UNIVERSITY OF GHANA
COLLEGE OF BASIC AND APPLIED SCIENCES

MEASURING AND SIMULATING SHORELINE MORPHODYNAMICS IN THE VOLTA DELTA,
GHANA

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THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA,
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DECLARATION

This thesis is the result of original research work undertaken by Mr. Philip-Neri Jayson-Quashigah in the Department of Marine and Fisheries Sciences (DMFS) of the University of Ghana. The research was carried out under the supervision of Professors K. Appeaning Addo and George Wiafe and Dr. B. Amisigo. All references cited in the study have been dully acknowledged.

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ABSTRACT
Coastal erosion is a major challenge facing coastal regions globally. It is projected to increase on regional to global scale as sea levels continue to rise. To manage the situation sustainably, coastal managers require relevant scientific information such as beach sediment and shoreline dynamics. Shoreline change measurement and simulation especially at local scale and at higher resolutions are relevant for decision making and engineering. A review of literature has brought to the fore that the Volta delta is a hotspot for coastal erosion; however, mainly low resolution remotely sensed imagery has been used to assess changes in the Volta delta of Ghana, which compromises the accuracy of the information. In this study, different sets of high-resolution datasets from Unmanned Aerial Vehicles (UAV) surveys and satellite imagery, as well as numerical modelling using Littoral Processes FM (Flexible Mesh) are adapted to estimate historical beach sediment and shoreline dynamics and predict future evolution under sea level rise up to the mid-century.
The results show a net loss of beach sediment on the western side of the Volta Delta up to 9,000m³ whilst the eastern side experienced net gain up to 12,100 m³ in the short term. Relatively, short-term erosion rates were higher compared to the medium term shoreline erosion. Simulation of future conditions indicates an increase in shoreline erosion rates by 4 cm/y by mid-century with sea level rise of 13 cm at Old Ningo. Consequently, the shoreline will recede up to 70m inland, which will negatively influence livelihoods and aesthetic value of the area. The study recommends soft engineering approach such as sediment beach nourishment or the Dutch ‘sand motor’ system to protect the shoreline and the community. Regulations should also be enforced to halt nearshore sand and gravel mining.

ACKNOWLEDGEMENTS

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DEDICATION

To our Good and Loving Father in Heaven be all glory now and forever. I dedicate this work to my dear wife Gladys Ama Assan and our son Jadon Xorlali Jayson-Quashigah. I also dedicate it to my parents and entire family, my supervisors especially Professor Appeaning Addo for the immense role he played in my academics and to my pastor Samuel Dotse for standing with me all this while.
TABLE OF CONTENTS

DECLARATION........................................................................................................................................i

ABSTRACT ..............................................................................................................................................ii

ACKNOWLEDGEMENTS .................................................................................................................. iii

DEDICATION ........................................................................................................................................iv

TABLE OF CONTENTS .......................................................................................................................v

LIST OF FIGURES ...........................................................................................................................xi

LIST OF TABLES ...............................................................................................................................xv

LIST OF ABBREVIATIONS .............................................................................................................xvii

CHAPTER ONE..................................................................................................................................1

INTRODUCTION ...............................................................................................................................1

1.1 Overview .......................................................................................................................................1

1.2 Background....................................................................................................................................3

1.3 Aim and Objectives .....................................................................................................................5

1.3.1 Research Objectives .............................................................................................................5

1.3.2 Justification of the Study .......................................................................................................6

1.4 Research Methodology ...............................................................................................................8

1.5 Thesis Structure ............................................................................................................................9

CHAPTER TWO................................................................................................................................10

LITERATURE REVIEW ..................................................................................................................10

2.1 Introduction ...............................................................................................................................10
2.2 Coastal Deltas .................................................................................................................. 10
  2.2.1 Formation of Deltas ................................................................................................. 11
  2.2.2 Delta Morphodynamics .......................................................................................... 12
  2.2.3 Classification of Deltas .......................................................................................... 12
  2.2.4 Climate change and Deltas ...................................................................................... 14
  2.2.5 Population growth in Deltas ................................................................................... 15
  2.2.6 Subsidence in Deltas .............................................................................................. 15
2.3 Measuring and Monitoring Delta dynamics ................................................................. 16
  2.3.1 UAVs in Coastal Zone Monitoring ......................................................................... 18
  2.3.2 General workflow for UAV .................................................................................... 21
2.4 Morphodynamics Modelling ....................................................................................... 24
  2.4.1 Model selection ....................................................................................................... 24
  2.4.2 Shoreline Change modelling using Littoral Processes FM (One-line Model) ........... 26
    2.4.2.1 Some Governing Equations .............................................................................. 28
  2.4.3 Summary of Basic Assumptions Underlying One-line Models ............................... 30
2.5 Overview of the Bight of Benin .................................................................................... 30
  2.5.1 Location and Oceanography .................................................................................. 30
  2.5.2 Erosion trends; causes and interventions ............................................................... 31
2.6 The Volta Delta: An Overview ..................................................................................... 32
  2.5.1 Oceanographic conditions ..................................................................................... 33
  2.5.2 Historical erosion in the delta: factors and interventions ....................................... 34
2.5.4 Modelling Efforts in the Delta.................................................................35

2.5.5 Conclusion...............................................................................................36

CHAPTER THREE........................................................................................................37

ASSESSING SHORT-TERM BEACH VOLUME DYNAMICS IN THE VOLTA DELTA: AN APPLICATION OF UNMANNED AERIAL VEHICLES (UAVs)........37

3.1 Introduction ....................................................................................................37

3.2 Study Sites ....................................................................................................39

3.3 Methods .........................................................................................................41
  3.3.1 Data collection and pre-processing ........................................................41
  3.3.2 Data processing .......................................................................................44
  3.3.3 Geomorphic Change Detection ..............................................................44
  3.3.4 Shoreline extraction ...............................................................................45
  3.3.5 Shoreline Change Analysis ....................................................................46
  3.3.6 Grain size analysis ..................................................................................47

3.4 Results ............................................................................................................48
  3.4.1 Morphological Changes at Old Ningo (Site A) ........................................48
  3.4.2 Morphological Changes at Fuveme (Site B) ...........................................53
  3.4.3 Morphological Changes at Keta (Site C) ................................................58
  3.4.4 Sediment Characteristics ......................................................................62

3.5 Discussion .....................................................................................................63
  3.5.1 Beach volume dynamics across the three sites ......................................63
LIST OF FIGURES

Figure 1. 1: Map of the Study Area (Source: Codjoe et al., 2020). The 5m contour limits the extent of the Volta delta .................................................................................................................. 4

Figure 1. 2: Flow Chart of Study Objectives .................................................................................. 7

Figure 2. 1: Tripartite classification of Deltas in River, Tide and Wave dominated categories based on Galloway, 1975 (Source: Bhattacharya, 2006) ............................................................................. 13

Figure 2. 2: Workflow for Application of UAVs (Westoby et al., 2012) ...................................... 23

Figure 2. 3 Schematic showing shoreline change estimation using the 1-Line Theory (source: Hanson and Kraus, 2011) .......................................................................................................................... 27

Figure 3. 1: Map of the Volta delta showing the three study sites and the sediment sampling sited .................................................................................................................................................. 40

Figure 3. 2: Establishment of Control Points ................................................................................... 41

Figure 3. 3: Distribution of GCPs for the three survey sites (Site A: Old Ningo, Site B: Fuveme, and Site C: Keta) ......................................................................................................................... 42

Figure 3. 4: Surveying and coordination of control points (Right is an existing Survey Pillar) ........................................................................................................................................... 43

Figure 3. 5: DEM showing a sand mining site (indicated in the red box) and the intertidal zone (red arrow) .................................................................................................................................. 48

Figure 3. 6: Spatial variation of erosion and sedimentation at Old Ningo over different periods spanning January 2017 to April 2018 .................................................................................................. 50

Figure 3. 7: Areas of erosion and accretion (left), and sediment volume change (right) at Old Ningo (January 2017 to April 2018). Red and blue bars indicate erosion and accretion respectively, while grey bars show no change ........................................................................... 51

Figure 3. 8: GCP number 5 (indicated by the red arrow) buried under the sand (about 20cm)-depth marked by a blue line (Photo Credit: Emmanuel Brempong) ........................................... 52
Figure 3. 9: Beach profiles showing deposition on the back beach and erosion of
berm/shoreline ..................................................................................................................52

Figure 3. 10: Shoreline Linear Regression Rate (LRR) of Change at Old Ningo (January
2017 to April 2018) (alongshore from west to east) ......................................................53

Figure 3. 11: Spatial variation of erosion and sedimentation at Fuveme over different
periods spanning (June 2016 to April 2018) .................................................................55

Figure 3. 12: Area of erosion and accretion (left), and sediment volume change (right) at
Fuveme (June 2016 to April 2018). Red and blue bars indicate erosion and accretion
respectively, while grey bars show no change ...............................................................56

Figure 3. 13: A swash bar that developed close to the Volta estuary (Photo Credit: Author,
6th April 2017) ...............................................................................................................57

Figure 3. 14: Beach profiles from the high eroding section of the beach......................57

Figure 3. 15: Shoreline Linear Regression Rate (LRR) of Change at Fuveme June 2016 and
April 2018 .......................................................................................................................58

Figure 3. 16: Spatial variation of erosion and sedimentation at Keta over different periods
(June 2016 to April 2018). The black triangles show the location of the groynes.............60

Figure 3. 17: Sediment erosion and accretion at site C from June 2016 to April 2018: (a)
Area change and (b) volume change. Red and blue bars indicate erosion and accretion
respectively while grey bars show no change ...............................................................61

Figure 3. 18: Beach profile plot for (a) downdrift and (b) updrift of the groyne to the east
.........................................................................................................................................61

Figure 3. 19: Shoreline Change at Keta between June 2016 and April 2018.................62

Figure 3. 20: Grain size distribution across the study area (red triangle indicates the location
of the Volta estuary) .................................................................................................63
Figure 3.21: Impacts of erosion at the western section of the study area (a) A beach resort being undermined and (b) houses being destroyed in the background (Photo Credit: Author and Emmanuel Brempong, 12th January 2017) ........................................................................................................64

Figure 3.22: June 2016 Drone Orthophoto Overlaid with April 2017 Shoreline (red line). The red arrow shows the remains of the only school in the community which was completely destroyed by April 2017. ........................................................................................................64

Figure 3.23: Aerial view of a portion of Fuveme Showing the beach being built up (Photo by Author; April 2018). The red line shows the previous shoreline position (August 2017) and the red circle shows where the bar had developed previously while the blue arrow shows the extent of the beach that has been built (Over 80m). .................................................................65

Figure 3.24: Gravel mining from nearshore at Old Ningo: (a) heaps of mined gravel along the beach ready for sale (b) gravel being transported via wheelbarrows to a waiting vehicle across the tidal pool in the background. ........................................................................................................68

Figure 4.1: Comparison of Low-Resolution Multispectral imagery (a) and a Pan-sharpened version of the same image (b). ........................................................................................................74

Figure 4.2: Comparison of modelled and observed wave parameters: (a) wave height (Hs) (b) wave period (Tp) and (c) wave direction (Dir.) ........................................................................................................77

Figure 4.3: Erosion trends along the Old Ningo Coastline: (a) base period (2005 to 2013), (b) current situation (2013 and 2017) and (c) overall changes (2005 to 2017).................................80

Figure 4.4: Erosion trends along the Fuveme Coastline: (a) base period (2005 to 2013), (b) current situation (2013 and 2017) and (c); overall changes (2005 to 2017).................................82

Figure 4.5: Erosion trends along the Keta Coastline: (a) base period (2005 to 2013), (b) current situation (2013 and 2017) and (c) overall changes (2005 to 2017).................................83
Figure 4.6: A plot of shoreline change and means of the various wave variables showing the means for the years with shoreline change (for the purposes of plotting, 90° shore orientation is subtracted from wave directions) .................................................................85

Figure 5.1 Map of the Study Area showing the smaller domain indicated by the red line 93

Figure 5.2: Model domains: (a) Overall modelled domain bathymetry showing the location of profiles (b) smaller domain showing the four profiles .................................................................95

Figure 5.3 Measured cross-shore profiles for (a) Ada and (b) Keta in the Volta delta (Source: Bollen et al. (2011) and Nairn and Dibajnia (2004)) .................................................................97

Figure 5.4 Beach profiles extracted from high-resolution DEM for Old Ningo (refer to Chapter 3). .........................................................................................................................................................97

Figure 5.5: Raw profiles extracted from the bathymetry and edited profiles used for the modelling ...............................................................................................................................................98

Figure 5.6: Nearshore wave rose for the nearshore location .................................................99

Figure 5.7: A plot of the resampled Sea Surface Elevation .........................................................101

Figure 5.8: Map showing the modelled (a) and observed (b) shoreline change at Old Ningo .........................................................................................................................................................106

Figure 5.9: A comparison of modelled and observed alongshore shoreline change for larger domain .........................................................................................................................................................107

Figure 5.10: Plot of modelled and observed shoreline change for Old Ningo .......................109

Figure 5.11: Future shoreline change pattern (up to 2050). The red box shows the area that was not resolved correctly .........................................................................................................................................................111
LIST OF TABLES

Table 2. 1: A comparison of some model parameters for GenCade, GENESIS, Littoral Processes FM and UNIBEST .................................................................26

Table 3. 1: Flight Sites, Dates and Number of Flights.................................43
Table 3. 2: Summary of sediment volume/depth changes at Old Ningo (January 2017 to April 2018) ........................................................................49
Table 3. 3: Summary of sediment volume/depth changes at Fuveme (June 2016 to April 2018) ..............................................................................54
Table 3. 4: Summary of sediment volume/depth changes at Keta (June 2016 to April 2018) ..............................................................................59

Table 4. 1: Satellite Imagery and Orthophoto acquired for the study sites (date format: dd/mm/yyyy) ........................................................................73
Table 4. 2: Estimated Positional Error for Image Categories (in meters) ................76
Table 4. 3: Estimated Erosion and Accretion Rates for Old Ningo, Fuveme and Keta ........................................................................79
Table 4. 4: Alongshore shoreline change extent in percentages for Old Ningo, Fuveme and Keta .................................................................79
Table 4. 5: Minimum values for wave height (Hs), period (Tp) and direction (Dir.) across the two periods .................................................................81
Table 4. 6: Mean values for wave height (Hs), period (Tp) and direction (Dir.) across the two periods .................................................................81
Table 4. 7: Pearson’s Correlation Coefficients (r) with the P values between Erosion and Wave Variables ........................................................................84
Table 4. 3: Minimum values for Hs, Tp and Dir across the two periods ..........79
Table 4. 4: Mean values for Hs, Tp and Dir across the two periods ..................................79
Table 4. 5: Average Erosion and Accretion Rates for the three sites ..................................81
Table 4. 6: Alongshore Erosion extend across the three sites .............................................81
Table 4. 7: Correlation Coefficients (r) between Erosion and Wave Variables ..................85
Table 5. 1: Profile Start Point and Orientation for larger domain .......................................96
Table 5. 2: Profile Start Point and Orientation for Smaller domain .....................................96
Table 5. 3 Nearshore Wave Conditions Table Limits .......................................................103
Table 5. 4: Modelled Results and oceanographic parameters .............................................110
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AR4</td>
<td>Fourth Assessment Report</td>
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<tr>
<td>AR5</td>
<td>Fifth Assessment Report</td>
</tr>
<tr>
<td>DECCMA</td>
<td>Deltas, Vulnerability and Climate Change: Migration and Adaptation</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
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<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
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<tr>
<td>DHI</td>
<td>Danish Hydraulic Institute</td>
</tr>
<tr>
<td>Dir</td>
<td>Wave Direction</td>
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<tr>
<td>DoD</td>
<td>DEM of Difference</td>
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<tr>
<td>D_{50}</td>
<td>Mean grain diameter</td>
</tr>
<tr>
<td>FM</td>
<td>Flexible Mesh</td>
</tr>
<tr>
<td>GCP</td>
<td>Ground Control Point</td>
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<tr>
<td>GMG</td>
<td>Ghana Metre Grid</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>Hs</td>
<td>Significant Wave Height</td>
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<tr>
<td>HWL</td>
<td>High Water Line</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>KSDP</td>
<td>Keta Sea Defence Project</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>LiDAR</td>
<td>Light Detection and Ranging</td>
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<td>LITPACK</td>
<td>Littoral Processes and Coastline Kinetics</td>
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<td>MSL</td>
<td>Mean Sea Level</td>
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<tr>
<td>MS:</td>
<td>Multispectral</td>
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<tr>
<td>MVS</td>
<td>Multi View Stereopsis</td>
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<tr>
<td>NADMO</td>
<td>National Disaster Management Organisation</td>
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<tr>
<td>Pan:</td>
<td>Panchromatic</td>
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<tr>
<td>RCPs</td>
<td>Representative Concentration Pathways</td>
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<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
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<tr>
<td>SfM</td>
<td>Structure from Motion</td>
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<tr>
<td>SIFT</td>
<td>Scale Invariant Feature Transform</td>
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<tr>
<td>SLR:</td>
<td>Sea Level Rise</td>
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<tr>
<td>SSE</td>
<td>Sea Surface Elevation</td>
</tr>
<tr>
<td>Tp:</td>
<td>Wave Period</td>
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<tr>
<td>UAV:</td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
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<tr>
<td>3D</td>
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CHAPTER ONE

INTRODUCTION

1.1 Overview

Globally, over a billion people are estimated to live within 100 km of the shoreline, while about 800 million reside within 10 m of the observed sea level (Elko et al., 2014). Although deltas cover only about 5% of the global land area, they host over 500 million of the coastal population (Kuenzer and Renaud, 2012). Deltas have remained a preferred human habitat due to their productivity, rich biodiversity and means of transport along the waterways and thus are of important ecological and economic value (Ericson et al., 2006; Overeem and Syvitski, 2009). Economically, deltas hold about 30% of the world’s oil, coal and gas deposits (Bhattacharya, 2003). Consequently, the population in deltaic regions globally is expected to grow at a fast rate over the coming decades as more people are expected to move in, to exploit the resources. Deltas are however fragile and can change drastically with slight modifications in environmental controlling factors especially sea level rise as well as human exploitation (Overeem and Syvitski, 2009; Wong et al., 2014).

Most of the world’s deltas have a significant proportion of land area lying within 2 m above sea level (Syvitski et al., 2009). As a result of the observed rate of sea level rise (SLR) of 3.2 mm/y (Church et al., 2013), these regions are already experiencing coastal erosion and inundation, saltwater intrusion and increased exposure to storm surge. These risks are expected to increase significantly as sea level rise is projected to increase due to climate change (Church et al., 2013). This will be further compounded by accelerated land subsidence due to groundwater abstraction in deltaic regions (Erban et al., 2014; Syvitski, 2008). For example, based on the Intergovernmental Panel on Climate Change’s (IPCC)
fourth assessment report (AR4) projections (Solomon et al., 2007), it is estimated that areas liable to flooding in deltas will increase by 50% by the year 2100 (Syvitski et al., 2009). The combined impact of sediment reduction, relative sea level rise, human accelerated land subsidence, as well as land use changes and river management on channels and banks will continue to stimulate a widespread degradation of deltas, which threatens ecosystems, natural resources and economic operations (Le Xuan, 2010; Wong et al., 2014).

In light of these observed and predicted threats to deltas, there is a great interest in the design of sustainable shoreline management within deltas (Foufoula-Georgiou, 2013). To fulfil this, local policymakers, managers, and engineers require more accurate and efficient science-based new assessment tools to explain and forecast medium to long-term shoreline variability. This will also enable proactive solutions for building more resilient deltas and provide better guidance for reducing delta vulnerability (Elko et al., 2014).

Whereas large deltas such as the Ganges-Brahmaputra-Meghna (GBM), the Mississippi and the Mekong have received much attention (Angamuthu et al., 2018; Chaturvedi, 2013; Kuenzer and Renaud, 2012; Syvitski, 2008), some smaller deltas, especially those in developing countries like Ghana, are less studied and are data-sparse. This presents a great challenge to developing models for understanding the coastal dynamics to inform management in many developing countries. These smaller deltas including the Volta delta, however, are increasingly being exposed to the impacts of climate change (Tessler et al., 2015) and as such require better management.

This study uses remote sensing and modelling approaches as well as available historical data to understand the evolution trend of the Volta delta shoreline system in Ghana at a higher
resolution. The approach includes the use of Unmanned Aerial Vehicles (UAVs), and adapting existing deterministic models for hindcasting and predicting shoreline dynamics in the delta. Hitherto, such models and monitoring efforts are generally scanty for the Volta delta and hence the need to fill this gap building on works carried out elsewhere in the Gulf of Guinea and other places (Almar et al., 2015; Giardino et al., 2018).

### 1.2 Background

The Volta Delta (Figure 1.1) forms one of the most prominent geomorphic and coastal features along the eastern coast of Ghana. The region is home to diverse and rich ecosystems such as mangroves, lagoons, and marshes. It also hosts about 4% of the Nation’s total population of about 24.6 million (Ghana Statistical Service, 2012) and serves as an important hub for fishing and farming activities. Furthermore, oil exploration activities are expected to commence soon in the delta, as Swiss African Oil and PET Volta Investments have been awarded a new exploration and production licences for onshore operation in the region (Nyavor, 2016).
Figure 1.1: Map of the Study Area (Source: Codjoe et al., 2020). The 5m contour limits the extent of the Volta Delta.

The Delta is considered to be at risk from increased exposure to sea level rise, flooding, storm surge, salinization, coastal erosion and subsidence (Tessler et al., 2015). Studies within the Delta revealed that sections of the shoreline have been eroding since the mid-1880s, but the situation has been exacerbated by the damming of the Volta River in 1965 (Anthony, 2015; Ly, 1980). This has reduced the fluvial sediment influx to the Volta Estuary by about 90% and therefore negatively affected the sediment budget (Anthony et al., 2016). Other studies have also identified that the Keta sea defence project, which was a major intervention to curb the menace of increased erosion, is having a ‘knock-on effect’ on the downdrift side (Angnuureng, et al., 2013; Appeaning Addo, et al., 2011; Jayson-Quashigah, et al., 2013). There have also been reports by the National Disaster Management Organisation (NADMO) of Ghana on frequent flooding in the Delta. The region is currently
experiencing increased storm surge activities and erosion making top stories in the news (Akpabli, 2017). These issues place life, property and development in the Volta delta at risk. There is, therefore, the need for improved and more efficient morphological assessment approaches in the region to facilitate effective mitigation efforts.

Sustainable management of deltas requires monitoring and modelling systems that encapsulate the spatial/temporal dependencies of the dynamics of the biophysical hazards. These spatial and temporal dependencies have not been well researched within the Volta delta. This research seeks to answer the following questions:

1. What has been the recent trend (short to long term) in shoreline morphological dynamics in the Volta Delta?

2. What is the role of wave climate on shoreline dynamics within the Delta?

3. What are the expected future trends with regards to projected sea level rise scenarios in the Volta delta?

1.3 Aim and Objectives

The overall aim of this research is to assess short to long term changes in shoreline in the Volta delta at higher resolution using field measurement and modelling techniques in coastal morphodynamics and to evaluate the effects of future sea level rise (SLR) on these dynamics. The study will inform better management and adaptation policy decisions.

1.3.1 Research Objectives

1. Estimate short term (up to 2 years) beach sediment dynamics in the Volta Delta using high-resolution Digital Elevation Models (DEMs) from Unmanned Aerial Vehicles (UAVs)
2. Assess medium term (a decade) shoreline response to wave climate in the delta using high-resolution satellite imagery

3. Model and predict future shoreline morphodynamics in the Volta delta using the Littoral Processes FM model by the DHI.

1.3.2 Justification of the Study

Access to current, comprehensive, and reliable spatial information is necessary for decision making in integrated coastal zone management in Ghana. The eastern coast of Ghana, which includes the Volta delta, has been identified as a hotspot for coastal erosion and is considered vulnerable to sea level rise (Wiafe et al., 2013; Tessler et al., 2015). However, a review of literature has brought to the fore limited research on coastal morphodynamics in the Delta. Existing studies including, Appeaning Addo, (2016) and Jayson-Quashigah et al. (2013) have relied on relatively coarse data which affects the quality of the research results.

Therefore, the first objective implements a new approach for estimating beach morphodynamics using high-resolution DEMs thereby providing finer estimates of beach dynamics. The second objective quantifies the influence of wave climate forcing on medium-term shoreline variability in the delta. The third objective adapts an existing 2D morphodynamic model (Coastal Processes FM) to understand the future trends in shoreline morphodynamics in the Volta delta considering the impacts of climate change. Such information is relevant for building resilient deltas. Figure 1. 2 shows the linkages between the research objectives.
The results from this study will provide high-resolution estimates of beach volume dynamics across the Volta delta. This will allow for more robust decision-making and support sustainable development of the Delta region. Furthermore, the use of UAVs for beach monitoring is new to the region and this study provides an innovative approach, which can be adopted for monitoring beach dynamics in our data-sparse sub-region.
1.4 Research Methodology

This work was based on the premise that shoreline dynamics in the Volta delta has been assessed using low-resolution data, which compromises the results that have been reported. Furthermore, the impact of sea level rise on shoreline dynamics has not been fully researched in the Delta.

To achieve the aim of assessing short to long term changes in shoreline in the Volta delta at higher resolution and to evaluate the effects of future sea level rise (SLR) on these dynamics, different approaches and data are adopted and implemented. They include:

I. The use of UAV surveys to assess beach volume and shoreline dynamics and to estimate sediment volume change and shoreline change rates along the Volta delta coast for the short-term (2016-2018). This involved the generation of high-resolution DEMs and Orthophotos. DEMs were differenced to assess volume changes while shorelines were digitised from the orthophotos to assess erosion rates. Uncertainties for these changes were quantified.

II. Secondly, high-resolution orthophoto and satellite imageries were acquired from different sources for the period between 2005 and 2017. The imageries were pre-processed and shorelines extracted to compute medium-term (12 years) shoreline changes. Wave parameters (height, period and direction) were also extracted from existing model for the Volta delta for the same period (Giardino et al., 2018). The shoreline changes were correlated with wave parameters using Pearson’s linear correlation to assess the role of waves in shoreline dynamics in the Delta. Uncertainties were identified and reported.
III. Finally, future predictions of shoreline dynamics were carried out using the Littoral Processes FM model. These predictions were done under the scenario of sea level rise up to mid-century (2050). Model predictions were validated using a baseline shoreline change assessment using satellite imageries for the period between 2005 and 2017.

1.5 Thesis Structure

The structure of the thesis flows from the objectives outlined above. Chapter 2 reviews literature on deltas, shoreline monitoring, and modelling as well as a background to the Volta delta. Chapter 3 looks at a high-resolution approach to the short-term measuring of beach morphodynamics using UAVs. In chapter 4, an assessment of medium-term shoreline variability using remote sensing approach and the impact of wave climate are reported. A two-dimensional morphodynamic model (Coastal Processes FM from MIKE) is set up and validated for the Volta delta to predict future conditions under increasing sea levels in Chapter 5. Key findings from the study are synthesised and conclusions drawn in Chapter 6 with recommendations for future studies.
CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Globally, deltas are important regions of agricultural and industrial production and other economic activities. They are also areas of ecological importance including wetlands. There are various attempts to understand the dynamics of deltas and promote sustainable development (Angamuthu et al., 2018; Appeaning Addo, 2016; Dandekar and Thakkar, 2014; Porebski and Steel, 2006). To put this study in context, a review of works done on deltas, nearshore morphodynamics, shoreline monitoring and modelling as well as the application of new remote sensing technologies such as Unmanned Aerial Vehicles (UAVs) is relevant. The rest of this chapter reviews literature on the various components of the study and is organised according to four broad components (sections 2.2, 2.3, 2.4 and 2.5). The next section (2.2) looks broadly at deltas, their definition, types as well as climate change and anthropogenic impacts, and planning sustainable deltas. Sections 2.3 and 2.4 review coastal monitoring and modelling, respectively. The application of UAVs and MIKE 21 Littoral Processes FM modelling suite are discussed in more detail. The last section (2.5) is dedicated to a review of the Volta delta focussing on previous works that have been carried out in the Delta and to identify gaps in knowledge.

2.2 Coastal Deltas

Defining a delta is seen as a complicated and recurring requirement in delta scholarship (Collins, 2015). Generally, a delta can be defined as ‘a discrete bulge of the shoreline formed at the point where a river enters an ocean, sea, lake, lagoon or other standing body of water’ (Bhattacharya, 2003). This definition, though broad, clearly cuts off deltas that do not
typically show protuberance. There is also the geological point of view, which looks at a
delta as a pile of gravel, sand, and mud that is being dumped at a continent’s edge at the
mouth of a major river (Cox, 2015). By this definition, delta as a term may imply a wide
river valley filled with riverine deposits since sea level began to rise 40 to 60 million years
ago during the early Tertiary period (Davidson and Paradise, 2015). Wright (1977) gave a
more detailed and specific definition of a delta as “coastal accumulations, both subaqueous
and subaerial, of river-derived sediments adjacent to, or in close proximity to, the source
stream, including the deposits that have been secondarily moulded by various marine agents,
such as waves, currents, or tides.” This definition in context includes deltas that do not
necessarily show shoreline protuberance and has been adopted for this study.

2.2.1 Formation of Deltas

Deltas are formed when a sediment-laden lotic enters a lentic body of water, loses its
capability to carry the sediment and deposits it. In coastal areas specifically, deltas are
formed when sediment supply exceeds the rate of redistribution by coastal processes such
as waves, tides, and currents (Bird, 2008). A key characteristic of deltas, therefore, is the
ability of the connected fluvial system to deliver and deposit sediment more rapidly than
local sea level rise, subsidence or the rate at which sediment can be removed by coastal
erosive processes (Ericson et al., 2006). The delta system is naturally dynamic being
controlled by the interaction between boundary conditions and the forcing factors (Ericson
et al., 2006; Syvitski and Saito, 2007). Fundamentally, they are regressive in nature, which
implies their deposits portray a seaward migration or progradation of the shoreline
(Bhattacharya, 2003).

Deltas occur at a wide range of scales: from basin-scale depositional systems (e.g.
Mississippi) to smaller components of other depositional systems such as bayhead deltas
within large estuarine or lagoonal systems (e.g. Volta delta). Their sizes and shapes vary based on the pattern and rate of sediment yield, configuration of the coast, nearshore bathymetry, as well as waves and currents (Bird, 2008). They also vary from being completely wave-dominated (e.g. Sao Francisco Delta) to tide-dominated (e.g. the Fly Delta) or fluvial dominated (e.g. Mississippi Delta) (Bhattacharya, 2003).

2.2.2 Delta Morphodynamics

Dynamics in deltaic regions is controlled by a complex interaction of factors including sediment supply, accumulation reflecting sea level fluctuations, offshore slope and coastal energy such as waves and tides (Overeem et al., 2005; Syvitski, 2005). Due to this complex interaction, the morphological record of the adjacent coastal zone is strongly modified by erosion and re-deposition by storms, waves and fluvial incision. River processes dynamically interact with ocean processes (mainly waves and tides) to control a delta’s form (Overeem and Syvitski, 2009). Every delta is consequently a result of the precise balance of these controlling processes over time (Overeem and Syvitski, 2009). Other forces at play include land subsidence, sea level rise, and changes in river flow magnitudes due to damming and climate change (National Research Council, 2012). Human activities such as sediment removal, groundwater extraction, damming of rivers, coastal defences all play a role in the modification of deltas (i.e. erosion and subsidence).

2.2.3 Classification of Deltas

Deltas have been classified into three broad groups (with transitional classes, see Figure 2.1) based on the levels of fluvial, tidal and wave processes influencing the dynamics in the delta (Galloway, 1975; Hori and Saito, 2007). This tripartite classification is the best-known system for deltas, which is based on a concept initially proposed by Fisher (1969). The classes are the tide, river and wave-dominated deltas. For river or fluvial-dominated deltas,
the rate and volume of sediment inputs exceed the capability of other energy sources to substantially modify the morphology (Galloway and Hobday, 1983). These deltas normally prograde into basins with low tides and wave energy, and are associated with a large number of small terminal distributary channels (Olariu and Bhattacharya, 2006). They are also characterised by channel mouth-bars and other abundant depositional features. A classic example referred to in the literature is the modern Mississippi delta with others such as the Volga and Lena deltas (Bhattacharya, 2003; Bhattacharya, 2006; Hori and Saito, 2007).

Tide-dominated deltas are characterised by an estuarine-like river-mouth and are among the world largest (e.g. the Ganges-Brahmaputra and Fly). Such deltas experience tidal ranges exceeding 3m. They are progradational and characterised by muddy tidal flats and mouth-
bars being reworked mainly by tidal currents into shore-normal tidal bars (Cummings et al., 2016; Goodbred and Saito, 2012).

Wave-dominated deltas are those in which wave action causes significant sediment transport overriding all other processes (Davis and Hayes, 1984). A major characteristic of wave-dominated deltas is the existence of a smoothly developed delta front, made up of well-developed coalescent beach ridges (Cummings et al., 2016; Galloway and Hobday, 1983). The Volta delta in its current state is considered as wave-dominated (Roest, 2018).

2.2.4 Climate change and Deltas

Globally, sea levels are on the rise due to the changing climate, with current rates estimated to be 3.22 mm/yr, which is double the rate during the 20th century (Church et al., 2013). Deltas have been identified to be particularly vulnerable due mainly to their low-lying nature. Most of the world’s deltas have a significant proportion of their land area lying below 2m above the mean sea level (Syvitski et al., 2009). Most of the world’s deltas are already experiencing inundation, erosion, saltwater intrusion, storm surges because of the sea level rise. These impacts will be exacerbated as sea levels are projected to rise further (Church et al., 2013).

Based on the IPCC's fourth assessment report (AR4) projections (Solomon et al., 2007), Syvitski et al. (2009) estimated that areas liable to flooding in deltas will increase by 50% at the end of the century (2100). Furthermore, reduction in sediment supply to deltas through damming of rivers upstream will exacerbate the already eroding shoreline of deltas. This, combined with land-use changes and river management on channels and banks, will lead to increased degradation of deltas, which threatens ecosystems, natural resources and economic operations (Le Xuan, 2010; Wong et al., 2014).
2.2.5 Population growth in Deltas

Deltas across the globe hold some of the world’s highest population. It is estimated that over 500 million people live in deltaic regions, which account for only 5% of the global land area (Elko et al., 2014; Overeem and Syvitski, 2009). Mega deltas such as the Ganges-Brahmaputra-Meghna (GBM), Mekong and Nile alone are host to about 250 million people (Foufoula-Georgiou, 2013). This population is expected to grow significantly (Szabo et al., 2016) as deltas remain a preferred human habitat due to their productivity, rich biodiversity, and means of easy transport along waterways and thereby providing important ecological and economic values (Ericson et al., 2006; Overeem and Syvitski, 2009).

As the population in deltas grow, increasing pressure is placed on resources such as freshwater (both surface water and groundwater) for domestic, industrial, hydropower and recreational uses (Vörösmarty et al., 2004). Consequently, rivers are dammed, while groundwater extraction increases leading to human-induced subsidence, loss of ecosystems, etc. (Wesenbeeck et al., 2014). In addition, there is competition for space, which results in development on wetlands and beaches, worsening the impacts of flooding, erosion and subsidence, among others (Coleman et al., 2008; Syvitski, 2007).

2.2.6 Subsidence in Deltas

Subsidence refers to the lowering of the geodetic land surface relative to a geodetic datum and varies locally, depending upon rates of lowering influenced by isostatic fluctuation, faulting and compaction (Cavalié et al., 2015; Stanley, 1997). In most of the world’s deltas, reduction in sediment reaching the delta due to damming has been identified as a major culprit for delta subsidence (Dandekar and Thakkar, 2014; Syvitski et al., 2009). This is compounded by economic advancements which have led to massive extraction of groundwater for industrial, agricultural and domestic purposes as well as petroleum
Deltas such as the Mekong are subsiding at a rate of about 1.6 cm/yr. (Schmidt, 2015) while the rate in the Po delta since the 2000s is estimated to be 6 mm/yr (Fabris et al., 2014). Both rates exceed the annual rate of sea level rise, which currently stands at 3.2 mm/yr. This presumes that human accelerated subsidence in deltas, if not checked will have a more devastating impact than all the other factors combined. In the Volta delta, subsidence rate is estimated to be between 1-2 mm/yr based on other deltas (Appeaning Addo, 2018a).

### 2.3 Measuring and Monitoring Delta dynamics

Monitoring of coastal zones (which includes deltas) provides relevant information for coastal management and intervention purposes and is increasingly required by policymakers, researchers, and engineers. Over the decades, scientist and researchers have adopted various methods to effectively monitor the constantly changing coastal environment (Marfai and Almohammad, 2008). These methods differ in their approach, accuracy, cost, duration, coverage and what they measure (Appeaning Addo et al., 2008). The various methods can be broadly classified into ground-based surveys, airborne surveys, satellite-based surveys and sea-based surveys (Mason et al., 2000).

Ground-based survey methods range from simple optical measures using rods and measuring tapes and total stations to measurements using Global Positioning Systems (GPS) or Differential-GPS (DGPS) tools and ground terrestrial laser scanners (TLS) as well as video methods (Labuz, 2016; Mills et al., 2005). These methods are much simpler to implement and can yield high accuracies (for example of beach profiles) along transects surveyed (Mason et al., 2000). The main challenges associated with these methods include restriction to smaller areas, difficulty during poor weather, time-consuming and reduced accuracy from survey points or transects (Ford, 2013; Labuz, 2016; Sutherland, 2007).
Video monitoring systems can now collect data even in poor weather conditions and have the additional advantage of capturing changes in the intertidal zone (Davidson et al., 2007; Nieto et al., 2010). Studies by Davidson et al. (2006) and Mitasova et al. (2004) applied these methods to monitor various aspects of the dynamic coastal zone. More recently, a video system has been established to monitor nearshore processes at Dzita in the Volta delta (Angnuureng et al., 2019). DGPS has also been used in the Volta delta for shoreline monitoring (Wiafe et al., 2013).

The advent of aerial photogrammetry allowed the use of aerial photographs which presented a more effective approach for monitoring coastal zones and have been in uses since the early 1990s (Baily and Nowell, 1996). They can provide up to 0.01 m ground resolution, dependent on user requirements and are also relatively more accurate (Klemas, 2009). Additionally, they have the capability for stereo pair mapping, allowing for the production of digital elevation models (DEM}s). Other researchers have used aerial photographs to monitor shoreline change and map coastal habitats (Appeaning Addo et al., 2008; Ekebom and Erkkilä, 2003; Moore, 2000; Sesli et al., 2009; Smith and Zarillo, 1990). Furthermore, there have been developments in airborne Light Detection and Ranging (LiDAR) and interferometry, which makes it possible to acquire more rapidly, dense and more accurate elevation data over an area (Klemas, 2009). However, airborne surveys are generally limited by poor weather conditions, laborious field preparation as well as the high cost of equipment and data collection (Darwin et al., 2013; Mason et al., 2000). The development and use of UAVs for aerial photography are discussed separately (see section 2.3.1).

The use of satellite imagery for coastal monitoring is well established with a wide variety of sensors available since the 1970s (Whitehead and Hugenholtz, 2014). Satellite imageries cover larger areas and provide multispectral and stereo pair images (Boak and Turner, 2005). They have the added advantage of short revisit time, provide multi-spectral data and have
the capability for stereo pair mapping. Ground resolution varies from kilometres to very high resolutions of 1.65m and sub-meter for panchromatic bands (Purnamasayangsuksih et al., 2016). Satellite imageries have been extensively used in the field of coastal monitoring (Kuleli, 2010; Natesan et al., 2015; Ryu et al., 2002; Tamassoki et al., 2014). However, they are affected by cloud coverage and can be expensive, especially when working with higher resolution imagery (Casella et al., 2016; Klemas, 2015).

2.3.1 UAVs in Coastal Zone Monitoring

Recent advancements in remote sensing platforms have resulted in the development of small UAVs commonly referred to as drones (Colomina and Molina, 2014; Whitehead and Hugenholtz, 2014). UAVs have emerged as more flexible alternatives in aerial photography due to their relatively low cost of operation, support for more frequent missions, appreciable areal coverage, improved ground resolution, and ease of use (Nex and Remondino, 2014; Ventura et al., 2017; Wallace et al., 2012). UAVs have the capability of performing missions and acquiring data autonomously and are capable of collecting data in inaccessible coastal environments (Casella et al., 2017; Colomina and Molina, 2014).

Furthermore, UAVs are capable of generating orthophotos and DEMs with resolutions lower than 10cm (Harwin and Lucieer, 2012). These high-resolution products facilitate the quantification of morpho-sedimentary changes including nearshore and longshore sediment transport and are also used in hydrodynamic numerical modelling (Klemas, 2015). They have been used in the mapping and monitoring of wetlands, coral reefs, shoreline, beach topography and bar dynamics (Turner et al., 2016; Ventura et al., 2017).

Studies by Vousdoukas et al. (2011) employed UAVs to generate high-quality time-averaged images that were used to provide information on nearshore sandbar morphology, the location of rip channels and the dimensions of the swash zone. Compared with satellite
imagery and the ARGUS video system, the UAV approach provided better results in terms of spatial coverage, rapid deployment, low operational cost, and output. Other studies have also shown that the accuracies achieved using UAVs out-match those obtained from the use of conventional aerial photography (Goncalves and Henriques, 2015).

Mancini et al. (2013), demonstrated that the high degree of the workflow using UAVs and absolute vertical accuracy of 20cm achieved by the Digital Surface Models (DSMs) makes them potentially useful in the fields of natural hazards, disaster response and high-resolution terrain analysis. Moreover, the study compared data from UAV point cloud, terrestrial laser scanner (TLS) and Global Navigation Satellite System (GNSS) survey and reported that they compare favourably (see also Chikhradze et al., 2015; Hackney and Clayton, 2015).

Delacourt et al. (2009) developed a new system of photogrammetric helicopter (DRELIO) to generate DEM for a coastal area. The system allowed for the generation of 3cm resolution DEM with accuracy better than 3cm. The study further showed that bathymetry can also be derived using the DRELIO system where the water is sufficiently clear. The system which produces DEM concurrent to that of LiDAR appears now to be more flexible and efficient than the other UAV helicopters equipped with electric engines and is also less expensive than LiDAR (Delacourt et al., 2009). The system is also well suited for the coastal environment with the ability to withstand wind speeds greater than 50 km/h.

Harwin and Lucieer, (2012), in their study, revealed that sub-decimetre terrain change in coastal areas can be monitored using UAV data. Their focus was to access the accuracy of the whole data capture and geo-referencing instead of just looking at one aspect (which is mostly the case). The results were compared to those from DGPS and total station surveys, which indicated that when flying at 40-50 m, an accuracy of 2.5-4 cm could be achieved and this is within the magnitude of what can be obtained from DGPS. It was therefore concluded
that the use of UAV multi-view stereopsis (MVS) technique for 3D surface reconstruction and monitoring of natural landscapes has a lot of potential for coastal erosion monitoring.

Also, Casella et al. (2014) combined UAV imagery with numerical models to analyse wave run-up after two different swells in Borghetto, Santo Spirito Municipality of the Liguria Region of Italy. Maximum wave run-up was determined on the images acquired, using the wet/dry boundary. DEMs were generated from the data at an accuracy of 12 cm and merged with bathymetric data, which was then used to simulate wave run-up. The results were compared to the observed values and they were consistent with Root Mean Square Deviations (RMSDs) less than 50 cm. Their conclusions emphasise the important role drones could play in the future of coastal morphological change and modelling.

According to Klemas (2015), one intense area of application of UAVs is the mapping and monitoring of tidal wetlands (see also, Chabot and Bird, 2013). UAVs are being used to monitor flamingos at Al Wathba Wetland Reserve in Abu Dhabi (Swan, 2014). This brings to light yet another advantage of UAVs, being their ability to access difficult-to-reach areas while taking into consideration environmental sensitivities through minimisation of human presence (Swan, 2014). Birdsong et al. (2015) explored the application of UAVs for managing and conserving aquatic resources in four Texas Rivers. The UAVs were used in mapping invasive salt cedar that has degraded instream habitat conditions; to map instream meso-habitats and structural habitat features as a baseline prior to watershed-scale habitat improvements; to map enduring pools in the Blanco River during drought conditions to guide smallmouth bass removal efforts and also to quantify river use by anglers (Birdsong et al., 2015). These were among the initial steps to assess the full range of UAV applications in aquatic resources management. It was discovered that the UAV approach was cost-effective and time-efficient providing higher quality data over traditional survey methods (Birdsong et al., 2015).
Furthermore, Bryson et al. (2016) used Kite Aerial Photography for mapping intertidal landscapes. They developed high-resolution DEM and multispectral terrain models of the intertidal rocky shores by combining imagery from visible and near-infrared wavelengths. The results revealed the potential of mapping intertidal plants (micro- and macro-algae) and animals (gastropods) as well as detecting changes at scales that are not achievable by traditional remote sensing platforms. In a related study, Dugdale (2007) evaluated the use of imagery from UAV for mapping intertidal microalgae on Seal Sands, Tees Estuary, UK. The study used various classification methods to extract the features and confirmed the prospects of UAV application in mapping intertidal features. Casella et al. (2016) and Murfitt et al. (2017) have also applied UAVs to the study of coral reefs.

Other applications include the development of an ultra-lightweight L-band digital Lobe-Differencing Correlation Radiometer (LDCR) for airborne UAV sea surface salinity mapping (McIntyre and Gasiewski, 2007). Cook et al. (2013) also conducted experiments on using UAVs for coastal meteorological research in New Zealand. The results from the UAV suggest the reliability of the approach for coastal meteorology. With further development in the UAV technology, cameras that are more sophisticated can be carried on-board, making its application in the coastal zone unlimited.

2.3.2 General workflow for UAV

The workflow for the application of UAVs follows the standard photogrammetry approach with slight deviations in image processing (Figure 2.3). The first stage is the fieldwork component, which involves establishing Ground Control Points (GCPs) and the acquisition of the images. The images then go through a structure-from-motion (SfM) workflow as described by Westoby et al. (2012). A first step in the SfM workflow is the identification of matching features in each image that are resilient to changes in image scaling and rotation.
and partially invariant to changes in illumination conditions and camera viewpoint. This is generally implemented using the popular Scale Invariant Feature Transform (SIFT) algorithm (Lowe, 2004; Snavely, 2011).

In the succeeding process, the identified points are used in a 3-D reconstruction using a bundle adjustment system which estimates the camera pose and extracts a low-density or sparse point cloud (Westoby et al., 2012). The sparse point cloud is then densified using multi-view stereopsis algorithms such as the Clustering View for Multi-view Stereo (CMVS) and the Patch-based Multi-view Stereo (PMVS2) (Furukawa and Ponce, 2010; Furukawa et al., 2010; Turner et al., 2012).

The next step is the manual identification of the GCPs, which are then used to transform the cloud points from relative to an absolute coordinate system. The cloud points are interpolated to generate DEMs or digital surface models (DSMs).
Several photogrammetric software packages are available for such automated processing including open source and commercial packages. The open sources available include Bundler and CMVS (Furukawa and Ponce, 2010), Apero and Mic-Mac (Rupnik, et al., 2017), VisualSFM (Wu, 2013). Commercial packages include Agisoft Photoscan (Agisoft, 2014), Pix4D (Pix4D, 2019), 3DF Zephyr (3Dflow, 2019) and 3Dsurvey (3Dsurvey, 2019).
2.4 Morphodynamics Modelling

2.4.1 Model selection

Morphodynamics modelling is an area that has seen appreciable advancement over the recent decades with various models being developed. Such models have become valuable tools for coastal engineers and researchers for assessing erosion problems and to aid the design of coastal interventions (Lesser et al., 2004; Pender, 2013). The development of morphodynamics models has progressed from simple analytical models through 1D network, coastal profile, coastline, and multi-line models to depth-averaged two-dimensional (2D) models by 1990 (Lesser et al., 2004). These depth-averaged models were developed with sophisticated quasi-3D extensions which are able to account for the undertow profile (Lesser et al., 2004; Roelvink and Reniers, 2011). From the 1990s, there have been developments in fully 3D models which include separate solvers for bedload transport and 3D suspended sediment which keeps track of the bed compositions and evolution during each time step (Gessler et al., 1999). Morphological models can be classified generally into process-based (which represents all relevant sediment transport processes) and behaviour-based (which uses simple parameter descriptions of the general behaviour of the morphological system at larger scales) (Amoudry and Souza, 2011).

A number of models have been developed, validated and applied to various coastlines across the globe. Amoudry and Souza (2011) reviewed five widely used modelling systems for coastal morphological and sediment transport. These are ROMS, Delft3D, ECOMSED, TELEMAC and MIKE 21/3 modelling systems. They indicated that these model options might present some distinct advantages and disadvantages with respect to some pertinent issues for coastal zones, both numerical and physical.
Though the development of 3D models has advanced, they are computationally demanding, making them more suitable for short to medium-term analysis. The one-line approach, also known as the conservation-of-sand-volume approach remains the preferred choice for evaluating long term shoreline evolution (Thomas and Frey, 2013). Thomas and Frey (2013) reviewed four of these one-line models, namely, GENESIS (Generalised model for Simulating Shoreline Change), GenCade (Genesis + Cascade), UNIBEST (Uniform Beach Sediment Transport) and the Littoral Processes FM.

Comparatively, the study concluded that all the models represent the same major processes driving shoreline change with many small variations in approaches or capabilities. However, the Littoral Processes FM allows for a more rigorous approach for calculating longshore transport with calculations in a 2D grid (cross-shore and vertical) (Thomas and Frey, 2013). Furthermore, among the four models, only Littoral Processes FM allows for varying cross-shore profiles, depth of closure and grain size (Table 2.1). In addition, it allows for wave-current interactions which play a key role in wave dynamics and sediment transport (Romero, Lenain, and Melville, 2017; Wiberg, 2005). The model also has an integrated modular structure which makes it easy to use (Townsend et al., 2014).
Table 2.1: A comparison of some model parameters for GenCade, GENESIS, Littoral Processes FM and UNIBEST

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GenCade</th>
<th>GENESIS</th>
<th>Littoral Processes FM</th>
<th>UNIBEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of closure</td>
<td>Constant</td>
<td>Constant</td>
<td>Variable</td>
<td>N/A</td>
</tr>
<tr>
<td>Cross-shore profile</td>
<td>Constant</td>
<td>Constant</td>
<td>Variable</td>
<td>N/A</td>
</tr>
<tr>
<td>Grain size</td>
<td>Constant</td>
<td>Constant</td>
<td>Variable</td>
<td>N/A</td>
</tr>
<tr>
<td>Wave-current interaction</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Internal Wave model</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Time and space varying source and sink</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

This study adopts the MIKE Littoral Processes FM Model (formerly called LITPACK - Littoral Processes and Coastline Kinetics) package, which has been widely used and validated at various sites (Anastasiou and Sylaios, 2016; Hendriyono et al., 2015; Rajab and Thiruvenkatasamy, 2016; Saengsupavanich et al., 2008; Thach et al., 2007). The model has also been successfully implemented in the region as part of the Ada Sea Defence Project along the eastern coast of Ghana (Bolle et al., 2015).

2.4.2 Shoreline Change modelling using Littoral Processes FM (One-line Model)

The one-line models, though simple, remain versatile tools for shoreline evolution analyses (Reeve and Valsamidis, 2014). In general, one-line models were developed on the principle that the beach profile shape remains constant as it advances or retreats so that changes in shoreline is directly related to imbalances in longshore transport (Townsend et al., 2014; Thomas and Frey, 2013). Cross-shore sediment transport is, however, assumed to cancel out over the longer term and therefore negligible (Hanson and Kraus, 2011; Larson et al., 1987). In addition, longshore transport is assumed to occur uniformly along the beach from berm
height $D_B$ down to the depth of closure ($D_c$), beyond which no appreciable profile change takes place (Figure 2.3).

Figure 2.3 Schematic showing shoreline change estimation using the 1-Line Theory (source: Hanson and Kraus, 2011)

The Littoral Processes FM package, developed by the Danish Hydraulic Institute (DHI), is arguably one of the widely used one-line models (Guner et al., 2017; Qiu, 2013). It is a deterministic model that simulates non-cohesive sediment transport in points and along quasi-uniform coastlines (DHI, 2017). The model integrates simultaneously changing waves, tides, currents and sediment transport to determine shoreline positions accordingly by numerically solving the equations of mass continuity and momentum (Rajasree and Deo, 2018).

At the centre of the Littoral Processes FM module is a Quasi Three-Dimensional Sediment Transport Model (STPQ3D). This model calculates instantaneous and time-averaged hydrodynamics and sediment transport in two horizontal directions in a point. Principally, the Quasi-3D hydrodynamics model is the solution of the force balance across the water column expressed as:

$$\tau = \rho v_t \left| \frac{\partial \bar{u}}{\partial z} \right|$$

2.1
Where $\rho v$ is the viscosity, $U$ is the flow velocity and $z$ is the height above the bed.

The time-averaged flow velocity ($\bar{U}$) is determined by integration. The temporal and vertical variations of shear stress, turbulence, flow velocity and sediment concentrations are resolved. The time evolution of the boundary layer due to combined wave/current motion is also resolved by means of the integrated momentum approach of Fredsøe (1984). The force balance includes contributions from the near-bed wave orbital motion, forces associated with wave breaking (gradients of radiation stresses) and the sloping water surface.

### 2.4.2.1 Some Governing Equations

To assess the non-cohesive sediment transport for a given area, the vertical diffusion equation is resolved. The Longshore and cross-shore momentum balance equation (2.2) is also solved to obtain the cross-shore distribution of wave heights, wave setup, longshore currents, and sediment transport for a given cross-shore bed profile and for a given time duration.

\[
-\frac{1}{\rho} \frac{\partial \bar{S}_{xx}}{\partial x} = g (D + b) \frac{\partial b}{\partial x}
\]

Where;

- $\bar{S}_{xx}$ = the radiation stress normal to the coast
- $D I$ = the water depth
- $b$ = the wave-induced water level variation
- $\rho$ = the density of the seawater
- $g$ = the acceleration due to gravity

The shoreline evolution is then evaluated by solving the sand continuity equation that considers the impact of sediment sources and sinks as well as the diffraction from any structure. The continuity equation for sediment volumes is expressed by:
\[
\frac{\partial y_c(x)}{\partial t} = - \frac{1}{h_{act}(x)} \frac{\partial Q(x)}{\partial x} + \frac{Q_{sou}(x)}{h_{act}(x)\Delta x}
\]

2.3

where,

\( y_c(x) \) = distance from the baseline to the coastline
\( t \) = time
\( h_{act}(x) \) = height of the active cross-shore profile
\( Q(x) \) = longshore transport of sediment expressed in volumes
\( x \) = Longshore position
\( \Delta x \) = Longshore discretization
\( Q_{sou}(x) \) = Source/sink term expressed in volume

From an initial position of \( y_{int}(x) \), the evolution of the shoreline is determined by solving the above equation, using an implicit Crank-Nicholson scheme (DHI, 2017). The longshore transport rate is very key and is given at any position as a function of the wave climate, current, cross-shore profile, sediment properties and the coastline orientation (DHI, 2017).

The changes in the cross-shore profile are determined with the help of the bottom sediment continuity equation (2.4).

\[
\frac{\partial z}{\partial t} = - \frac{1}{(1-n)} \frac{\partial q}{\partial x}
\]

2.4

Where;

\( n \) = the porosity of the bed,
\( q \) = sediment flux,
\( t \) = time and
\( z \) = the height above bed and
$x =$ horizontal coordinate

2.4.3 Summary of Basic Assumptions Underlying One-line Models

One-line models in summary work with the following general assumptions:

- The beach profile shape remains constant.
- The shoreward and seaward vertical limits of the profile are constant.
- Sand is transported alongshore by the action of breaking waves and longshore currents.
- The detailed structure of the nearshore circulation is ignored.
- There is a long-term trend in shoreline evolution.
- There is an adequate sand supply (i.e., an infinite supply of sand is assumed).

2.5 Overview of the Bight of Benin

2.5.1 Location and Oceanography

The Volta delta, which is the focus of this study, is situated in the Gulf of Guinea and specifically within the Bight of Benin. The Bight encompasses the coastlines of Ghana, Togo, Benin and Nigeria. This region is characterised by an embayed sand-barrier system which extends from the Volta delta in the west to the Niger delta in the east and is dotted with lagoons and marshes (Allersma and Tilmans, 1993; Almar et al., 2015). The continental shelf is narrow with widths ranging between 20 and 80 km and characterised by steep slopes. There are reported sub-marine canyons around Nigeria and Ghana, which contribute to sediment loss in the region.
The beaches along this coast are in the reflective to immediate state (Almar et al., 2015). The guinea current flows offshore from west to east with a unidirectional and large longshore drift towards the east. The tidal regime is microtidal between 0.3 m to 1.8 m for neap and spring tidal ranges respectively. The waves reaching the coast of two origins: the sea generated by the weak, local monsoon; and swell generated by storms in the southern part of the Atlantic Ocean (Allersma and Tilmans, 1993). The locally generated waves hardly exceed 1.25 m in height with maximum periods between 3-4 s. The height of the swell waves may reach between 2-3 m with periods varying between 8 and 20 s and generally arrive between the south and south-west direction (Allersma and Tilmans, 1993; Anthony and Blivi, 1999). Also, storms are very rare in this region with a south-westerly monsoon wind with speeds that hardly exceed 6 m/s (Allersma and Tilmans, 1993).

The region is characterised by two major River deltas namely the Niger delta in Nigeria and the Volta delta in Ghana among other smaller rivers. The Niger delta is a mega arcuate-shaped delta spanning approximately 450 km (Dada, et al., 2018) while the Volta is much smaller extending for about 150 km (Appeaning Addo, et al., 2018a).

2.5.2 Erosion trends; causes and interventions

Historically, erosion has been reported for most of this coast, which is predominantly sandy. The Niger delta, for example, is reported to be eroding as high as -30 m/yr erosion for the western section of the delta (Dada, et al., 2019). Around Cotonou in Benin, an erosion rate of up to -10 m/yr is reported (Almar et al., 2015; Kaki, 2011). Along the Volta delta coast in Ghana erosion rates varying between -1.86 m/yr to some extreme rates exceeding -17 m/yr (Angnuureng et al., 2013; Appeaning Addo, 2016; Boateng, 2012). The establishment of Ports (Tema, Lome and Cotonou) and the damming of rivers such as the Volta River have been reported to greatly influence the shoreline dynamics along this coast (Giardino et al.,
Additionally, sand extraction from these beaches contributes significantly to the erosion trends observed (Kaki, 2011).

2.6 The Volta Delta: An Overview

The definition for the Volta delta adopted for this study is that of Appeaning Addo et al. (2018a), which refers to the area lying below the 5m contour around the Volta estuary. By this definition, the shoreline studied extends approximately 150 km from Ghana’s border with Togo to Ningo-Prampram (see Figure 1.1). This coastal belt is characterised by a sandy coast barely 2m above mean sea level (MSL). The Volta River was a major source of sediment supply for the east of the Delta but this has reduced drastically after the construction of the Akosombo Dam and hence, the delta in its current stage is considered as wave-dominated (Roest, 2018). Sediment currently reaching the delta is mostly from the up-drift with the current top layer having a $D_{50}$ of 0.6mm (Roest, 2018). The area is also characterised by two major coastal lagoons (Keta and Songor; both RAMSAR Sites) and a number of tidal pools (Figure 1.1).

Morphologically, the delta is characterised by relatively steep and narrow sandy beaches with the upper beach face being approximately 1:3 and the lower beach face ranging between 1:10 to 1:15 (Anthony, 2015; Roest, 2018). These profiles vary across the delta, influenced by sediment characteristics (e.g. grain size, shape and weight) and the waves. According to Anthony (2015), the massive spit characterising the delta occurred recently (post-mid-Holocene) in response to a westward shift in the river mouth and increased sequestration of sand by the Volta through enhanced wave refraction in the area south of Keta. The continental shelf here is narrow, extending for about 15 to 33 km in width (Anthony, 2015; Appeaning Addo et al., 2018a)
Geologically, the area is within the Keta Basin, comprising late quaternary rocks and unconsolidated sediments of clay, loose sand and gravel deposits (Appeaning Addo et al., 2018a; Jayson-Quashigah et al., 2013). The 20 m top layer is made up of 7 m fine sand underlain by clay and weathered shale (Herrmann and Bucksch, 1989).

2.5.1 Oceanographic conditions
Waves reaching this coast consists of swell waves from south-south-west (S-SW) direction (Angnuureng et al., 2016). The average significant wave height is about 1.4 m (Nairn and Dibajnia, 2004) while the annual maximum reaches 2.5-3 m with periods between 6 and 16s (Nairn and Dibajnia, 2004; Roest, 2018). Seasonal variations occur, with the highest waves arriving between July and August, while the lowest waves occur around January and February (Roest, 2018). There is little variation in the direction of waves approaching this coast and this accounts for some of the highest rates of unidirectional longshore sand drift in the world with reported rates between 0.3 and 1.5 million m$^3$/yr at most points (Almar et al., 2015; Laïbi et al., 2014; Nairn and Dibajnia, 2004). The tidal regime is semi-diurnal with a range of about 1 m and a spring tide average of 1.5 m (Nairn and Dibajnia, 2004).

Various estimates have been reported for the pre-dam sediment yield from the Volta River. Tilmans, (1993) reported 2.5 million m$^3$/yr before the construction of the Dam while Boateng et al., (2012) estimated the pre-dam supply at 71 million m$^3$/yr which was reduced to 7 million m$^3$/yr after the construction of the Dam. Anthony and Blivi (1999) reported 1 million m$^3$/yr for the pre-dam period. From these estimates, only Boateng et al., (2012) provided a clear methodology for their estimates. Though these estimates cannot be directly confirmed, Nyarko et al. (2016) through sediment dating reported that sedimentation rates at the Volta estuary reduced drastically from 1.08 gcm$^{-2}$y$^{-1}$ before the construction of the Dam to 0.50 gcm$^{-2}$y$^{-1}$ (50% reduction) after the Dam construction.
Presently, the sea level is rising at a rate of about 3.1 mm/yr and is predicted to continue changing in conformity to the global trend (Sagoe-Addy and Appeaning Addo, 2013; Appeaning Addo et al., 2018a). This will contribute significantly to increased coastal erosion and flooding in the Volta delta (Evadzi et al., 2017).

The basic winds along the study area are southwest monsoons. It blows from the south-west direction (210°-240°) from the sea to land at about 45° angle to the coast and it is approximately in the same direction with the waves (Angnuureng et al., 2013). During the Harmattan season (December-February), winds occasionally blow from the northeast. The monthly average wind speed ranges between 1.7 and 2.6 m/s (Angnuureng et al., 2013).

2.5.2 Historical erosion in the delta: factors and interventions

According to Nairn et al. (1998), investigations into coastal erosion problem along this coast dates back to 1929, when the first engineering report was published on Keta (Coode, 1929). This report suggests that erosion has been occurring since the 1860s. This has been followed by several other studies confirming erosion along the deltaic coast (Appeaning Addo, 2015; Boateng, 2012; Jayson-Quashigah et al., 2013; Ly, 1980). Reported rates of erosion from these studies range between 2.7 m/yr and 8m/yr with some locations experiencing rates as high as 17 m/yr between 1984 and 2011 (Angnuureng et al., 2013). These rates are relatively high resulting in the destruction of infrastructure and livelihoods along the deltaic coast. For example, it is estimated that over 70% of the original Keta Township is now under the sea (Fiadzigbey, 2005).

Generally, the large longshore sand transport in the area is the main cause of erosion (Nairn and Dibajnia, 2004). However, this has been exacerbated by the construction of the Akosombo Dam as well as the Tema harbour (located west of the study area), which has led to a drastic reduction in sediment supply to the delta region hence creating a huge deficit.
Prior to the completion of the dam, a study by Freedman (1955) indicated the negative impacts of the project on coastal erosion at Keta (Nairn et al., 1998).

According to Evadzi et al., (2017), sea level rise contributes to about 31% of coastal erosion along the coast of Ghana. Their study further estimates that areas with coastal slopes less than 0.4% may experience inundation up to 20m by the year 2050 based on IPCC’s AR5 RCPs (Wong et al., 2014).

More recently, there has been the construction of the Keta sea defence project, Atorkor sea defence project and the Ada sea defence project in the Delta to help alleviate the impact of erosion. Though these interventions have solved the problem at the specific sites, there is evidence of ‘knock-on effects’ as erosion has increased in general on the downdrift side of these hard structures.

2.5.4 Modelling Efforts in the Delta

As part of research and engineering interventions, there have been some modelling activities within the delta to understand shoreline dynamics. Such attempts date back to the early 1980s whereas part of initial plans to build a sea defence projects at Keta, Delft Hydraulics conducted some preliminary studies (Roelvink et al., 1995; Tilmans, 1993; Walstra, 1994). Further modelling was carried out during the implementation of the Keta sea defence project (Nairn and Dibajinia, 2004) and the Ada sea defence project (Bolle et al., 2015; Bollen et al., 2011).

Aside from these site-specific modelling efforts in support of coastal engineering works in Ghana, there have been two reported regional level models for the West African sub-region (Almar et al., 2015; Giardino et al., 2018). The focus of both studies was to gain insights into the current and future longshore drift and the impact of human interventions using hindcast and future sea level rise scenarios. Though Giardino et al. (2017) carried out a more
detailed modelling for the Volta delta area, their focus was regional sediment transport and therefore did not consider the local shoreline dynamics. The results of their study include high-resolution nearshore wave data as well as regional sediment transport rates.

2.5.5 Conclusion

From the review of literature, erosion rates reported for the Volta delta have been mainly estimated using low-resolution (temporal and spatial) data by previous studies (Angnuureng et al., 2013; Appeaning Addo et al., 2011; Appeaning Addo, 2016; Boateng, 2012; Jayson-Quashigah et al., 2013; Kusimi and Dika, 2012). Consequently, the reported rates are compromised and mostly do not capture the seasonal dynamics, as well as alongshore details, required for appropriate interventions. This study fills this gap by using high-resolution satellite imagery to estimate the shoreline erosion rate. Furthermore, these existing studies do not take into account, beach volume dynamics due to unavailability of high-resolution DEMs for the delta. This study assesses beach volume dynamics from high-resolution DEMs constructed from UAV surveys. Aside from the regional level models (Almar et al., 2015; Giardino et al., 2018), which assessed regional-scale impacts of sea level rise on shoreline dynamics, there is not much work at the local level hotspots to assess future trends. Wiafe et al. (2013) and Boateng (2009) attempted an inundation assessment of a section of the Volta delta considering sea level rise. However, the input DEM was coarse (90m) and the approach used was a simple bathtub model, which again compromises the results. This study addresses this gap by adapting an existing numeral model to assess the impact of sea level rise on the shoreline at Old Ningo.
CHAPTER THREE

ASSESSING SHORT-TERM BEACH VOLUME DYNAMICS IN THE VOLTA DELTA: AN APPLICATION OF UNMANNED AERIAL VEHICLES (UAVs)

3.1 Introduction

Sandy beaches, such as those of the Volta delta, are sensitive to erosional and depositional processes due to the action of waves, littoral current, tides, wind, sediment transport and anthropogenic activities, among others (Bird, 2008; Kaliraj et al., 2017). Consequently, these beaches undergo constant changes, making them very dynamic, with changes occurring on times scales of days (short term) to decades (long term) and at varying spatial scales (Taaouati et al., 2011). Understanding the short to medium term variability at higher resolutions is very critical for developing models that can simulate and predict the dynamics in coastal environments (Mancini et al., 2013; Yoo and Oh, 2016). High-resolution data is also vital for coastal zone engineers and managers as well as scientists for efficient decision-making and for the design and implementation of appropriate engineering interventions (Stive et al., 2002).

Monitoring morphological changes requires accurate, high-resolution (temporal and spatial) images and digital elevation models (DEMs). This is, however, not readily available using conventional data collection methods (Casella et al., 2016; Long et al., 2016; Turner et al., 2016). Studies have shown that conventional approaches such as field measurements including the use of Global Positioning System (GPS), airborne LiDAR, airborne stereophotogrammetry, among others present challenges such as large efforts, high cost or low temporal and spatial resolution of data collection (Klemas, 2015). As a result, most beach morphological analyses have relied on simple beach profiling and 2D shoreline
analysis which do not fully explain the beach volume dynamics (Yoo and Oh, 2016). Recent advancements in the UAV technology, also known as drones, as well as new developments in digital photogrammetry, higher resolution DEMs and orthophotos are constructed with improved accuracies, which lend themselves for better geomorphic change analysis along the coast.

Clearly, along the coast of the West African sub-region and specifically in the Volta delta of Ghana, studies on beach volume dynamics are scanty. This can be attributed to the inadequate and coarse resolution of existing topographical data as well as the high cost of in-situ measurements. A study by Senechal et al. (2014) used GPS profile measurements to monitor beach cusps at Grand Popo in Benin but did not estimate sediment volume dynamics. In designing the Keta sea defence project, Nairn et al. (2004) did sediment budget analysis using a coastal process-based model (COSMOS) and validated the results using shoreline positions and rates of filling for constructed headlands. Allersma and Tilmans (1993), estimated sedimentation rate at specific sites along the West African coast using topographic maps and bathymetric charts of low resolution. Also, Antia (1989) studied beach cusp dynamics along a 3 km stretch of the Ibeno coast in Nigeria using a simple Emery method of beach profiling. His work also estimated volumetric changes using the 2D profiles. These approaches generally overlook some of the details along the shoreline due to the low spatial resolution and may underestimate the volume changes (Eelsalu et al., 2015).

The main objective of this chapter is to assess the short-term variations in beach sediment volume using DEMs derived from Unmanned Aerial Vehicle (UAV) surveys at three sites along the Volta delta. This provides a more detailed (high-resolution) 3D morphological changes occurring along the beach for a short term (approximately 22 months). The study contributes to methods for measuring beach topographic change and provide relevant
information for coastal morphological model validations and engineering interventions in the Volta delta and the sub-region at large.

3.2 Study Sites

The three study sites are located within the Volta delta which has been defined to include all areas around the Volta Estuary lying below the 5m contour (Appeaning Addo et al., 2018a). This area is also referred to as the eastern coast of Ghana (Boateng, 2012), with the coastline stretching approximately 150km from Ghana’s eastern boundary with Togo to Prampram in the west (Figure 3.1). The beaches are sandy and erosional with the zone classified as a hotspot for coastal erosion and recording some of the highest rates of erosion (up to 8m/yr in the past) (Boateng, 2012; Ly, 1980). Consequently, there has been significant destruction of houses and livelihoods. It is estimated that over 70% of the original township of Keta has been lost to sea erosion (Akyeampong, 2001; Fiadzigbey, 2005). In response to the devastation caused by coastal erosion along this coast, there has been major sea defence intervention over the period including the Keta sea defence project, Dzita-Atorkor sea defence and more recently Ada sea defence. These projects include the construction of groynes at all three sites, revetment at Dzita and Keta and beach nourishment at Keta and Ada (Bollen et al., 2011; Nairn and Dibajnia, 2004). Though these projects have stabilised the shoreline locally, erosion is still ongoing especially downdrift of these structures (Angnuureng et al., 2013; Appeaning Addo, 2015; Jayson-Quashigah et al., 2013).

The selection of the three sites was informed by the erosion trends observed from the longer-term shoreline analyses (Boateng, 2012; Wiafe et al., 2013). The sites are Old Ningo (A), Fuveme (B) and the Keta sea defence site (C) (Figure 3.1). Site B and C are located downdrift of the estuary, while site A is located updrift.
Figure 3.1: Map of the Volta delta showing the three study sites and the sediment sampling sited.

Site ‘A’ records historical high rates of erosion (8.7 m/yr) according to a study by Boateng (2012) with evidence of destruction of houses and livelihood (see Figure 3.21). The closest human intervention is a recent breakwater constructed at Asogli (about 16km west of the site). Site B recently recorded high rates of erosion and tidal flooding with the destruction of houses and property (Appeaning Addo et al., 2018b). This site is situated between two major sea defence projects namely, the Ada and Atorkor projects (Figure 3.1). Site C is generally more stable due to the sea defence structure in place but exhibits knock-on effects at the down-drift of the structure (Angnuureng et al., 2013). These selected sites represent three scenarios; a steadily eroding beach (site A), a very dynamic beach (site B) and a relatively stable artificial beach (site C). Each survey site stretches approximately 2 km alongshore and about 300m across-shore. However, for analyses purposes, the cross-shore extent was limited to the landward edge of the beach.
3.3 Methods

3.3.1 Data collection and pre-processing

The study relied mainly on primary data collected from drone surveys. Data collection involved about 4-5 beach surveys at each of the three sites from June 2016 to April 2018 using a DJI Phantom 3 professional drone with a 4k camera (12 megapixels). The first stage of the monitoring campaign involved the establishment and coordination of Ground Control Points (GCPs) to the Ghana Metre grid. The approach followed similar standards used by the Ghana Survey Department (Ofori-Boadu, 2006) and consists of GCPs built with concrete pillars buried to ground level and clearly marked (Figure 3. 2). Site ‘A’ and ‘B’ had eight (8) pillars each, while site ‘C’ had 10 pillars due to the presence of the groynes on the beach (a more complex topography) (Figure 3. 3). Studies have shown that a minimum of four or five symmetrically distributed points is required in photogrammetry (Miříjovský and Langhammer, 2015; Wolf et al., 2000) for geo-referencing. The minimum of eight GCPs adopted in this study, therefore, satisfied this minimum requirement.

Figure 3. 2: Establishment of Control Points
Using a static Differential GPS (D-GPS) method with reference to established national coordinated control points, each pillar was observed for up to 25 min on the average (Figure 3. 4) in order to reduce the Root Mean Square Error (RMSE) to the barest minimum. Data were post-processed using standard algorithms in Topcon post-processing software (see Appendix A for XYZ information). The resultant RMSE values were less than 0.04m for both vertical and horizontal accuracies.

![Figure 3. 3: Distribution of GCPs for the three survey sites (Site A: Old Ningo, Site B: Fuveme, and Site C: Keta)](image)

Flight paths were then pre-planned using the DroneDeploy web platform (DroneDeploy, n.d.). The height was set at 150 m above ground level to allow for wider coverage (about 200m swath width) of the beach while maintaining a considerably high ground sampling distance of 7 cm (0.07 m). A frontal overlap of 80% and a side overlap of 70% were defined to improve stereoscopy and 3D reconstruction. The actual field campaigns were designed to coincide with low tides as much as possible using available tide forecast (Tide-Forecast,
2018) and to cover periods of low and high wave heights (April and August). Table 3.1 shows details of the surveys for the various sites. Depending on wind conditions, each flight lasted between 30 min to 1 hour. Mobile GCPs (patterns printed on A0 flexible white materials; refer to Appendix B) were placed on the permanent GCPs before every flight to allow for easy identification during image processing.

Figure 3.4: Surveying and coordination of control points (Right is an existing Survey Pillar)

Table 3.1: Flight Sites, Dates and Number of Flights

<table>
<thead>
<tr>
<th>Site</th>
<th>Site Description</th>
<th>Flight Dates</th>
<th>Total Flights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td>Old Ningo, no intervention (slow eroding coast)*</td>
<td>12th January 2017, 7th April 2017, 24th August 2017, 12th April 2018</td>
<td>4</td>
</tr>
<tr>
<td>Site C</td>
<td>Groyne 5 and 6 of the KSDP at Kedzi</td>
<td>23rd June 2016, 5th April 2017, 14th August 2017, 11th April 2018</td>
<td>4</td>
</tr>
</tbody>
</table>

* This site was started later due to financial challenges
+ Half of the images lost due to technical challenges
3.3.2 Data processing

Averagely, 400 images were captured during each flight. These images were manually filtered to remove blurred or overexposed shots, as well as images that had the landing gear of the drone showing due to strong winds. This reduced error in the final point cloud. A 3D scene reconstruction was performed using Structure from Motion (SfM) and Multi-View Stereo (MVS) algorithms (Smith et al., 2015; Snavely, 2011) implemented in Agisoft Photoscan software (Agisoft, 2018). This package was selected based on findings by Sona et al. (2014), who observed that algorithms used in Agisoft Photoscan produced more reliable results compared to the other software tested.

The structure from motion analyses (SfM) include (1) image alignment which involves detection and matching of image features, providing the basic image structure (Mancini et al., 2013), (2) pixel-based dense stereo reconstruction using the aligned data and the ground control points and (3) building of orthophoto and DEM. Where artificial objects exist along the beach (including fishing boats and buildings), the DEM was classified to extract as much as possible only the bare ground thereby reducing exaggeration of topographic heights.

3.3.3 Geomorphic Change Detection

A standard DEM of Difference (DoD) approach was adopted for assessing morphological change and beach sediment budget estimation (Brasington et al., 2003; Wheaton et al., 2010). The DoD was generated by subtracting an earlier DEM from a newer DEM:

\[
\Delta DEM = Z_2 - Z_1
\]

where ‘\(\Delta DEM\)’ is the DoD, \(Z_2\) is the recent DEM and \(Z_1\) is the older DEM.

The cross-shore limits of the DEMs were the vegetation line (end of the back beach) and the low watermark (since the flights were taken at low tide). The breaker zone was not
considered in the analyses because the sensor on the UAV deployed does not penetrate water. The alongshore extent was approximately 1.8 km for all sites.

The individual total RMSE from the image processing was used as the uncertainty for each DEM. The total RMSEs for the DEMs were propagated as:

$$\delta u = \sqrt{(\delta z_1^2 + \delta z_2^2)}$$

where $\delta u$ is the propagated error, $\delta z_1$ and $\delta z_2$ are the errors from the individual DEMs determined from geo-referencing. This propagated error was used as a minimum level of detection threshold ($\text{min}_\text{LoD}$) to distinguish actual surface changes from the inherent noise (Brasington et al., 2003; Wheaton et al., 2010).

3.3.4 Shoreline extraction

Various proxies have been adopted for shoreline position including vegetation line, low water mark and high water mark (Fletcher et al., 2012; Romine et al., 2016). The high water line (HWL) has been widely used (Boak and Turner, 2005; Moore, 2000) and is visually determined as a change in tone left by the maximum run-up from a preceding high tide. This line is easily identified on orthophotos and satellite imageries. The HWL has been used in studies related to Ghana and the Volta delta (Angnurueng et al., 2013; Appeaning Addo et al., 2008; Appeaning Addo, 2015; Boateng, 2012; Jayson-Quashigah et al., 2013) and has, therefore, been adopted for this study.

The HWL was easily identifiable in the high-resolution images acquired for this study. The line was digitized in an ArcGIS environment by the same person and at a consistent scale from each drone imagery. A total of between 4-5 shoreline positions were extracted for each site.
3.3.5 Shoreline Change Analysis

The extracted shorelines were compiled in the GIS environment (ArcGIS 10.4) into a single shapefile and assigned appropriate attributes including date and accuracy. This is required for calculating the shoreline change rates using the Single Transect (ST) method. Historical changes were estimated relative to an offshore baseline position, which was manually delineated. Perpendicular transects were cast at 20m interval alongshore to adequately characterise the changes along the beach (Fletcher et al., 2012).

For rate of change estimation, a number of statistical approaches have been developed for estimating shoreline rate of change including the endpoint rate (EPR), linear regression rate (LRR), weighted linear regression (WLR) and jack-knifing (JK) (Dolan et al., 1991; Genz et al., 2007). The linear regression approach has been widely used (Appeaning Addo et al., 2008; Hapke et al., 2006; Kuleli, 2010). It calculates a ‘best fit’ line to the shoreline data points for each transect using the least-squares method. The approach is considered statistically robust and allows for the use of other statistical methods to ascertain the quality of the fitted line and estimate the variance of the data. The LRR approach is, therefore used for calculating the rates of change in this study.

The rate of change analyses was implemented using functions in AMBUR (Analysing Moving Boundaries Using R) which was developed by Jackson et al. (2012) and freely distributed. Aside from being open source, the tool is customizable to perform additional tasks and analyses, including linear regression forecasting. The tool estimates, among others, raw changes, EPR, LRR and WLR rates at each transect.

3.5.6 Error Estimation for shoreline change

Four main sources of error are identified and estimated as shoreline positional accuracy in this study (Table 4.2). These are the ground sampling distance ($E_p$), geo-referencing error
\((E_g)\) (obtained from the average RMSE from geo-referencing), the digitizing error \((E_d)\) estimated to be 1.5 of a pixel as well as a tidal error \((E_t)\) (the tidal range for the area) (Ford, 2013; Li et al., 2001). The total positional error \((E_r)\) for each shoreline is then estimated using the expression:

\[
E_r = \sqrt{(E_p^2 + E_g^2 + E_d^2 + E_t^2)}
\]

For these analyses, the ground-sampling error was 0.07 m, the geo-referencing error was 0.1 m, digitizing error was 0.15 m and tidal error was 1m for all images. Total positional error for each shoreline position was estimated to be 1.02 m.

An annualised error was estimated for each site using Equation 3.4 to account for the uncertainty in the rate of change at each transect (Fletcher et al., 2012; Hapke et al., 2006; Moore, 2000). The annualised rates were 1.5, 1.25 and 1.25 m/yr for Old Ningo, Fuveme and Keta, respectively.

\[
E^\sigma_x = \frac{\sqrt{E_a^2 + E_b^2 + E_c^2 + \cdots + E_z^2}}{T}
\]

Where \(E_a, E_b, \ldots, E_z\), are the individual shoreline positional error and \(T\) is the time that has elapsed (Appeaning Addo et al., 2008; Jayson-Quashigah et al., 2013).

3.3.6 Grain size analysis

To determine the granulometric characteristics and textural properties of the beaches surveyed, sediment samples were collected from about six locations (18 samples) across the study area for grain size analysis. Sampling was done at the back beach, high water mark and at the low watermark for each site using a hand trowel up to recommended depths of 10-15cm (Rashedi and Siad, 2016). The six samples were sent to the lab, oven-dried at about 80° C for up to 2 days and then analysed using the popular sieve analysis (Blott and Pye,
The sieves were fixed on a mechanical shaker and shaken for about 15 min to sort the sediments. The sieve sizes used were 1000, 710, 500, 355, 250 and 63 μm. Grain size calculations were based on the formulae proposed by Folk and Ward (1957).

3.4 Results

The resolution of the DEMs generated was less than 30cm with vertical accuracies ranging between 0.95 and 30 cm (Higher RMSE’s where mostly recorded when weather conditions/illumination was poor resulting in higher errors in point matching) while the orthophotos had a ground resolution of approximately 7 cm. Such high resolution and accuracies increased confidence in the identification of various beach features including areas of sand mining and the intertidal slope (Figure 3.5).

![Figure 3.5: DEM showing a sand mining site (indicated in the red box) and the intertidal zone (red arrow)](image)

3.4.1 Morphological Changes at Old Ningo (Site A)

This beach was relatively narrower covering an area of 60, 226 m² and recorded a net loss of sediment. For the entire period of analysis (January 2017 to April 2018), 26,612 m² of the
beach (representing 84%), experienced erosion (Figure 3.6) with a net sediment volume loss of about 12,610 m$^3$ (see Table 3.2) at a rate of $788 \pm 111$ m$^3$/month. Pixel-based depths of erosion and deposition range between -2 and 1 m (Figure 3.7). From January to April 2017, a net change of -3,728 m$^3$ was estimated, which almost doubled to -6,696 m$^3$ from April to August 2017. The net change reverted to a much lower level of -2,348 m$^3$ between August 2017 and April 2018. Sediment imbalance (departure from equilibrium) for the beach was approximately -34%. This indicates a large deficit in the sediment budget for this beach compared to the other sites.

Table 3.2: Summary of sediment volume/depth changes at Old Ningo (January 2017 to April 2018)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion (Volume-m$^3$)</td>
<td>6,676 (± 1,033)</td>
<td>9,479 (± 1,317)</td>
<td>6,516 (± 1,202)</td>
<td>11,198 (± 1,666)</td>
<td>15,571 (± 1,478)</td>
</tr>
<tr>
<td>Average Depth of Erosion (Height-m)</td>
<td>0.39 (± 0.06)</td>
<td>0.39 (± 0.05)</td>
<td>0.26 (± 0.05)</td>
<td>0.36 (± 0.05)</td>
<td>0.59 (± 0.06)</td>
</tr>
<tr>
<td>Deposition (Volume-m$^3$)</td>
<td>2.948 (± 1,041)</td>
<td>2.783 (± 833)</td>
<td>4.167 (± 937)</td>
<td>2.350 (± 723)</td>
<td>2.964 (± 955)</td>
</tr>
<tr>
<td>Average Depth of Deposition (Height-m)</td>
<td>0.17 (± 0.06)</td>
<td>0.18 (± 0.05)</td>
<td>0.21 (± 0.05)</td>
<td>0.17 (± 0.05)</td>
<td>0.17 (± 0.06)</td>
</tr>
<tr>
<td>Net Volume Change m$^3$</td>
<td>-3728 (± 1,466)</td>
<td>-6696 (± 1,558)</td>
<td>-2,348 (± 524)</td>
<td>-8,847 (± 1,816)</td>
<td>-12,607 (± 1,781)</td>
</tr>
<tr>
<td>Sediment Imbalance (%)</td>
<td>-19</td>
<td>-27</td>
<td>-11</td>
<td>-33</td>
<td>-34</td>
</tr>
</tbody>
</table>

Spatially, the highest rates of erosion were recorded in the western section of the study area, which is closer to the Gyankai estuary (Figure 3.6). Field observations revealed the development of an offshore bar just at the mouth of the estuary, which could be influencing the dynamics observed.
Figure 3.6: Spatial variation of erosion and sedimentation at Old Ningo over different periods spanning January 2017 to April 2018.
Sediment deposition at this site occurred mainly at the back-beach due to wave overtopping, which is migrating the berm crest landward. Consequently, two of the GCP’s, which were at ground level, had been buried to an estimated depth of about 20 cm (Figure 3. 8) during the last field campaign in April 2018. The phenomenon is also evident from the time series plot of beach profile from the eastern section of the beach (Figure 3. 9). This information is relevant for establishing realistic boundary condition for beach and dune erosion models (Hancock and Kobayashi, 1994).
Over the period, the short-term rate of shoreline erosion estimated was -3.5 ± 1.5 m/yr (Figure 3. 10). Within a period of 16 months (1.3 years), the analysis also revealed erosion along the entire coast with the shoreline moving inland over 8 m at the western section. Average accretion rate was low at 0.6 ± 1.5 m/yr.
3.4.2 Morphological Changes at Fuveme (Site B)

At site B, analysis spanned over a longer period (22 months representing 1.8 years) due to an earlier start date for monitoring. The Fuveme beach was comparatively wider across-shore covering a total area of 131,721 m$^2$. Over the period from June 2016 to April 2018 about 64,000 m$^2$ (representing 52%) of the beach experienced deposition with a net gain of 5,142 m$^3$. Approximately 69,188 m$^3$ of sediment was eroded while 74,400 m$^3$ was deposited. This represents a positive imbalance of only 2%. Deposition mostly occurred at the eastern section in conformity with the eastward longshore drift (Figure 3.11 and 3.12). The average depth of erosion was 1.08 m while the average depth of deposition was 1.38 m.

From June 2016 to August 2016, erosion was dominant (57%) with a net volume of 80,455 m$^3$ removed and 60,434 m$^3$ deposited (see Table 3.3). Between August 2016 and April 2017, there was increased deposition 62,400 m$^3$ due mainly to the influx of sediment into the area and this was evidenced by the development of a swash bar towards the estuary (Figure 3.13). From April 2017 to April 2018, sediment deposition still dominated with about 57% of the area experiencing deposition and a net gain of 12,669 m$^3$. 

Figure 3. 10: Shoreline Linear Regression Rate (LRR) of Change at Old Ningo (January 2017 to April 2018) (alongshore from west to east)
Table 3.3: Summary of sediment volume/depth changes at Fuverme (June 2016 to April 2018)

<table>
<thead>
<tr>
<th>Measured parameters</th>
<th>Period</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jun-2016 to Aug-2016</td>
<td>Aug-2016 to Apr-2017</td>
<td>Apr-2017 to Apr-2018</td>
<td>Overall</td>
<td></td>
</tr>
<tr>
<td>Erosion (Volume-m³)</td>
<td>80,455 (± 6,874)</td>
<td>49,481 (± 4,253)</td>
<td>36,309.80 (± 6,385)</td>
<td>69,188 (± 10,020)</td>
<td></td>
</tr>
<tr>
<td>Erosion (Height-m)</td>
<td>1.15 (± 0.10)</td>
<td>1.06 (± 0.09)</td>
<td>0.87 (± 0.15)</td>
<td>1.08 (± 0.16)</td>
<td></td>
</tr>
<tr>
<td>Deposition (Volume-m³)</td>
<td>60,434 (± 2,206)</td>
<td>62,379 (± 6,319)</td>
<td>48,978 (± 8,270)</td>
<td>74,330 (± 8,421)</td>
<td></td>
</tr>
<tr>
<td>Deposition (Height-m)</td>
<td>1.14 (± 0.10)</td>
<td>0.90 (± 0.09)</td>
<td>0.90 (± 0.15)</td>
<td>1.38 (± 0.16)</td>
<td></td>
</tr>
<tr>
<td>Net Volume Change m³</td>
<td>-20,022 (± 8,635)</td>
<td>12,898 (± 7,177)</td>
<td>12,669 (± 1,449)</td>
<td>5,142 (± 3,089)</td>
<td></td>
</tr>
<tr>
<td>Percentage imbalance (%)</td>
<td>-7</td>
<td>6</td>
<td>7</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.11: Spatial variation of erosion and sedimentation at Fuveme over different periods spanning (June 2016 to April 2018)
Figure 3.12: Area of erosion and accretion (left), and sediment volume change (right) at Fuveme (June 2016 to April 2018). Red and blue bars indicate erosion and accretion respectively, while grey bars show no change.

This site was particularly very dynamic showing evidence of high erosion as well as deposition over the period. From June 2016 to April 2018, the shoreline had moved over 60 m indicating massive erosion at the western section of the coast and accretion at the eastern section. This short-term erosion had led to the destruction of several houses including the only school in the community. In addition, one of the GCPs established over 50 m from the shore was lost to erosion.
Figure 3. 13: A swash bar that developed close to the Volta estuary (Photo Credit: Author, 6th April 2017)

Figure 3. 14: Beach profiles from the high eroding section of the beach

A critical look at these profiles (Figure 3. 14) from the main frontage of the village (the highly eroding section) shows over 2m depth of erosion over the entire period. It also captures the accretion that has occurred between August 2017 and April 2018.
Lateral shoreline change analysis confirms the high short-term erosion (up to rates of over 30 m/y) at the frontage of the Fuveme village (Figure 3.15), which had led to the destruction of many structures including houses and public facilities. It also shows similar rates of deposition on the eastern corner. Mean erosion and accretion rates of -16 ± 1.25 m/yr, reaching a high of -40.4 m/yr and 17.5 ± 1.25 m/yr, reaching 34.2 m/yr was recorded for this site.

3.4.3 Morphological Changes at Keta (Site C)

For site C, the analysis was carried out over the same period between June 2016 and April 2018, as site B. The site also had a wide beach with a total area of ≈106,400 m². For the entire period, the volume of eroded sediment was 22,222 m³ (39.5%) while deposition was 34,023 m³ with the depth of erosion and deposition being 1.06 m and 1.39 m respectively (Table 3.4). Spatially, this site exhibits a more stable beach with erosion and accretion patterns concentrated around the shoreline (Figure 3.16).

Elevation change values range from -3 to 2 m for this site (Figure 3.17). A net gain of 11,801 m³ of sediment (representing a relatively higher positive imbalance of 11%) was
recorded. Between April 2017 and August 2017, the volumes of sediment erosion and deposition were 13,200 m$^3$ and 34,400 m$^3$ respectively, with a net volume of 21,200 m$^3$ (22% gain). From August 2017 to April 2018 there was a net loss of 6,400 m$^3$ (representing a 15% deficit).

Table 3.4: Summary of sediment volume/depth changes at Keta (June 2016 to April 2018)

<table>
<thead>
<tr>
<th>Measured parameters</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion (Volume-m$^3$)</td>
<td>34,892 (± 6,702)</td>
</tr>
<tr>
<td>Erosion (Height-m)</td>
<td>1.41 (± 0.27)</td>
</tr>
<tr>
<td>Deposition (Volume-m$^3$)</td>
<td>36,615 (± 11,812)</td>
</tr>
<tr>
<td>Deposition (Height-m)</td>
<td>0.84 (± 0.27)</td>
</tr>
<tr>
<td>Net Volume Change m$^3$</td>
<td>1.723 (± 5.81)</td>
</tr>
<tr>
<td>Percentage imbalance (%)</td>
<td>1</td>
</tr>
</tbody>
</table>

Furthermore, erosion was rampant downdrift of the groynes while deposition occurred updrift, which is a well-known effect of hard sea defence structures (Figure 3.16). It can also be inferred from the spatial distribution that the threshold used was effective since there was no change on the groynes as expected. As well, there is evidence of wave overtopping leading to deposition of sediment on the back beach.
Figure 3.16: Spatial variation of erosion and sedimentation at Keta over different periods (June 2016 to April 2018). The black triangles show the location of the groynes.
Figure 3.17: Sediment erosion and accretion at site C from June 2016 to April 2018: (a) Area change and (b) volume change. Red and blue bars indicate erosion and accretion respectively while grey bars show no change.

Figure 3.18: Beach profile plot for (a) downdrift and (b) updrift of the groyne to the east.

Comparing profiles downdrift of the groyne to those updrift the groyne confirms sediment trapping up drift of the groynes resulting in progradation of the shoreline, while sediment is being removed down drift the groynes leading to erosion (Figure 3.18). Furthermore,
though there is a cyclical pattern of shoreline movement, there is also evidence of cumulative erosion. This is because though accretion occurs, the shoreline has not been able to recover to its original position in June 2016 for the period of study.

Shoreline change analyses (Figure 3. 19) confirms the observed trends from the volume change dynamics. It was observed that the highest rates of erosion and deposition occurred at the downdrift of the most eastern groyne, which is the last groyne of the Keta sea defence project. Mean erosion rate was \(-2.5 \pm 1.25 \text{ m/yr}\) reaching a maximum of \(-6 \text{ m/yr}\) while that for accretion was \(4 \pm 1.25 \text{ m/yr}\) reaching a maximum of \(10 \text{ m/yr}\).

![Figure 3.19: Shoreline Change at Keta between June 2016 and April 2018](image)

3.4.4 Sediment Characteristics

The results of the sediment analysis as shown in Figure 3.20 indicates that the beaches comprise 100% sand at all three sites. The samples fall within the medium to coarse sand range with median or D\(_{50}\) values ranging between 482.3 and 920.2 μm. Samples from the western section of the study site have a relatively finer grain size compared to those from the east. The values are similar to those reported by earlier studies for Ada ranging between 600 and 900 μm (Bollen et al., 2011) and for Keta with beach face sizes reaching over 800 μm. However, during the construction of the Keta sea defence, the recommended beach fill did not exceed 700 μm (Nairn and Dibajnia, 2004).
3.5 Discussion

3.5.1 Beach volume dynamics across the three sites

Across the three sites studied, varying patterns of erosion and accretion were observed. These variations are similar to those reported by previous studies. For this period, Old Ningo experienced a net loss of about 8,850 m$^3$ of sediment with 83% of the beach experiencing erosion. The percentage imbalance for this beach was -33%. Correspondingly, the shoreline has eroded at an average rate of -3.5 m/yr. This erosion rate is threatening coastal infrastructure with evidence of destruction of houses (Figure 3.21) at the western end of the study area. The pattern observed across the three sites also show higher erosion during season of high wave energy (around August) which results in higher rates of littoral transport.
Figure 3. 21: Impacts of erosion at the western section of the study area (a) A beach resort being undermined and (b) houses being destroyed in the background (Photo Credit: Author and Emmanuel Brempong, 12th January 2017)

Fuveme had a net gain of 12,670 with 57% of the beach experiencing deposition over the one year. The area had also experienced high erosion with many houses lost to erosion and people displaced (Figure 3. 22).

Figure 3. 22: June 2016 Drone Orthophoto Overlaid with April 2017 Shoreline (red line). The red arrow shows the remains of the only school in the community which was completely destroyed by April 2017.

By April 2018, the beach fronting the Fuveme Community had begun rebuilding (Figure 3. 23) with over 60 meters of land regained. This presupposes a form of cyclical event ongoing
in the area, which can be investigated further with a longer term of monitoring. By the same
time, the bar, which had formed updrift (see Figure 3.14), had also decayed.

Figure 3.23: Aerial view of a portion of Fuveme Showing the beach being built up (Photo by Author; April 2018). The red line shows the previous shoreline position (August 2017) and the red circle shows where the bar had developed previously while the blue arrow shows the extent of the beach that has been built (Over 80m).

There was a positive 7% departure from equilibrium indicating an almost stable situation.

Keta, similar to the situation at Fuveme, had a net gain of 12,100 m³, however, with a greater part of the beach experiencing deposition (68%) with a higher positive departure from equilibrium by 18%. This indicates more sediment is reaching Keta (from the estuary and the Cape) compared to Old Ningo and Fuveme. The values recorded for Keta were similar to reported infilling volumes during the construction of the sea defence groynes which vary between 5,000 and 25,000 m³ for periods of weeks up to 3 months (Nairn and Dibajnia, 2004).

3.5.2 Factors affecting beach volume dynamics across the three sites

In general, the eastward littoral drift associated with the Volta delta coast is the main driver of the trends observed in beach sediment dynamics (Anthony et al., 2016). With the associated high energy from the relatively high waves recorded in this region (Roest, 2018), this translates to large volumes of sediment carried downdrift. However, the significant
differences in volume across the sites indicate there are local sources contributing to the sediment budget dynamics. Ly (1981) examined two main sources of sediment for the eastern coast classified as allochthonous and autochthonous.

Allochthonous sources, according to Ly (1981), is derived from rivers and streams to the eastern coast. His study, however, concluded that after the construction of the Akosombo Dam, the Volta River delivers only fine sediment to the coast due to the trapping of coarser sediments from upstream by the Dam. Such fine sediments (less than 150 μm) are easily suspended and deposited offshore and, therefore, do not contribute much to the beach sediment budget. Though the trends observed in this study seems to suggest the Volta River still contributes to sediment to the east (due to higher rates of sediment transported in the east), the sediment grain-size analyses reveal that the grain sizes are much larger than those reported for the River (Ly, 1981). This confirms that contribution from the Volta River could definitely not be a major source.

Ly’s (1981) study, however, reports that the main source of sediment to the beach budget is autochthonous, coming from erosion of unconsolidated Quaternary deposits exposed at the shoreline and transported eastward. This is the most plausible explanation of the dynamics observed. Nevertheless, the presence of relatively finer sediments at Old Ningo (502.3 μm) and at Goi (482.3 μm) further west (Figure 3.20), point to the fact that the updrift area may not be a major source of coarse sediment contribution to the budget near the estuary (Ada and Fuveme), which have relatively coarser grain size (891 μm). Ly (1981) reported similar trends for the entire coast of Ghana observing finer beach sediment in the west as compared to the east. The fine sediments are easily suspended and sometimes deposited beyond the littoral zone, further confirmed by Nairn et al. (1998) who reported that the area is prone to huge loss of sediment to the offshore zone.
Nairn et al. (1998) revealed that the coastline in this area is characterised by migrating sand waves from small beach cusps to larger (300 m long) tongues of sand. This phenomenon, they reported, results in fluctuations in shoreline position up to 50 m or more over a period of several weeks. During the period of study, a swash bar measuring over 500 m had formed by August 2017 at Fuveme close to the estuary (Figure 3.13). This had however decayed completely by April 2018 serving as a local source of sediment for the beach immediate downdrift (see Figure 3.23). These dynamics observed at Fuveme supports the view that migration of sand waves contributes significantly to the sediment budget on the eastern coast of the Volta delta. Furthermore, sediment analyses for the immediate west of the estuary (Ada) records similar grain size (920.2 μm) to that of Fuveme which further suggests by-passing of sediment to reach the eastern part of the estuary. The construction of the Ada sea defence could, therefore, be having a significant effect on the sediment budget at Site B which had experienced high erosion in the short term. This can, however, be confirmed with longer-term historical shoreline analysis. There was also evidence of a nearshore underwater bar at the mouth of the estuary with waves breaking offshore (Figure 3.13), which could also be supplying sediment to this coast.

Additionally, field observations reveal anthropogenic contributions to beach volume erosion, particularly at Old Ningo. Nearshore gravel mining (Figure 3.24) is rampant along this coast and informal interviews with residents indicate that this activity is on the rise.
3.6 Conclusion and Recommendations

This study has demonstrated the use of UAVs in measuring and monitoring sediment volume dynamics in the Volta delta. This approach is innovative and is applied in the Delta for the first time. High-resolution DEMs (<26 cm) with vertical accuracies less than 30cm were constructed and used for sediment budget analysis. Overall, the Volta delta beaches are highly dynamic with high rates of erosion and accretion in response to wave regimes and human interventions along the coast. Sediment volume input is higher on the eastern side of the Delta compared to the west due to inputs from local sources such as migrating sand waves and the erosion of the shoreline updrift. For the comparable period between April 2017 and April 2018, the western part of the estuary experienced a net volume erosion of \(-8,847 \pm 1,861 \text{ m}^3\) while the eastern sites experienced between 5,142 m³ and 12,086 ± 3,089 m³. A more detailed analysis of the individual sites revealed erosion and accretion patterns on the eastern side of the estuary. Additionally, the study suggests that sediment from the Volta River is contributing less to the coastal sediment budget for the beaches.

The UAV approach used here provides estimates of beach sediment budget in the Volta delta for the first time. The approach can be replicated across the Gulf of Guinea to estimate...
regional dynamics. It can also be used to estimate the rate of sand mining along our beaches, which is relevant to engineering and management. The results can also be used to validate model outputs in the Delta. Sediment volume dynamics could be explored further with a longer period and more frequent surveys at the established monitoring sites to fully capture the seasonal effects. This will provide data that is more robust for coastal engineers and managers. The study also recommends further investigations on the nearshore bathymetry to identify its role in beach dynamics in the delta, which was beyond this study.
CHAPTER FOUR

SHORELINE VARIABILITY IN RESPONSE TO WAVE CLIMATE IN THE VOLTA DELTA OF GHANA

4.1 Introduction

Studies have shown that shoreline positions, especially those of sandy beaches, fluctuate both spatially and temporally in response to various processes (Pender, 2013; Slott et al., 2006; Stive et al., 2002). These processes include rising sea levels due to climate change, subsidence, increased wave attack, reduction of fluvial sediment supply, extraction of sand from the beach, interception of sediment supply by longshore drifting, a change in the angle of incidence of waves and increased storminess (Bird, 2008). Among these factors, rising sea levels and wave dynamics have been identified as some of the main drivers of modern shoreline change (Bird, 2008). As sea levels rise, it is expected that shorelines (especially sandy ones) would recede to maintain equilibrium beach profile (Sanford and Gao, 2018). Additionally, wave heights are expected to increase in the face of changing climate and sea level rise (Sterl and Caires, 2005; Woolf, 2002).

Waves drive significant topographical and shoreline changes within very short time scales (hours to months) and sometimes at very small spatial scales (a meter) through the removal, transport and deposition of sediments (Goncalves and Henriques, 2015). The exact response of the shoreline varies locally and temporally and understanding the local response from medium to long term and at higher resolutions is critical for selecting suitable coastal management options (Mancini et al., 2013; Stive et al., 2002). However, research at such high temporal and spatial resolutions are limited, mainly as a result of limited observational data which inhibits effective coastal interventions especially in developing countries where data is scanty (Pianca et al., 2015; Stive et al., 2002).
Though there have been some attempts to study the role of waves in coastal erosion at the regional scale (Almar et al., 2015), such studies are generally limited at the local level. In the case of the Volta delta of Ghana, existing studies on shoreline change, have relied on low-resolution satellite imagery such as Landsat and historical maps with associated large uncertainties (Angnuureng et al., 2013; Appeaning Addo, 2015; Jayson-Quashigah et al., 2013). Furthermore, due to the low temporal resolution of such data, seasonal or inter-annual variabilities are ignored and the role of waves is not quantified. Consequently, there is a limited understanding of the response of the shoreline to wave and other oceanographic and anthropogenic factors across the various time scales (medium to long term) and alongshore.

The objective of this chapter is to investigate shoreline variability in the Volta delta with over a decade span of high-resolution satellite imagery from three selected sites. Variability is characterised across the three sites and the observed changes correlated with nearshore wave variables under sea level rise including significant wave height ($H_s$), period ($T_p$) and direction ($Dir$) from available modelled data (Giardino et al., 2018). The results will contribute to knowledge on shoreline morphodynamics in the Volta delta of Ghana. It will also provide relevant information in support of the move towards more sustainable management of the eroding Volta delta shoreline.

4.2 Methodology

The study was carried out at the three selected sites of Old Ningo (A), Fuveme (B) and the Keta sea defence site (C) (refer to Figure 3.1). The sampled sites are described in detail in Chapter 3. However, in this chapter, the alongshore extents of the areas are extended based on available data. Each site exceeds 4 km with Old Ningo being the longest, stretching approximately 20 km based on available data.
4.2.1 Data collection and pre-processing

Two main sources of secondary data were used: (1) historical imagery acquired from the Digital Globe Foundation in the United States of America and the Ghana Survey Department and (2) modelled wave data for the area acquired from Deltares in The Netherlands. The historical imagery includes an orthophoto, and satellite imageries from Quickbird, World View 2 and 3 as well as GeoEye multispectral satellites (Table 4.1). The imageries span a period of 12 years between 2005 and 2017.

Pan-sharpening was carried out on the multispectral (MS) bands using the high-resolution panchromatic (PAN) bands to improve the resolution of the MS bands and improve shoreline extraction. Various methods exist for pan-sharpening including the Intensity-Hue-Saturation (HIS), the principal component substitution (PCS) and the Gram-Schmidt (GS) methods, which belong to the component substitution (CS) approaches. These methods are fast and easy to implement with good visual and geometric results (Amro et al., 2011; Maurer, 2013). The GS approach was adopted for this study. It has been extensively used in other studies (Liang et al., 2009; Mura et al., 2015) and was initially invented by Laben and Brower in 1998 and later patented by Eastman Kodak (Laben and Brower, 2000).

The first step of this approach was to create a low-resolution pan band by computing a weighted average of the MS bands. Next, these bands were decorrelated using the Gram-Schmidt orthogonalization algorithm, treating each band as one multi-dimensional vector. The resulting low-resolution pan band was used as the first vector, which is not rotated or transformed. The high-resolution pan band was then replaced by the low-resolution pan band, and all bands were finally back-transformed in high resolution (ESRI, 2016). This approach increased the resolution and at the same time preserve the spectral characteristics (Laben and Brower, 2000).
Table 4.1: Satellite imageries and orthophoto acquired for the study sites (date format: dd/mm/yyyy)

<table>
<thead>
<tr>
<th>Imagery Type</th>
<th>Old Ningo</th>
<th>Fuveme</th>
<th>Keta</th>
</tr>
</thead>
<tbody>
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<td>QuickBird (0.61 m Pan and 2.4 m Multispectral)</td>
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<td>-</td>
<td>17/08/2013</td>
</tr>
<tr>
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<td>16/04/2014</td>
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<td></td>
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<tr>
<td>World View -2 (0.46 m Pan and 1.84 m Multispectral)</td>
<td>-</td>
<td>15/07/2017</td>
<td>23/05/2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30/09/2014</td>
<td>15/01/2014</td>
</tr>
<tr>
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<td></td>
<td>23/05/2014</td>
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<td>GeoEye -1 (0.41 m Pan and 1.65 m Multispectral)</td>
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</tr>
<tr>
<td></td>
<td>17/01/2015</td>
<td></td>
<td>11/05/2010</td>
</tr>
<tr>
<td></td>
<td>17/10/2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>02/06/2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orthophoto (0.50 m RGB)</td>
<td>2005</td>
<td>2005</td>
<td>2005</td>
</tr>
<tr>
<td>Total</td>
<td>9 images</td>
<td>14 images</td>
<td>14 images</td>
</tr>
</tbody>
</table>

Visual assessment of the results using this approach showed a much-improved representation of the shoreline proxy (HWL) as seen in Figure 4.1.
The pan-sharpened images were re-projected to Ghana Metre Grid (GMG) system and geo-referenced to the 2005 orthophoto acquired from the Ghana Survey Department in GMG projection. This was used as the reference image as it has been coordinated to the national grid using existing national established control points. A minimum of 10 landmarks (for each site) visible on both images was used as control points for geo-referencing based on the 1st order polynomial and nearest neighbour resampling. The resulting RMSEs from the geo-referencing were less than 0.60 m.
4.2.2 Shoreline extraction

The HWL was easily identifiable in the high-resolution images acquired for this study (refer to section 3.34 for details of shoreline extraction using the HWL). The line was digitized in an ArcGIS environment by the same person and at a consistent scale. A total of between 9 to 15 shoreline positions were extracted for the three sites. Prior to change analyses, the shorelines were overlaid and estuarine areas were cleaned to reduce spikes in shoreline change rates.

4.2.3 Shoreline change analysis

For the description of the method used see section 3.3.5 (Chapter 3)

4.2.4 Error Estimation for shoreline change

Four main sources of error were identified as discussed in section 3.3.6 (Chapter 3) and the total positional error ($E_r$) for each shoreline, was then estimated using Equation 3.3 (Table 4.2). An annualised error was estimated for each site using Equation 3.4 (Chapter 3) to account for the uncertainty in the rate of change at each transect. The annualised rates were 0.56, 0.62 and 0.42 m/yr for Old Ningo, Fuveme and Keta, respectively.

4.2.5 Wave Climate Data

To estimate the role of wave dynamics on shoreline change, the wave parameters including significant wave height ($H_s$), wave period ($T_p$) and direction ($Dir$) were extracted for nearshore wave conditions modelled by Giardino et al. (2018). They used the Simulating Waves Nearshore (SWAN) model with wind and wave inputs from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analyses (ERA-Interim) datasets. These datasets have been widely validated against buoy and altimeter data with acceptable correlation (Almar et al., 2015; Sterl and Caires, 2005). The bathymetry was extracted from
the General Bathymetric Charts of the Ocean (GEBCO) and was supplemented with depths from Admiralty charts to improve the nearshore area (Giardino et al., 2018).

Table 4.2: Estimated Positional Error for Image Categories (in meters)

<table>
<thead>
<tr>
<th>Image</th>
<th>Ground sampling distance ($E_p$)</th>
<th>Digitizing error ($E_d$)</th>
<th>Tidal range ($E_t$)</th>
<th>Geo-referencing error ($E_g$)</th>
<th>Total error ($E_r$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QuickBird</td>
<td>0.61</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>1.65</td>
</tr>
<tr>
<td>World View -2</td>
<td>0.46</td>
<td>0.7</td>
<td>1</td>
<td>0.6</td>
<td>1.44</td>
</tr>
<tr>
<td>WorldView -3</td>
<td>0.31</td>
<td>0.5</td>
<td>1</td>
<td>0.6</td>
<td>1.31</td>
</tr>
<tr>
<td>GeoEye -1</td>
<td>0.41</td>
<td>0.7</td>
<td>1</td>
<td>0.6</td>
<td>1.42</td>
</tr>
<tr>
<td>Orthophoto</td>
<td>0.50</td>
<td>0.8</td>
<td>1</td>
<td>-</td>
<td>1.37</td>
</tr>
</tbody>
</table>

Wave propagation from offshore to nearshore was based on an overall coarse grid and detailed nearshore grids. The nearshore grids had a resolution of 50m and 100m cross-shore and longshore directions, respectively. To reduce computational time, the ERA-Interim input dataset was reduced to a number of classes representing the annual climate conditions (Giardino et al., 2018). A hindcast simulation was carried out for the period between 1985 and 2015. Using this as the baseline, future conditions were forecasted based on IPCC’s 8.5 Climate Change (CC) scenario with a sea level rise of 1 m by 2100.

For the purpose of this study, the performance of the model results was assessed by comparing it with observed data from a nearshore wave rider buoy measurement using existing statistical approaches (Lemke et al., 2017). The observed hourly data spanned the
period between 20th February and 15th March 2010 (less than 1 month). The International Marine and Dredging Consultant (IMDC), Antwerp, Belgium as part of the construction of the Ada Sea Defence project collected this data. The buoy was deployed at a 10 m depth at the location 0.52496° E and 5.77210° N.

Modelled and observed data were compared using a bias measure from literature (Lalbeharry, 2002; Lemke et al., 2017). The bias \( V \) measures the deviation between the model data and the observed data (Equation 4.2). The bias estimates indicates that the modelled wave heights were generally overestimated (by 0.104m) (Figure 4.2).

\[
V = m' - o' \tag{4.2}
\]

Where \( m' \) and \( o' \) are averages of modelled and observed data respectively.

![Figure 4.2: Comparison of modelled and observed wave parameters: (a) wave height \( H_s \) (b) wave period \( T_p \) and (c) wave direction \( Dir. \)](image)
Mean $T_p$ was also overestimated (by 1.775s) while the $Dir$ was generally underestimated (by 4.413°) respectively. For this study, the data is considered acceptable for analysis as error measures are considered acceptable with $H_s$ overestimations less than 30 cm (5%) (Stopa et al., 2016).

Linear correlation analysis including Pearson correlation coefficients was carried out between the shoreline change and each of the wave variables ($H_s$, $T_p$ and $Dir$) to ascertain the relationship between each pair. Though this relationship is more complex than just linear, Sanford and Gao (2018) in their study indicated that simple calculations of Pearson’s correlation coefficients yielded the most information with little value addition when multiple linear regression is used.

4.3 Results

Results from the shoreline change and wave data analyses are presented here. Overall, all three sites exhibited different patterns of erosion and accretion at varying rates. Old Ningo on the west is dominated by erosion while Fuveme immediate east of the estuary recorded the highest rates of erosion in the current situation while Keta on the Far East recorded the highest accretion and reveals a more stable shoreline. To assess the impact of human interventions, the result was divided into two periods, 2005 to 2013 (considered as the base period) and 2013 to 2017 (as the current situation, which represents the period after the construction of the Ada and Atorkor Sea Defences in the area).

4.3.1 Shoreline and wave dynamics at Old Ningo (updrift)

Old Ningo is located on the up-drift side of the Volta estuary and was dominated by erosion for the entire period of analysis (2005 to 2017). Erosion rates were at an average of 1 m/yr with 79% of the beach eroding. The average rate of accretion for the entire period was
approximately 0.3 m/yr (see Table 4.3). Higher rates of erosion and accretion were experienced around the estuaries with individual rates reaching over 12 m/yr.

The average rate of erosion for the base period was approximately 1 m/yr with 40% of the beach eroding, this however more than doubled to approximately 3.5 m/yr during the second period with over 90% of the beach experiencing erosion. Individual erosion rates reached as high as 15 m/yr close to the estuary. The alongshore pattern was irregular with accretion dominating during the base period and at the updrift side of the study area. This, however, switches for the current situation with erosion dominating and recording higher rates at the downdrift section (Figure 4.3).

Analysis of the acquired modelled wave data revealed a slight increase in wave height over the entire period if minimum wave heights are considered (Table 4.5). The mean values do not, however, reveal such an increase (Table 4.6) and this could be due to the differences in the span of the two periods.

Table 4.3: Estimated Erosion and Accretion Rates for Old Ningo, Fuveme and Keta

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Erosion (m/yr)</td>
<td>Accretion (m/yr)</td>
<td>Erosion (m/yr)</td>
<td>Accretion (m/yr)</td>
</tr>
<tr>
<td>Old Ningo</td>
<td>-1</td>
<td>0.8</td>
<td>-3.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Fuveme</td>
<td>-12</td>
<td>4.4</td>
<td>-31</td>
<td>-</td>
</tr>
<tr>
<td>Keta</td>
<td>-5.5</td>
<td>4.5</td>
<td>-8.1</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Table 4.4: Alongshore shoreline change extent in percentages for Old Ningo, Fuveme and Keta

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Erosion (%)</td>
<td>Accretion (%)</td>
<td>Erosion (%)</td>
</tr>
<tr>
<td>Old Ningo</td>
<td>40</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Fuveme</td>
<td>44</td>
<td>56</td>
<td>100</td>
</tr>
<tr>
<td>Keta</td>
<td>35</td>
<td>65</td>
<td>45</td>
</tr>
</tbody>
</table>
Figure 4.3: Erosion trends along the Old Ningo Coastline: (a) base period (2005 to 2013), (b) current situation (2013 to 2017) and (c) overall changes (2005 to 2017)

Table 4.5 shows the minimum values for wave height (Hs), period (Tp) and direction (Dir), while Table 4.6 shows the mean values for the same wave parameters. The mean wave height for the base period was 1.06 m with a minimum of 0.47 m while minimum Tp and Dir were 4.169 s and 160.844°. The minimum Hs went up slightly to 0.51 m in the current situation indicating a general increase in wave height. The minimum period for waves arriving here increased to 5.31 s with wave angles shifting clockwise by 2.3° (163.11°).
Table 4. 5: Minimum values for wave height (Hs), period (Tp) and direction (Dir.) across the two periods

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hs (m)</td>
<td>Tp (s)</td>
</tr>
<tr>
<td>Old Ningo</td>
<td>0.4678</td>
<td>4.169</td>
</tr>
<tr>
<td>Fuveme</td>
<td>0.4557</td>
<td>3.6077</td>
</tr>
<tr>
<td>Keta</td>
<td>0.2098</td>
<td>2.3578</td>
</tr>
</tbody>
</table>

Table 4. 6: Mean values for wave height (Hs), period (Tp) and direction (Dir.) across the two periods

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hs (m)</td>
<td>Tp (s)</td>
</tr>
<tr>
<td>Old Ningo</td>
<td>1.0625</td>
<td>8.8759</td>
</tr>
<tr>
<td>Fuveme</td>
<td>1.1025</td>
<td>8.6396</td>
</tr>
<tr>
<td>Keta</td>
<td>0.6965</td>
<td>8.0774</td>
</tr>
</tbody>
</table>

4.3.2 Shoreline and wave dynamics at Fuveme

The shoreline immediately east of the Volta estuary, exhibited a very dynamic character with high rates of erosion and accretion. Overall, erosion and accretion rates averaged at 7.2 m/yr and 5.8 m/yr, respectively, with 52% of the shoreline experiencing accretion (Table 4. 3 and Table 4. 4).

For the base period (representing the period before the Ada sea defence updrift), shoreline deposition dominated (56%) in the alongshore extent at an average rate of 4.4 m/yr. The updrift and downdrift corners were, however, eroding at higher rates of 12 m/yr. After the construction of the defence (2013), erosion dominated the entire coast at an average rate of 31 m/yr and some areas reaching as high as 84 m/yr (Figure 4. 4).
For the wave climate, waves reaching this area had slightly higher $H_s$ with a mean of 1.11 m and arriving at an angle of 157° at 8.6 s intervals. During the base period, the mean wave height was 1.1 m, arriving at 171° and 8.6 s periodicity. This increased slightly to a mean wave height of 1.12 m and at a slightly higher angle of 188° but the same period of 8.6 s. The minimum values also show a slight increase in all three-wave variables (Table 4.5 and Table 4.6).

4.3.3 Shoreline and wave dynamics at Keta

The shoreline at Keta was predominantly accreting (65%) over the entire study period at an average rate of 4.3 m/yr (Table 4.3 and
Table 4. 4) with the remaining, shoreline primarily downdrift of the last groyne (Figure 4.5), eroding at a rate of 5.3 m/yr. For the base period, rates of erosion and accretion were 5.5 and 4.5 m/yr respectively, increasing to 8 m/yr and 6.3 m/yr, respectively, during the current situation (see Table 4. 3).

Figure 4. 5: Erosion trends along the Keta Coastline: (a) base period (2005 to 2013), (b) current situation (2013 and 2017) and (c) overall changes (2005 to 2017)

This site recorded the lowest wave height with a mean of 0.69 m for the base period. These waves generally arrive almost perpendicular to the shoreline at an angle of 142.33° with a periodicity of about 8 s. Mean wave height increased slightly to 0.68 m for the current situation with a period of 7.8 s while the angle increased by about 2° to 144.32° (see Table 4. 5 and Table 4. 6).
4.3.4. Correlation Results

Figure 4.6 shows the plots of shoreline change against the mean wave variables for the three sites. From the correlation analysis carried out between erosion and the wave parameters at Fuveme, there exists a strong negative relationship between erosion and wave heights, suggesting that as wave height increases, erosion (negative value) also increases. However, there was a moderate correlation between erosion and wave period (Table 4.7).

Reference source not found.

Old Ningo, on the other hand, showed a moderate positive correlation between erosion and wave height and between erosion and direction with a weak correlation between erosion and wave period. The third site, Keta, showed a weak correlation between erosion and all three-wave parameters. Comparing the three sites, only Fuveme had a significant correlation for wave height and direction at the 95% confidence.

Table 4. 7: Pearson’s Correlation Coefficients (r) with the P values between Erosion and Wave Variables

<table>
<thead>
<tr>
<th></th>
<th>Hs</th>
<th>Tp</th>
<th>Dir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Ningo</td>
<td>-0.4544 (p=.3)</td>
<td>-0.1481 (p=.7)</td>
<td>-0.4224 (p=.3)</td>
</tr>
<tr>
<td>Fuveme</td>
<td>-0.7701 (p=.02)</td>
<td>-0.5419 (p=.2)</td>
<td>-0.8251 (p=.01)</td>
</tr>
<tr>
<td>Keta</td>
<td>0.2474 (p=.6)</td>
<td>-0.3971 (p=.4)</td>
<td>-0.1171 (p=.8)</td>
</tr>
</tbody>
</table>
Figure 4.6: A plot of shoreline change and means of the various wave variables showing the means for the years with shoreline change (for the purposes of plotting, 90° shore orientation is subtracted from wave directions)
4.4 Discussions

4.4.1 Erosion/Accretion Patterns

The three sites exhibited varying rates of erosion and accretion. In general, the base period from 2005 to 2013 recorded relatively lower rates of erosion across all three sites with Fuveme recording the highest rate of $12 \pm 0.62$ m/yr. The erosion rates increased significantly (almost tripled) for the current situation (2013-2017) with rates reaching $31 \pm 0.62$ m/yr for Fuveme without any accretion. Aside the role of the wave climate, which is discussed subsequently, the construction of a sea defence updrift of the site could have also contributed to the extremely high erosion rates at Fuveme for the current situation. This is because sediment that would have by-passed the estuary and contribute to the budget at the site is now being trapped by the groynes updrift thereby reducing the contribution from the alongshore drift. Consequently, the sediment along the shoreline is eroded to offset this deficit.

Similarly, erosion rates at Old Ningo more than tripled from $1 \pm 0.56$ m/yr for the base period to $3.5 \pm 0.56$ m/yr as the current situation. Even though there was no intervention updrift, there are increasing anthropogenic activities nearshore such as sand and gravel mining, which community members confirmed is on the increase. This could be negatively affecting the sediment budget thereby contributing to the increased erosion. Positively, the Afitsedor and Gyankai Lagoons are contributing some sediment to the budget (Boateng et al., 2012), which may be slowing down the rate of erosion. At the current rate of erosion (3.5 m/year), properties, as well as landing sites for fishermen in the community, are threatened (see Figure 3.21 in Chapter 3).

Even though there were increased erosion rates at Keta over the study periods (from 5.5 m/yr to $8.1 \pm 0.42$ m/yr, the alongshore extent and magnitude of change were lower compared to
the other two sites. The erosion is predominantly limited to the downdrift side of the groyne system (Figure 4.5), which is a well-documented effect of hard engineering structures along this coast (Angnuureng et al., 2013; Boateng, 2009; Jayson-Quashigah et al., 2013). Between the groynes, sediment trapping is predominant (Figure 4.5) and this beach can be considered as quite stable over the period of study (dominated by accretion, Figure 4.5) because of the groyne system in place.

Overall, Old Ningo is predominantly eroding though at a much slower rate compared to Fuveme and Keta sites. Fuveme recorded the highest rates of erosion and accretion with alongshore variability and a seasonal pattern, which was not very clear for the period under study. Keta, on the other hand, is predominantly accreting with dominant erosion only on the downdrift side of the groyne system (see Figure 4.5).

4.4.2 Wave impact on erosion

Erosion patterns exhibited trends that correspond to the wave climate. Using minimum wave heights (due to differences in the span of the two periods), there was about 1% (6cm) average increase in wave height over the two periods with mean period increasing by 1.17s. Wave angles shifted clockwise by 7%. Though these changes were relatively small, the results indicated that they have the potential to affect shoreline morphodynamics significantly, as sea levels continue to rise, as is the case for Fuveme. These slight increases reflected across all three sites corresponded to increasing erosion over the period of study.

Across the three sites, the correlation results show that the effects of the wave height and direction are only significant (at 95% confidence level) at Fuveme. This could, to some extent, explain the alongshore variability in erosion and accretion patterns at this site as evidenced by the formation and decay of various types of nearshore bars which are wave formed (Ashton and Giosan, 2011). Furthermore, the wave attack is skewed to one direction and
leads to a phenomenon described as the ‘morphological groyne effect’ where there is increased instability on the downdrift side of the estuary as a result of the rotation of the shoreline (Ashton and Giosan, 2011; Giosan, 2007). This further confirms that the Volta estuary at its current state is wave-dominated (Roest, 2018).

The moderate correlation between erosion and wave height and direction at Old Ningo indicates that though they play a role, other factors contribute significantly. Giardino et al. (2018) for example reported a high rate of sediment transport away from this area (about \(-1 \times 10^6 \text{m}^3/\text{yr}\) ), which among others may be contributing more to erosion. Their analyses show that the rates generally decrease eastward. Wave period, however, shows a very weak correlation and this could be due to the relatively short wave periods experienced as studies elsewhere have shown (den Heijer, 2005).

Keta recorded weak correlation for all three-wave variables and this is an indication of the dominance of other factors such as the effects of the groynes, beach nourishment, relatively lower wave activity and a lower rate of sediment removal (Giardino et al., 2018; Nairn and Dibajnia, 2004). The groynes are in effect trapping sediment from the longshore drift at a rate, which is sufficient to offset the effect of waves (Perdok, 2002; Williams et al., 2016) and could explain the weak correlation established between erosion and wave variables.

4.5 Conclusion and Recommendations

The role of wave climate in shoreline dynamics was explored in this study using high-resolution time-series satellite imageries and modelled wave data for the period spanning 12 years. The results revealed that the role of wave climate in shoreline dynamics varies across the deltaic coastline of the Volta. Though it plays a key role at the Volta estuary, its forces weaken away from the estuary giving way to other variables, which are not explored critically in this study.
The results further indicate that the Keta sea defence is effective at cancelling out the effect of the wave on erosion. This has led to a more stable shoreline for the Keta area. In addition, it emerged that Old Ningo is eroding consistently and must be given the appropriate attention. Some of the highest rates of erosion along the deltaic coast have been recorded at Fuveme (31 m/yr) which is having a devastating effect on the small community.

The study recommends that appropriate intervention measures should be put in place at Old Ningo by the government and other stakeholders to help curb the erosion situation. These can include (1) bringing to a halt the nearshore gravel mining, which is aggravating the situation, (2) offsetting of the deficit through beach nourishment and (3) a managed retreat approach.

The study further recommends long term monitoring schemes to should be in place to further explore the dynamics reported here as well as capture other variables. This will be beneficial for integrated and sustainable management of the coastal zone. Additionally, the study contributes to the achievement of sustainable development goals (SDG) 14.A, by contributing to scientific knowledge on vulnerable deltas such as the Volta delta to help build more resilient coastal communities.
CHAPTER FIVE

SIMULATING FUTURE SHORELINE EVOLUTION IN THE VOLTA DELTA: A CASE STUDY OF OLD NINGO

In this chapter, the future evolution of the shoreline at Old Ningo in the Volta delta was predicted using the Littoral Processes FM numerical model by DHI. Propagated nearshore waves from Giardino et al. (2018) are used to calculate sediment transport along the coast and used for predicting shoreline dynamics. Modelled sea surface elevation based on IPCC RCP 8.5 was also used as input. The main objective is to predict future morphological dynamics under sea level rise up to mid-century (2050) which includes shoreline change and alongshore sediment transport along this coast.

5.1 Introduction

Globally, coastal erosion is threatening most of the world’s beaches including coastal infrastructure and livelihoods (FitzGerald et al., 2008; Pianca et al., 2015). According to the IPCC’s Fifth Assessment Report (AR5), this threat is expected to increase with rising sea levels as a result of climate change (Wong et al., 2014). Studies have shown that a sustained sea level rise of up to 10 cm can result in a 15 m shoreline erosion with an order of magnitude higher than inundation due sea level rise (Leatherman et al., 2000). However, such responses will vary locally based on geomorphology and other coastal conditions (Chand and Acharya, 2010; Romine et al., 2016) hence requiring different intervention approaches. This requires evaluations to be carried out for specific locations to ascertain their responses to such changes.

Deltaic regions particularly are considered more vulnerable due mainly to their low-lying nature and the associated complex interactions (Wei and Wu, 2014). Again, they are home
to some of the most productive ecosystems such as mangroves and hosts over half a billion of the world’s total population including megacities (Coleman et al., 2008; Foufoula-Georgiou, 2013). Consequently, human accelerated subsidence and development in deltaic regions are compounding the vulnerability of this already fragile environment.

The Volta delta is not an exception to these problems. The effects of rising sea levels are being felt with erosion rates and tidal flooding on the increase (Appeaning Addo et al., 2018b). This has led to the destruction of coastal infrastructure and loss of livelihoods in many communities such as Fuveme, Keta and Old Ningo in recent years (Appeaning Addo et al., 2018b). Although there have been some interventions such as the Keta, Atorkor and Ada sea defence projects, erosion is on the ascendency in other communities and continues to threaten properties and livelihoods. The situation is expected to worsen as sea levels continue to rise to about +0.21 to +0.6 m by 2050 as a result of climate change (Kebede et al., 2018; Boateng et al., 2016).

Management of erosion in the Volta delta is challenging. A major requirement for coastal managers and policymakers, therefore, is the ability to understand and predict shoreline dynamics at the local level for effective management. This has led to an increasing interest in more effective monitoring and numerical modelling efforts to capture historical trends and predict future dynamics (Balouin et al., 2004; Su et al., 2017). Existing models include the Littoral Processes FM (by DHI), UNIBEST CL+ (by Deltares, Inc.) and GENESIS (by USACE and University of Lund).

In this study, future shoreline evolution under climate change was simulated for Ningo within the Volta delta. Based on historical shoreline analysis reported in Chapter Four of this study, Old Ningo is experiencing chronic erosion at an average rate of about -1 m/yr (2005-2017) while on the longer-term Boateng (2012) reported a rate of -8.7 m/yr (1895-
2002) for the same area. This has led to the loss of land, property (including beach resorts) and landing site for fishermen in the area. Using 2005-2017 as the validation period, future simulations were carried out up to 2050 based on future wave conditions (Giardino et al., 2018) and sea surface elevation simulations.

5.2 Methodology

5.2.1 Study Site

Among the three sites (Keta, Fuveme and Old Ningo), which have been analysed previously using historical data, Old Ningo was selected for this modelling. This site was selected because of persistent erosion observed along the entire coast, which is threatening infrastructure and livelihood. Additionally, this site is closer to the Port city of Tema and is increasingly becoming a hub for settlement and industries (Ghana Statistical Service, 2014). There are no coastal management systems in the vicinity and the community members have been agitating for government intervention to curb the erosion menace. It expected that with time, there would be a need for intervention; hence, this study will provide relevant scientific information.

The site forms part of the Ningo-Prampram District and stretches approximately 22 km from Prampram in the West to Ayitepa in the East (Figure 5.1). The area lies between longitudes 0°5’ and 0°17’ East and latitudes 5°40’ and 5°50’ North. The coast is dotted with three main lagoons namely Moyo, Afitsedor and Gyankai Lagoons. Estimates show that only the Afitsedor and Gyankai lagoons supply significant sediment to the beach at rates of approximately 78 and 907 m³/yr respectively (Boateng et al., 2012).

Waves generally arrive from the S-SW direction with a mean nearshore height of 1.2 m every 11 s. The area is influenced by the Guinea Current, which moves from west to east at average rates ranging between 0.5-1.5 m/s (Appeaning Addo et al., 2018a; Roest, 2018).
This current drives sediment transport along the coast with modelled values between Accra and the Volta River ranging from $500 \times 10^3$ to $1400 \times 10^3 \text{ m}^3/\text{yr}$ (Giardino et al., 2018). Tides are semidiurnal with an average tidal range of 1 m (Appeaning Addo et al., 2018a).

A smaller domain comprising the shoreline fronting the Old Ningo Community was selected for detailed monitoring. The section is the most affected by coastal erosion along this stretch of shoreline with evidence of houses destroyed. The shoreline stretches approximately 4.2 km at an angle of about 88 degrees. It is bounded to the west by the Gyankai Lagoon and terminates in the eastern direction at Moyo Lagoon.

5.2.2 Littoral Processes FM Model

The Littoral Processes FM model integrates a number of modules including the non-cohesive sediment transport (LIST), longshore current and littoral drift (LITDRIFT), coastline evolution (LITLINE), cross-shore profile evolution (LITPROF) and the sedimentation in trenches (LITTREN) modules. The LITDRIFT and the LITLINE modules
were used in this study to simulate longshore drift and shoreline evolution. The LITDRIFT simulates the cross-shore distribution of wave height, set-up and longshore current for a profile. It calculates the net and gross littoral transport for sections over a period. It takes into consideration the interaction between the water level and the profile at the incident sea state (Burcharth et al., 2007). The LITLINE module simulates the evolution of the shoreline along a quasi-uniform coastline by solving the continuity equation (refer to Equation 2.3, Chapter 2). The model is based on the one-line theory of coastal evolution and calculates position using hydrodynamics inputs, sediment characteristics and gradients in sediment transport (Alhaddad, 2016; Arya et al., 2014). The subsequent sections describe the input data used to set-up the model.

5.2.3 Input Data

5.2.3.1 Bathymetry and Topography

For bathymetry, existing nautical charts were acquired from the Ghana Ports and Harbour Authority. The scanned maps were then digitised in ArcGIS. This was used to compliment the GEBCO global data. NASA’s 1 arc second (30m) global SRTM was used for land topography. These were combined and gridded in MIKE 21 flexible mesh using the nearest neighbour interpolation method. Four profiles based on the shoreline orientation were extracted from the 2D bathymetry for the shoreline evolution modelling (Figure 5.2). For the smaller Domain (Old Ningo), four separate profiles were extracted.

The grid spacing along each profile was 10 m with 303 and 800 grid points for the small and large domains respectively. The alongshore grid spacing for the shoreline was 10 m with 428 grid points for the small domain and 20 m with 1140 grid points for the larger domain. These resolutions were considered adequate to capture the various features both alongshore and cross-shore (Arya et al., 2014; Thach et al., 2007). The offshore start point and
orientation of the individual grids are shown in Tables 5.1 and 5.2 for the larger and smaller domains respectively.

Figure 5. 2: Model domains: (a) Overall modelled domain bathymetry showing the location of profiles (b) smaller domain showing the four profiles.
<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Easting</th>
<th>Northing</th>
<th>Orientation (LPFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>180500</td>
<td>624300</td>
<td>345</td>
</tr>
<tr>
<td>Profile 2</td>
<td>185039</td>
<td>626101</td>
<td>340</td>
</tr>
<tr>
<td>Profile 3</td>
<td>190190</td>
<td>628305</td>
<td>340</td>
</tr>
<tr>
<td>Profile 4</td>
<td>195853</td>
<td>630713</td>
<td>340</td>
</tr>
<tr>
<td>Profile 5</td>
<td>200927</td>
<td>632800</td>
<td>335</td>
</tr>
</tbody>
</table>

Table 5.2: Profile Start Points and Orientations for Smaller Domain

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Easting</th>
<th>Northing</th>
<th>Orientation (LPFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>188298.0</td>
<td>633090.4</td>
<td>176.2</td>
</tr>
<tr>
<td>Profile 2</td>
<td>189376.0</td>
<td>6633177.8</td>
<td>176.8</td>
</tr>
<tr>
<td>Profile 3</td>
<td>190427.5</td>
<td>633262.3</td>
<td>177.2</td>
</tr>
<tr>
<td>Profile 4</td>
<td>191614.9</td>
<td>633346.8</td>
<td>176.5</td>
</tr>
</tbody>
</table>

The extracted profiles, however, did not capture the nearshore (up to about 300m offshore) due to the coarse resolution of bathymetric data used. The profiles were more gentle (approximately 1:100) than the expected (< 1:50) (Nairn and Dibajnia, 2004; Roest, 2018) and did not give the desired results during test runs. To get a more realistic profile, the extracted profiles were modified manually based on other measured nearshore profiles at Ada and Keta in 2004 and 2013 respectively (Figure 5.3) following Bollen et al. (2011) and Nairn and Dibajnia (2004). In addition, the intertidal profiles extracted from the drone survey DEMs (Figure 5.4) show relatively steep profiles as compared to the ones extracted. Using this background information, the nearshore profiles were manually modified to mimic reality. Figure 5.5 shows how the final profiles with a nearshore slope of 1:50 that was used for the shoreline modelling plotted over the raw extracted profiles.
Figure 5.3 Measured cross-shore profiles for (a) Ada and (b) Keta in the Volta delta (Source: Bollen et al. (2011) and Nairn and Dibajnia (2004)).

Figure 5.4 Beach profiles extracted from high-resolution DEM for Old Ningo (refer to Chapter 3).
5.2.3.2 Nearshore Waves

The details of the wave data used are discussed in section 4.2.5. The modelled six (6) hourly wave data from Giardino et al. (2018) was used as input. This nearshore waves approach the coast from approximately south direction as shown in Figure 5.6. The overall trend shows only a slight increase in the wave height, period and direction over the period under study. This is expected as studies indicate an increase in wave height up to only 3% and a clockwise change in direction up to 2° by the end of the century (2070-2100) compared to the base period of 1979-2009 (Giardino et al., 2018; Hemer et al., 2013).
5.2.3.4 Sediment Characteristics

Grain size analysis was carried out for the Volta delta using samples from 12 sites along the delta coastline and is described in section 3.3.5. The results indicate an average grain size of 0.5 mm for the Old Ningo area with sizes ranging between 0.4 mm for the intertidal zone and 0.6 mm for the back beach. For this study, the average grain size of 0.5 mm was used as uniform input for the modelling.

5.2.3.5 Sea Surface Elevation (SSE)

Projections of future sea levels were produced using the hydrodynamic model POLCOMS-the Proudman Oceanographic Laboratory Coastal Ocean Model by the UK Meteorological Office (Holt and James, 2001). POLCOMS is a three-dimensional baroclinic model suitable for both coastal and shelf areas and for deeper water. It was run for the coastal region of the Gulf of Guinea to about 200 km out from the shelf break, with a resolution of 0.1° in latitude and longitude and 40 vertical levels distributed on a hybrid z-sigma scheme. The model
included tidal forcing through the boundary conditions, with 8 harmonic components: Q1, O1, P1, K1, N2, M2, S2 and K2. Forcing at the ocean surface came from regional climate models run at 25 km resolution (Janes et al., 2019). Three climate models were used, selected to give a range of conditions under the high carbon concentration scenario Representative Concentration Pathway (RCP) 8.5: CanESM2, CNRM-CM5 and HadGEM2-ES. Ocean boundary conditions, including sea surface height, were provided daily using outputs from the same global climate models used to drive the regional climate model for the atmosphere. Freshwater input from the Volta River was based on hydrological modelling using the same set of regional climate models (Jin et al., 2018); for other rivers the flows were based on present-day values (Araujo et al., 2014; Mayorga et al., 2010) and did not change during the model run.

In addition to the sea surface elevation taken from the global models and the tidal component, an increment was added to the boundary condition to represent mean sea level rise. Values were based on global projections for sea level rise based on thermal expansion and ice melt (Church et al., 2013), which was adjusted to give a regional value using a pattern-scaling approach. Sea level rise due to local subsidence was not included since subsidence has not been measured for the delta. The values used gave a rise of 0.28 m by mid-century and 0.79 m for end-century, compared to the year 2000.

The model produced hourly values of SSE at each grid cell for the period 1970 to 2099. The combined effects of the mean sea level rise, the tidal forcing, and the atmospheric conditions provided by the global climate model influence the SSE. For this study, these hourly values were extracted from the location 0.20° E and 5.51° N for the period between 2005 and 2050. The data were resampled to six (6) hourly average (Figure 5.7) to ensure uniformity with the wave data for input into the shoreline modelling.
5.2.3.6 Other Input Parameters
Reported average seasonal guinea current speed and direction were also used as input for the model. The rates range between 0.5 -1.5 m/s in a west-east direction (Giardino et al., 2018; Wiafe et al., 2013). In the absence of a time-series data, the mean value of 0.5 m/s (Roest, 2018) was used as a constant value for this model.

5.2.4 Model Setup
The larger model domain was first defined using the 2D bathymetry obtained from the MIKE 21 Mesh generator. This was also used as the background for the smaller domain. The littoral drift model was then set up to calculate the longshore transport for the five (5) cross-shore profiles extracted from the bathymetry. A six (6) hourly time step was chosen for the model based on the input data. The model was set up for the period between 2005 and 2050 making approximately 67,000 steps.
Water level and wave time series files were prepared using the MIKE Zero Time Series tool. Both parameters were varying in time but constant in the modelling domain. The uniform sand option was chosen with a default relative density of 2.65, an average grain size of 0.5 mm and a fall velocity of 0.08 m/s. The fall velocity ($\omega$) was estimated using the formulation by Pounce expressed as:

$$\omega_s = \sqrt{\frac{4(s-1)gD}{3C_D}}$$

Where $s$ is the relative density of the sediment, $D$ is the sediment grain size, $C_D$ is the drag coefficient and $g$ is the acceleration due to gravity. The drag coefficient depends on the Reynolds number, shape and roughness of the particle and is given by:

$$Re = \frac{\omega_s D}{v}$$

Where $Re$ is the Reynolds number, $v$ is the kinematic viscosity coefficient.

Default bed parameters including ripples, porosity and critical shield were maintained. The 5th order Stokes wave theory, which is best for shallow water conditions (DHI, 2017) was selected.

The second stage was to generate littoral drift tables as input for shoreline evolution modelling using the same parameters. The table limits were determined from analyses of input datasets. Table 5.3 shows the limits of the table.
Table 5.3 Table Limits for Nearshore Wave Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>No. of Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Height (m)</td>
<td>0.316</td>
<td>2.884</td>
<td>22</td>
</tr>
<tr>
<td>In-coming wave angle (°)</td>
<td>156.573</td>
<td>240.420</td>
<td>20</td>
</tr>
<tr>
<td>Wave period (s)</td>
<td>2.397</td>
<td>15.911</td>
<td>16</td>
</tr>
<tr>
<td>Mean water level (m)</td>
<td>0.332</td>
<td>1.953</td>
<td>22</td>
</tr>
<tr>
<td>Regional Current Speed (m/s)</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Finally, the shoreline evolution model was set-up. The additional parameters included the shoreline position and orientation. The 2005 shoreline digitised from the 2005 orthophoto was used as the initial shoreline position. The position was determined as the distance from a straight baseline (see Figure 5.2) to the shoreline at every 20 m and 10 m interval alongshore for the large and small domain, respectively.

The model also requires an offshore contour limit for sediment transport, which is equivalent to the depth of closure. To estimate the depth of closure, the Hallermeier (1978) relationship which is widely used was adopted. The formula is expressed as:

\[ d_t = 2.28H_e - 68.5 \left( \frac{H_e^2}{gT_e^2} \right) \]  \hspace{1cm} 5.3

Where \( H_e \) is the effective wave height or the top 0.137% waves in a year, \( T_e \) is the associated wave period and \( g \) is the gravitational force. \( H_e \) can be defined as:

\[ H_e = \bar{H}_s + 5.6\sigma_s \]  \hspace{1cm} 5.4
Where $\bar{H}_s$ is the annual mean significant wave height and $\sigma_s$ is the associated standard deviation of the significant wave height (Brutsché et al., 2014; Hallermeier, 1978).

The estimated depth of closure using a mean wave height of 1.04, wave period of 9 s and a standard deviation of 0.28 m was 5.4 m, which compares favourably with to -4.3 m reported for the Delta (Roest, 2018) and between -4.19 m and -5.72 m for Accra to the west of the study area (Appeaning Addo et al., 2008). Sediment contribution from the Gyankai lagoon was added as a point source with a rate of 0.00002874 m$^3$/s (Boateng et al., 2012).

5.2.5 Future Shoreline Evolution

Two variables influenced the future shoreline position. They include SSE (with a rise to about 40 cm by 2050) and wave climate with a slight increase in wave height and direction. All other variables including regional current were held constant since there was no time-series data. No management intervention is considered, the purpose was to assess how the future shoreline will behave without any human intervention.

5.2.6 Model Calibration

LITPACK simulates both sediment transport and shoreline evolution hence reported sediment transport rates and shoreline evolution were used to calibrate the model. The main source of data for model calibration and validation was historical shoreline analyses based on high-resolution satellite imageries (Anastasiou and Sylaios, 2016). The data spanned the period between 2005 and 2017.

Bed roughness is considered as one of the basic calibration parameters (DHI, 2017) and sediment transport is strongly dependent on it (van Rijn, 2007). This roughness in the real world will vary based on the grain size, shape and the presence or absence of bed-forms.
Furthermore, it will also vary over time as waves and currents will transport sediment and alter the position and shape of the bed load. To vary the roughness across shore depends on sediment data collected and in most cases, a uniform value is accepted to reduce the complexity of the model.

For this model, four values of bed roughness were used to calibrate the model based on the $d_{50}$ value for the area (Alhaddad, 2016). These are:

- $K_s = 10*d_{50}$  
  Nikuradse (1993)
- $K_s = 2.5*d_{50}$  
  Soulsby (1997)
- $K_s = 30*d_{50}$  
  (DHI, 2016)
- $K_s = 0.8$  
  (user-chosen constant bed roughness)

A final bed roughness of 0.8 m and a fall velocity of 0.05 m/s gave acceptable sediment transport rates (between 0.4 and 1.4 million m$^3$/yr) comparable to those reported for the area, which range between 0.4 million m$^3$/yr and 1.5 million m$^3$/yr (Bolle et al., 2015; Giardino et al., 2018; Nairn and Dibajnia, 2004).

5.2.7 Model Limitations

First, the bathymetry and topographic data used for this study were quite course and were artificially modified to reflect measured data in the Delta. Results can be improved with actual field measurement of these parameters, which could not be undertaken in this project due to financial limitations. For this study also, the estuarine area was ignored in the modelling because the shifting of the river mouth and the bar formation is not adequately resolved using one-line models. Though these limitations exist, the model after some calibration was considered representative of the conditions existing in the area.
5.3 Results

4.3.1 Model Validation Results for the Larger Domain

Erosion rate estimated from high-resolution satellite imageries from 2005 to 2017 was approximately $1 \pm 0.56$ m/yr for the larger domain. From the modelling, a rate of 1.02 m/yr was reported indicating a deviation of 0.02 m. However, while the actual measurement revealed about 79% alongshore erosion, the modelling reported erosion was about 55% thereby spatially underestimating the alongshore extent of erosion by 24%. The spatial plot shows the intermittent distribution of accretion along the coast (see Figure 5.5).

The model was able to capture some of the erosion hotspot along the coast at similar rates; however, in other areas, accretion spots were predicted instead of erosion. For example, focusing on the frontage of the Old Ningo Community (area marked ‘O’ on Figure 5.5), the model captured this area as accreting at an average rate of 1.5 m/yr instead of erosion at an average rate of 1.3 m/yr.

Figure 5. 8: Map showing the modelled (a) and observed (b) shoreline change at Old Ningo
Comparing the individual rates, the highest rates of erosion from the observed analysis was about -5 m/yr while the model recorded -6 m/yr (see Figure 5.6). Accretion rates were overestimated with the model reporting about 4 m/yr at peak while the observed was about 1 m/yr (Figure 5.9). There was an extremely weak correlation ($r = 0.006$) between the modelled and the observed rates.

Figure 5.9: A comparison of modelled and observed alongshore shoreline change for larger domain

Further analyses were not carried out with the larger domain since it was not able to resolve the alongshore distribution of erosion properly due to the various shoreline rotations along the coast. This model can be improved through further calibration using in-situ data such as wave, bathymetry and cross-shore sediment characteristics, which was not readily available for this study.
4.3.2 Model validation results for the smaller domain (Old Ningo)

Average erosion rate from the shoreline analyses for Old Ningo was 0.77 m/yr with 98% of the shoreline eroding and an accretion rate of 0.2 m/yr. The model results gave a slightly lower average erosion rate of 0.71 m/yr with 78% of the shoreline eroding and much higher accretion rate of 1 m/yr. The highest erosion rate recorded for the individual transects was 5.9 m/yr, but for the observed data, this was underestimated by the model to 1.8 m/yr. Individual accretion rates were, however, overestimated by the model with the highest being 2.5 m/yr while the observed data recorded 0.6 m/yr.

The extreme western corner of the shoreline, which covers the closest section of the Old Ningo Community to the shoreline, was not properly resolved due to the rotation in the shoreline orientation, which resulted in sheltering from the direct impact of waves. This problem can be resolved if a higher resolution of wave data or a more detailed 3D approach is used. This section was therefore discarded from further analyses. It was also noted that erosion rates were highly overestimated where there was a slight rotation in the shoreline at around 3.9 km (Figure 5.10).

In general, there was a relatively better agreement with modelled and observed data (weak positive correlation, \( r = 0.2 \)) as compared to the larger domain. Despite the weak correlation, the average erosion rates are quite representative of the rates observed along this coast (see Table 5.4). Figure 5.10 shows the comparison between the observed and modelled results.
Table 5.4: Modelled results and oceanographic parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion (± 0.56 m/yr)</td>
<td>0.71</td>
<td>0.73</td>
<td>0.75</td>
</tr>
<tr>
<td>Accretion (± 0.56 m/yr)</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Mean Transport (m³/yr)</td>
<td>1,816,400</td>
<td>1,817,000</td>
<td>1,818,000</td>
</tr>
<tr>
<td>Mean Water Level (m)</td>
<td>1.07</td>
<td>1.15</td>
<td>1.2</td>
</tr>
<tr>
<td>Mean Wave Height (m)</td>
<td>0.979</td>
<td>0.966</td>
<td>0.982</td>
</tr>
<tr>
<td>Wave Period (s)</td>
<td>8.76</td>
<td>8.73</td>
<td>8.81</td>
</tr>
<tr>
<td>Wave Direction (degrees)</td>
<td>171.8</td>
<td>173.2</td>
<td>173.1</td>
</tr>
</tbody>
</table>

Figure 5. 10: Plot of modelled and observed shoreline change for Old Ningo

All four profiles recorded a net loss of sediment with transport rates ranging from 397,000 m³/yr to $2.1 \times 10^5$ m³/yr. The average rate of transport for the entire period was approximately $1.8 \times 10^5$ m³/yr. The first profile (western) recorded the highest transport rate; an indication of the west-east littoral drift reported for the coast of Ghana.
4.3.3 Future Shoreline Evolution at Old Ningo

As noted earlier, the results for the larger domain are not presented here since they were less reliable. For the purpose of comparison, the future state is divided into 2 twelve-year periods namely Future I (2020-2032) and Future II (2034-2046). This was in reference to the base period, which covers a period of twelve years (2005-2017). The results revealed a slight increase in erosion rates with reference to the modelled baseline rate of 0.71 m/yr. The rate of erosion increased by 2 cm/yr to 0.73 m/yr in Future I, with the shoreline moving as much as 30 m inland at some transects. Other sections of the shoreline experienced accretion at a rate of 0.4 m/yr with the land advancing seaward less than 20 m.

This increase corresponds to a clockwise rotation of the wave direction by 1.5° with a slight decrease in wave height (1 cm) and wave period, which was less than one (1) milliseconds. Water levels, however, went up by 8 cm from the base period with an average of 1.07 m. Sediment transport rate also increased by 1,400 m³/yr. Overall, about 78% of the beach, experienced erosion (Figure 5.11).
Figure 5.11: Future shoreline change pattern (up to 2050). The red box shows the area that was not resolved correctly.

For the second future period (Future II), erosion rates will increase by 4 cm/yr from the baseline rates to 0.75 m/yr. The shoreline is projected to move as much as 70 m from the baseline. Consequently, the small bar separating the tidal pools and the sea will be breached leading to inundation of the adjacent low-lying areas. This corresponds to an increase in water levels of up to 13 cm. Although there was an increase in wave height and period (0.3 cm and 0.05 s), this can be considered negligible. There was a 1.3° rotation clockwise in wave angles and an increase in sediment transport by 1600 m³/yr (5.4).

Overall, a long-term erosion rate of 0.72 m/yr is estimated, which is slightly higher than that of the base period by 1 cm/yr. This long-term rate is also lower than the short-term changes reported for the two future periods.
5.4 Discussion

5.4.1. Model Validation

In general, the model underestimates the baseline alongshore erosion by 16% while underestimating erosion rates by 0.06%. These variations are within acceptable ranges (Zhang, Zhang, Zhai, and Chen, 2007) with differences of less than 20%. Spatial analysis of the results shows that the model did not fully resolve the small changes in the orientation both for the large and small domains investigated. Consequently, accretion was reported where the angles change slightly instead of erosion, as well as overestimation of erosion rates and accretion rates. However, it is evident that the model was able to capture the erosion trends observed in the area.

Giradino et al. (2018) reported rates between 500,000 to 1,400,000 for the area between Accra and the Volta delta from their regional model. This model reports slightly lower and much higher rates between 300,000 and 2,100,000 m\(^3\)/yr. This indicates that for the broader domain and to some extent the smaller domain, alongshore sediment transport seems to vary significantly and this could be observed from the changes in shoreline orientation.

5.4.2 Future Trends of shoreline change at Old Ningo

The shoreline trends simulated in this study suggests that erosion rates will increase slightly. Sediment transports increased slightly over the period by 1,500 m\(^3\), relative to the base period (2005-2017). This will culminate into a slight increase in erosion rate by 0.04 m/yr by the end of the century with the shoreline receding up to 70 m landward. Among the variables, only water level and wave direction show an increase over the periods consistent with erosion rates. Wave height and period showed a drop in ‘Future I’, then an increase in ‘Future II’, which does not correspond to erosion trends observed. With rising sea levels, waves will break closer to the shoreline, which means more wave energy will be dissipated.
at the coast and result in increased erosion. A study by Enríquez et al. (2017) projected small increments in wave heights although their impacts can be devastating in combination with a rise in mean sea level. This phenomenon could explain why even though wave heights did not go up in ‘Future I’ there was still increased erosion.

For the entire period, the sea level increased by 13 cm and had a significant influence on coastal dynamics with the shoreline eroding up to 70 m. Other studies have confirmed that a sustained sea level rise of 10cm can cause a significant increase in erosion up to 15 m and places many coastal cities at risk (Leatherman and Douglas, 2000). It must be noted that future rates do not capture anthropogenic contributions such as sand mining. Though this is rampant along this coast, there were no reliable estimates to include in the model. This can significantly influence the evolution trends in the future if not regulated.

5.4.3 Impacts of Future shoreline evolution

For the eastern section of the shoreline, most of the beach will be eroded by 2050 leading to loss of landing sites for the fishermen. Behind this beach is a wetland system, which is being used for salt mining. Once the sandbar is breached, this entire system including the low-lying areas adjacent will be flooded. Consequently, this will change the ecosystem as well as affect the salt mining activities of the people.

5.5 Conclusion and Recommendations

This study simulated shoreline dynamics at Old Ningo between 2005 and 2050 using the Littoral Process FM model from DHI. The validation results show an acceptable agreement between modelled and observed erosion rates for the period between 2005 and 2017. However, the model generally underestimates alongshore magnitude of erosion while overestimating accretion. The model results also suggest relatively high sediment transport
rates, which could not be validated against any in-situ data. These high sediment transport rates, however, resulted in shoreline erosion trends close to observed rates.

Erosion rates are projected to increase by 4 cm/yr by mid-century in response to increasing water levels. These findings are consistent with those from similar studies elsewhere. The land in the area will retreat to about 70 m leading to the loss of the narrow beach. This will affect the livelihoods of the fishermen and the community at large.

Appropriate interventions such as controlling of sand mining from the nearshore and sea defence system should be put in place to protect the community from the impacts of erosion.
CHAPTER SIX

SYNTHESIS, CONCLUSION AND RECOMMENDATIONS

6.1 Synthesis

In an attempt to measure and predict shoreline morphodynamics in the Volta delta of Ghana, this thesis set out to achieve three main sub-objectives. The first objective was to assess in the short-term (up to two years) beach volume and shoreline dynamics at a higher resolution using data from UAV. The second objective assessed the medium-term shoreline response to wave climate dynamics in the Volta delta. The third and final objective predicted the future evolution of the shoreline using one-line modelling approach up to mid-century (2050) under sea level rise.

The following sections summarise the outcomes of this research and demonstrate how these outcomes fulfil the objectives of the study as well as the overall aim.

6.1.1 Short term beach volume and shoreline dynamics using UAV data

Beach volume changes, as well as shoreline changes, were estimated for the Delta using high-resolution data from UAV surveys. This analysis spanned the period between 2016 and 2018 (short term). Overall, the Volta delta beaches are highly dynamic with high rates of beach erosion (between -3.5 and -16 m/yr) and accretion (between 0.6 and 17.5 m/yr) response to wave regimes and human interventions along the coast. Comparing the three sites studied, sediment volume input is higher on the sites east of the Delta (Fuveme and Keta) which recorded a net gain between 5,142 to 12,669 m$^3$. Comparatively, the west (Old Ningo) experienced a net loss between 8,847 to 12,607 m$^3$. This is due to inputs from both local sources such as migrating sand waves and the erosion of the shoreline up drift and the eastward transport of sediments. Additionally, it was observed that sediment from the Volta
River is contributing less to the coastal sediment budget at the estuary and downdrift. This was inferred from the sediment size distribution observed along the delta. The estimation of these rates indicates that the objective has been achieved.

6.1.2 Medium-term shoreline response to wave climate

In the medium term, shoreline change rates were estimated using shorelines extracted from orthophoto and satellite imageries for the period between 2005 and 2017. The estimated rates of erosion and accretion were relatively lower (between -1 and -7.2 m/yr and 0.3-5.8 m/yr, respectively) compared to the short-term rates. This indicates that the shoreline is able to recover to some extent after a period of high erosion through accretion (which occurs during the season of low waves (around April as observed at Fuveme)).

The results of the wave impact analysis showed that the role of wave climate in shoreline dynamics varied across the deltaic coastline. Wave height, which translates to wave energy, plays a significant role at the Volta estuary; however, the impact weakens for the two other sites, which are farther from the Volta estuary. The wave impacts are weakest at the Keta sea defence site, which suggests that the structure is effectively reducing the effect of waves on erosion. Consequently, the beach is more stable and showing a higher net gain of sediment volume. Based on the above, the second objective has been achieved.

6.1.3 Future shoreline evolution at Old Ningo

Considering the future trends, predictions were made using one model (Littoral Processes FM) at Old Ningo up to the year 2050. The results show that the shoreline will continue to erode at a relatively higher rate of (an increase of about 4 cm/yr). As well, longshore sediment transport rates will increase in the future because of increasing wave heights, which will negatively affect shoreline dynamics. The shoreline will recede up to 70 m at some sections of the shoreline by 2050. This recession will erode the available beaches and lead
to the inundation of the back beach, the wetland and the livelihoods that are connected. The results also indicate lower long-term rates compared to the short and medium-term rates. The third objective, which looks at future impacts under sea level rise, has been successfully achieved.

6.2 Conclusion

The study has provided insight into the short-term beach volume and shoreline dynamics, shoreline change and the impact of wave climate as well as the future evolution of the Volta delta shoreline under climate change. The study has additionally demonstrated the applicability of UAVs for high-resolution assessment of beach volume and shoreline dynamics along the Volta delta coast and in the Gulf of Guinea.

Beach dynamics have been assessed for the first time in the Volta delta using different sets of high-resolution datasets. The study identified that the short-term erosion rates are relatively higher, compared to the medium to long-term rates. This is mainly because the shorelines are able to recover to some degree after high rates of erosion during high-energy seasons. At the observed rates of erosion, communities such as Old Ningo and Fuveme are under varying levels of erosion threat. The model prediction for Old Ningo indicates that the narrow beach protecting the wetland, which is being used for salt mining, will be breached by the year 2050 leading to inundation of the saltpans if no action is taken. In addition, the landing site (beaches) will be lost. This will socio-economic activities of the people.

Predominantly, the shoreline west of the Volta estuary is predominantly eroding while the eastern beaches are predominantly gaining sediment. From sediment analyses, it was obvious that the updrift coast (west of the Volta estuary) and the Volta River are contributing less sediments to the beaches downdrift. Rather, local sources of sediment such as from shoreline erosion and migrating sandbars contribute sediments to the downdrift beaches. The
study also demonstrated that the use of high-resolution DEMs to assess beach dynamics gave more insight for the short-term as compared to using lateral erosion rates.

This study overall has assessed the historical and future trends of shoreline dynamics in the Volta delta based on high-resolution data which improves the confidence in the results. These results improve the understanding of dynamics along the Volta delta coast. It further demonstrates the applicability of UAVs for beach monitoring in the region.

6.3 Recommendations

Though the main aim of this study has been achieved through the accomplishment of the specific objective, it has been recognised that there were some limitations hence the following are recommended:

- It was observed that the Old Ningo beach is predominantly eroding with less sediment input from other sources. The future rates of erosion will be higher under sea level rise. An appropriate erosion management plan should be designed for this area to increase resilience against future erosion. Beach nourishment or the Dutch ‘sand motor’ system can be explored for this zone to augment the sediment deficit. In addition, regulations should be enforced to control nearshore sand mining.

- The extreme rates of erosion and accretion recorded close to the Volta estuary (Fuveme) are predominantly being driven by wave action. Erosion is, however, dominates leading to the destruction of property and livelihoods. Engineering options that reduce the impact of waves such as offshore breakwaters can be explored. Beach nourishment may not be effective considering the large and erratic movement of sediment for this site.
• The shoreline is more stable in the Keta area because of the defence structure in place. However, high erosion is occurring down-drift of the structure confirms which confirms the ‘knock-on effect’ of the groynes. The study recommends that future shoreline management along the delta shoreline should be skewed towards soft engineering options as much as possible.

• Longer-term trend analysis using high-resolution data from UAVs at more dense sites across the delta and along the entire Ghana coastline. This higher resolution long-term dataset will provide the relevant data for more rigorous analysis; capture the full seasonal trends, shoreline recovery after storms, etc.

• Collection of high-resolution in-situ data such nearshore bathymetry and wave parameters will provide good data to improve model calibration and performance.

• Erosion simulations using 3D models to help improve future predictions.
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148


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APPENDIX A: Ground Control Points

Linear unit: Meters
Angular unit: DMS
Projection: GHANA-TM
Datum: WGS84
Geoid:
Time Zone: GMT Standard Time

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APPENDIX B: GCP Markers

Sample Marker Printed on AO

Marker Placed on a GCP and being surveyed
APPENDIC C: Sediment Volume and depth Change Error bars for the period April 2017 to April 2018

Volume Change for **Old** Ningo

Depth Change for **Old** Ningo

Volume Change for Fuveme

Depth Change for Fuveme
Volume Change for Keta

Depth Change for Keta
APPENDIC D: Graphs and Report from Shoreline Change Analyses for Keta

Range of Change
Graphs and Report from Shoreline Change Analyses for Fuveme

Range of Change
Graphs and Report from Shoreline Change Analyses for Old Ningo

Range of Change
APPENDIX D: Sample Model Output for Smaller Domain

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NoDynamicItems 6

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Item    y coordinate coast    Geographical coordinate meter
Item    Littoral drift    Sediment Transport meter^3/sec
Item    Integrated drift    Acc. Sediment transport meter^3
Item    Accumulated volume    Sediment volume per length unit meter^3/meter

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167
APPENDIX E: Some Field Pictures

Trinity Preparing to Fly drone at Fuveme

Crossing the River to Fuveme by boat

Establishing Permanent GCPs at Keta

Dr. Rovere and Philip Jayson doing RTK

ZMT and Ghana Team in the Field

Flying Drone at Keta