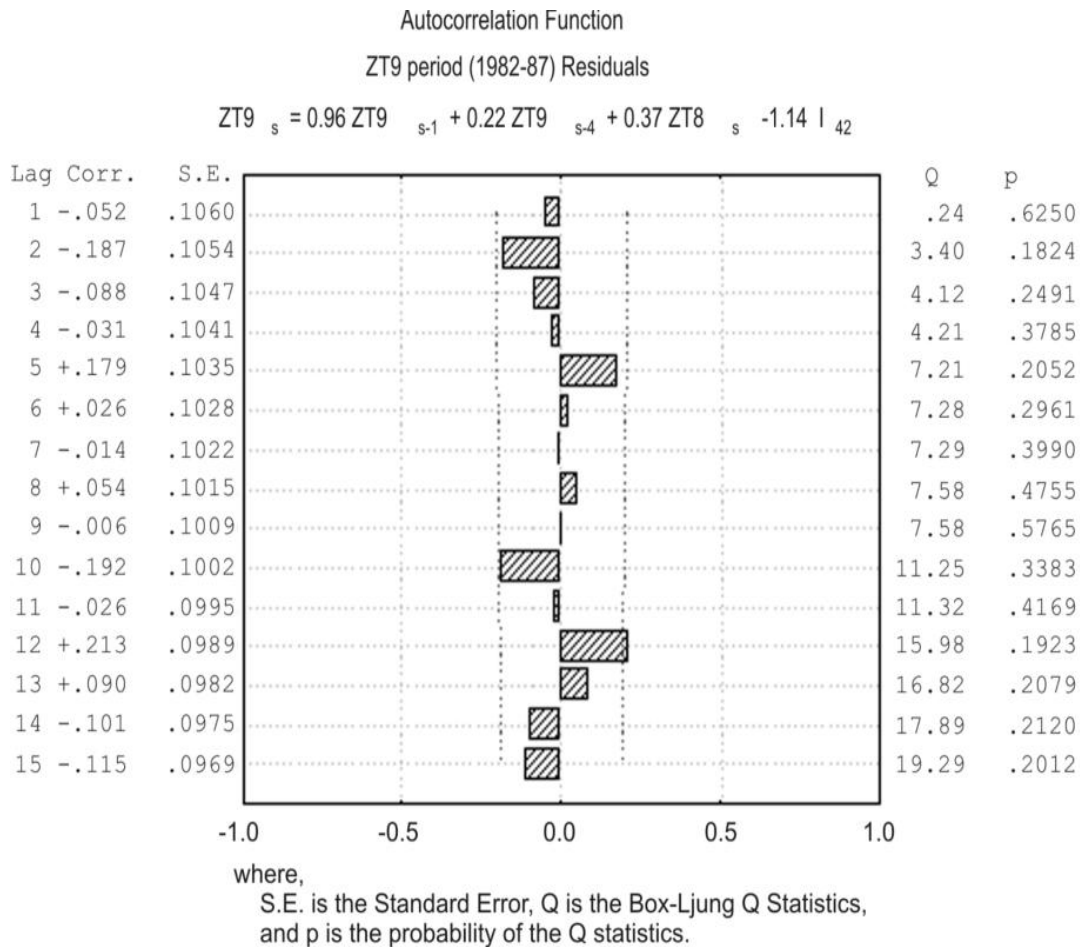
The results permit the selection of models that best represent each of the 13 subseries. While space considerations prevent presentation of all the graphical and statistical outputs representative results were, nevertheless, discussed to highlight statistically valid best fit models. An examination of the parameters of each of the fitted models reveals that second-order spatial cyclical autoregressive (CAR-2) models provide the best fit to the ZT1 (1941–42), ZT2 (1946–51), ZT4 (1956–61), ZT9 (1982–87), and ZT12 (1997–02) subseries. All the T-ratios are above the critical values and the p values are also significant at the 0.05 level. The statistical results (see Table 6.1) of the ZT9 (1982–87) model were used as an example to highlight the suitability of the CAR-2 model.

Table 6.1 demonstrates that the second-order autoregressive coefficients for ZT9 are 0.905 and the temporal autoregressive coefficient for ZT8 coefficient is 0.371. The T-ratios are above the critical values.

**Table 6.1: Statistical results of second-order cyclical spatial autoregressive model for ZT9 (1982–1987) subseries**

<b>Variable:</b> ZT9 (Net positional change in 1982-87 temporal span).				
<b>Regressors:</b>		T7STEP42, ZT8		
<b>Length of seasonal cycle:</b>		4		
<b>FINAL PARAMETERS:</b>				
<b>Number of residuals</b>		86		
<b>Standard error</b>		0.34611262		
<b>Analysis of Variance:</b>				
	<b>DF</b>	<b>Adj. Sum of Squares</b>	<b>Residual Variance</b>	
<b>Residuals</b>	82	10.082585	0.11979394	
<b>Variables in the Model:</b>				
	<b>B</b>	<b>SEB</b>	<b>T-Ratio</b>	<b>Approx. Probability</b>
<b>CAR1</b>	0.9052529	0.4694853	19.281815	0.00000000
<b>CAR2</b>	0.2235251	0.11005681	2.030979	0.04549712
<b>T8STEP42</b>	-1.1399915	0.30839754	-3.696500	0.00039360
<b>ZT8</b>	0.3718423	0.05045565	7.369687	0.00000000
<b>MODEL SUMMARY</b>				
<b>Correlation Between Dependent Variable and Model Fit</b>				
<b>R</b>	0.91			
<b>R square</b>	0.84			
<b>Durban Watson</b>	2.37			
<b>Degrees of Freedom</b>	84			
<b>Significance</b>	0.000			
Where, Length of spatial cycle 1 = 300 meters; therefore, cycle 4 represents 1200 meters.				
<b>CAR1</b>	= First-order Spatial Cyclical AR (autoregressive)			
<b>CAR2</b>	= Second-order Spatial Cyclical AR			
<b>T8STEP42</b>	= Spatial Intervention of series at lag 42 (300 x 42 = 12600 m)			
<b>ZT8</b>	= Temporal AR (autoregressive)			

The correlation coefficient of 0.91 is indicative of a strong relationship and the  $R^2$  value of 0.84 for all the variables suggest that 84% of the variance is accounted for by the model. Moreover, the intervention coefficient for the period is 1.139 with an approximate probability of 0.000, thereby indicating that a significant change occurred in the coastal system at the 12,600 m mark. At this location extensive retreat of the coast occurred and is represented by the community of Good Hope (see Figure 2, at profile number 42 in the dataset). Given the fact that there is also no autocorrelation in the plot (Figure 6.4) of the residuals in the model, as indicated by the non-significant Box-Ljung statistics, then the CAR-2 model can be accepted with confidence.



**Figure 6.4: Correlogram of model for ZT9 (1982–1987) subseries.**

It is also significant to note that the ZT9 (1982–87) period is approximately 40 years from the ZT1 (1941–46) period which also experiences a similar CAR-2 process. This cyclic process could be associated with the movement of mudshoals which have been found to have a 36-year cycle along the coast of Guyana (Augustinus, 1987; Lakhan et al., 2006). Within the long-term cycle of coastal advance and retreat there are also localized pseudo-cycles of coastal change as evident from the CAR-2 model of the other time periods (ZT1, ZT2, ZT4 and ZT12). In the ZT9 model there is noticeable evidence of cyclic behavior in the coastal system with a period of four spatial cycles (approximately 1200 m).

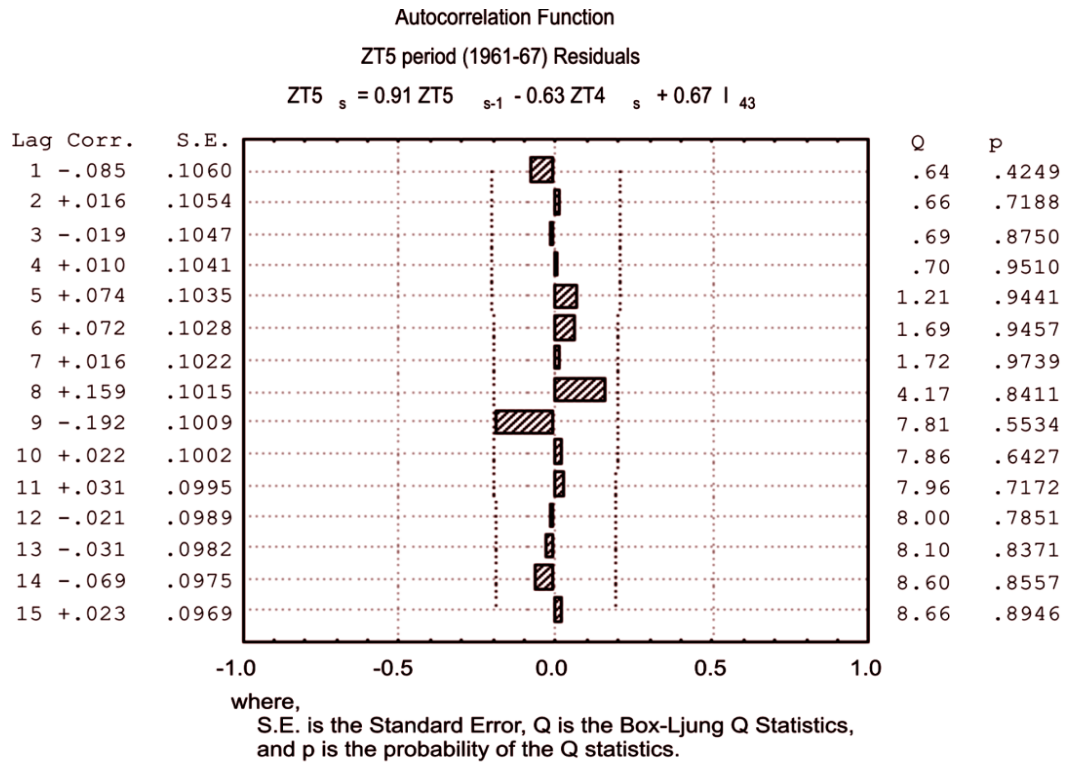
The results also permit the selection of a first-order spatial autoregressive (SAR-1) to fit the ZT3 (1951–56), ZT5 (1961–67), ZT7 (1972–77), ZT10 (1987–92) and ZT11 (1992–97) subseries. This model is different from the previously selected CAR-2 model because instead of oscillating like the CAR-2 process more of a scalloped pattern is exhibited. The statistics for the SAR-1 models demonstrate that all the p-values are significant. The T-ratios are also above the critical levels. The SAR models for these time periods provide strong evidence of a long memory response, associated with random events (i.e., random shocks), within the series. This can be expressed as an autoregressive function of the previous value of the series. Representative results from the ZT5 (1961–67) were presented in Table 6.2 to substantiate the selection of the SAR-1 model.

From Table 6.2 it could be seen that the spatial autoregressive coefficient for ZT5 is 0.913, and the temporal autoregressive coefficient with ZT4 is 0.634. The correlation coefficient is 0.93 representing a strong relationship whereas the  $R^2$  value of 0.877 suggests that 87% of the variance is accounted for by the model.

**Table 6.2: Statistical results of the first-order spatial autoregressive model for the ZT5 (1961–1967) subseries**

<b>Variable:</b> ZT5 (Net positional change in 1961-67 temporal span).				
<b>Regressors:</b> T5STEP42, ZT4				
<b>Length of seasonal cycle:</b> 4				
<b>FINAL PARAMETERS:</b>				
<b>Number of residuals</b> 86				
<b>Standard error</b> 0.35011923				
<b>Analysis of Variance:</b>				
	<b>DF</b>	<b>Adj. Sum of Squares</b>	<b>Residual Variance</b>	
<b>Residuals</b>	<b>83</b>	<b>10.389008</b>	<b>0.12258347</b>	
<b>Variables in the Model:</b>				
	<b>B</b>	<b>SEB</b>	<b>T-Ratio</b>	<b>Approx. Probability</b>
<b>SAR1</b>	<b>0.91315585</b>	<b>0.4480618</b>	<b>20.380130</b>	<b>0.00000000</b>
<b>T5STEP43</b>	<b>0.67456889</b>	<b>0.30494789</b>	<b>2.212079</b>	<b>0.02970881</b>
<b>ZT4</b>	<b>-0.63482549</b>	<b>0.09622213</b>	<b>-6.597500</b>	<b>0.00000000</b>
<b>MODEL SUMMARY</b>				
<b>Correlation Between Dependent Variable and Model Fit</b>				
<b>R</b>	<b>0.93</b>			
<b>R square</b>	<b>0.877</b>			
<b>Durban Watson</b>	<b>2.13</b>			
<b>Degrees of Freedom</b>	<b>84</b>			
<b>Significance</b>	<b>0.000</b>			
<b>Where, Length of spatial cycle is 1800 meters.</b>				
<b>SAR1</b>	<b>= First-order Spatial AR (autoregressive)</b>			
<b>T5STEP43</b>	<b>= Spatial Intervention of series at lag 43</b>			
<b>ZT4</b>	<b>= Temporal AR (autoregressive)</b>			

In addition, there is no autocorrelation in the plot (see Figure 6.5) of the residuals of the model as indicated by the non-significant Box-Ljung statistics.



**Figure 6.5: Correlogram of model for ZT5 (1961–1967) subseries.**

Although the oscillations associated with the CAR-2 model are absent the SAR-1 model, nevertheless, emphasizes that the coastal system is being affected by random shocks which initiate changes that persist for several time intervals after the application of a random shock. Evidently, erosion and accretion can still occur along the coast even though mudshoals are not present. A certain lag period, therefore, exists before the full effects of mudshoals are dissipated from the coastal system.

In addition to CAR-2 and SAR-1 models the results also indicate that a space-time autoregressive moving average (STARMA) model provides the best fit for the ZT6 (1967–72), ZT8 (1977–82), and ZT13 (2002–07) subseries. Results of the ZT13 subseries

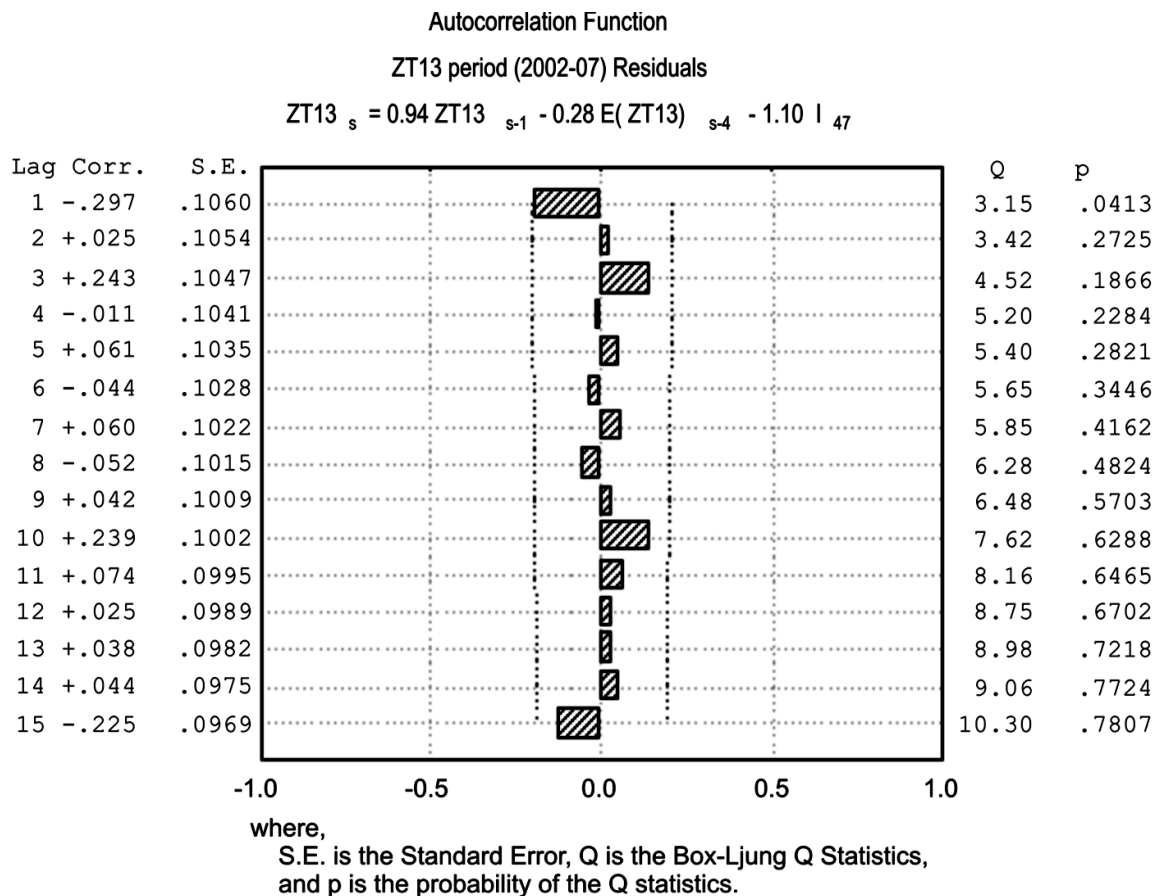
are presented in Table 6.3 to demonstrate the statistical validity of the STARMA model.

**Table 6.3: Statistical results of the space-time autoregressive moving average model for the ZT13 (2002–2007) subseries**

<b>Variable:</b>		<b>ZT13 (Net positional change in 2002-2007 temporal span).</b>		
<b>Regressors:</b>		<b>T12STEP42, ZT12</b>		
<b>Length of seasonal cycle:</b>		<b>4</b>		
<b>FINAL PARAMETERS:</b>				
<b>Number of residuals</b>		<b>86</b>		
<b>Standard error</b>		<b>0.37018</b>		
<b>Analysis of Variance:</b>				
	<b>DF</b>	<b>Adj. Sum of Squares</b>	<b>Residual Variance</b>	
<b>Residuals</b>	<b>83</b>	<b>9.4736</b>	<b>0.172834</b>	
<b>Variables in the Model:</b>				
	<b>B</b>	<b>SEB</b>	<b>T-Ratio</b>	<b>Approx. Probability</b>
<b>SAR1</b>	<b>0.96271</b>	<b>0.0273</b>	<b>21.7863</b>	<b>0.00000000</b>
<b>SMA1</b>	<b>-.29742</b>	<b>0.1017</b>	<b>-2.3847</b>	<b>0.0001</b>
<b>T12STEP47</b>	<b>-1.600</b>	<b>0.3384</b>	<b>-2.9769</b>	<b>0.0012</b>
<b>ZT12</b>	<b>-0.31897</b>	<b>0.08976</b>	<b>-3.2472</b>	<b>0.0001</b>
<b>MODEL SUMMARY</b>				
<b>Correlation Between Dependent Variable and Model Fit</b>				
<b>R</b>	<b>0.92</b>			
<b>R square</b>	<b>0.89</b>			
<b>Durban Watson</b>	<b>2.47</b>			
<b>Degrees of Freedom</b>	<b>83</b>			
<b>Significance</b>	<b>0.000</b>			
<b>SAR1</b>	<b>= First-order Spatial AR (autoregressive)</b>			
<b>SMA1</b>	<b>= Spatial Moving Average at Cycle 4</b>			
<b>T12STEP47</b>	<b>= Spatial Intervention of series at lag 47</b>			
<b>ZT12</b>	<b>= Temporal AR (autoregressive)</b>			

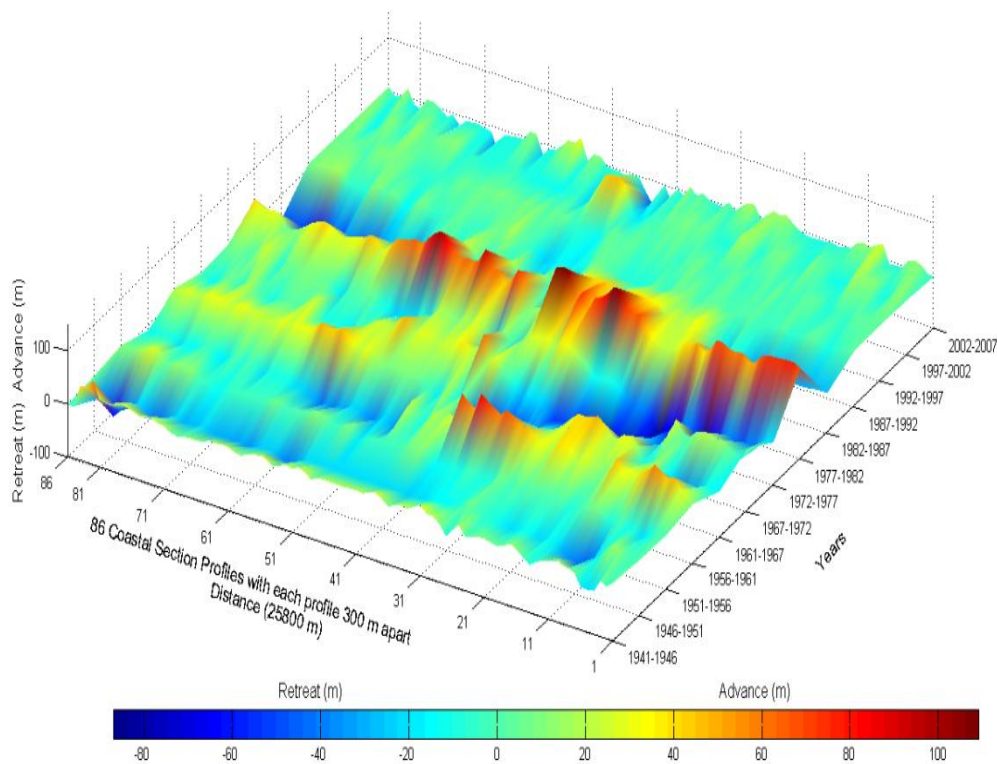


The AR coefficient parameter is 0.96 and the moving average parameter is 0.297. The ZT12 coefficient is 0.318 and the approximate probabilities are 0.000, 0.001, and 0.001 respectively at an alpha of 0.005. The series is also interrupted or intervened at lag 47 where the intervention coefficient is 1.6 at a probability of 0.001. The r value of 0.92 indicates that the relationship is strong, whereas the  $R^2$  value of 0.89 denotes that 89% of the variance of ZT13 is accounted for by the model. Residuals on the correlograms show no signs of autocorrelation as illustrated by the non-significant Box-Ljung statistics. Figure 6.6 shows that all the autocorrelations are within the 5% confidence bands.



**Figure 6.6: Correlogram of model for ZT13 (2002–2007) subseries.**

The high AR1 component and its associated coefficient value suggest that a first order autoregressive process exists within the ZT13 period. The statistically significant MA (1) parameter suggests that the processes operating in the coastal system have a short memory, and are transitory in nature. This means that there are points in the space-time series where accretional and erosional rates are not persistent. Evidently, temporal stochastic processes are forcing rapid changes in the coastal system. The spatial and temporal variations in coastal advance and retreat which are represented by the time series models can also be visualized on a three-dimensional space-time map (Figure 6.7) obtained with MATLAB version 7.5 software (MathWorks, Inc., 2007).



**Figure 6.7: Three-dimensional space-time map of coastal retreat and advance (1941–2007).**

Over time and through space there are varying amounts of accretion and erosion at each of the 86 profiles. This illustrates the interrelatedness of temporal and spatial patterns in coastal advance and retreat. Interestingly, the same profiles (i.e., 75–86) exhibit increasing rates of erosion for two different time periods (1941–46 and 1982–87). This observation lends support to the CAR-2 model results which indicate a long-term erosional cycle. This cycle is also associated with shorter cycles because there is a distinctive erosional trend along profiles 1–30 for the 1967–77 period. The time series map is therefore useful for highlighting erosional hotspots. The “scalped” pattern of erosion and accretion that is occurring through space presents evidence of a spatial autoregressive process as indicated by the first-order spatial autoregressive model. The noticeable changes which were occurring in certain sections of some of the profiles also point to the fact that stochastic processes are forcing erosional and accretional responses.

## **6.9 Discussion and Conclusion**

The time series modelling results presented in this paper emphasize that variations in coastal accretion (i.e., advance) and erosion (i.e., retreat) along the Guyana coast are indicative of both temporal and spatial autoregressive processes. These processes could be considered as cyclic, and long memory processes punctuated by short memory and random processes. Interestingly, the data arising from the influence of these processes could be fitted to various types of time series models. The AOR data for the 13 subseries were, therefore, described by second-order spatial cyclic autoregressive models, first-order spatial autoregressive models, and space-time autoregressive moving average models. These models reflect that the coast, at different times and spatial scales, responds to either independent or combined cyclic or pseudo-cyclic or random temporal processes.

Hence, as reported by other researchers (for example, Li et al., 2005; Miller and Dean, 2007; Southgate, 2008) patterns in the data could be related to hydrodynamic forcing processes.

The second-order spatial cyclic autoregressive models which fit the ZT1, ZT2, ZT4, ZT9, and ZT12 subseries reflect the presence of a cyclic process that is operating in Guyana's coastal system. One documented cyclic process in Guyana's coastal system is propagating mudshoals, which influence a dominant erosional cycle of approximately 36 years (Augustinus, 1987; Lakhan et al., 2006). Upon entering Guyana's coastal system the mudshoals migrate slowly along the coast and have the cumulative effects of dampening wave energy, and altering the flow of currents and nearshore circulation cells. Accretion takes place on the coast directly opposite a mudshoal whereas erosion normally occurs in those areas where the mudshoal is not present. When a mudshoal propagates away from an area along the coast that section of the coast becomes exposed to the effects of erosive waves, tides and currents. The recurring patterns of coastal advance and retreat along the coast were therefore depicted by the CAR-2 model which also indicates the occurrence of pseudo-cycles of erosion and accretion of shorter durations. The cyclical morphological states in the coastal system have also been observed elsewhere. One good example is from the Dutch coast where Wijnberg and Terwindt (1995) reported cyclic changes in bar morphology of either 4 or 15–18 years.

The results also highlight that the subseries ZT3, ZT5, ZT7, ZT10 and ZT11 were best represented by a first-order spatial autoregressive model. This model describes what happens when a random shock is applied to a spatial series. The effects of this shock will likely persist for some length of time, and therefore signify the influence of a long

memory response in the coastal system. In effect, the coast will continue to advance or retreat even though the influencing factor or factors are not noticeable. Previous (Allersma, 1971; Eisma and Van Der Marel, 1971) and ongoing field investigations by the second author observe that the erosional or accretional effects of mudshoals remain for extended periods of time long after mudshoals have migrated or dissipated.

In addition to cyclic, and long memory response processes the Guyana coast is also under the influence of short memory processes where the effects of temporal processes are not persistent. Hence, ZT6, ZT8 and ZT13 subseries suggest that retreat and advance patterns along the coast are transitory in nature. The changing morphodynamic states are comparatively temporary whereby positional shifts in the coastline start and end rather abruptly. These transitory morphological changes along the coastal system could be attributed to not only the impacts of propagating mudshoals, but also to the influences of temporal stochastic processes. These stochastic forcing processes could be higher than normal water levels, extreme wind-generated waves and currents, and strong nearshore circulation flows. Several studies (for example, Dalrymple and Pulwarty, 2006; Van Ledden et al., 2009; ) have reported on the impacts of hydrodynamic forcing processes which effect erosional changes to Guyana's coastal system. While these temporal stochastic processes are of short durations they tend to recur over time, and cause erosional impacts at one or more spatial locations.

Without doubt, the Guyana coast is governed by a combination of interacting processes which have the effects of causing the coast to either advance or retreat for different temporal durations and varying spatial scales. The time series models can, therefore, be utilized to provide valuable insights on not only the nature and

characteristics of these processes, but also on the changes effected by these processes. The time series modelling results can also be supplemented with a space-time three-dimensional map to visualize coastline changes in the spatio-temporal continuum. Understanding the dynamics of these coastal changes, especially the advance and retreat patterns of the coast, is very important because in addition to being fundamental to the study of coastal evolution knowledge of the spatial and temporal behavior of the coastline also have direct applications in coastal engineering projects involving beach nourishment, and in the sighting of coastal structures (Larson and Kraus, 1994). For planning purposes, the procedures presented in this paper can be applied by coastal resource managers not only in Guyana but elsewhere, to detect, predict and visualize the shifts in advance and retreat phase states occurring in the coastal system.

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## CHAPTER 7

### GENERAL DISCUSSION AND CONCLUSIONS

#### 7.1 Discussion

More than 50% of the present global population lives in the coastal zone, and an increasing number of coastal residents are confronted with numerous problems relating to flooding, sea level rise, salt water intrusion, destruction of wetlands and freshwater systems, and collapse of nearshore fisheries (O’Riordan et al., 2000). To better protect and manage the world’s vulnerable coastal systems, including the Guyana coast that is being studied here, it is necessary to conduct research that will provide reliable and timely insights to existing and expected problems in the coastal system. In this respect, this thesis focused on utilizing and combining practical geospatial techniques with predictive models to understand both the past and expected behaviour of the coastal system. By incorporating data from multiple sources (archival, field, topographic maps, remote sensing) into a GIS and then analyzing and modelling the data the various objectives and hypotheses of the thesis were obtained. This was done through an incremental and integrated approach whereby the attainment of the first objective facilitated completion of each of the other objectives and hypotheses.

To attain the first objective and first hypothesis of the research, a GIS was used to analyze, identify, predict, and visualize the spatial and temporal advance and retreat changes occurring along the coast of Guyana. In Chapter 4, it was demonstrated that the GIS was parameterized with data from an empirical time series (1941–1987) on coastline advance and retreat, digital data from topographic maps (1964 and 1986), and data extracted from remotely-sensed images (1992 and 2002). Several ArcGIS 9.2 (ESRI,

2007) functions were then utilized to identify, analyze, and map the positional shifts which occurred along the coastline. Temporal diagrams were then prepared to highlight which time periods exhibited the most change along the coastline. Following this, the data were then used in the GIS to map and highlight areas along the coast that either retreated or advanced. The results demonstrated several areas along the extent of the coast that exhibited persistent retreat patterns, and other advancing sections of the coast. Prediction was also done for the coastline in the year 2016. The map that was produced to highlight the spatial areas that will change along the coastline in the year 2016 demonstrated several areas along the coast of Guyana that will likely retreat. The results from the analysis and mapping permit acceptance of the hypothesis that advance and retreat of the coast of Guyana could be predicted with data incorporated in a GIS.

To further substantiate the acceptance of the first objective and first hypothesis, Chapter 5 extended the analysis on the modelling and prediction of spatial locations which either advanced or retreated over time. With the use of additional GIS functions (Spatial Analyst, 3D Analyst, and Triangulated Irregular Networks) the advance and retreat coastal data were processed to visually determine the amount of sediments that were gained or lost during periods of advance or retreat of the coastline. Two distinct periods of coastal retreat were observed. Evidently, some areas along the coast experienced retreat associated with major losses of sediments approximately 30 years apart.

To obtain further insights on the spatial variations in retreat and advance patterns along the coastline, Chapter 5 also processed additional remote sensing images which were incorporated into the GIS database. The band ratio method was used to extract

coastlines from which accretional and erosional data were obtained. This method was selected after evaluating several other coastline extraction techniques.

The Digital Shoreline Analysis System (DSAS), an ArcGIS extension, was then utilized to predict changes along the coastline. By using the coastlines extracted from the remotely-sensed images, the DSAS was able to predict rate of change at each of the 86 transect profiles. From the predicted results it was possible to identify locations along the coast which were advancing, and also those locations which were retreating. These results provided the verification to fully accept the hypothesis that a GIS-based approach could be used to predict coastline changes. Interestingly, the results lead to the recognition of erosional “hotspots.” These areas matched those which were identified through field observations. Here it is significant to note that the DSAS predicted that the Guyana coast is experiencing an erosional trend.

With the GIS highlighting varying magnitudes of accretion and erosion along the coast, the acquired data were modelled with statistical techniques to gain insights on the spatio-temporal processes influencing the variations in coastline changes. In Chapter 6 the second objective of this thesis was therefore satisfied whereby statistical time series models were identified to reflect the temporal stochastic processes operating in Guyana’s coastal system. Box Jenkins (1970; 1976) modelling procedures were generalized to incorporate spatial locations, and were then utilized to investigate the stochastic behaviour of the coastal system.

By organizing and structuring the data to reflect different temporal resolutions, results were obtained to demonstrate that the Guyana coast could be described by second-order spatial cyclic autoregressive models, first-order autoregressive models, and space-

time autoregressive moving-average models. Each of the models suggests differences in the stochastic processes influencing changes along Guyana's coastline. The second-order spatial cyclic autoregressive models suggest the existence of cyclical advance and retreat patterns along the coast. Similar results were also highlighted by the GIS, where it was observed that distinct retreat patterns along the coast occurred approximately 30–36 years apart. Evidently, the coastline responded to the propagation and stabilization of mudshoals which have a cyclicity pattern of about 36 years (Allersma, 1971; Augustinus, 1987; Lakhan et al., 2006). This finding permits acceptance of the second hypothesis which states that second-order spatial cyclic autoregressive models could be fitted to empirical coastline change data. Accepting this hypothesis served to fulfill the second objective of the thesis which is to identify statistical time series models that best reflect cyclic stochastic processes operating in Guyana's coastal system.

In addition to the identification of second-order autoregressive models, this research also found that for some time intervals the coastline change data could be fitted to space-time autoregressive moving average models. These models suggest the existence of short memory, transitory processes influencing Guyana's coastal system. Since positional shifts along the coastline have been identified and predicted it could be concluded that the statistical models are appropriate to reflect the presence of temporal stochastic processes in the collected data. Hence, the third hypothesis could also be accepted because the data for some time intervals could be fitted to space-time autoregressive moving average models.

To extend and utilize the data and information incorporated into the GIS another objective of the research was fulfilled whereby an innovative spatio-temporal

information-based system (STIBS) for decision-making was formulated. This was done on the premise that a GIS is useful for assessing, analyzing and identifying patterns of change in the coastal system, but is ineffective for providing timely solutions and simulations to spatial problems in the coastal system. To obtain success in investigating and solving problems related to erosion and flooding in Guyana's coastal system Chapter 3 presents an innovative Spatial Temporal Information Based System (STIBS) which integrates various subsystems to handle data and information flows. The system has tremendous analytical capabilities because it combines a diverse array of physical and social datasets and computer-based models to form components of a flexible and interactive information-based system. With the inclusion of a model-based subsystem and a spatial information dialogue and display subsystem researchers and policymakers could simulate various scenarios of coastline advance and retreat and other processes in the coastal system. A simulation test done with the GUYSIM model (Lakhan, 2002), which was incorporated in the STIBS, permitted visualization of coastline changes for the years 2016 and 2031. Interestingly, the results indicated a long-term process of coastline retreat, interrupted by shorter periods of coastline advance. With an increase in sea level rise the results suggested a long-term trend of coastline retreat. When fully operational, the STIBS has the capabilities of making decisions and providing solutions to ongoing and future problems along vulnerable coastlines.

## **7.2 Validation and Sensitivity of Modelling Results**

To determine the accuracy of the results in the thesis, various validation and sensitivity tests were applied. The sensitivity analysis is an inevitable step in model validation (Lakhan 2005) whereas validation is the process of determining the degree to

which the model is an accurate representation of the real world for the perspective of the intended uses. The results obtained from time series modelling procedures were tested by a series of well-defined steps outlined by Lakhan (2005). The following model Identification, Verification, Selection and Validation methods were used in this thesis.

### ***Model Verification***

Two important elements of checking are to ensure that the residuals of the model are random, and to ensure that the estimated parameters are statistically significant. To ascertain whether the residuals are white noise, the residuals from the estimated model are used to calculate the autocorrelation coefficients. The Portmanteau lack of fit test (Q statistic) is usually applied for testing the independence of a time series. Q statistic is appropriate for determining the goodness-of-fit of autoregressive models fitted to data on shoreline changes.

### ***Best Model Selection***

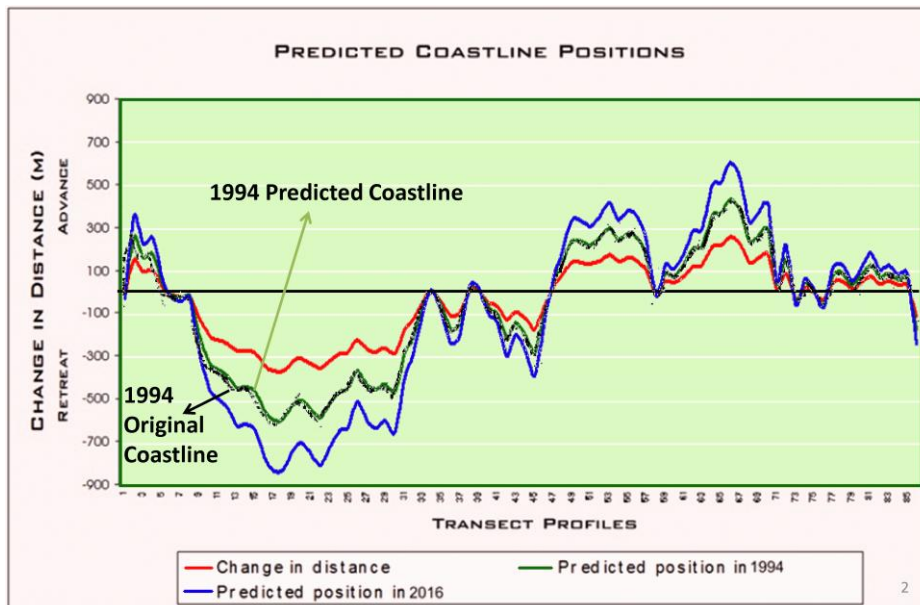
In coastal time series analysis, it is possible that several appropriate models can be used to represent the given data set. A selection criterion is different from the model identification methods as mentioned above. To choose the best model from the different adequate models, several model selection criteria have been proposed (Hannan, 1980). Some well-known model selection criteria based on residuals are Akaike Information Criterion (AIC), Parzen Criterion for Autoregressive Transfer (CAT) function and the Schwartz's Bayesian Criterion (SBC). Of the various selection criteria, the AIC is widely used in time series model fitting because it increase the speed, flexibility, accuracy, and simplicity involved in choosing the "best" model (Lakhan 2005). In addition, the ACI



facilitates the selection of parsimonious model that, at the same time, provides a good statistical fit to the data being modeled.

### ***Model Validation***

Fenster et al. 1993 stated that historical rates of coastline change are good indicator for predicting future coastline positions. Coastline positional changes stored in the GIS for 1964 were extrapolated for a 30 year period to the year 1994. The predicted coastline was then compared to the original 1994 coastline extracted from the field data and remote sensing image. Both coastlines were then overlaid in the GIS. Areas of similarities and variations were obtained, and percentage variation values were computed. As shown by Figure 7.1, there is a close similarity between the actual 1994 coastline of Guyana and the predicted 1994 coastline.



**Figure 7.1: Similarity between original and predicted 1994 Guyana’s coastline**

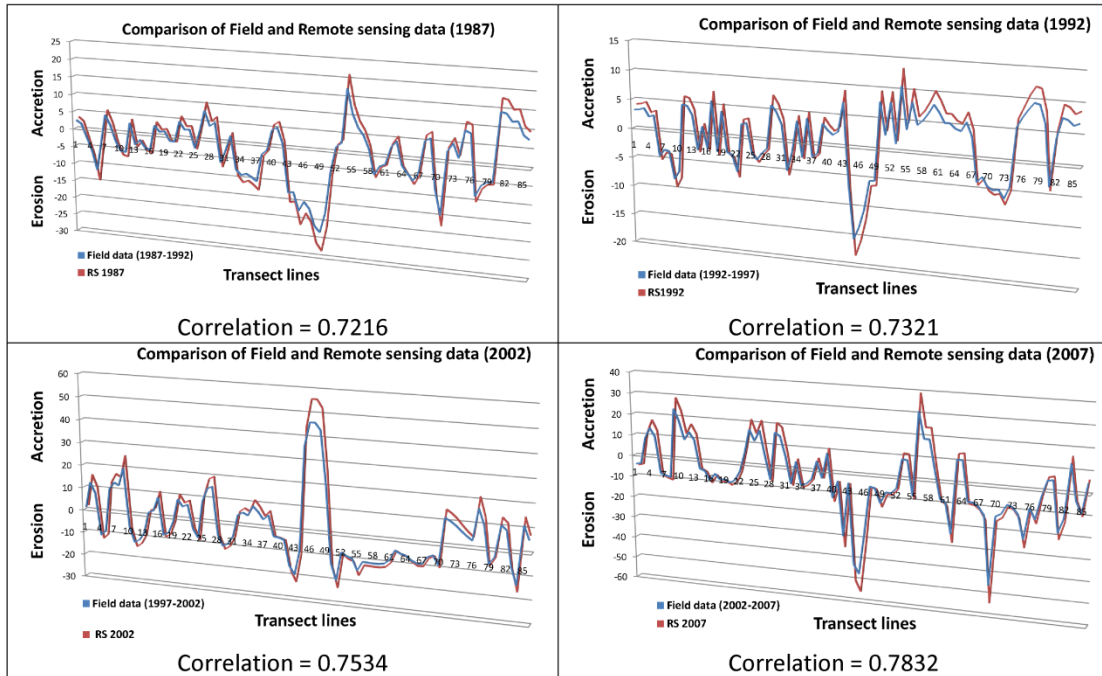
According to Sutherland et al. (2004), the performance evaluation of numerical models of coastal morphology against observation is an important part of establishing the credibility of that model. It could be done by the judgement of goodness-of-fit and comparing predicted with observed behaviour. The performance of any model can be assessed by calculating its bias, accuracy and skill. Bias is the measure of the difference in the central tendencies (mean, median) of the predictions and observations whereas; accuracy is a measure of the average size of the difference between a set of predictions and the average error of the observation. A model may still have a low accuracy even when there is no bias in it. It can be determined by using root mean square error (RMSE).

To calculate accuracy of ground control points (GCP) selection, I used the following root mean square errors (RMSE) equation:

$$\text{RMSEs} = \sqrt{\left( \sum_{i=1}^n (\mathbf{x}_{\text{ref},i} - \mathbf{x}_{\text{pr},i})^2 + \sum_{i=1}^n (\mathbf{y}_{\text{ref},i} - \mathbf{y}_{\text{pr},i})^2 \right) / n}$$

A RMSE (output) of <1 pixel is probably acceptable for a TM and ETM scene with a ground resolution of 30 meters. The RMSE value was 0.16 pixel (4.8m) in my results which showed higher accuracy (see chapter 4 and 5 results).

For the validation of remote sensing results of 1987, 1992, 2002 and 2007, the correlation was determined between remote sensing and field data which is based on the average of 5-year time period along the coast of Guyana (See Figure 7.2). As shown in Figure 7.2, there is a strong correlation between the collected field data and the remote sensing data. The correlation value for various time periods ranges from 0.7216 to 0.7832.



**Figure 7.2: Comparison between field and remote sensing data of 1987, 1992, 2002 and 2007 along the coast of Guyana in terms of correlation**

Based on the aforementioned tests it could be stated with confidence that the results presented in the thesis are valid and acceptable.

### 7.3 Conclusion

Based on the documented literature this is one of the first research efforts to use empirical data, remotely-sensed images, geospatial techniques, and time series modelling techniques to investigate the advance and retreat of a coastline. By parameterizing the GIS with data from multiple sources it was possible to analyze, identify, model, predict, and visualize changes along the coast of Guyana. The GIS-based analysis and modelling highlighted not only transitory states of the coastline in the spatial and temporal domains, but also the existence of a cyclical pattern of coastline advance and retreat. Evidently, a

long cycle of approximately 30 years is superimposed by shorter cycles of coastline advance and retreat. The GIS-based modelling procedures proved to be beneficial in highlighting when and where there will be shifts in the coastline. Areas of positional shift could be visualized with the use of a spatio-temporal information-based system. This spatial information-based system could be used as a practical planning tool for the identification of erosional “hotspot” areas along the coast. This could facilitate proactive decision-making in coastal protection. By using time series modelling techniques this research highlights the importance of data modelling. The space-time autoregressive models which were identified reflect the underlying stochastic processes operating in Guyana’s coastal system. There are both long-term memory and short memory processes which influence coastline changes. The long memory processes could be associated with the stabilization and dissipation of mudshoals while the short memory processes are indicative of temporal stochastic processes like waves, winds, and currents. Recognition of the underlying processes operating in the coastal system is vital for the development of coastal management strategies at all temporal scales. Hence, the results from this thesis allow the claim to be made that GIS-based analysis and prediction procedures, and statistical time series modelling techniques are the most appropriate for spatial-temporal investigations of coastline changes.

#### **7.4 Ongoing and future work**

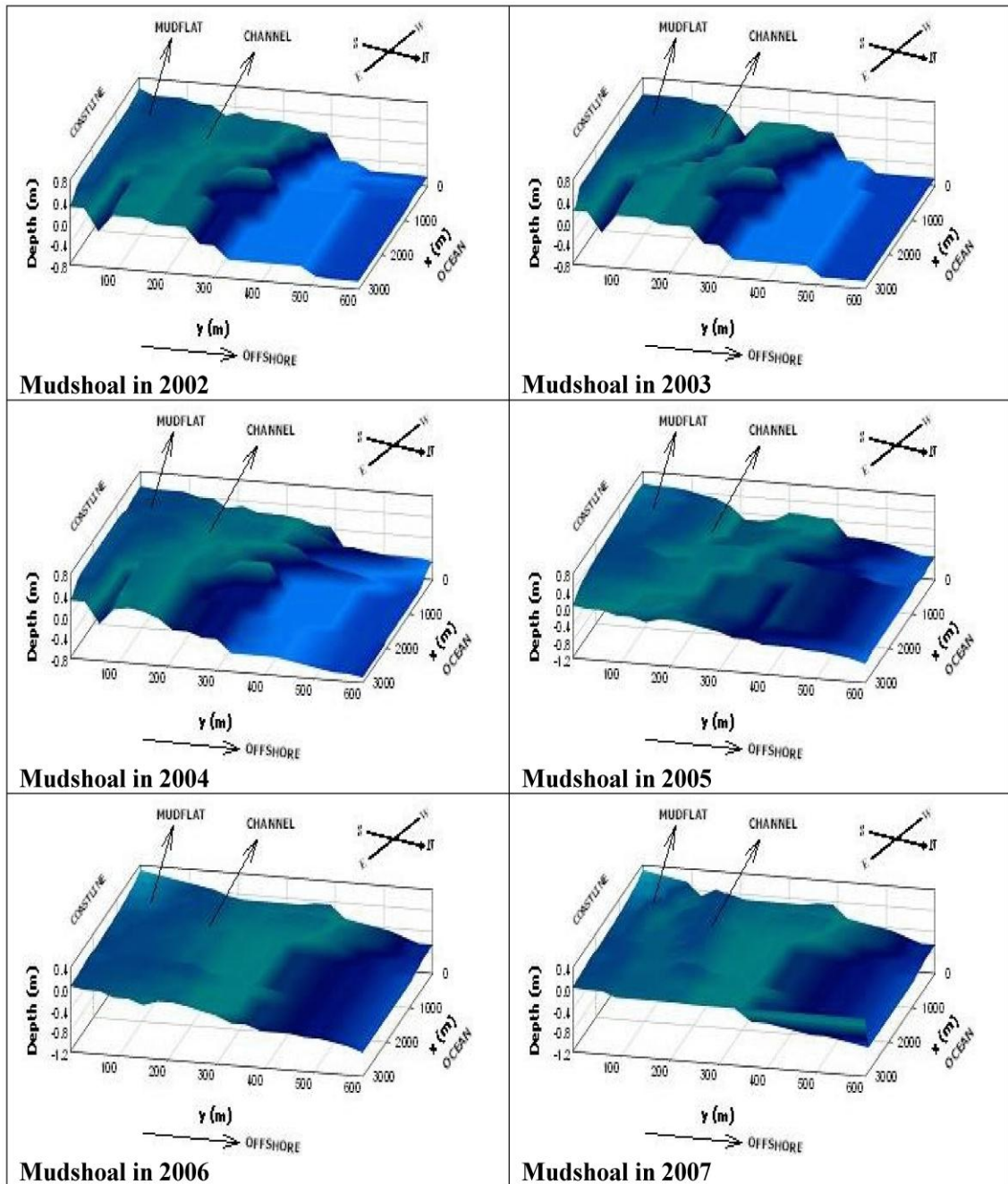
This thesis prompts not only the continuation of the current research, but has also created avenues for further investigations into the dynamics of coastline changes, and the use of spatial information systems to study these changes. In this respect, I am currently continuing my research efforts to develop and operationalize computer simulation models

in the STIBS. Models for various coastal and environmental processes are now being scripted into the STIBS. One major endeavour involves the utilization of expert systems software with the capabilities for building, maintaining knowledge, and query-based applications. The Modelling and Decision Support Framework developed by HR Wallingford-Halcrow (United Kingdom) is now being operationalized in the STIBS for making decisions on the management of erosion and flooding.

With the finding that cyclic processes like mudshoals have an impact on the advance and retreat of Guyana's coastline, research is also being done to better understand the dynamics of mudshoal propagation, stabilization, and dissipation. Based on the data that were collected in Guyana, graphical plots (see Figure 7.3) have been made to illustrate the process of temporal changes that are occurring in the mudshoal system along the Guyana coast. Each mudshoal configuration shown in Figure 7.3 is being inputted into the GIS. Various GIS functions are being used to calculate the volume of sediment in each of the plots. Doing this will provide valuable information on the amount of sediment lost from the mudshoal system.

To determine the long-term changes in the mudshoal system Landsat ETM+, SPOT and Ikonos images will also be incorporated into the GIS. Hopefully, sufficient images will be obtained to analyze the mudshoal system from its initial stages of formation to its final stages of dissipation. This will permit an understanding of the recurrence of mudshoals in Guyana's coastal system. The influence of these mudshoals on the coastline could then be traced from their initialization, stabilization, and dissipation stages. As a consequence quantitative information could be obtained on how

mudshoals affect the advance and retreat of the Guyana coast. This information can then be incorporated into the STIBS for long-term planning purposes.



**Figure 7.3: Graphical plots of mudshoals changes along the coast of Guyana over the time period 2002-2007**

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