CHAPTER-I

INTRODUCTION
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1.1 BACKGROUND

Coastal zone is defined as a triple junction where the land, water and air interact with each other. All over the world, coastal zone is characterized by a variety of complex environments like the beaches, estuaries, dunes and marshes, evolved through an assortment of processes like the fluvial action, estuarine dynamics, tidal effects and neo-tectonic activity. Remote sensing and Geographical Information Systems (GIS) is used as a tool to provide information on the coastal zone and associated features which, in turn, will aid in an easy evaluation of the beach resources in any coastal vicinity.

The research is about shoreline dynamics in the coastal area of Le Morne (North) Zone, La Paradis to Public Beach zone, La Pavillion to Berjaya zone, Mauritius using multisource spatial data. Methods commonly used for determining erosion/ accretion trends involve measurements of the shoreline or high water mark and low water mark using aerial photographs and high resolution satellite images. The detailed shoreline change analysis has been carried out at Le Morne - Berjaya beaches based on the shoreline changes using GIS analysis along the Le morne north - Berjaya coastline 10 km distance.

In the year 2011, the Republic of Mauritius had a population of about 1,257,900 and a Gross Domestic Product (GDP) of Mauritian Rupees 78.546 million (Mauritius Central Statistics Office). The significant sectors of the economy of the Republic of Mauritius are based on agriculture (40 per cent of land is under sugarcane), export-orientated textile manufacturing and tourism. Absence of proper planning in connection with the coastal development and inadequate enforcement have resulted in uncontrolled construction of buildings and other structures such as seawalls, jetties and groynes along the coast. The coastal processes including the offshore conditions (cyclone waves, surge, tides, and sea level rise), the transformation of the offshore waves over the reefs and across the lagoons and the near shore waves, currents and beach erosion are dealt in this research.
Coastal erosion is ubiquitous around the Le Morne coast. The causes are both natural and man-made. The coast has been evolving over geological time as a consequence of eustatic sea level rise. Another important factor is the climate regime which has eventually has gradually shaped the coastal region. Climatic factors have been directly involved in the process of weathering and erosion. Beach shape, coastal vegetation and lagoon biotypes, at a particular site, are a reflection of coastal processes which develop as a consequence of the integration of various agencies and climate elements including winds, waves, rainfall and temperature.

In the Le Morne lagoon, the reef is further out, about 4 km from the shore of north to west Le Morne. The low energy shores of northern part of the Le-Morne are mostly muddy, mixed with pebbles expect for a stretch of sandy beach at Le Morne public Beach. However, the near-shore region of Le Morne has a high deposition of fine, silt and clay. On average, this extends for about 100 m towards the channel slope. The channel is found at distance of 250 m from the shore of the La Pavilion area. Sea grass is from the major habitats inshore of the Le Morne whereas coral patches, mainly branching corals, are found towards the channel slope. Any development on this coastline would necessitate evaluation of the coastal and ecological processes. Dunes are present inshore, southern coast of Le Morne has low-lying terrain behind the dunes and is subject to flooding. The two important features of the Le Morne lagoon are the presence of a deep channel and an islet of the Le Morne beach. The channel drains into the big pass near the La Pavilion area.

The back reef has a high cover of calcareous substrate. Sea grass is found near-shore and the northern tip of the islet as well as along the channel slope. The Le Morne peninsula is very shallow due to accretion of fine sand and silt. The beach at the Le Morne peninsula is predominantly sandy. Distance to the reef from shore varies from 900 m to 980 m at or near the Berjaya area. There are two passes in that region and these passes are however difficult to maneuver during heavy cyclone.

Path corals are developed quite extensively opposite the Berjaya area and this extends in the north direction towards the passes L-Ambulate. The Pointe sub-oust region is poorly colonized with coral colonies. However, macro-algae, mainly sargassum and turbinaria are the dominant bottom features. The lagoon floor is denuded of sand, which is mostly of Pleistocene rock. The beach is steep, strongly suggesting the wave climate in that region. South of Le-Morne there is a patch of
calcareous substrate colonized mostly with sea grass, coral colonies and algae. The channel in that region however, has a higher percentage of coral colonies, with varying degrees of impact from fine sediment and fishing practice.

The eastern beach is sandy until the foot slope of the Le Morne Mountain. However, this beach is under influence from near shore silting and extensive sea grass bed. Sea grasses regularly gets washed up the beach. The outer reef south of the Le Morne peninsula has a high percentage cover of macro algae. Coral cover on the outer slope shows marked increase on the west reef of the peninsula.

The southwest point of the Le Morne is where the public beach is located. The public beach sits between the Berjaya Resort and the Indian Resort hotels. The public beach shore consists of a healthy beach with no coastal structures. However, the public beach shoreline has little or no effective coastal vegetation mostly with exposed sand under a few Filao trees and some beach rock is visible offshore of the Berjaya Hotel building with the red roof. The Le-Morne area sand transport pathways from the source of the sand at the outer edges of the lagoon into the shore are visible from the “streamers” discussed next chapters. The large pass at the south end of the Le Morne lagoon allows large waves to penetrate the lagoon and also represents a pathway for net offshore loss of sand to an offshore sink. It is likely that the main transport pathways along the Le Morne beach consist of onshore transport to the shore and then along-shore transport to the north and south end of the west facing shore. The net long-shore sand transport may be towards the north for most of the west facing shore. Historically, the beach feature would have grown towards the north and south. However, at the south end, in the vicinity of the public beach the growth may be limited by the presence of the large pass. Waves penetrate this pass and transport any accumulated sand in the area of the public beach further to the east.

The expansive shelf/reef-flat at the Le Morne appears to have been developed on a pre-existing ancient reef surface. Within the lagoon formed by the shelf/reef-flat, a large sand spit, anchored by Le Morne Brabant, extends some 4 km from its northerly tip to its southerly tip. Sand transport directions along the westerly side of the spit are variable and are a result of a complex pattern of waves breaking over the reefs, waves propagating through the passes and currents passing within the lagoons and out through the passes. Further to the north, along the west shore, near-shore
current is nearly always in a northerly direction, irrespective of the wind direction and the tidal movements (Muller et al., 1991).

At the public beach, the beach slope is steep (about 1:5) and rises up approximately 2 m above MSL to the backshore berm. Lack of beach management permits uncontrolled vehicle and pedestrian access over the dune, limiting its ability to sustain native coastal vegetation and stabilize the shore. The beach at Indian Resort, near the public beach, is also quite steep (approximately 1:6) due to coarse sediments and relatively large swell reaching the beach.

Further to the south beaches appear to be relatively stable and structure free with no apparent evidence of long term erosion. Certainly, erosion will occur during cyclonic events, particularly those accompanied by high surges. McIntire and Walker (1964) reported 4.3 m of embankment erosion at “Le Morne” (exact location uncertain, but likely near southerly extent of Dina Robin Resort) during Cyclone Carol in 1960. They also reported a maximum flotsam height of 2.1 m above MSL at Le Morne as a result of Carol. Much of the hotel development along the west shore is located within the dynamic beach zone, especially portions of the Berjaya. Doxiadis (1994) reported that the beach berms directly facing the hotel area were flattened and compacted during construction, which contributed to a destabilizing of the beach. Beach rock can be seen diverging from the present shoreline at Dina Robin and parallel to the shore at Berjaya, approximately 30 m offshore.

Le Morne coastal area is an extremely dynamic zone. Approximately 100 m offshore one of the hotels was an overturned colony of table coral more than 2 m in diameter. Ripple marks indicate shoreward transport of sediment, with the leeside offshore and the stoss side onshore. Sediment could be observed moving shoreward with every surge episode. The wave and current activity here is, however, very variable. Sometimes, the undertow seawards is very strong and, at other times, it is equally strong landwards. The shelf/reef flat is a bypassing zone: sediment produced by the reef moves quickly over the hard ground, to the beach. At places along the present coastline, there are submarine outcroppings of calcareous substrate, elevated perhaps a half meters above the sands and only a few meters from the beach.
1.2 COASTAL DYNAMICS

Mauritius, a small island state with a total land surface area of 1,865 km$^2$, is situated at 20° South latitude and 58° East longitude, in the Indian Ocean. Coastal and marine resources are of vital importance to the national economy. The coastline of Mauritius is 322 km in length and surrounded by fringing coral reefs (except opposite the river mouths, estuaries) enclosing a lagoon area of 243 m$^2$ (Mauritius Oceanographic Institute). The island is endowed with sandy beaches, protected bays and calm lagoons, factors that have permitted development of both fishing and tourism. The coastal zones attract human settlements, hotel development, tourism and other associated economic activities. Mauritius’ coastal area has geomorphologically complex processes such as coastal erosion and related beach degradation, which are considered major environmental problems all over the Mauritius coast.

The island is located in a vulnerable region in relation to intensity and frequencies of natural and environmental disasters. The coast along north to south point of Le Morne has sustainable shoreline erosion occurring all the time. Multi-year shoreline mapping has been considered as a valuable task for coastal monitoring and assessment.

A beach is defined as a part of the coast that is washed by waves or tides. The beaches are changing constantly because of its proximity to the ocean and the land; a beach is subjected to natural events and processes common to both the realms. The shape of the beach is a product of the coastal processes such as the uplift and subsidence and the wearing down of land by erosion, transport and deposition. In order to understand and appreciate the coastal processes, an investigation of the shoreline changes is crucial and the identification and understanding of the coastal processes will make available basic spatial and GIS data for evaluating them. The integration of spatial and non-spatial data with the GIS derived benefits in terms of visualization and analysis of coastal processes, but also increased the spatial analysis capabilities of the GIS tools, which are being used to enable decision-making with the help of modelling of coastal dynamics. This has also led to the concept of Spatial Decision Systems (SDS), which have helped the GIS community to describe a system that is explicitly designed to address complex spatial problems.

The advantages of using Geographic Information Systems (GIS) for integration of various thematic layers derived from satellite data with other secondary
data such as the socio-economic and cultural data are significant for integrated coastal zone management practices. Such an approach helps in initiating an integrated system for coastal zone regulation and management perspectives.

A historical trend analysis has evolved over the last few decades, based on earlier efforts to investigate shoreline changes (Study on coastal erosion in Mauritius, June 2003). Since the early 1980s, computer-based Geographical Information Systems (GIS) software has been developed to digitally catalogue shoreline data and facilitate the quantification of shoreline change rates (May et al., 1982; Leatherman, 1983; Thieler et al., 2005). At the same time, a thorough review and critique of the procedures that have been employed to make the estimates has been conducted by several authors (Dolan et al., 1991; Crowell et al., 1997; Douglas et al., 1998; Douglas and Crowell, 2000; Honeycutt et al., 2001; Fenster et al., 2001; Ruggiero et al., 2003; Moore et al., 2006; Genz et al., 2007). Several other studies using satellite data have proved their efficiency in understanding various coastal processes (the Study on coastal erosion in Mauritius, June 2003; Nayak and Sahai, 1985). One approach that has been developed to evaluate the potential for coastal changes is through the development of a Coastal Vulnerability Index (CVI) (for example, Gornitz and Canciruk, 1989; Gornitz, 1990; Gornitz et al., 1994; Thieler and Hammar-Klose, 1999). The Coastal Impact and Impact Mitigating Measures are however based on shoreline changes (Ram Anand Bheeroo, 2009) at Trou aux Biches Beach. Recently, the U.S. Geological Survey (USGS) has used this approach to evaluate the potential vulnerability of the U.S. coastline on a national scale (Thieler and Hammar-Klose, 1999) and on a more detailed scale for the U.S. National Park Services (Thieler et al., 2002).

The U.S. Geological Survey (USGS) approach has reduced the index to include six variables (geomorphology, shoreline change, coastal slope, relative sea-level change, significant wave height, and tidal range) which have been considered as the most important in determining a shoreline’s susceptibility to sea-level rise (Thieler and Hammar-Klose, 1999). Simultaneous and continuous monitoring of coastal changes is necessary for the proper assessment of impact of the changes and for designing viable land use and protection strategies. This is done studying the shoreline erosion/accretion pattern within the study area from the multi-temporal aerial photos and satellite images for the past 43 time periods of 1967-1975, 1975-

There have been dramatic changes to the delta shorelines during the 20th century, which are generally attributed to natural and man-made factors (UNDP/UNESCO, 1978). They are:

(1) Reduction in the Nile discharge and sediment load to the Rosetta mouth due to the construction of water control structures along the Nile. Six barrages and 3 dams were built on the Main Nile and its two branches. Since the building of the High Aswan Dam in 1964, sediment discharge at the Nile promontories has reduced to near zero. Subsequently, the Niles’ promontories have been subjected to dramatic erosion.

(2) A natural reduction of Nile floods resulting from climatic changes over East Africa.

(3) Waves and currents continue to move sediment alongshore, resulting in a major reorientation of the coastline as some beaches (< 1 per cent), heavy minerals (1-90 per cent) and beach pebbles (1-3 per cent).

The zone of coastal dunes along the eastern barrier is truncated by the shoreline and occupies the backshore from 2 km east of the lagoon inlet for a length of about 19 km eastward. The coastal dunes of American coast have a maximum width of 1.5 km and reaches an elevation of up to 20 m. Frithy in 1988 observed yearly an individual dune, at 3.2 km along the inlet, indicate that an encroaching of coastal zone by 2 to 3m/year.

In the last two decades, the role of remote sensing in coastal studies has been well initiated in the Indian coast (Subramanian et al., 1986 and Nayak et al., 1989). Nair (1987) has done coastal geomorphological mapping for Kerala using Landsat satellite imagery and aerial photographs. Several endeavors have been made use of satellite data and have proved its efficacy in coastal landforms and the action (Nayak, 1994; Johannessen et al., 1993, Hill et al., 1994; Ahmad and Neil, 1994). Consequently, Gupta et al. (1988) has worked with integrated remotely sensed data, namely, Landsat 1 MSS imagery, Salyut 7 KATE space borne photograph and aerial photograph for extraction of coastal geology and geomorphic landforms in south Kanara district of Karnataka. Moreover, the recognition of different objects, in the imageries is based on tone, texture, location, size and association while the key has
been developed at SAC (Nayak, 1991). Similarly, Cracknell et al. (1982) have studied digital image processing of Landsat MSS data to delineate different estuarine environment. In addition, the various remote sensing sensors are used in the interpretation of coastal landforms like the numerous cut-off tanks, meander bars, and creeks, through radar images (Lewis and Macdonald, 1970; Koopmans, 1973; Madhavan et al., 1994).

The shoreline erosion causes problems, when its development approaches (Li, 1997) for example residential area. The vegetation line is a valuable additional indicator of shoreline position. By identifying the wet/dry line, one can use for the estimation of the low tide terrace (Dolan et al., 1980; Smith and Zarillo, 1990). Paine and Morton (1989) have compared multi-temporal shorelines (1974 and 1982) and vegetation lines mapped from aerial photography. In combination with satellite images and high-resolution aerial photographs, many have successfully used to monitor such long-term shoreline changes and morphological changes in the estuaries (Nayak and Sahai, 1985; Prabhakar Rao et al., 1985; Shaik et al., 1989; Vinodkumar et al., 1994). Correspondingly, satellite data information by virtue of its repetitive (temporal), multi-spectral and synoptic nature, can provide images that will enable us to observe or study the measure of changes of shoreline and its associated features (Bartlett and Klemar, 1980). Moreover, to update the erosion data more frequently, high-resolution satellite imagery will be used in future for erosion monitoring (Li and Lia, 1998).

1.3 SCOPE OF THE STUDY

Spatial technologies like the GIS and remote sensing are proven to be a useful tool for providing information on coastal dynamics mapping at different spatial and spectral resolution datas. These technologies can be used to evaluate the coastal process including the shoreline changes, and coastal landforms. The coastal zone management relies mainly on the understanding and modeling of these processes, which in turn, calls upon a large number of disparate data sets. The most effective way to model these data, facilitate analysis and allow clear visualization by geospatial analysis.

The present study area is enriched with valuable shoreline studies. So, shoreline has attracted the attention of various research agencies. The National
Oceanographic Data Center (NODC) has identified the shoreline studies as one of the thrust areas, in order to fill-in the gap and examines the feasibility of shoreline change studies in the coastal zone of Le Morne - Berjaya beaches.

Three-dimensional GIS represents three dimensional perspective models for topography and bathymetric modeling. Also, it provides surface and sub-surface historical shoreline changes with their location coordinates in regular intervals. The resulting output provides an understanding of the coastal erosion and accretion of both lateral and vertical dimension from the available field satellite data. It is to 'see' into the shoreline from different perspectives. Such a model would provide considerable enhancement to the understanding of the coastal erosion along the beach profile of the area, the precise location of perspective suites of rocks and, ultimately, the exploration and targeting strategies for hotel development in the area. This three dimensional model will eventually help in predicting new target areas along the coastal stretch. Moreover, remote sensing and GIS technology could immensely be helpful for various governmental organizations like the National Oceanographic Data Center, Ministry of Fisheries, Mauritius Meteorological Center, Beach Authority and Ministry of Environment to locate coastal areas having favorable sites for future historical shoreline changes.

1.4 OBJECTIVES

The objectives of the study are:

- To examine historical shoreline changes and attempt an evolutionary trend analysis of the Le Morne area of Mauritius;
- To develop GIS for predictive modeling in order to understand the coastal dynamics along the Le Morne coast;
- To identify and map erosion / accretion and also stable coastal areas as well as identify the coastal ecological and habitat change along the Le Morne coast; and
- To examine and assess anthropogenic developmental activities along the coastal zone to understand the manner in which the coastal zone is influenced by human interaction and also to suggest strategies to control and regulate human activities towards coastal zone and shoreline change management.
1.5 LOCATION OF THE STUDY AREA

The study area map is shown in Figure 1.2. The Le Morne (North) Zone, La Paradis to Public Beach zone, La Pavillion to Berjaya zone coastline are located along the north-south shoreline of the study area and is a stretch approximately of 10 km, extending between 20° 26’ 05.17” S and 20° 27’ 57.34” S of latitudes and 57° 19’ 23.42” E and 57° 19’ 00.76” E longitudes. The republic of Mauritius (Figure 1.1) is surrounded by the Peninsula (West) and Indian Ocean (South). The island is endowed with sandy beaches, protected bays and calm lagoons, the factors that have permitted development of both fishing and tourism.

Figure 1.1: The location of Mauritius in the Indian Ocean
1.6 PHYSIOGRAPHY

The coastal features of the bay include raised calcareous features, pocket beaches, rocky shores, calcareous beach rock, low cliffs, river and rivulets. With hotel development spanning over the last twenty years in this region, modifications to coastal features have been steady. These features include low wall revetment to contain raised sandy beaches, creation and reprofiling of beaches, dredging, rock revetment and jetties.

The River Citron influences both bathymetric features as well as ecosystems of the bay. The relatively deep channel on the shallow sea floor is a continuation of the river bed. Fine sediments in the bay as well as the river are focused onto the channel due to difference in gradient as well as circulation pattern. The bay has high diversity of coral and certain regions have high coral coverage. Sea grass is observed mostly along the frontage of Le Morne beaches. The bay covers an area of more than 38 ha. It presently has about 8 km of sandy beaches, most of which have been reprofiled (Figure 1.3).

GIS analysis (Figure 1.4) of the coastal features of the site, from the geo-referenced aerial photos as well as recent survey, shows that there have been changes in the coastal morphology mostly due to human interventions. This research is having mostly pocket beaches.
1.6.1 Coastal Conditions and Processes

The coastal zone is in a delicate, dynamic balance with the powerful driving forces of the ocean, such as the cyclonic waves, surges and tides, and the reef-lagoon-beach ecosystems, which provide wave protection as well as produce sediments for the beaches. The coastal conditions and processes such as the tides, sea level rise, offshore wave climate, storm surge, near shore wave transformation and shoreline change (erosion/sedimentation) are readily observable.

1.7 REGIONAL GEOMORPHOLOGY AND GEOLOGY

Maps of geomorphology, soils and profile line of the study area, described in Chapter III which is a qualitative profile of the study area, show that the region under study has had fresh lava flows during the intermediate lava series as well as superficial formations such as alluvium and carbonated formations. Sandy beaches of calcareous formations are predominant in the Le Morne (North) Zone, La Paradis to Public Beach zone, La Pavillion to Berjaya zone. Sand dunes along the Le Morne
coast have been greatly exploited over the last thirty years.

The Le Morne coast is bordered by raised calcareous formations, evidence of sea level fluctuations in the geological times, pocket beaches, rocky shores and fresh water drainages in the form of a river as well as rivulets. Topography around this bay is rather well pronounced, suggesting that the surface water runoff could be a potential source of impact on the ecosystems of the bay. The bay is colonised by dense coral cover in certain zones. A deep channel (Figure 1.4) with varying in depth of 3 m to 14 m runs the whole length of the bay from the east to the west sector. The channel starts at the outlet of the river Citron and exits generally in a direction offshore of the bay. The overall catchment area for the watershed that supplies river Citron with water is 39.5 km² in aerial extent.

![Coastal Geomorphology](image)

**Figure 1.4: Coastal Geomorphology**
1.8 TIDAL REGIME AND WAVES

Significant storm surges can be expected from long swells generated far to the south of the Le Morne and surrounding the Mauritius Island. These events have become an almost annual occurrence. Extreme storm surges occurred in May 1976, 31st May and 01 June 1987 (Mauritius Oceanographic Institute). In March 1995, the combined effect of a strong anticyclone and the tropical cyclone Ingrid, which while maintaining an intense circulation, developed a blocking situation between longitudes 50° E and 60° E and generated a fairly long longitudinal fetch south of the Le Morne and Mauritius. Swells of around 3 m to 4 m reached the Le Morne and Mauritius, causing much damage to the southern coast. Cyclones can cause immense flooding and loss of valuable infrastructures in many low-lying areas. Storm surge components include barometric pressure reduction in low-pressure cyclones, wind stress, Coriolis force and wave set up. Swash zone observation after cyclone Carol in 1960 was indicative of maximum wave run up levels on the beach and showed peak elevations of about 2 m to 3 m above mean sea level with some up to 4 m along the southern coast where the rift is absent or close to the shore. This compares to a maximum surge level of 0.9 m measured at the tide recorder in Port Louis. Hence, storm surge depends on many physical and environment factors.

1.8.1 Extreme Waves

Reliably measured observations are available from a Datawell b.v. directional wave rider buoy which has been deployed off Mahebourg coast in a water depth of 57 m (Table 1.1).

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<td>December</td>
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Source: Mauritius Oceanographic Institute
1.8.2 Sea Level Change

Sea Level Rise (SLR) as a consequence of climate change is a serious concern for small islands such as Mauritius, particularly with regard to coastal erosion. It has been found mathematically that the shoreline retreat rates are 50 to 100 times the rate of SLR (Bruun, 1962). The mathematical equation derived by Bruun has been modified by others (Dean and Maurneyer, 1983; Edelman, 1972), who have come to almost the same conclusion. Coastal erosion is already ubiquitous around the Le Morne, Mauritius. Hard measures taken to address the issue have, to a large extent, worsened the problem. It is expected that erosion would accelerate due to the projected increase in the rate of SLR with global warming. Taking into consideration the IPCC projection of 59 cm by the end of this century, this implies that the shoreline retreat could be in the range between 29 m to 59 m. The Le Morne, Mauritius is a coastal-based destination for tourists. Consequently, an accelerated SLR will impact very seriously on the sustainable socio-economic development of the country.

Figure 1.5: Sea level variations and trends from altimetry data (1993 – 2003)
Source: Mauritius Oceanographic Institute
1.9 LIMITATIONS OF THE STUDY

The present study area is enriched with valuable shoreline change studies. So, it has attracted the attention of various research agencies. Study has identified the shoreline erosion/deposits as one of the thrust areas in le morne. The present study, of shoreline change between Le-Morne - Berjaya beaches, Mauritius, has been carried out on different aspects of historical shoreline in conjunction with coastal dynamics and coastal zone management. There were no earlier systematic study been initiated to understand and evaluate the shoreline changes along this area using GIS and remote sensing techniques. So, the present research aims at evolving a geospatial system, which describes the efficiency and applicability of the same to the evaluation and management of historical shoreline changes of the study area. As expertise is also limited to certain areas, the focus of the study has been on features and themes that could be dealt with by the scholar in three years.

1.10 ORGANIZATION OF THE THESIS

The thesis is organized into seven commissioned chapters. They are briefly described here as to their salient features. Chapter I is a brief introduction to the research thesis. Chapter II explains the literature being reviewed to help design projects that genuinely respond to the needs of the study area. Chapter III presents an overview of the Le morne of Mauritius: A profile of the study area. Chapter IV describes the Research methodology, data collection and analysis. Chapter V presents an overview of the principles for Coastal Dynamics: Shoreline change in the Le Morne coast of Mauritius. Chapter VI presents an overview of the principles for shoreline change detection modeling for Le Morne coast of Mauritius. Finally, chapter VII provides conclusions and Recommendations.