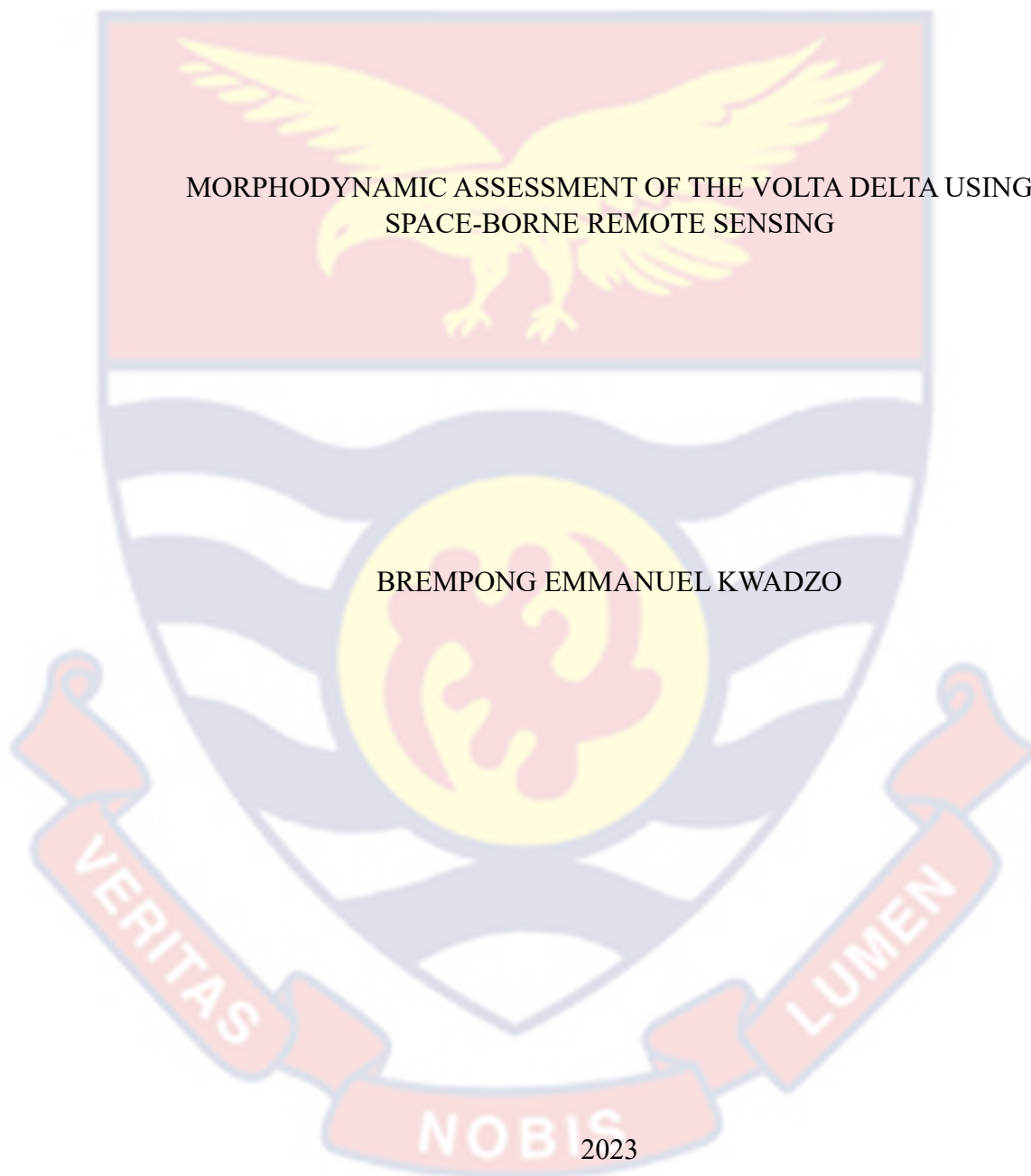


UNIVERSITY OF CAPE COAST

MORPHODYNAMIC ASSESSMENT OF THE VOLTA DELTA USING
SPACE-BORNE REMOTE SENSING

BREMPONG EMMANUEL KWADZO





© Brempong Emmanuel Kwadzo
University of Cape Coast

UNIVERSITY OF CAPE COAST

The background of the page features a large, faint watermark of the University of Cape Coast crest. The crest is a shield divided into three horizontal sections. The top section is red and contains a yellow eagle with its wings spread. The middle section is white with blue wavy lines representing water. The bottom section is blue with a yellow sun-like symbol in the center. A red banner wraps around the bottom of the shield, containing the Latin motto 'VERITAS NOBIS' in white capital letters.

MORPHODYNAMIC ASSESSMENT OF THE VOLTA DELTA USING
SPACE-BORNE REMOTE SENSING

BY
BREMPONG EMMANUEL KWADZO

Thesis submitted to the Department of Fisheries and Aquatic Sciences, School
of Biological, College of Agriculture and Natural Sciences, University of
Cape Coast, in partial fulfillment of the requirements for the award of Doctor
of Philosophy degree in Oceanography and Limnology.

AUGUST 2023

DECLARATION**Candidate's Declaration**

I hereby declare that this thesis is the result of my original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature 

Date 09/10/2023

Name: Brempong Emmanuel Kwadzo

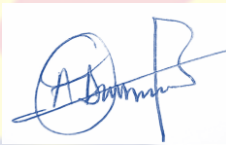
Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of the thesis laid down by the University of Cape Coast.

Principal Supervisor's Signature 

Date 09/10/2023

Name: Dr. Precious Agbeko D. Mattah

Co-Supervisor's Signature 

Date 09/10/2023

Name: Dr. Bapentire Donatus Angnuureng

Co-Supervisor's Signature 

Date 09/10/2023

Name: Dr. Rafael Almar

ABSTRACT

The stability and sustainability of deltas around the world are endangered by pressing global problems including sea level rise, land subsidence, erosion, biodiversity loss, urbanization, and climate change, requiring harmonized and collaborative strategies for effective mitigation. Over the past decade, the Volta Delta in Ghana has experienced adverse consequences of these impacts, including recurrent and accelerated flooding and erosion as well as the loss of valuable wetland ecosystems. This study focused on analyzing the changes in the delta's morphodynamics using remote sensing approaches. This study employs the use of satellite-based SAR-Interferometry, Extreme Coastal Water Levels (ECWL), and Pleiades stereo images to estimate land subsidence rates and the extent of coastal flooding in the Volta Delta of Ghana. The results from the study revealed that the Keta Lagoon and Songor Lagoon areas located immediately at both the east and west of the Volta Delta exhibit varying rates of subsidence, reaching up to 4 mm/yr and about 20% of the entire Volta Delta, including vulnerable sand barriers, could be sited below the mean sea level. Furthermore, almost 40% of the Keta area is susceptible to flooding including significant sites like beach resorts and historical landmarks with the wave run-up as the primary contributing factor. The study underscores the importance of creating a robust monitoring framework to regularly assess the conditions in the Volta Delta and West Africa, facilitating a better understanding of delta dynamics, identification of key drivers, and the generation of essential data for future research and early warning systems, all critical for long-term resilience.

LIST OF PUBLICATIONS

- **Brempong, E. K.,** Almar, R., Angnuureng, D. B., Mattah, P. A. D., Avornyo, S. Y., Jayson-Quashigah, P. N., & Teatini, P. (2023). Future flooding of the Volta Delta is caused by sea level rise and land subsidence. *Journal of Coastal Conservation*, 27(3), 24. (DOI: [10.1007/s11852-023-00952-0](https://doi.org/10.1007/s11852-023-00952-0)).
- **Brempong, E. K.,** Almar, R., Angnuureng, D. B., Mattah, P. A. D., Jayson-Quashigah, P. N., Antwi-Agyakwa, K. T., & Charuka, B. (2023). Coastal Flooding Caused by Extreme Coastal Water Level at the World Heritage Historic Keta City (Ghana, West Africa). *Journal of Marine Science and Engineering*, 11(6), 1144. (DOI: [10.3390/jmse11061144](https://doi.org/10.3390/jmse11061144)).
- **Brempong, E. K.,** Almar, R., Angnuureng, D. B., Mattah, P. A. D., (2023). Application of InSAR-derived DEM; A Pilot study for Beach evolution. *Journal of Remote Sensing* (Submitted).

KEYWORDS

Coastal Flooding

Digital Elevation Model

FABDEM

InSAR

Persistent Scatter Interferometry (PS-InSAR)

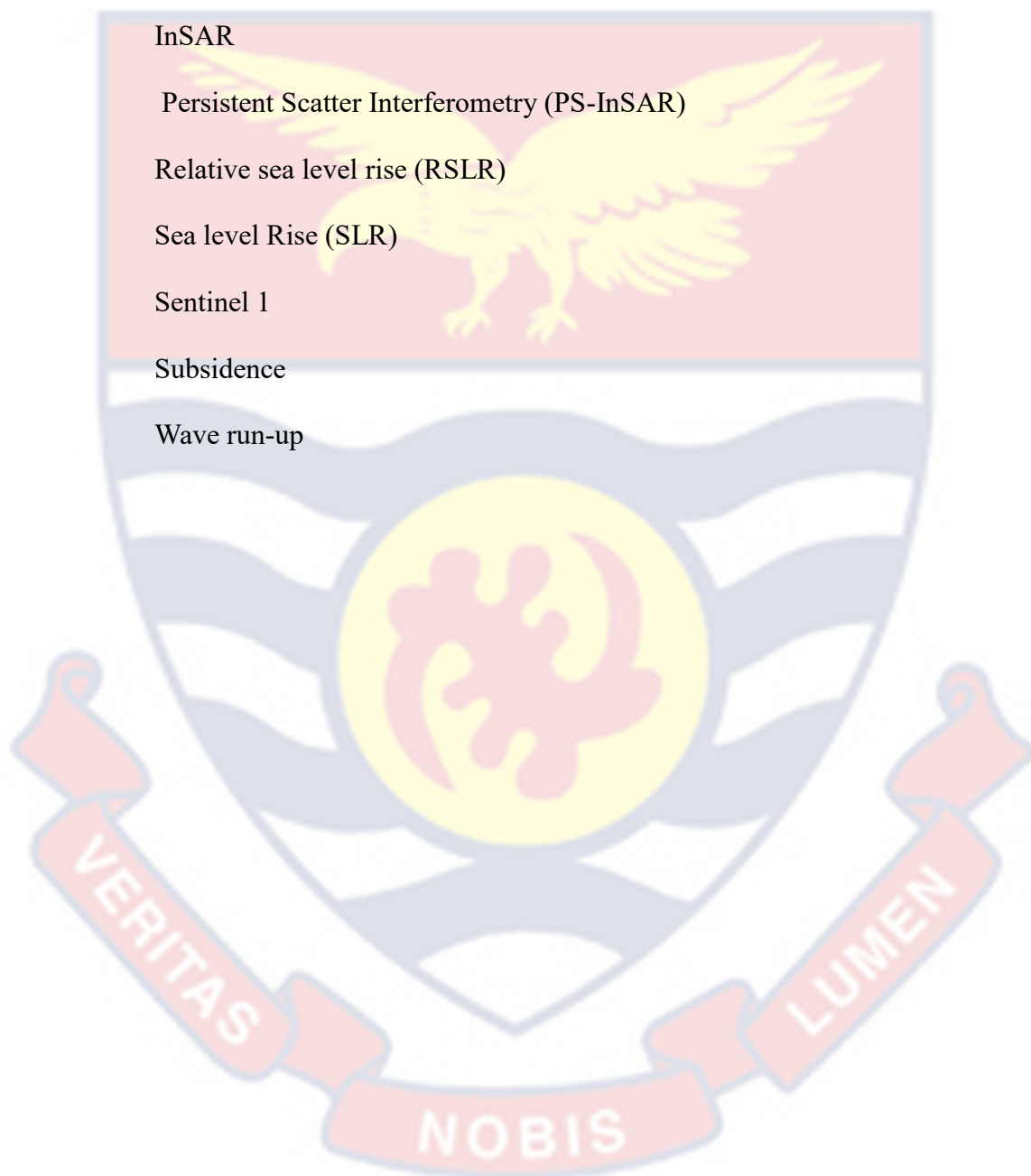
Relative sea level rise (RSLR)

Sea level Rise (SLR)

Sentinel 1

Subsidence

Wave run-up



ACKNOWLEDGEMENTS

I express my deepest gratitude to my supervisors, Dr. Precious Agbeko Mattah and Dr. Donatus Angnuureng from the Centre for Coastal Management (CCM) UCC, and Dr. Rafael Almar from the IRD Laboratory for Studies in Geophysics and Spatial Oceanography (LEGOS). Their invaluable guidance and support have been instrumental in this research.

I sincerely appreciate the financial support provided by the World Bank Group, the Government of Ghana, and the Africa Centre of Excellence in Coastal Resilience (ACECoR), Centre for Coastal Management (CCM), through the scholarship awarded for this program. Additionally, I extend my gratitude to the ACE partner IRD project LEGOS lab and the IRD JEAI Coast under Control in France for facilitating my travel and stay in France. Special thanks go to Prof. Denis W. Aheto (Director), Dr. Precious Mattah (Deputy Director), and the entire ACECoR team at CCM, University of Cape Coast, for their continuous support. I am also grateful to the lecturers and technical staff of the Department of Fisheries and Aquatic Sciences for their valuable contributions. Furthermore, I acknowledge the support and insights of Prof. Kwasi Appeaning Addo, Dr. Philip Neri Quashigah, Mr. Selasi Avornyo, Mr. Michael Biney, Mr. Blessing Charuka, Mr. Kwasi Twum Agyarkawah, and Miss Rael Adiambo. Their contributions have greatly enriched this work.

Finally, my heartfelt appreciation goes to all the students of ACECoR for their assistance throughout this program.

DEDICATION

To my parents, Mr and Mrs Brempong, my siblings, Caleb and Grace and Jeanne Essi Etonam Avekor.



TABLE OF CONTENTS

DECLARATION.....	ii
ABSTRACT.....	iii
LIST OF PUBLICATIONS.....	iv
KEYWORDS.....	v
ACKNOWLEDGEMENTS.....	vi
DEDICATION	vii
TABLE OF CONTENTS	viii
LIST OF TABLES	xiv
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS	xx
CHAPTER ONE	1
INTRODUCTION	1
Overview	1
Statement of Problem.....	3
Main objective;.....	5
Specific Objectives;.....	5
Significance of the Study.....	5
Limitations	6
Definition of some terms.....	7
General Methodology (including the Study Area)	9

Organization of the Study	11
CHAPTER TWO	12
LITERATURE REVIEW	12
Introduction	12
Deltas.....	12
Formation of Deltas	13
Classification of Deltas.....	16
Major Challenges and Factors Affecting Deltas	18
Application of Remote Sensing in Coastal Environments.	20
Major Coastal Processes that affect deltas.	22
Land Subsidence.....	22
Natural Drivers of Land Subsidence	25
Anthropogenic Drivers of Land Subsidence	28
Relative Sea Level Rise Effects On Delta.	30
Monitoring or Measuring Coastal Subsidence	37
General Limitations of InSAR or DInSAR	41
Synthetic Aperture Radar Missions	42
Sentinel-1 Mission.....	44
Global Positioning Systems as a Monitoring Tool	45
Coastal Flooding and Inundation.....	46
Significant contributors to coastal flooding.....	48

The Volta Delta of Ghana: An Overview	56
Conclusion.....	60
CHAPTER THREE	61
FUTURE FLOODING OF THE VOLTA DELTA CAUSED BY SEA LEVEL RISE AND LAND SUBSIDENCE	61
Abstract	63
Introduction	65
Material and Methods.....	68
Study Site.....	68
Vertical land motion.....	70
Digital Elevation Model (DEM).....	75
Extreme Coastal Water Level (ECWL)	76
Elevation projection with respect to MSL under RSLR scenarios analysis	78
Results	80
Vertical land displacement.....	80
Discussion	84
Conclusion.....	91
CHAPTER FOUR.....	93
COASTAL FLOODING CAUSED BY EXTREME COASTAL WATER LEVEL AT THE WORLD HERITAGE HISTORIC KETA CITY (GHANA, WEST AFRICA)	93

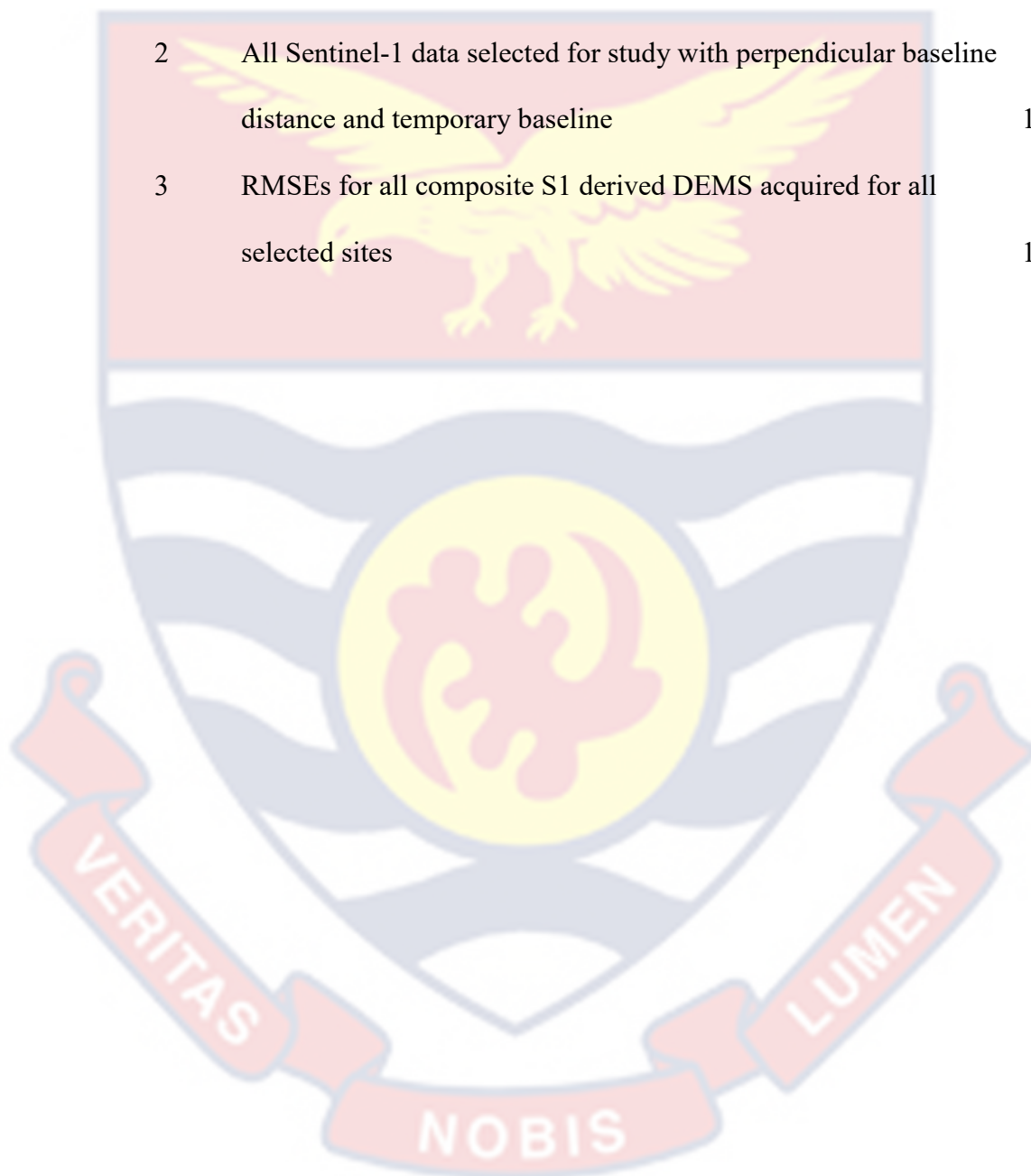
Abstract	94
Introduction	95
Materials and Methods	99
Study area	99
Pleiades Satellite Imagery and Acquisition	101
Hydrodynamic data.....	102
Workflow and Methodology	104
Pleiades-derived topography	104
Pleiades Imagery Pre-processing.....	105
Results	109
Percentile of Coastal flood occurrences.	109
Time spent in the 98th percentile.....	110
Flood extent mapping concerning percentiles.	112
Comparison of Pleiades DEM and ACE2 DEM.....	113
Hydrodynamic contributors of coastal flooding	114
Variability of ECWL parameters	115
Discussion	116
Conclusions	121
CHAPTER FIVE	122
APPLICATION OF INSAR-DERIVED DEM; A PILOT STUDY FOR BEACH EVOLUTION	122
Abstract.....	123

Introduction	124
Materials and Methods	128
Study area.	128
Sentinel 1 data and processing.....	130
FABDEM DEM description and usage	132
Correction of S1 DEM with FABDEM	132
Drone Data.....	132
Results	133
DEMs obtained from Sentinel 1 for the Volta Delta.....	133
Comparison of corrected DEMs of Sentinel 1 and FABDEM.	134
Correlation between Sentinel 1 DEM and other DEMs for all pilot sites.....	135
Correlation of Corrected Sentinel-1 DEM and FABDEM for all pilot study sites	136
Correlation of Sentinel-1 DEM and another Sentinel 1 DEM for all pilot study sites.	137
Correlation of Composite Sentinel 1 DEM and FABDEM for all pilot study sites	138
Root Mean Square Errors composites of all pilot study sites.....	139
Vertical profiles along Study site 2	140
Composite DEMS.....	141
Discussion	141

Conclusion.....	147
CHAPTER SIX.....	148
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS.....	148
CONCLUSIONS.....	150
RECOMMENDATIONS.....	153
REFERENCES	157
LIST OF APPENDICES	208
APPENDIX A -SAMPLE STAMPS LOG FILE FOR SUBSIDENCE DATA PROCESSING.....	208
APPENDIX B -SAMPLE MATLAB CODES FOR EXTREME COASTAL WATER LEVEL DATA ANALYSIS.....	210
APPENDIX C -SAMPLE MATLAB CODES FOR SENINEL 1 AND FABDEM CORRELATION AND RMSE ANALYSIS.....	212
APPENDIX D -SAMPLE CODES FOR PLIAEDES IMAGE PROCESSING	217
APPENDIX E -SAMPLE SENITNEL 1 GENERATED DEMS.....	219
APPENDIX F -IMAGE OF ABSTRACT PAGE OF OBJECTIVE 1	220
APPENDIX G -COVER PAGE OF PUBICATION FOR OBJECTIVE 2.....	221

LIST OF TABLES

Table		Page
1	The occurrence of coastal flooding was obtained from NADMO from 2002 to 2015	111
2	All Sentinel-1 data selected for study with perpendicular baseline distance and temporary baseline	131
3	RMSEs for all composite S1 derived DEMS acquired for all selected sites	139



LIST OF FIGURES

Figure		Page
1	Types of Deltas based on their formations	18
2	Anthropogenic and Natural factors affecting deltas	19
3	Schematic diagram of how remote sensing operates	20
4	Spatio-temporal distribution of remote sensing approaches used for coastal studies	21
5	Vertical Land Movement due to uplift and subsidence	23
6	Factors contributing to land subsidence	25
7	Crustal movement along a normal fault	26
8	Isostatic land deformation explained briefly	27
9	Simplified model of landward coastal retreat under SLR (based on the Bruun Rule)	34
10	InSAR data acquisition principle	40
11	Land elevation changes due to uplift and subsidence	43
13	Significant climate change factors contributing to coastal flooding	47
14	Map of the study area (Source: Codjoe et al., 2020). The 5m contour limits the extent of the Volta delta	57
15	DEM of the Volta Delta in the eastern coast of Ghana, Gulf of Guinea	70
16	Flow chart of the combined workflow of SNAP-StaMPS adopted in this study to process S1 images	74
17	Swaths covering study area A) IW swath scenes covering study area extent B) Three overlapping sub-swaths covering the study area	75

18	Example of extreme coastal water level and relative SLR trends from 1993 to 2100 as obtained by considering ECWL rate of 3.3 mm/yr from Almar et al., 2021 and LS rate of 4 mm/yr from S1 assuming LS rate is constant based on RCP 8.5 scenario	78
19	Map showing vertical displacement rates in the Volta Delta from 2015 to 2021	81
20:	(a) Vertical displacement rate for Songor area; (b) Vertical displacement rate for Keta area; Average time series of the vertical displacement for ; (c) the Songor area and ; (d) the Keta lagoon area from 2015 to 2021	81
21	Elevation projection map of the Volta Delta using SLR for RCP 8.5	83
22	A graph of; a) Coastal inundation changes and b) area flooded during ECWL for all sea level rise scenarios where Sea Level Rise (SLR) is blue , and Relative Sea Level rise (RSL) is red	83
23	A map showing the general ecosystem of the Volta Delta with salt mining locations	89
24	Coastal flooding at Ketu South in the Volta Delta	91
25	A map of the study area showing; A) an image of Ghana with all regions and the Volta Delta shaded in yellow; B) an image of the Volta Delta showing all the districts, and C) an image of Keta District with Pleiades multi-spectral satellite image superimposed showing the major towns and tourist sites in the Keta District of the Volta Delta, Ghana (Gulf of Guinea, West Africa)	100

- 26 An image of the tri-stereo images (PHR1A) acquired on the 20th
of October 2020 for the Keta study area (made using google earth) 102
- 27 A summary of the methodology for NASA's Ames Stereo
Pipeline software (ASP) for Structure from Motion procedure
workflow implemented in this study. This approach derives
DEMs and orthophotos from satellite imagery 107
- 28 A percentile distribution plot of extreme coastal water levels
from 1994 to 2015 showing the 30th, 60th and 98th percentile
with occurrences of coastal flooding obtained from NADMO
in blue dots 110
- 29 Time spent by an occurrence at the 98th percentile in hours per
year from 1994 to 2015, showing blue dots of maximum annual
ECWL data and red trend line from 1994 to 2015 112
- 30 Flood extent mapping for each scenario of ECWL where; A)
30th percentile of ECWL with 19 % of the area being potentially
flooded, B) 60th percentile of ECWL with 29 % of the area being
potentially flooded, C) 98th percentile of the area being
potentially flooded 113
- 31 A) An orthophoto of the Pleiades imagery for the Keta
municipality with a red line B) The zoomed-in orthophoto of the
selected transect and a purple box showing the beach area. C)
Elevation variation for Pleiades and ACE2 with a purple box
showing the beach area of the transect. D) A box plot of elevation
along the transect shows the distribution of Pleiades and ACE2
imagery elevation values 114

32:	Hydrodynamic contributors to coastal flooding at 98 %, showing the contribution of all parameters in ECWL at 98 % of ECWL. The extreme left shows a stacked bar plot of all parameters, with Wave R, Tide, SLA and DAC showing the dominance hierarchy	115
33	Variation in contributors of ECWL from 1994 to 2015 using the yearly mean deviation of all parameters for 98 % of ECWL from 1994 to 2015	116
34	The imagery of beach resorts affected by ECWL; A) An aerial view of two major beach resorts (Aborigines beach resort and Agblor Lodge) in Keta without flooding. B) Gradual flooding of the Agblor Lodge and Aborigines beach resort being affected by ECWL; C) An aerial view of wave overtopping in the Keta area due to ECWL	120
36	Detailed flow chart of S1 Dem processing (Adopted from Braun (2021)	131
37	Sample of Sentinel-1 derived DEM of Volta Delta for pilot study	134
38	A representation of corrected selected areas with FABDEM of Volta Delta for the pilot study and FAB DEM for the selected study areas	135
39	A correlation of selected areas of Volta Delta for the pilot study and FAB DEM for the selected study areas	136
40	A correlation between selected sites of Volta Delta for the pilot study and FABDEM data	137

- 41 A correlation between selected sites of Volta Delta for pilot study
and selected S1 data 138
- 42 A correlation between composite of Sentinel 1 for all sites of
Volta Delta and FAB DEM for the selected study areas. Where a)
a plot of correlation coefficient when composited DEM are
corrected with FABDEM b) a plot of correlation coefficient
when composite DEMs are corrected and smoothened with
FABDEM c) a plot of correlation coefficient when composite
DEMs are not corrected and smoothened with FABDEM 139
- 43 Shows the general evolution of the DEM profile in study Site 2.
In general, S1 composited DEM, has a maximum height of 1.8m
whiles the UAV and FABDEM have a maximum height of 7 m
and 3.9 m, respectively. The profiles show a general beach shape
which could include beach berms 140
- 44 A spatial plot of the DEMs after they are composited for each site 141

LIST OF ABBREVIATIONS

ACE	Altimeter Corrected Elevations
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ALOS:	Advanced Land Observing Satellite
AR6:	IPCC Sixth Assessment Report
ASP	Ames Stereo Pipeline
AVISO:	Archiving, Validation and Interpretation of Satellite Oceanographic data
CNES	Centre national d'études spatiales
DAC	Dynamic Atmospheric Conditions
DECCMA:	Deltas, Vulnerability and Climate Change: Mitigation and Adaptation
DEM:	Digital Elevation Method
DGPS:	Differential Global Positioning System
DInSAR:	Differential Interferometry Synthetic Aperture Radar
EOSDIS	Earth Observing System Data and Information System
FABDEM	Forest And Buildings removed Copernicus DEM
FES2014	Finite Element Solution Tide Model 2014
GCP:	Ground Control Point
GIS:	Geographic Information System
GNSS:	Global Navigation Satellite System
GPS:	Global Positioning System
InSAR:	Interferometric Synthetic Aperture Radar
IPCC:	Intergovernmental Panel on Climate Change



IW:	Interferometric Wide Swath
KSDP:	Keta Sea Defence Project
LS	Land Subsidence
MATLAB	Matrix Laboratory
MERIT:	Multi-Error Removed Improved-Terrain
NADMO:	National Disaster Management Organisation
PS:	Persistent Scatterers
PSI:	Persistent Scatterer Interferometry
PSInSAR:	Permanent Scatterer InSAR
RCP	Representative Concentration Pathways
RSLR:	Relative Sea Level Rise
RPC	Rational Polynomial Coefficient
S-1:	Sentinel- 1
SAR:	Synthetic Aperture Radar
SBAS	Small Baseline Subset InSAR
SLC:	Single Look Complex
SALE	Sea Level Anomaly
SLR:	Sea Level Rise
SNAP:	Sentinel Application Platform
SRTM:	Shuttle Radar Topography Mission
StaMPS:	Stanford Method for Persistent Scatterers
SWH:	Significant Wave Height
TOPS:	Terrain Observation by Progressive Scans
TOPSAR:	Terrain Observation with Progressive Scans SAR
TRAIN:	Toolbox for Reducing Atmospheric InSAR Noise

USGS: United States Geological Survey

UTM Universal Transverse Mercator

VV: Vertical Co-polarization

WGS84 World Geodetic System 1984



CHAPTER ONE

INTRODUCTION

Overview

Deltas are geographical features characterized by their convex shape, forming at the juncture where a river meets a lake or the ocean. Its creation is primarily attributed to the accumulation of sediment carried by the river's flow (Nicholls et al., 2007). These formations result from the interplay of river currents, tides, and wave forces, featuring notable characteristics such as branching river channels and sediment layers. Deltas serve as crucial ecosystems, providing numerous benefits like fertile agricultural land, fisheries, and essential transportation hubs.

The susceptibility of delta formation results from multiple factors, including the compaction of sediment due to the extraction of oil, gas, and water from the underlying sediments, the trapping of sediment in reservoirs upstream, coastal engineering activities, and the rising global sea level (Nicholls et al., 2011). Globally 85% of deltas have suffered severe flooding in the past decade, resulting in the temporary submersion of approximately 260,000 km² of land, including both agricultural and urban regions across key deltas such as the Mekong, Ganges-Brahmaputra, and Nile (Poulos et al., 2022). Projections are that the vulnerability of these deltas to flooding could increase by 50% in the twenty-first century as a result of sea-level rise (Lewis & Ernstson, 2019). In addition, the adverse impacts of climate change, such as the intensification of sea-level rise, and increased coastal flooding, raise significant concerns (Seeger et al., 2023; Yin et al., 2020).

In addition to that, since deltas are of low elevations, they are at the forefront

of this impact (Angamuthu et al., 2018). These impacts result in saltwater intrusion into freshwater sources, threatening agriculture and drinking water supplies, and exacerbating erosion.

The vulnerabilities encountered by deltas have extensive and interconnected repercussions (Balica et al., 2012). These vulnerabilities, encompassing factors such as increasing sea levels and floods, have the potential to displace communities residing in deltaic regions, leading to considerable societal and economic disruptions. Considering the projected coastal flooding (Nicholls et al., 2022), it is crucial to recognize that this issue will impact people living in deltas, particularly those in developing and least-developed economies such as Ghana. Human activities can exacerbate the impact of coastal flooding. Withdrawing water from subterranean reservoirs along coastal areas can cause land to sink, increasing vulnerability to floods. In addition, the geology of the coast also plays a critical role in influencing land subsidence and flood risk (Nicholls et al., 2021). Moreover, the establishment of man-made structures such as seawalls can disturb the inherent dynamics of beaches, resulting in erosion and compounding the potential for flooding. The menace of coastal inundation and the impact of ocean surges represent substantial dangers to the well-being of coastal populations, ecological systems, and essential structures. Hence, it is crucial to conduct regular mapping and monitoring of deltas to gain insights into their dynamic nature. This practice is essential to enable the implementation of effective mitigation and adaptation measures to address the impacts. Moreover, at the local level, valuable insights obtained from regular monitoring can inform the formulation of policies that will enhance governance structures in deltaic regions, leading to improved management and decision-

making (Addo et al., 2018a).

Through a comprehensive understanding of these complex processes, proactive measures can be formulated to create a buffer for the deltas and provide enhanced recommendations for weakening their susceptibilities. In the end, the research seeks to play a role in safeguarding and promoting the sustainable governance of the Volta Delta.

Statement of Problem

The major factors that influence the evolution of the delta area are erosion and accretion, chiefly driven by diminished drastic changes in sediment deposition resulting from sediment retention and the obstruction of irrigation runoff due to the presence of dams (Grases et al., 2020). The Volta Delta region faces significant challenges related to subsidence and sediment retention (Appeaning et al., 2018), which have negative impacts on both the densely populated areas and the coastal ecosystems that provide valuable services. Dandekar and Thakkar (2014) indicates that around 70% of the studied deltas are confronted with the said challenges. Failing to address sediment retention issues and implement appropriate mitigation measures could lead to a scenario by 2050 where over 8.7 million people and approximately 28,000 km² of deltaic areas across 33 deltas will experience increased flooding and erosion. Additionally, the threat of flooding from storm surges will affect larger populations and geographic regions (Dandekar & Thakkar, 2014). However, there is very little information available on the impact of relative sea level rise as well as the major natural and anthropogenic factors playing a role in all these.

Previous research on the Volta Delta has mainly focused on its ecological, socio-economic, and coastal morphodynamics aspects. Regrettably, research within the West African sub-region has predominantly attributed findings on coastal hazards to climate change (Angnuureng et al., 2018; Appeaning Addo et al., 2011; Jayson-Quashigah et al., 2019). As a result, the increasing occurrence of coastal flooding or inundation has largely been attributed to eustatic sea level rise, with limited consideration given to the potential influence of land subsidence and other local hydrodynamic parameters. The scarcity of research on vertical land movement in the Volta Delta prevents a thorough understanding of the frequency and severity of coastal hazards and the potential influence of topographical alterations on their occurrence. This knowledge gap is especially critical in the vulnerable low-lying coastal zone. Consequently, there is a deficiency in effective coastal zone management strategies and insufficient integration of proactive measures for mitigation and adaptation. This shortfall results in a fragmented non-scientific approach to addressing coastal hazards in the region.

The assessments by the Deltas, vulnerability, and Climate Change: migration and Adaptation (DECCMA) emphasized the significance of identifying and giving priority to areas at risk for policy and humanitarian efforts. Though efforts have been made there is still little understanding of the factors that contribute to morphological changes in the delta. Moreover, there is a requirement for comprehensive data on the current patterns of flooding and subsidence rates. This will enable the acquisition of precise and up-to-date information, facilitating informed decision-making and effective management of the delta region.

Consequently, a thorough research methodology becomes essential for tackling the morphological shifts within the delta, taking into account the multitude of factors driving these transformations. To attain sustainable delta management, it is imperative to establish monitoring and modeling frameworks that encompass the spatial and temporal interconnections among diverse biophysical risks. However, limited research has focused on understanding these spatial and temporal changes in the Volta delta. This study seeks to;

Main objective

The overall aim of this research is to evaluate subsidence and the extent of flooding within the Volta Delta.

Specific Objectives

- To estimate the land subsidence rates as a consequence of relative sea level rise over the 21st century.
- To determine the predominant oceanographic factors affecting the Volta Delta using Keta as a case study.
- To explore the use of SAR-derived DEM for temporal beach change detection.

Significance of the Study

Coastal risks in the Volta Delta are influenced by unknown factors that have not been sufficiently investigated. A review on the Volta Delta highlights the lack of a comprehensive study examining the combined impact of land subsidence and climate change, which is essential for a comprehensive understanding of the complex mechanisms underlying the recurring occurrences of flooding and

erosion in the delta (Appeaning et al., 2018). The DECCMA team evaluated hazards and vulnerabilities to climate change in the Volta Delta. The findings show that the risk levels vary from medium to high, with water bodies posing a relatively lower risk. The highest-risk districts are mainly situated in the Volta Delta. It is however important to understand the various driver directing the current evolution of the Volta Delta. This study holds significance in understanding and tackling challenges within the Volta Delta, ensuring the effective deployment of suitable measures for risk management and adaptation.

Limitations

While the primary goal of this investigation was successfully met through the fulfillment of the three main objectives and resolution of the five research questions, certain constraints were encountered as outlined as follows:

- In the study, about 414 SAR images were used for the entire study area, each with a size of approximately 8 Gigabytes for InSAR processing. This required a high-specification Personal Computer (PC). Ideally, InSAR products have higher coherence when the time intervals between image acquisitions are shorter, typically within a 6-day cycle. However, due to limitations in PC specifications, a smaller number of SAR images with wider acquisition intervals (days) were processed in batches, resulting in lower overall coherence of the final products. To improve coherence, it is recommended to use a larger number of SAR images with six-day intervals between acquisitions for subsequent InSAR processing.
- A limitation of the current approach lies in the geometries of the satellite data used, which primarily capture vertical movements and

do not adequately account for horizontal movements within the study area. To overcome this, it is recommended to employ both ascending and descending geometries in subsequent InSAR processes. This will enable a more comprehensive analysis of land movements in different directions.

- Utilizing a Differential GPS survey is vital for confirming or substantiating the deformation rates obtained from remote-sensing InSAR analysis. Nonetheless, due to the inaugural nature of this research, there was a lack of readily accessible GPS data to verify subsidence rates.
- The Digital Elevation Models (DEMs) used to estimate topographical changes and project bathtub Relative Sea Level Rise (RSLR) had a resolution of 90 meters, which could not mask smaller-scale topographical variations.
- The study relied on regional or global data for hydrodynamic parameters such as tide, waves, and atmospheric conditions. Using such data may introduce inaccuracies in the findings.

Definition of some terms

Land Subsidence: Subsidence refers to the gradual sinking or settling of the Earth's surface caused by natural or human-induced factors such as tectonic activity, groundwater or hydrocarbon extraction, and sediment compaction.

Coastal flooding: Coastal flooding occurs when water from the ocean or other bodies of water inundates coastal areas, temporarily submerging the land. It is

typically caused by events like storm surges, heavy rainfall, and rising sea levels.

InSAR: InSAR (Interferometric Synthetic Aperture Radar) is a remote sensing technique that uses radar images acquired from space to measure precise ground surface deformations. It involves comparing the phase differences between radar images to create interferograms that reveal surface elevation changes.

Interferogram: An interferogram is an image produced by interferometric techniques like InSAR. It displays the phase differences between radar images, allowing the detection of ground surface deformations.

Phase: Phase, in the context of remote sensing, refers to the measured difference in the wavefront of radar signals. Phase information is used in interferometric techniques to determine changes in surface elevation or displacement.

Sea level rise: Sea level rise refers to the long-term increase in the average level of the Earth's oceans, primarily caused by climate change-induced thermal expansion of seawater and the melting of ice caps and glaciers.

Relative sea level rise: Relative Sea level rise refers to the change in sea level relative to the land surface at a specific location, considering both changes in ocean level and changes in land elevation.

Orthophoto: An orthophoto is a geometrically corrected aerial photograph or satellite image that accurately represents the Earth's surface, typically used as a base map in mapping and surveying applications.

Digital Elevation Model (DEM): A Digital Elevation Model (DEM) is a digital representation of the Earth's surface topography, consisting of a grid of

elevation values that allows for the visualization and analysis of terrain characteristics.

Bathtub model: The bathtub model is a simplified representation of coastal flooding that assumes a constant sea level rise. It compares the gradual increase in sea level to the filling of a bathtub, illustrating how lower-lying areas become submerged over time.

General Methodology (including the Study Area)

The investigation of the evolution of morphodynamics in the Volta Delta of Ghana has been ongoing even though major processes such as subsidence have not been considered. This research is built upon that premise. Furthermore, there has been limited assessment of how subsidence and sea level rise interact. Understanding this interaction is crucial to fully grasp the complex processes driving flooding and coastal erosion in the delta over different time scales.

The study employed specific research methodologies;

- a) The Interferometric Synthetic Aperture Radar (InSAR) method, was employed in this study. Interferograms displaying land deformation rates were created by processing 138 Single Look Complex (SLC) Sentinel-1A images, with each image covering one of three sub-swaths spanning the entire study area. These images spanned from January 2015 to December 2021, encompassing a six-year timeframe. Additionally, flood simulations were conducted to assess the impacts of relative sea level rise and various sea level rise scenarios using a basic bathtub model across multiple projected timelines.
- b) Secondly, to assess the predominant oceanographic factors affecting the Volta Delta using Keta municipality as a case study; the study used a tri-stereo

photogrammetry approach to derive a satellite-based DEM and Extreme coastal water levels. This study specifically utilized parameters such as Sea Level Anomaly (SLA), Wave run-up (R), tide (T), and other atmospheric conditions (DAC). All these parameters were referenced to the WGS84 datum. The tide data was extracted from the global tide FES 2014 model. The Atmospheric pressure and winds component (DAC), Altimetric-derived SLA were downloaded using AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic) data with the support of the Centre National d'Etudes Spatiales (CNES). All Wave run-up data were obtained from ERA-Interim reanalysis, which provides global climate and weather data from 1979 onward at a resolution of $0.5^{\circ} \times 0.5^{\circ}$.

c) Ultimately, the investigation involved assessing the application of SAR-derived DEMs for monitoring temporal beach alterations, with the Volta Delta serving as a focal point; the study utilized In-SAR techniques to generate DEMs, followed by a thorough evaluation involving comparisons and corrections with FABDEM data. With the Volta Delta of Ghana as a case study, all Sentinel-1 DEMs were corrected with FABDEM.

Organization of the Study

This thesis comprises six (6) chapters, including the list of references and appendices. Chapter 2 reviews the literature on deltas and the application of remote sensing techniques for coastal monitoring, a brief background on the Volta Delta, the exposure of the delta to coastal hazards and the role of subsidence, the natural and human-induced drivers of subsidence, its impacts and methods of detection. Chapter 3 estimates subsidence rates in the Volta Delta using the InSAR technique while simulating the delta's flood risk exposure. Chapter 4 uses Keta municipality as a case study to assess the predominant oceanographic factors affecting the Volta Delta. Chapter 5 explores the use of SAR-derived DEM for temporal beach changes using the Volta Delta as a case study. Finally, Chapter 6 synthesizes the research findings with conclusions and recommendations for prospective studies.

CHAPTER TWO

LITERATURE REVIEW

Introduction

Deltas

Deltas are unique coastal systems that are intricately connected to both land-based fluvial and coastal processes, making them naturally dynamic. However, defining the area of a delta can be challenging due to its depositional nature, which often lacks a distinct and identifiable boundary (Nicholls et al., 2007). The complexity of deltas make them difficult to manage since they are highly sensitive to multiple drivers and can undergo co-evolution and lock-in. Deltas can be defined in several ways, including identifying the farthest upstream distributary or the expanse of Holocene sediments (Laignel et al., 2023). In essence, deltas are created by a river's entry into a body of water. Alternatively, a broader definition characterizes deltas as coastal deposits of sediment from rivers situated near or in direct proximity to the originating stream. Deltas consists of three main geomorphic environments of deposition: the subaerial delta plain dominated by river processes, the delta front where the river and basinal processes interact, and the delta which is primarily muddy (Posamentier & Walker, 2006). Deltas can be found on all continents and in all climates, with Southeast Asia having the highest delta hotspot density. Caldwell et al. (2019) identified 2174 deltas globally based on the extent of geomorphic activity created by deltaic channel movement and progradation while considering eight environmental variables (Caldwell et al., 2019). However, most coastal deltas result from the accumulation of sediment carried by the river and deposited at its mouth, typically made up of sand, silt, and clay. The accumulation of

sediment gradually builds up over time, creating new land. The size and shape of a delta are influenced by several factors, including the type and quantity of sediment, the river's flow rate, and the intensity of tides and waves in the coastal environment. Deltaic environments are home to a variety of habitats, such as wetlands, mudflats, and shallow-water areas, which provide important ecological services such as filtering pollutants, supporting fisheries, and protecting shorelines from erosion. Deltas are crucial for human settlement and development, as they provide fertile soils for agriculture and support various economic activities, such as fishing, oil and gas extraction, and shipping. However, deltas face several natural and human-induced threats, including sea-level rise, subsidence, sediment depletion, and land use change.

Formation of Deltas

Most of the world's current deltas began forming in the lower Holocene period, around 6500 to 8000 years ago, when the rate of sea-level rise slowed down, allowing for fluvial sediment loads to accumulate along many coasts (Ericson et al., 2006). Although various factors like tectonic displacement, climate, and basin morphology contributed to their formation, the significant decrease in sea-level rise appears to be the primary factor (Anzidei et al., 2014). Deltas are complex and dynamic systems, shaped by interconnected processes, and extensively studied in contemporary and prehistoric sequences. However, their shape and stratigraphy are highly variable due to factors such as tectonics, eustasy, basin geology, and climate. Deltas form at the interface between land and sea, where large rivers deposit sediment loads, creating broad coastal plains. As rivers approach their mouths, their velocity and carrying capacity decline, leading to the accumulation of sediments and the formation of a deltaic

lobe. The size and shape of a delta are influenced by factors including sediment composition, volume, river flow speed, and coastal conditions. While modern deltas can include outside sediments from currents or wave changes, their ability to maintain sediment is vital for their resilience in the face of climate variations and rising sea levels (FitzGerald et al., 2008).

A delta is a landform shaped by the convergence of a river and a larger body of water like an ocean or lake. Its creation spans thousands of years and hinges on factors including the river's sediment load, wave and tide strength, geographic and geological features, and sea-level fluctuations. The process involves sediment deposition as the river slows down, leading to the gradual accumulation of land near the river mouth (Nicholls & Tol, 2006). This sediment buildup forms distinct channels and landforms, often shifting due to changing dynamics. Erosion, subsidence, and human activity further influence the delta's evolution, making it a complex and dynamic feature crucial for coastal ecosystems and landscapes. Over time, as sediment continues to deposit, multiple channels or distributaries emerge, which eventually spread and fan out into the water body. These channels become more intricate, and sediment accumulates around them, ultimately forming a delta. The shape of the delta depends on various factors, such as the volume and sediment load of the river, the slope of the land, and the strength of the tides and waves. Deltas can have different shapes, including fan-shaped, bird's foot, or cuspate. Deltas are dynamic environments that undergo continuous transformations through physical processes like erosion, deposition, and subsidence. The sediment and nutrients carried by rivers play a significant role in the formation and preservation of deltaic plains (Bianchi & Allison, 2009). Over time, deltas can

develop into highly productive ecosystems, supporting diverse habitats like wetlands, mudflats, and shallow-water areas. These ecosystems provide several ecological services, including filtering pollutants, supporting fisheries, and protecting shorelines from erosion. Most of the present-day deltas started forming during the Holocene epoch, between 6500 and 8000 years ago when the rate of sea-level rise slowed down.

The creation of Holocene deltas is ascribed to various elements including tectonic shifts, climatic conditions, drainage-basin structure, and basin composition. However, the most prominent factor seems to be the reduction in the rate of rising sea levels. Deltas represent ever-changing settings, undergoing constant alteration due to interlinked physical processes guided by diverse aspects like tectonic activity, global sea level fluctuations, basin geological properties, and climatic patterns. These combined influences give rise to the diverse forms and layering found within deltas (Syvitski et al., 2022). A range of favorable and ideal variables, including the ability to retain sediment, is necessary for the development and preservation of deltas in the face of climate change and sea-level rise. Deltas are crucial environments for the formation of highly productive coastal plains that support diverse habitats, provide essential ecological services, and play a significant role in the global carbon cycle. Extensive research on contemporary and prehistoric delta sequences has led to a better understanding of the critical processes and facies present in deltaic environments.

Classification of Deltas

Deltas, formed at river mouths, have diverse traits and can be categorized by different methods. Various classification systems are employed, as outlined below:

I. Deltas can be categorized based on the primary processes that shape their formation:

- a. River-Dominated Deltas: These deltas are shaped by the dominant influence of rivers, characterized by a high influx of sediment and the deposition of coarse-grained materials. Examples of river-dominated deltas include the Nile Delta and the Mississippi Delta.
- b. Wave-Dominated Deltas: In these deltas, the shaping forces of waves and tidal actions play a significant role. They tend to possess smoother coastlines and finer-grained sedimentary deposits. The Ganges Delta and the Rhine-Meuse Delta exemplify wave-dominated deltas.
- c. Tide-Dominated Deltas: These deltas are extensively impacted by tidal currents and typically form in regions with substantial tidal ranges. The Amazon Delta and the Brahmaputra Delta serve as illustrations of tide-dominated deltas.

II. Deltas can be classified based on their shape:

- a. Arcuate Deltas: These deltas exhibit a curved or semicircular shape and are typically found in regions with moderate wave and tidal energy. Examples of arcuate deltas include the Nile Delta and the Indus Delta.
- b. Bird's Foot Deltas: These deltas feature multiple distributaries that extend into the sea, resembling the shape of a bird's foot. The

Mississippi River Delta and the Ebro Delta are examples of bird's foot deltas.

- c. Cuspate Deltas: These deltas have a triangular or pointed shape and are often formed in areas with strong waves and tidal energy. An example of a cuspate delta is the Tiber Delta in Italy.

Based on Sediment Discharge:

- a. High Sediment Discharge Deltas: These deltas are formed in regions with significant sediment supply from the river, resulting in rapid accumulation and extensive land growth. The Mekong Delta and the Yellow River Delta are examples of high sediment discharge deltas.
- b. Low Sediment Discharge Deltas: These deltas are formed in areas with lower sediment supply, leading to slower land accumulation and less extensive growth. The Nile Delta and the Niger Delta are examples of low sediment discharge deltas.

IV. Deltas can be classified based on their geological age and developmental stage:

- a. Active Deltas: These deltas are currently undergoing deposition and substantial land growth due to ongoing sedimentary processes. Examples of active deltas include the Amazon Delta and the Ganges-Brahmaputra Delta.

- b. Abandoned Deltas: These deltas were previously active but have stopped growing due to alterations in river courses or fluctuations in sea levels. The historical distributaries of the Mississippi River Delta provide an example of an abandoned delta. It's important to note that some deltas can exhibit characteristics of multiple classifications, making them

complex and dynamic landforms. The classification of a delta may also evolve due to geological, environmental, or anthropogenic influences.

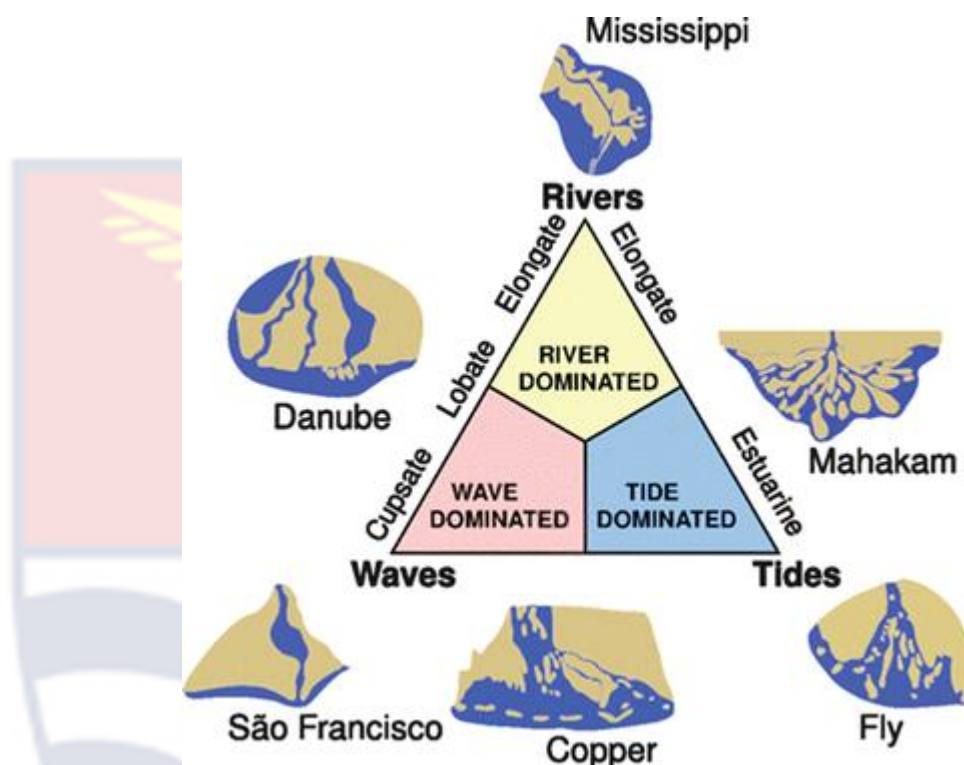


Figure 1: Types of Deltas based on their formations. (Brown and Nicholls, 2015).

Major Challenges and Factors Affecting Deltas

Deltas encounter a range of difficulties that can impact their stability and duration (Brown and Nicholls, 2015). These obstacles include the rise in sea levels, which leads to land erosion and submersion, resulting in the loss of habitats, displacement of populations, and a decline in economic activities (refer to Figure 2). Both natural and human-induced land subsidence can also heighten the vulnerability of delta regions to flooding and submergence. Additionally, human interventions like the construction of dams, reservoirs, and other activities can disrupt the natural flow of sediment to the delta, causing erosion and land loss (Anthony et al., 2015). Deltas are also susceptible to

natural disasters such as floods, tropical storms, hurricanes, and tsunamis. Human activities such as urbanization, industrialization, agriculture, and mining contribute to pollution, destruction of habitats, and changes in land use (Overeem & Brakenridge, 2009). The challenges faced by deltas are further compounded by the effects of climate change, which intensify existing issues. Addressing these multifaceted challenges requires a comprehensive and inclusive approach that considers the intricate interactions between physical, ecological, social, and economic factors (Brown and Nicholls, 2015). Effective management of deltas necessitates collaboration among various stakeholders and the implementation of adaptable and integrated strategies. To ensure the sustainable development and resilience of deltas, it is crucial to have a comprehensive understanding of these challenges and to adopt proactive measures. By doing so, we can work towards overcoming these obstacles and safeguarding the future of deltas.

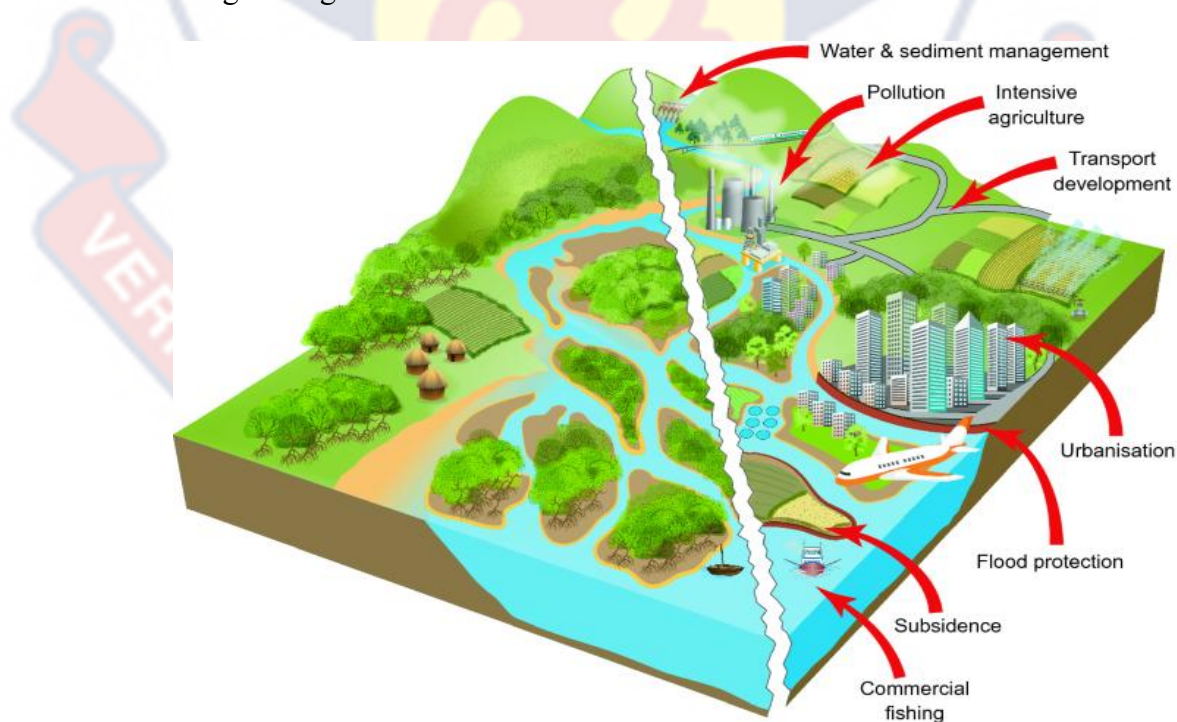


Figure 2: Anthropogenic and Natural factors affecting deltas (Brown and Nicholls, 2015)

Application of Remote Sensing in Coastal Environments

Remote sensing plays a crucial role in the monitoring and management of coastal environments (Klemas, 2009; Silva et al., 2008). It offers valuable applications that contribute to understanding and protecting coastal areas.

Firstly, remote sensing (refer to Figure 3) enables the continuous mapping and monitoring of coastal features, such as wetlands, beaches, and seagrass beds (Klemas, 2013). This provides essential information regarding their spatial distribution and changes over time. Secondly, by analyzing remote sensing data, changes in coastal ecosystems, including erosion, pollution, and invasive species, can be identified and tracked (Huang & Asner, 2009).

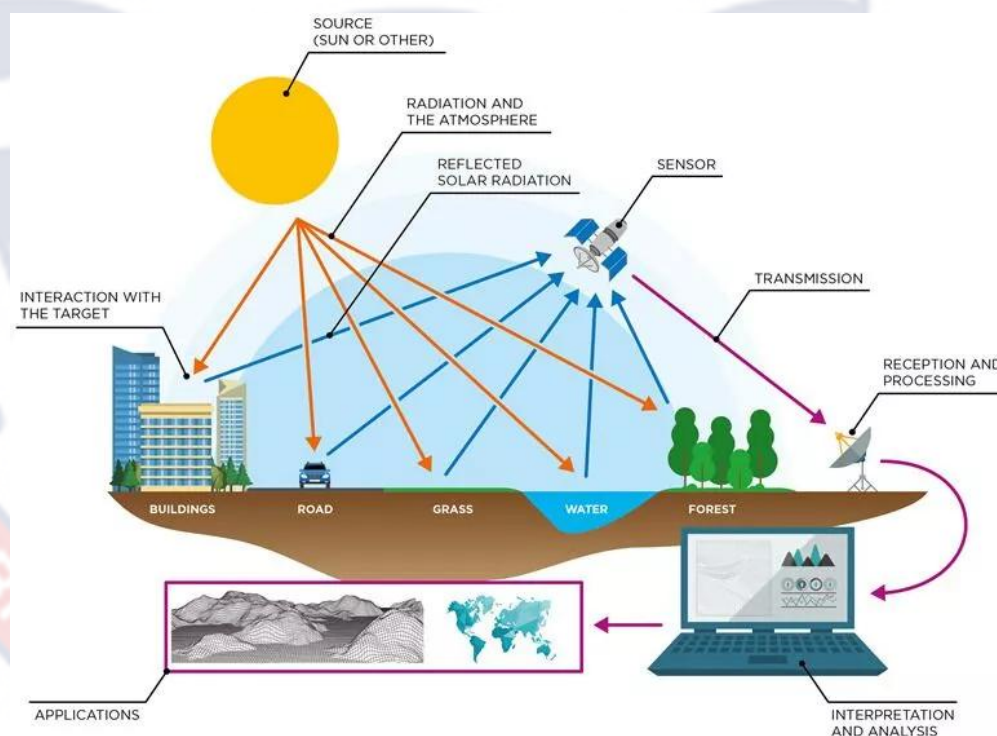


Figure 3: Schematic diagram of how remote sensing operates
Source: <https://geolearn.in/the-basic-concept-of-remote-sensing>

This information is vital for effective ecosystem management and conservation efforts. Additionally, remote sensing allows for the monitoring of various water quality parameters in coastal areas, such as salinity, turbidity, and chlorophyll

concentration (Erena et al., 2019; Mohseni et al., 2022). This facilitates assessing water health, identifying pollution sources, and implementing appropriate remedial actions. Moreover, remote sensing plays a critical role in predicting the impacts of climate change on coastal regions (Figure 4).

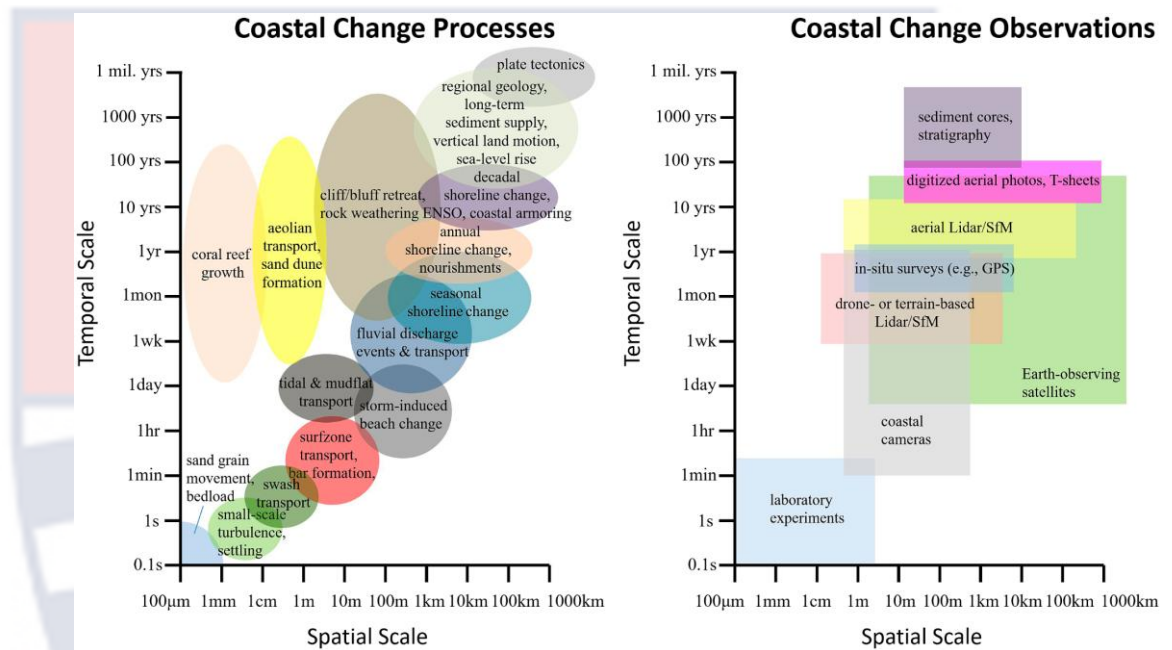


Figure 4: Spatio-temporal distribution of remote sensing approaches used for coastal studies. Source; Vitousek et al. (2023)

It enables the assessment of potential effects, such as sea-level rise and storm surge, thereby facilitating proactive planning and adaptation strategies. Remote sensing data significantly contributes to coastal planning and management activities. It supports the development of coastal infrastructure, conservation of coastal resources, and efficient response to coastal disasters by providing accurate and up-to-date information. Remote sensing data is collected through various platforms, such as satellites, aircraft, and ground-based sensors (refer to Figure 3). The selection of the platform depends on specific requirements, with satellites covering larger areas and aircraft providing higher resolution for smaller areas. The collected remote sensing data is then transformed into

diverse products, including maps, images, and three-dimensional models. These products play a crucial role in decision-making processes related to coastal development, resource management, and disaster response.

The importance of remote sensing in coastal environments is evident through its specific applications, such as mapping and monitoring coastal wetlands, identifying changes in coastal ecosystems, monitoring water quality, predicting climate change impacts, and facilitating coastal planning and management. This powerful tool is actively utilized by coastal managers, scientists, and policymakers to make informed decisions and safeguard these vital ecosystems.

Major Coastal Processes that affect deltas

The ever-changing nature of deltas results from various coastal processes that influence their development and stability. Processes like land subsidence, sediment transport, and rising sea levels not only shape these areas but also increase their vulnerability. These factors work on different scales, creating significant challenges in managing and protecting the ecological and socio-economic roles of deltas.

Land Subsidence

Land Subsidence as a Contributing Factor to Relative Sea Level Rise.

Land subsidence plays a significant role in the increase of relative sea levels. This phenomenon refers to the gradual sinking or settling of the Earth's surface, resulting in a decline in elevation relative to sea level. As land subsides, it effectively raises the sea level above the land (Higgins, 2016a).

Subsidence arises from various natural or human-induced processes within the subsurface. It is especially prominent in deltaic areas, influenced by a range of natural factors that can be exacerbated by human activities (Brown and Nicholls, 2015).

These elements can lead to either the elevation of land, the sinking of land, or a blend of both outcomes (Figure 5).

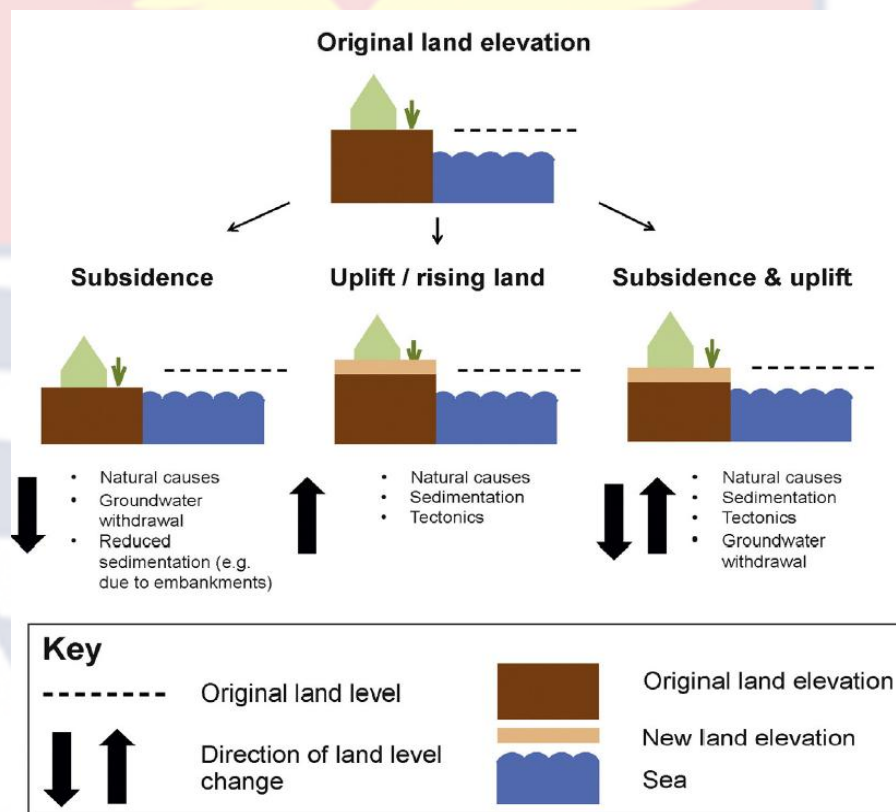


Figure 5: Vertical Land Movement due to uplift and subsidence.
(Brown & Nicholls, 2015)

Coastal subsidence significantly affects geological, ecological, and geomorphological dynamics, particularly about rising sea levels. The combined impact of eustatic sea-level alterations and subsidence is referred to as relative sea-level rise (RSLR) as per Ericson et al. (2006). People residing in low-lying coastal regions are confronted with potential hazards due to the combined consequences of sea-level rise and subsidence.

Tessler et al. (2018) stated that localized land surface subsidence is accelerating the rate of relative sea-level change. According to projected sea-level rise scenarios, there could be a 50% increase in the proportion of deltaic regions vulnerable to coastal flooding (Edmonds et al., 2020). The combination of relative sea-level rise (RSLR) and subsidence poses risks to low-lying areas, causing permanent flooding, intensified episodic inland floods, coastal erosion, and saltwater intrusion. Notably, large deltas experience an average annual RSLR of 6.8 mm/yr. Recognizing subsidence impacts is essential for informed land use, flood prevention, restoration planning, cultural heritage preservation, and resident protection (Da Lio & Tosi, 2018; Syvitski et al., 2009). To gain a comprehensive understanding of subsidence, it is necessary to consider the diverse factors that contribute to it, which can be broadly classified as natural and anthropogenic.

Factors Contributing to Land Subsidence

Hawkins (2005) identifies four primary types of land subsidence based on their origins: (a) voids formed by human-made or naturally present cavities near the surface (coal or stone mining); (b) extraction of fluids from deeper layers (water or oil extraction); (c) dissolution of soluble minerals in groundwater; and (d) the elimination of suspended fine particles (piping). However, the drivers of land subsidence can be broadly classified into natural and anthropogenic factors (Figure 6). While some of these drivers, mostly of natural origin, have limited impacts on human settlements and livelihoods due to their long temporal scales, human-induced drivers can cause local and regional-scale subsidence with high spatial variability over relatively shorter timeframes (Hawkins, 2005).

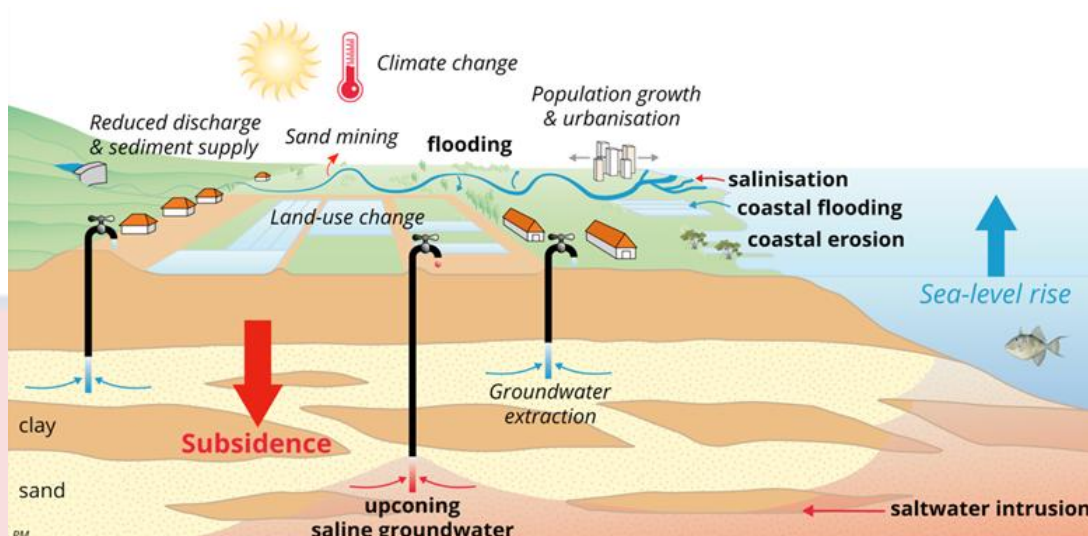


Figure 6: Factors contributing to land subsidence. Source: (Delta Alliance Secretariat, 2020)

Natural Drivers of Land Subsidence

Local and Basin Tectonics

Deltas located in basins undergoing subsidence have shown growth over the Holocene period due to gradual tectonic activities. The influence of tectonic settings on delta systems, while not extensively studied, presents significant possibilities for research (Goodbred & Kuehl, 2000). Tectonic movements encompass various scales, from broad to regional and intermittent processes.

The subsidence observed in such regions is primarily linked to plate-driven tectonic activities occurring across large geographic expanses. Areas with active faults (refer to Figure 7), hinge zones, or volcanic activity experience subsidence due to tectonic or volcanic processes (Aboudou Ango et al., 2023; Buiter et al., 2023).

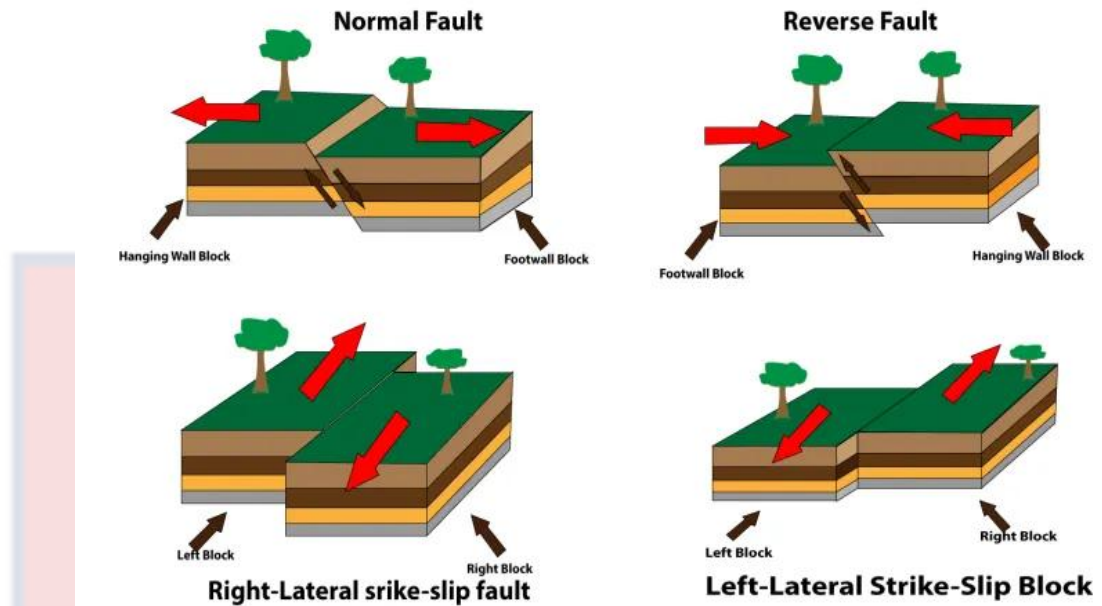


Figure 7: Crustal movement along a normal fault. Source: (Teixeira, 2023).

Isostasy

Isostatic adjustment refers to the Earth's crust reacting viscoelastically to changes in overlying material distribution. Deltas experience sediment-induced depression, leading to notable subsidence rates, up to 8 mm per year. Cyclic loading of surface and groundwater can cause vertical elastic deformation. Climate-driven ice and ocean redistribution additionally affect earth's shape. Isostatic adjustment is driven by density, rheology, and loading history variations, resulting in buoyancy forces that reshape the landscape (Shirzaei et al., 2020).

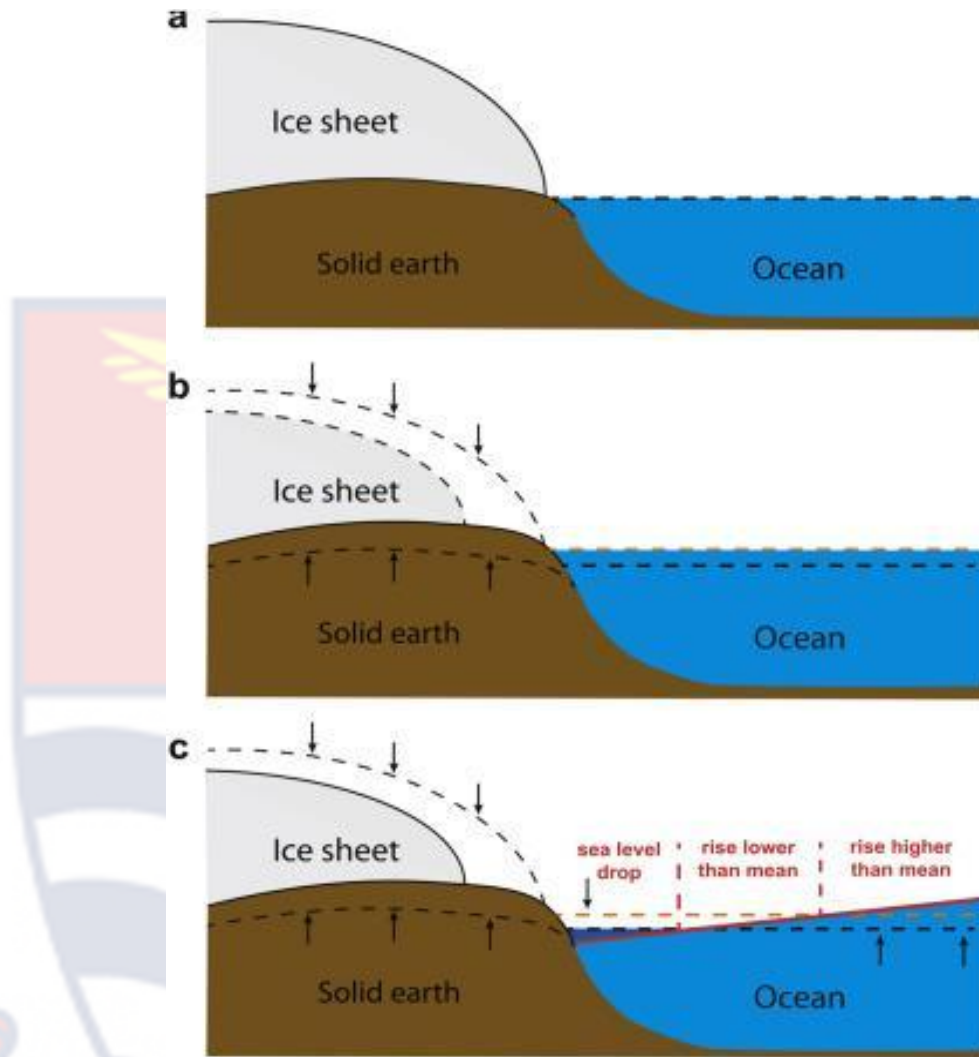


Figure 8: Isostatic land deformation explained briefly (De Boer et al., 2017).

Natural Loading and Compaction

Land subsidence occurs due to the gradual compression of compressible materials, causing uniform sinking rates, particularly in cohesive quaternary soils. The sinking of land, typically at rates lower than a few millimeters per year, is caused by mechanisms such as the drainage of pore fluids and the rearrangement of grains. This sinking results from the gradual compaction of compressible deposits due to greater load stress and drainage, and its extent is impacted by the surface geology. Especially prone to this process are cohesive Quaternary soils located in alluvial, lacustrine, or shallow marine environments.

These soils are particularly vulnerable due to factors like added material weight, the consolidation of sediment, or the upward shift in sea levels. This compression encompasses two processes: the expulsion of pore fluids and the reconfiguration of sediment particles into a denser formation. The expulsion of fluids leads to a decrease in volume and collapse, primarily occurring in fluvial deposits as the arrangement becomes more tightly compacted when pore pressure falls below the load pressure (Chaussard et al., 2013; Teatini et al., 2011; Syvitski et al., 2009; Yuill et al., 2009)

Natural Oxidation

River delta sediments contain a variety of materials including sands, silts, clays, and peats. In alluvial deposits saturated with water, organic matter decomposition occurs without oxygen, resulting in a faster accumulation rate than decomposition (Vegas-Vilarrúbia et al., 2010). However, in dry conditions, especially with peat, oxidation happens, releasing CO₂ into the atmosphere. This results in significant land sinking, characterized by loss of volume, soil compression, and subsidence due to carbon depletion (Hooijer et al., 2012; Koster et al., 2018; Rodriguez et al., 2021; Schmidt, 2015).

Anthropogenic Drivers of Land Subsidence

Fluid and Solid Extraction

The removal of groundwater or fluids during the extraction of natural resources triggers substantial land subsidence as it lowers pore pressures and induces contraction in sedimentary layers (Huang & Asner, 2009). Subsidence rates can escalate to several centimeters annually, particularly when fluids are withdrawn swiftly. The magnitude of subsidence fluctuates based on land utilization.

Mining, tunnelling, and drawing groundwater from deeper aquifers can also induce subsidence, compacting aquifer systems and posing hazards to infrastructure stability, surface disruptions, and heightened susceptibility to coastal flooding (Tomás et al., 2014).

Sediment Starvation

Deltas, which rely on the continual supply of sediment from upstream areas to counteract natural compaction, are facing challenges due to human activities that impede sediment replenishment, such as the construction of dams, levees, embankments, and coastal defense structures, as well as dredging activities (Hudson, 2021; Loucks, 2019). These interventions seize sediment, disrupt the inherent process of land accretion, and disturb the equilibrium that upholds the proximity of land elevation to sea level in pristine delta regions. Global assessments propose that a significant volume of sediment becomes retained upstream due to the presence of numerous large dams. This alteration in water course impedes the progress of roughly one-third of the sediment from reaching the coastal zone. This reduction in sediment conveyance poses a risk to deltaic ecosystems and their ability to independently sustain their health and stability (Raff et al., 2023; Zoccarato et al., 2018).

Land Drainage

Substantial coastal land subsidence manifests in areas once characterized by marshes and lagoons but subsequently reclaimed for agricultural use. This subsidence is principally driven by the compaction of recently deposited unconsolidated sediments and the reduction in ground elevation attributed to the oxidative degradation of peaty soils resulting from hydraulic reclamation

and agricultural practices (Canova et al., 2012; Choudhury et al., 2021). The depletion of groundwater levels by human activities in peat-rich coastal-deltaic plains has led to significant land subsidence and the release of carbon dioxide (CO₂) emissions in various locations, including the Venice Lagoon, Mississippi Delta, and Sacramento Delta (Koster et al., 2018). The drainage of wetlands for agriculture accelerates the oxidation of organic matter in the soil, leading to subsidence rates that surpass natural geological rates (Schipper & McLeod, 2006). This phenomenon encompasses the reduction of the groundwater level, initiating both the compression and aeration of the subjacent soil. This sequence ultimately leads to a reduction in volume, driven by the decomposition of organic matter.

Relative Sea Level Rise Effects On Delta

Relative sea level rise denotes the elevation increase in the mean oceanic surface concerning the contiguous landmass during a specified temporal interval. This phenomenon is predominantly steered by two key influencers: the global elevation of sea levels and the vertical oscillations in land position. The amplification in global sea levels is attributed to the thermal expansion of seawater due to rising temperatures and the influx of water ensuing from the dissolution of ice sheets and glaciers (Mimura, 2013; Nicholls et al., 2021). Conversely, vertical land motion can be subject to multifarious factors such as tectonic dynamics and alterations in the earth's lithospheric structure. The ramifications of relative sea level rise upon coastal human settlements are both noteworthy and diverse. A prominent outcome encompasses an escalated susceptibility to coastal inundation. Even minor increments in the mean sea level can engender more recurrent and intensified inundation incidents, thereby

inflicting harm upon infrastructure, precipitating property diminution, and necessitating the relocation of inhabitants (Nicholls et al., 2021).

Another repercussion stemming from the increase in relative sea level is coastal erosion. As the ocean extends its reach onto the land, it gradually erodes beaches, cliffs, and other coastal landforms. The rise in relative sea levels, driven by global sea level increase and vertical land shifts, has multifaceted implications for coastal communities. It heightens the risk of frequent and severe coastal flooding due to even minor elevations in average sea level, causing damage to infrastructure and property loss, alongside the displacement of residents. Additionally, this phenomenon triggers coastal erosion, gradually eroding beaches, cliffs, and coastal landforms, posing a dual threat by impacting natural environments and endangering human settlements and coastal infrastructure (Griggs & Reguero, 2021).

Moreover, the rise in relative sea levels bears significance for coastal ecosystems. The ingress of saline water into freshwater networks like rivers and aquifers holds the potential to influence both the quality and accessibility of water resources. This intrusion could further disturb the fragile equilibrium within coastal ecosystems, with potential repercussions for biodiversity and the sustenance of livelihoods reliant on fishing and tourism within these regions. As a response, coastal communities are enacting a range of strategies aimed at adapting to and alleviating the consequences arising from the increase in relative sea levels (Pramita et al., 2021). These include the construction of sea walls and levees to protect against flooding, beach nourishment projects to combat erosion, and the implementation of coastal management strategies to preserve and restore coastal ecosystems. Nevertheless, these strategies can

incur substantial expenses and might lack long-term viability. Land subsidence further contributes to the escalation of regional variations in relative sea level, heightening the likelihood of flooding, coastal erosion, saline water encroachment, and the depletion of wetlands and biodiversity. This array of challenges presents a complex predicament for residents inhabiting these regions (Wang et al., 2012). In summary, the rise in relative sea levels constitutes a substantial global challenge, carrying far-reaching consequences for coastal communities.

Inundation / Flooding

The sinking of land elevates the proneness to river-induced flooding and concurrently extends the coastal zones at risk of storm surges and tidal inundation, especially when compounded by variables like sea level rise, heightened precipitation, and severe meteorological events (Abidin, Andreas, Gumilar, & Brinkman, 2015; Chaussard et al., 2013; Irawan et al., 2021; Nicholls et al., 2021). The predicted elevation of sea levels amplifies the physical and societal impacts in regions prone to flooding (Cannon et al., 2020). The anticipated rise in sea levels intensifies the physical and societal consequences in areas susceptible to flooding (Cian et al., 2019; Mimura, 2013). The sub-Saharan African coast, with its approximately 148,000 km² of low-elevation coastal zone and a population of nearly 50 million, will be severely affected due to the combination of poverty, rapid urban growth, and the projected impacts (Cian et al., 2019). Moreover, the occurrence of flooding and enduring immersion plays a contributory role in the dissemination of vector-borne ailments such as cholera and malaria to inland areas, thereby compounding health vulnerabilities (Ntajal et al., 2022; Okaka and Odhiambo,

2018). Furthermore, the process of inundation can exacerbate coastal erosion by transporting submerged debris offshore, while also amplifying the impacts of coastal inundation by facilitating the penetration of storm-generated waves into greater inland distances (Appaning Addo et al., 2011).

Shoreline retreat and erosion

Coastal erosion and the recession of coastlines represent prominent ramifications arising from the escalation of relative sea-level rise (RSLR). The exact causes of coastal erosion, encompassing contributions from global warming, subsidence, and RSLR, pose challenges in precise determination. The morphology of a river delta's shoreline is shaped by the interplay of sediment accumulation, compaction, land movement, and fluctuations in sea levels (Gray, 2021).

Under conditions of steady sediment delivery and constant sea level, natural deltas can sustain a stable position in relation to the ocean. Nevertheless, the combined impacts of mechanisms linked to relative sea-level rise (RSLR) eventually culminate in coastal erosion and the withdrawal of coastlines. This is demonstrated in Figure 9 by Davidson-Arnott (2005) using the Bruun Rule (Nicholls, 2010; Higgins, 2016; Syvitski et al., 2009).

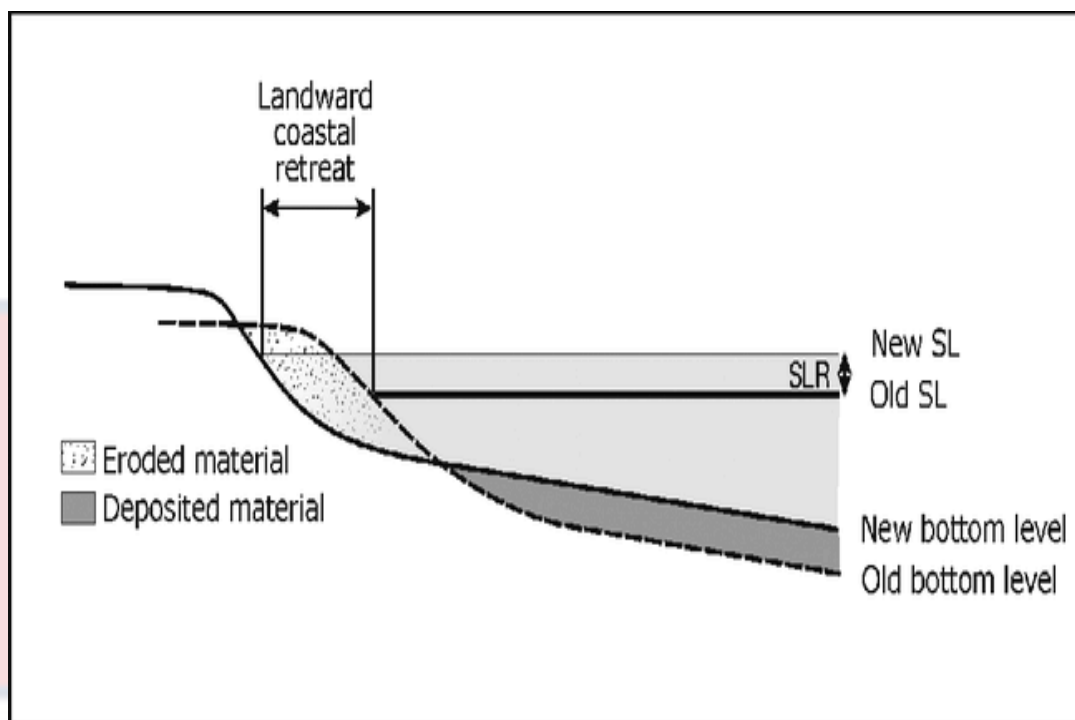


Figure 9: Simplified model of landward coastal retreat under SLR (based on the Bruun Rule) Source: Davidson-Arnott (2005)

The rising sea levels result in the erosion of sediment from sandy shorelines, which is then deposited on the nearby ocean floor (Figure 9). This phenomenon results in the gradual intrusion of the ocean onto coastal land or the withdrawal of beach areas, as elucidated by the findings of Appeaning Addo et al. (2011). Prevailing consensus suggests that the horizontal recession of shorelines is anticipated to outpace the vertical elevation of sea levels by a factor of 50 to 100, as articulated by Nicholls et al. in 2006. Presently, approximately 70% of the Earth's sandy coastlines are undergoing erosional processes, as empirically highlighted by Bird in 2008. Predictive models at a global scale prognosticate a substantial land diminution, with estimates ranging from 6,000 to 17,000 square kilometers by the year 2100. The envisaged escalation in global sea levels by the century's end is poised to induce the retrogression of sandy coasts by distances ranging from 4.5 to 88 meters across diverse geographical locales,

as meticulously detailed by Appeaning Addo et al., 2011 et al. in 2006. In regions characterized by subsidence phenomena, the ramifications of elevated sea levels will be exacerbated.

Wetland and Biodiversity Loss

Coastal areas, including essential ecosystems like mangrove forests, salt marshes, seagrass meadows, and macroalgal beds, are highly sensitive to changes and stresses due to their limited ability to adapt and recover independently. These ecosystems extend from the areas exposed during low tide to underwater zones. Rising sea levels are a major danger to coastal ecosystems, causing a drop in the benefits they provide, such as shielding against storms and offering habitats for young species. This situation can trigger significant social and economic shifts, especially in susceptible low-lying coastal areas (Carnero-Bravo et al., 2018; Lloyd et al., 2021). The consequences of elevated sea levels on coastal ecosystems encompass the perturbation and displacement of sediments, exposure to inundation, and interference with photosynthesis and respiration processes, particularly notable among submerged organisms and flora. This frequently leads to a state of excessive saturation in cells, surpassing their tolerance thresholds. Furthermore, the presence of rigid coastal fortifications constrains the landward migration of coastal ecosystems or habitats, effectively confining them between rising water levels and immovable barriers. This confinement results in a substantial reduction in the dimensions of saltmarshes and intertidal ecosystems (Lincoln et al., 2021). Wetlands, in deltas face increasing pressure from waterlogging and salinity stress when they cannot accumulate vertically at a rate that matches the rate of relative sea-level rise (Mazhar et al., 2022). The decline of wetlands and coastal ecosystems will

lead to the compromised functionality of these systems and the services they provide. Projections highlight a significant reduction in coastal wetlands, with estimates indicating that approximately a third of these wetlands could vanish when less than 40cm increase in sea-level occurs. This decline could further extend to impacting half of these wetlands if the sea level rises by 70cm (Newton et al., 2020).

Saltwater intrusion and the limited availability of freshwater resources.

The intrusion of saltwater presents a prominent ecological concern, particularly due to the substantial coastal population that relies on nearby aquifers as their water source (Abd-Elaty et al., 2021; Alfarrah and Walraevens, 2018). As sea levels rise, the hydraulic pressure along coastal margins becomes more pronounced, prompting the penetration of seawater into freshwater systems. Since a sea level increase of 1 meter corresponds to an approximate 40-meter reduction in freshwater thickness it cannot be taken for granted (Leuven et al., 2023). The variation in groundwater levels concerning local sea levels displays geographical diversity, a phenomenon shaped by localized land subsidence. This subsidence affects the boundary between saline and freshwater areas across a significant geographical range. As a result, the salinity within freshwater wells positioned distantly from submerged regions gradually increases over time.

Destruction of Infrastructure and Cultivated Land

Subsidence has notable effects, encompassing both direct outcomes like structural and infrastructural harm, and indirect consequences such as heightened risk of flooding and endangerment to human safety. Wu (2003)

explains that subsidence poses a risk to various structures such as bridges, roads, rail lines, storm drains, sewers, canals, levees, buildings, and pipelines, while also increasing the susceptibility to tidal flooding in coastal areas with low elevation (Wu, 2003). Elevating sea levels amplify the susceptibilities of regions situated at lower altitudes to flooding events, precipitating the eventual erosion and loss of previously reclaimed agricultural lands, alongside the destruction of infrastructure and buildings (Higgins, 2016a; Syvitski et al., 2009). Erosion exacerbates this situation by inflicting damage upon arable lands, while breaches in embankments frequently lead to inundations in agricultural domains, resulting in a notable reduction in overall productivity. Consequently, this complex sets of events lead to scarcities in food resources and decreased employment opportunities, with a particular emphasis on the adverse impact upon households with lower incomes. Beyond this, the intrusion of seawater yields deleterious effects on the quality of water, triggers processes of soil salinization, curtails microbial activity, and instigates the depletion of organic substances. As a cumulative effect, these factors conduce to the gradual attenuation of soil fertility.

Monitoring or Measuring Coastal Subsidence

Coastal subsidence can be monitored or measured using a variety of methods and procedures. Geodetic measurements, which use Global Navigation Satellite Systems (GNSS) and Interferometric Synthetic Aperture Radar (InSAR) to identify and quantify land-level variations over time, are one way. These measurements can provide useful information on subsidence rates and patterns. Another approach is to place tide gauges and continuous Global Positioning System (GPS) stations along the coast. Tide gauges monitor changes in sea

level, which might show subsidence indirectly if the land sinks relative to the sea. GPS stations can immediately track vertical ground movements, allowing the detection of subsidence. Remote sensing techniques such as satellite imaging and aerial photography can also be used. Thus, since subsidence in deltas is a complicated phenomenon that is influenced by several interconnected processes. To assess the consequences of these processes, which cut across conventional discipline boundaries, it is necessary to use techniques from sedimentology, solid-earth geology, oceanography, biology, hydrology, and engineering (Higgins, 2016b). The various techniques can be broadly divided into four categories: satellite-based, airborne, ground-based, and sea-based surveys (Mason et al., 2000). These approaches, accuracy level, costs, time frames, coverage, and the metrics they use vary (Appeaning Addo et al., 2008). As opposed to being integrated throughout numerous periods and spatial areas, many monitoring techniques simply record subsidence at a single location and point in time. To completely collect and define each subsidence component and make accurate predictions, it will be necessary to combine different approaches (Heleno et al., 2011; Teatini et al., 2012; Abidin, Andreas, Gumilar, & Wibowo, 2015; Fiaschi et al., 2018).

InSAR Technique as a Monitoring Tool

Since its introduction more than 30 years ago (Wang et al., 2019), SAR has found widespread application in Earth remote sensing, and its associated methods, including Interferometric SAR (InSAR), have assembled significant focus and appraisal within the scientific literature (Braun et al., 2021; Cian et al., 2019; Crosetto and Crippa, n.d.; Ferreira, 2014). InSAR is a remote sensing technique deploying radar waves to evaluate alterations in the Earth's surface

topography. Additionally, it serves as an active imaging sensor or radar apparatus fixed to an aircraft or artificial satellite, yielding intricate remote sensing visuals regardless of daylight or nocturnal conditions (Yastika et al., 2019). This method demonstrates its utility in tracking land subsidence and can be efficiently utilized under various weather conditions due to its operation within the microwave segment of the electromagnetic spectrum (Pepe and Calò, 2017). The InSAR technique operates by comparing multiple radar images of the same area captured at different times. Radar waves are emitted from a satellite towards the Earth's surface, and their reflections are recorded, including the phase information. Since the phase of radar waves is responsive to alterations in the space between the satellite and the Earth's surface, scrutinizing differences in phase between two images allows for quantifying surface shifts that transpired during those instances. The SAR data contains information about both the amplitude and phase of the radar signals reflected from the ground (Yastika et al., 2019). Through the utilization of multiple satellite orbits, the InSAR methodology extracts alterations in signal phase (interference) from two sets of SAR data gathered within the same area during distinct time intervals, as illustrated in Figure 10 (Erban et al., 2014; Pepe and Calò, 2017). As outlined by Yastika et al. (2019), the initial set of observed data is denoted as the "master," while the subsequent data is termed the "slave." InSAR evaluates land surface distortions by scrutinizing variations in phase between images captured at different time points while maintaining consistent observation geometry (Babae et al., 2020; Cian et al., 2019). The time series analysis of InSAR data is a vital tool in diverse realms of Earth observation research, facilitating the surveillance of changes occurring on the Earth's surface over varying time

spans. (Osmanoğlu et al., 2016). InSAR is highly effective at accurately measuring surface deformation over large areas, making it an essential tool for monitoring land subsidence.

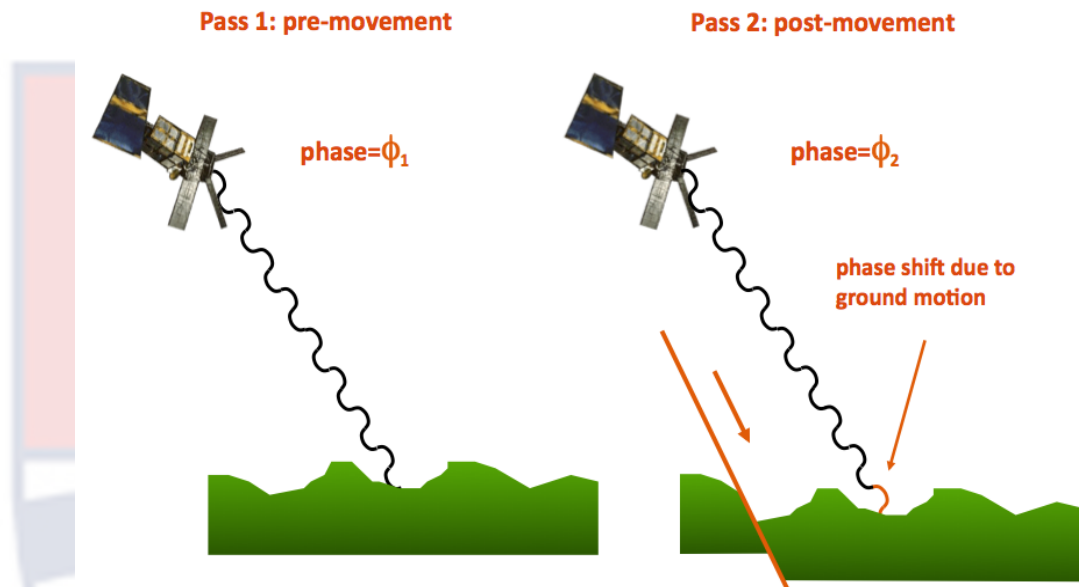


Figure 10: InSAR data acquisition principle. Source: Osmanoğlu et al. (2016)

Concerning InSAR for subsidence monitoring, there are several emerging techniques aimed at enhancing measurement accuracy and efficiency. These techniques include: One such technique is Persistent Scatterer InSAR (PS-InSAR). This method utilizes a subset of radar images known to be free of decorrelation to generate interferograms, thus improving the accuracy of subsidence measurements, particularly in regions with high levels of surface deformation. Another technique is Small Baseline Subset InSAR (SBAS). This approach involves the use of a subset of radar images with small baselines, which refers to the reduced distance between the satellite and the Earth's surface. By employing these radar images, SBAS mitigates the impact of atmospheric decorrelation and enhances the accuracy of subsidence measurements. Furthermore, the Multi-temporal InSAR technique is being

developed. This approach entails capturing a series of radar images over time and utilizing them to generate interferograms. By analyzing these interferograms, Multi-temporal InSAR enables the tracking of surface deformation over time and the identification of underlying causal factors.

In the field of regional monitoring, the remarkable effectiveness of InSAR analysis is evident through its wide spatial coverage and systematic data acquisitions (Taramelli et al., 2015). Researchers are particularly attracted to this method for two compelling reasons. Firstly, it provides a comprehensive depiction of deformation in two dimensions across distances that can span from tens to hundreds of kilometers. Secondly, it excels in measuring deformation with exceptional accuracy, primarily influenced by observable fluctuations in atmospheric conditions (Hanssen, 2001). This approach offers extensive opportunities for monitoring and studying a wide array of geological hazards. It enables the monitoring of earthquakes, volcanic activity, ice sheet dynamics, landslides, land subsidence, sinkholes, and numerous other phenomena (Ouchi, 2013; Crosetto et al., 2016; Osmanoglu et al., 2016; Fiaschi et al., 2018).

General Limitations of InSAR or DInSAR

Traditional InSAR constraints include atmospheric inhomogeneities, temporal and geometric decorrelation (Ferretti et al., 2001). One of the primary issues for InSAR is still separating deformation from atmospheric signals, which is brought on by the changing of atmospheric parameters in space and time (Hooper et al., 2013). Due to atmospheric phase artefacts that are challenging to eliminate from SAR interferograms, the accuracy of InSAR data may be greatly decreased (Tung & Hu, 2012).

Ionospheric and tropospheric effects are responsible for atmospheric delays, according to Bekaert et al. (2015). The differences in free electrons along the travel route that occur from ionospheric effects create a phase advance of the radar signal, which is more noticeable for longer wavelengths like P and L-band SAR. Tropospheric effects, on the other hand, result from differences in atmospheric conditions in the lower troposphere, which may sometimes result in signals in interferograms that are considerably bigger than the tectonic signals of interest and have a magnitude of up to 15-20 cm (Hooper et al., 2013; Bekaert et al., 2015). Additionally, the use of a large interferogram perpendicular baseline affects InSAR phase accuracy as well, where an increase in the perpendicular baseline increases the standard deviation of height measurements (Pepe & Calò, 2017).

Synthetic Aperture Radar Missions

More than fifteen (15) spaceborne SAR sensors are now operational, and several additional SAR systems are currently being developed or planned (Deng et al., 2012; Moreira et al., 2013; Wang et al., 2019), some of which are listed with attributes in Table 2.4. Data from these missions have been used for a variety of studies, however, Sentinel-1—offers highly frequent acquisitions with a consistent acquisition geometry (6-day repeating cycle)—constitutes a revolution in InSAR analysis, and can be accessed freely via the Copernicus Science Hub (<https://scihub.copernicus.eu/dhus/#/home>) (Cian et al., 2019).

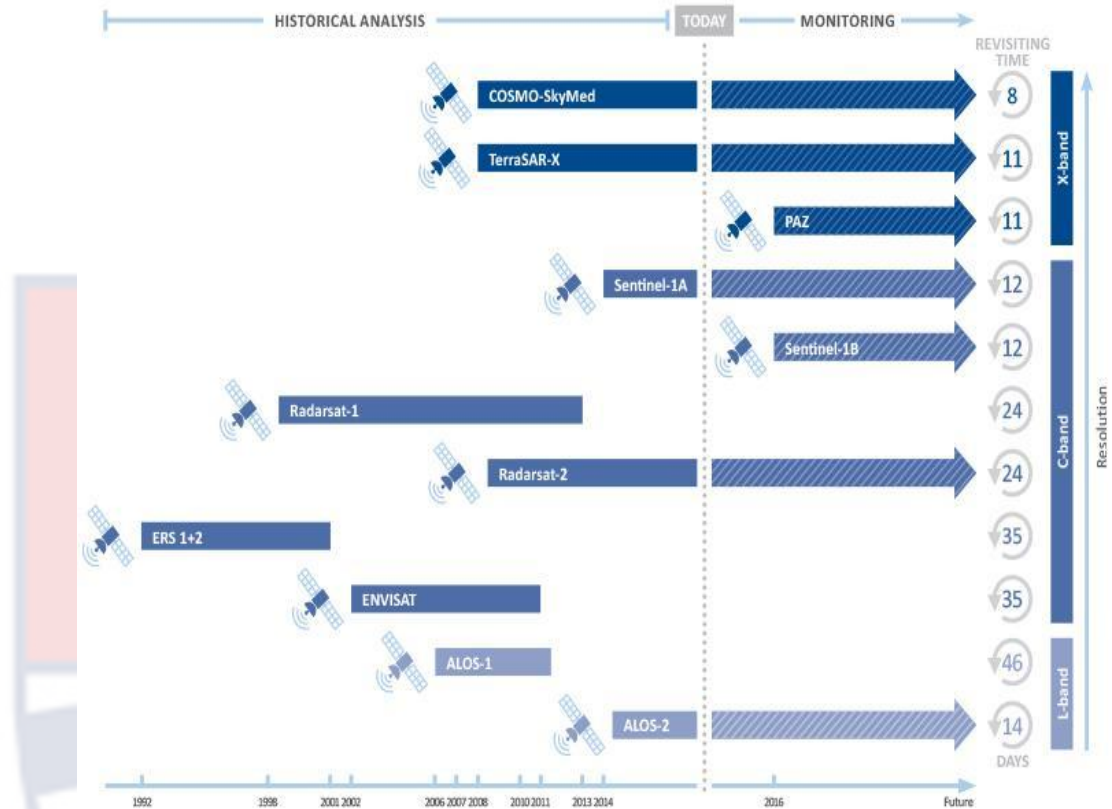


Figure 11: Land elevation changes due to uplift and subsidence (Brown and Nicholls, 2015)

Sentinel-1 Mission

The Sentinel-1 (S-1) satellites, which are routinely surveying the Earth's surface, provide useful information for monitoring deformation (Berger et al., 2012). For the primary acquisition mode, they offer C-band data consistency at a swath width of 250 km (Wegmüller et al., 2015). The sensor system repetition time of 6 days significantly enhances the temporal coverage compared to other datasets in the scientific community, and the data is freely available (van der Horst et al., 2018). The Sentinel-1 mission comprises two satellites: Sentinel-1A (S-1A) and 1B (S-1B) which were launched on 3rd April 2014 and 25th April 2016 respectively (European Space Agency, n.d).

Both satellites are positioned in a sun-synchronous, almost polar orbit at a height of around 693 km with the primary instrument being a 5.405 GHz C-band SAR (Sowter et al., 2016). The S-1 system was designed to provide medium-resolution applications with repeat-pass interferometric capabilities with unparalleled large area coverage (Torres et al., 2012). The novel Terrain Observation by Progressive Scans (TOPS) acquisition mode (De Zan and Guarnieri, 2006) is used to achieve wide-swath coverage, and it supports four imaging modes with varying resolution and coverage: Interferometric Wide Swath Mode (IW), Extra Wide Swath Mode (EW), StripMap (SM), and Wave (WV). Three and five subswaths of TOPS SAR modes are used to implement the IW and EW modes, respectively (Gonzalez, et al., 2016). The IW TOPS SAR data acquisition mode was used for this study and the acquisition process is shown in Figure 12 below:

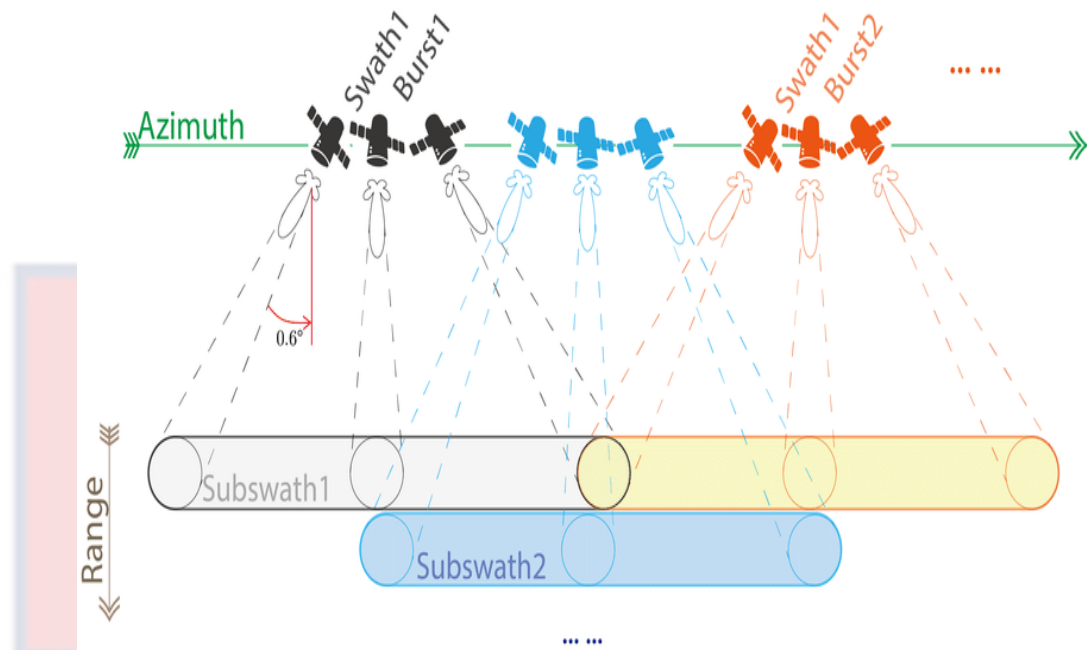


Figure 12 S-1 IW TOPS SAR data acquisition mode Source : Qin et al. (2018).

Global Positioning Systems as a Monitoring Tool

A more affordable technique to analyse ground deformations with precision up to a few millimetres in three dimensions was made possible in the 1990s with the advent of GPS, first Continuous (CGPS) and Differential (DGPS), and then Global Navigation Satellite System (GNSS) (Fabris et al., 2014). Yet, because of the significant expenses associated with equipment, site management, maintenance, and data analysis, this technology can only be applied in a constrained range of sites. The prevailing method for attaining precise real-world data continues to be traditional leveling and GPS technology, playing a vital role, such as in confirming and substantiating SAR-derived data (Fiaschi et al., 2018). There is a need to supplement remotely sensed data with other ground-based data due to InSAR's limitations (Gumilar, and Wibowo, 2015; Fiaschi et al., 2018; Teatini et al., 2012). Because InSAR can't fully capture erosion and deposition due to coherence loss and GPS is restricted in identifying

movements beneath sensor-mounted structures, using both techniques together is essential for a comprehensive approach (Higgins, 2016a). In areas with sediment deposition, particularly, ground-based measures of aggradation must be used in addition to GPS or InSAR (Higgins, 2016b). It is possible to calibrate PS data and eliminate systematic errors in SAR by using geodetic measurements from a few permanent GPS stations in the study region (Rucci et al., 2012). Static GPS techniques have the ability to quantify both horizontal and vertical alterations resulting from earth fissures and land subsidence, since they are capable of collecting accurate horizontal and vertical coordinates and therefore, in order for static GPS to achieve this level of precision, it might be necessary for each point to be observed for a minimum of 1.5 hours with the presence of at least 5 visible satellites (Ferguson et al., 2015). Other techniques involve utilizing archaeological methods, performing carbon dating, conducting geomorphic evaluations, taking measurements of landscapes, monitoring the levels of groundwater, studying neotectonics, and excavating tanks. These options represent a range of additional approaches.

Coastal Flooding and Inundation

Coastal flooding and inundation occur when water submerges coastal areas due to various factors such as storm surges, high tides, and sea-level rise (Figure 13). This naturally occurring event presents dangers to communities along the coast, as well as to ecosystems and structures. The severity of coastal inundation depends on how high the floodwater reaches inland, which is affected by the shape of the coastal terrain susceptible to flooding (Almar et al., 2021). Human-induced actions such as extracting groundwater in coastal areas can lead to land

sinking, elevating the potential for flooding hazards, also engineered protection structures like sea walls can disrupt natural beach processes and lead to erosion in adjacent areas, further increasing the risk of flooding. Inundation pertains to the volume of water that overtops dry land. Coastal regions experience inundation from various factors like unusually high tides, storm surges, continuous winds blowing towards the shore, and waves. In river and tidal estuary settings, excessive runoff from rainfall can also contribute to inundation. Remote sensing methods offer the capability to observe and chart coastal flooding and inundation, supplying crucial data for proficient management of hazards and readiness for disasters.



Figure 13: Significant climate change factors contributing to coastal flooding.
Source; Almar et al. (2021).

Significant contributors to coastal flooding

Sea level rise

Sea-level rise (SLR) caused by climate change and its effects on low-lying coastal areas has gained the attention of scientists, governments, and managers of coastal regions on a global scale (Church et al., 2013). Sea level rise poses a hazard to coastal ecosystems, diminishes ecological services, and may eventually result in significant socioeconomic changes, particularly in low-lying coastal ecosystems that are particularly sensitive (Carnero-Bravo et al., 2018). In the past two decades, the global average sea-level has increased by around 3.2 mm per year (Church et al., 2013). However, the rate of sea-level rise varies depending on the location due to specific factors in each area. According to the most recent projections from the Intergovernmental Panel on Climate Change (IPCC) (2021), increases in sea levels are anticipated to evidently exceed existing rates. These projections underscore an augmenting probability of elevated sea levels encroaching upon coastal zones, potentially fostering the intrusion of saltwater and the potential tainting of freshwater reserves from both surface and subterranean sources (Musa et al., 2015).

Moreover, the elevation of sea levels has the potential to result in deeper waters proximate to coastal shorelines, potentially inciting amplified wave and tidal dynamics, degradation of littoral landscapes, and the compromising of both infrastructure and ecological systems. Coastal ecosystems are additionally predisposed to heightened vulnerabilities as sea-level elevation engenders a decrease in biodiversity within these environments, ultimately converging towards noteworthy socio-economic shifts, particularly evident within coastal

ecosystems that are low-lying and susceptible to disturbances (Carnero-Bravo et al., 2018).

In a comparable manner, alterations in climate conditions also exert an influence on precipitation patterns, resulting in heightened rainfall occurrences within specified geographic regions. This phenomenon contributes to the inundation of river systems, consequently magnifying flooding incidents in coastal domains, as river discharges interact with these zones (Wahl et al., 2012). Moreover, episodes of intense precipitation can overwhelm drainage systems, fostering the accumulation of water and consequent flooding in coastal areas. Climate change further manifests its effects through storm intensity modulation. Elevated sea surface temperatures provide amplified energy for the initiation and amplification of potent storms like hurricanes, typhoons, and cyclones. Consequently, these heightened storms yield larger storm surges, engendering substantial coastal flooding upon their landfall (IPCC, 2022).

Collectively, climate-induced factors compound the severity of coastal flooding by intensifying the recurrence, magnitude, and geographical extent of flooding incidents. The enduring implications of climate change on coastal flooding introduce considerable complexities for coastal communities, ecosystems, and infrastructure. Tackling the ramifications of climate change, particularly pertaining to coastal flooding, necessitates the implementation of comprehensive strategies. These actions are essential for effectively combating and minimizing the effects of climate change (IPCC, 2022). Deltas, as a general phenomenon, are frequently impacted by climate change indicators including the rise in sea levels (Szabo et al., 2016), heightened occurrences of environmental perils such as typhoons, hurricanes, storm surges, and extreme

tides, alongside alterations in regional patterns, intensities, and temperatures of rainfall (Renaud et al., 2013). These climate-driven factors primarily stem from external influences, encompassing both marine and terrestrial origins, thereby constituting an escalating peril to the sustainability of deltas (Brown and Nicholls, 2015).

Storm Surge

Storm surges emanate from the interplay of several factors encompassing strong winds, atmospheric pressure fluctuations, tidal actions, coastal configurations, and external inputs (Bertin et al., 2015). Predominantly, wind action generates a hydrodynamic push of water towards the coastline over extended distances. The surge's amplitude is intrinsically linked to wind vigor, with atmospheric pressure exerting a secondary yet discernible influence. Tidal oscillations synergistically contribute to storm surges, their pinnacle potential contingent on localized tidal patterns. Concurrently, the morphology of coastal entities like bays and estuaries intricately modulates the amplitude of surge events. The outcomes of storm surges encompass consequential detriment to built environments, infrastructures, and human well-being. Disintegration of constructions, degradation of foundations, and unanticipated inundation in coastal domains are among their deleterious impacts. A comprehensive understanding of the intricate constituents composing storm surges stands essential for formulating effective strategies to mitigate their ramifications (Bertin, 2016).

Waves and wave run-up

While many studies primarily focus on the effects of rising sea levels, it's vital to understand that strong waves can lead to immediate and significant environmental impacts at a more confined geographical scale (De Oliveira & Bonetti, 2021). Intense wave occurrences can result in the dilapidation of beaches and sand dunes, along with inundation and extensive damage to communities situated along the coast. These waves frequently trigger concentrated or broader-scale flooding, which has a notable influence on the socioeconomic status of coastal regions (Hansom et al., 2015). Sandy coastlines, specifically, are vulnerable to changes in wave patterns that modify the movement of sediments along the shoreline, leading to flooding caused by the wave (Ribas et al., 2023; Vousdoukas et al., 2022). Waves play a critical role in shaping and preserving coastlines and deltas by redistributing sediment. However, in extreme scenarios, the energy carried by these waves can have destructive effects on coastal areas. Loose sediments along the coast are particularly vulnerable to substantial erosion and structural changes when exposed to extreme wave events (Hansom et al., 2015). Moreover, these waves have the capacity to carry water and sediment past the highest point of the beach, causing overflow and the accumulation of substances further inland, distant from the sea. Therefore, oceanic waves can be characterized as gravitational waves and can be explained as the aggregate of several sinusoidal waves in the open sea.

Each wave component can be characterized by; a wavelength L (or a wave number $k = 2\pi/L$), a height H , a period T (or an angular frequency $\omega = 2\pi/T$), and propagates at a phase velocity $C = L/T$.

The wave propagation can be simplified using different hypotheses, incompressible and non-viscous flow, irrotational fluid with constant density, sinusoidal wave on flat bottom, as such that the momentum equations can be linearized (Craik, 2004). The equation describing wave dynamics from deep water to shallow waters (although with limited validity) is called the linear dispersion relation (Equation 1), linking the wave celerity to the water depth.

$$\omega^2 = gk \tanh(kh) \quad \text{Equation 1}$$

Equation 1 states that longer waves travel faster than shorter waves, with g representing the gravitational constant and h representing the depth.

As waves approach the shore, their speed decreases due to the reduced depth and wavelength, while the period remains constant. To maintain the energy flux, the wave amplitude increases, resulting in shoaling, which is influenced by local bathymetry and wave conditions as examined by (Thornton & Guza, 1983) and (Elgar and Guza, 1985).

Furthermore, as the water depth decreases, the wave's propagation speed decreases, causing the wave's crest lines to deform and align parallel to the isobaths, a phenomenon known as refraction. Refraction becomes noticeable when the water depth (h) is less than half the wavelength (λ) and there are no nearshore currents.

Wave dissipation

Wave dissipation refers to the process in which waves lose energy and decrease in amplitude as they travel through a medium, such as water. It occurs through mechanisms like bottom friction, wave breaking, turbulence, wave-to-wave interactions, and wave shoaling. Wave dissipation plays a significant role in coastal areas, impacting wave characteristics, coastal morphology, and

sediment transport. Understanding wave dissipation is crucial for coastal engineering, hazard assessment, and effective management strategies. It involves the conversion of wave energy into other forms, resulting in a decrease in wave height and energy. This process occurs through interactions between waves, the seabed, other waves, and turbulence in the water column. Knowledge of wave dissipation helps predict wave behavior, design coastal structures, assess coastal hazards, and manage coastal ecosystems, considering the potential impacts on communities, infrastructure, and natural environments.

$$\xi b = \frac{\tan(\beta)}{\sqrt{\frac{H_b}{L_o}}} \quad \text{Equation 2}$$

where β = beach slope, H_b = swell amplitude at its breaking point L_o = offshore wavelength.

In the presence of wave breaking and a gentle beach slope, waves persist in their propagation, albeit with diminishing amplitudes as they encounter deeper water (Dulou et al., 2000).

This parameter establishes the relationship between the parameter H and the wave breaking parameter γ , where H is the product of γ and h . The wave breaking parameter γ , as determined by Fredsøe & Deigaard, (1992), has an approximate value of 0.8.

Tides

Tides occur regularly as the sea level rises and falls due to the gravitational forces of the Earth, Sun, and Moon. These tidal movements have a vital role in shaping sediment dynamics near the shoreline. The relative tide range, which compares the difference between high and low tides to the height of waves,

provides a measure of the impact tides have on a specific coast. Throughout the tidal cycle, different hydrodynamic zones such as the swash zone, surf zone, and shoaling zone undergo changes. In beaches with a significant tidal range, the widening of the beach and the flattening of its profile reduce the time waves spend interacting with a particular section of the beach. In such cases, tidal currents can even contribute to the movement of sediment along the coast through intricate interactions. Even on beaches dominated by waves with small tidal ranges, tides can still have a noticeable influence. As tides transition from low to high, the height and incidence of waves tend to increase, resulting in alterations in wave-breaking patterns and associated morphological processes. The shape and characteristics of coastal features like bays and estuaries affect the severity of storm surges, and the timing of tides can also impact the extent of these surges. Coastal flooding and storm surges pose significant risks to coastal communities, ecosystems, and infrastructure. Developing strategies to mitigate the impacts of storm surges and tides necessitates a comprehensive understanding of their underlying component.

Upstream River, Catchment Management and Sediment Imbalance

River dams and artificial reservoirs have important functions in generating power, providing water, and managing floods for communities in both regional and downstream areas (Tessler et al., 2015). However, the management practices employed in upstream rivers and catchments can disrupt sediment dynamics and have implications for coastal areas (Noe et al., 2020). Various methods, such as the construction of dams, reservoirs, and irrigation systems, weaken the intensity of river currents. As a result, suspended sediments are prompted to settle, and the flow of natural sediments towards coastal regions is

reduced. This disruption results in rivers becoming separated from floodplains, with detrimental consequences for ecosystems, species, and the conveyance of marine sediment to deltas and estuaries (Gierszewski et al., 2020). The alteration of sediment dynamics caused by upstream management practices focused on flood prevention, irrigation, and hydroelectric power generation has accelerated coastal erosion by diminishing the input of sand and silt to coastal landscapes. Over the past century, there has been a significant decrease in the transport of sediment from land to sea (Poulos & Collins, 2002). Sediment delivery to coastal areas has been greatly reduced or completely obstructed, with an estimated 25 to 30 percent of the world's suspended sediment flux trapped in reservoirs taller than 15 meters that are of human origin (Vousdoukas et al., 2022). The retention of sediment in populated deltas and coastal ecosystems leads to various outcomes, notably contributing to rising sea levels. Without intervention, approximately 9 million people and 28,000 square kilometers of deltaic land in 40 deltas worldwide could face increased flooding and coastal erosion by 2050 due to ongoing sediment retention (Ericson et al., 2006).

Population Growth, Urbanization and Land-use Patterns

Coastal areas, although limited in size, play a crucial role in supporting large populations and making significant contributions to the global economy (Tigheelaar et al., 2022). Deltas, in particular, attract significant human settlements due to the diverse services they provide, leading to concentrated populations in megacities (Syvitski & Saito, 2007). However, the processes associated with urbanization, rising sea levels, and population growth have

visibly impacted the physical characteristics of coastal zones (Syvitski et al., 2009).

In conclusion, coastal regions, although limited in size, are vital for supporting populations and contributing to the global economy. Deltas, with their services, attract human settlements; however, the impacts of urbanization, rising sea levels, and population growth have altered these coastal landscapes, making them more vulnerable to risks like floods, erosion, and biodiversity decline.

The Volta Delta of Ghana: An Overview

The coastal zone within the Gulf of Guinea, extending from Liberia to Nigeria and encompassing Sao Tome and Principe, exhibits a distinct geography characterized by its low-lying nature and the presence of steep, narrow shelves housing sandy and rocky beaches. With an annual precipitation surpassing 1100 mm, the region encounters a significant challenge posed by the rising sea levels, which exert a particularly pronounced impact on its low-lying coastal areas. The Gulf of Guinea undergoes considerable variability in sea surface temperatures across the year and is influenced by processes such as upwellings and tidal movements. Functioning as a coast dominated by wave actions, it is notably susceptible to both remote south swell waves and locally-generated wind waves. The primary sources of sediment in this region are the Volta and Niger rivers, while erosion is driven by human activities and disruptions to the transport of sediment along the shoreline. Alarming trends of severe erosion along the West Africa shorelines pose a significant threat to densely populated areas. The vulnerability of the Gulf of Guinea coast is determined by a range of

factors, including the geomorphology of the coastline, tides, wave patterns, and the intensity of rainfall. Particularly for the Volta delta

According to a study by Appeaning Addo et al. (2018), the Volta delta is defined as the coastal area below the 5-meter contour within the Accra-Ho-Keta Plains, spanning approximately 150 kilometers of coastline from the border of Ghana with Togo to Ningo-Prampram. The delta covers an area of 2237.48 square kilometers within the 5-meter elevation contour, but when considering administrative boundaries, its coverage extends to about 4562 square kilometres.

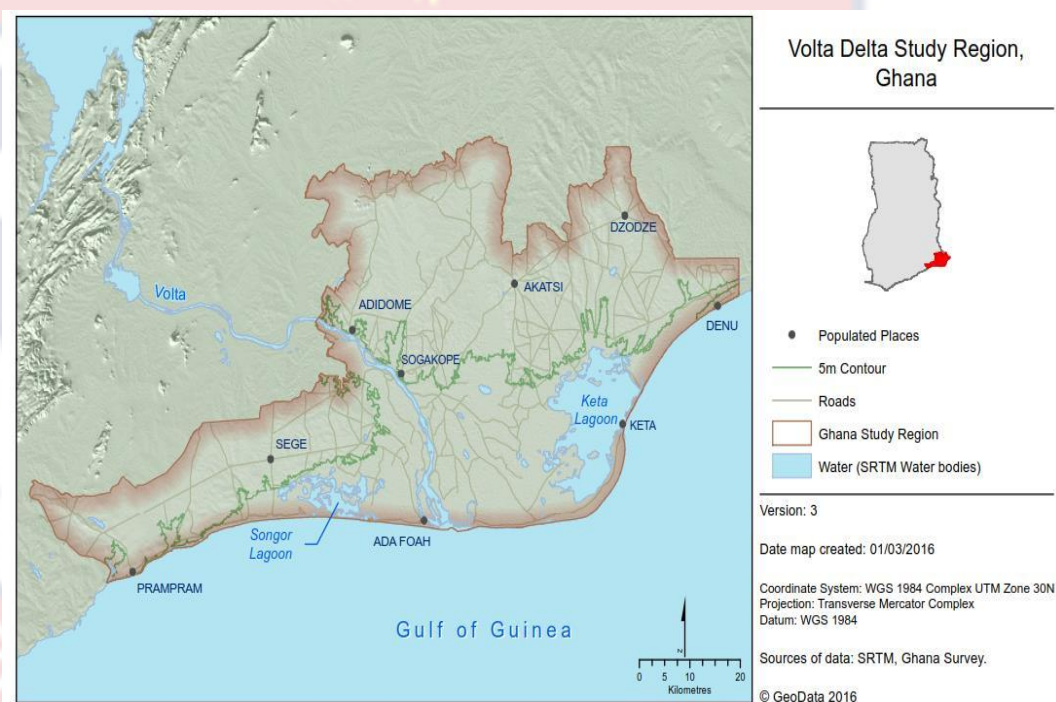


Figure 14: Map of the study area (Source: Codjoe et al., 2020). The 5m contour limits the extent of the Volta delta

The delta is situated in the Keta Basin and is geologically characterized by late quaternary formations and loose sediments, including clay, sand, and gravel deposits. The basin itself is underlain by acidic and basic gneisses and schists from the Dahomeyan system, visible along its northern borders. The uppermost

layer of the delta comprises approximately 7 meters of fine sand overlying weathered shale and either organic or inorganic clay with high compressibility. Along the delta's coastline, there is a narrow shelf ranging from 15 to 33 kilometers in width. The shoreface of the coast remains fairly uniform and moderately steep, with a gradient of 1:120 to 1:150 descending to a depth of 15 meters. This depth marks the point where significant wave-induced sediment movement comes to a halt (Addo et al., 2018a). The sediment properties and wave dynamics play a role in shaping the profile variations across the delta. After the construction of the Akosombo Dam, the Volta River's contribution of sediment to the eastern part of the delta significantly decreased, resulting in a wave-dominated delta. At present, the majority of sediment transported to the delta comes from sources located further up the coast. The upper layer of the delta showcases a typical grain size with a median value (D_{50}) of 0.6 millimeters. Notably, the delta encompasses two substantial coastal lagoons, namely Keta and Songor, both of which hold RAMSAR Site designations. Additionally, the area includes tidal pools and various land cover features. The research area experiences southwest monsoons as the prevailing winds, which blow in a similar direction as the southwest waves (210° - 240°) at an angle of around 45° to the shore. The nearshore bathymetry and coastline orientation influence the behaviour of ocean waves, which, in turn, shape the delta front. The formation of the large spit that characterizes the delta is attributed to the westward movement of the river mouth and increased sand accumulation resulting from higher wave refraction south of Keta. Swell waves reaching the coast from the south-southwest direction are unobstructed and average around 1.4 meters in height, with an approximately 11-second interval, and varying

intensity, often from moderate to high. As these waves break, their energy dissipation leads to the creation of longshore currents, which move sediment along the shoreline from west to east. This process contributes to one of the highest annual rates of unidirectional longshore sediment drift globally, with estimates ranging from 1 to 1.5 million cubic meters per year.

Tides in the area follow a semi-diurnal pattern, featuring a tidal range of approximately 1 meter. The mean spring tide reaches 1.5 meters. These tides produce mild currents that have minimal impact on shoreline morphology. Various studies have reported different estimates for the pre-dam sediment yield of the Volta River. Various studies recorded an annual sedimentation rate of 2.5 million cubic meters, while Boateng et al. (2012) estimated it to be 71 million cubic meters per year. Anthony and Blivi (1999) reported a rate of 1 million cubic meters annually. Nevertheless, Nyarko et al. (2016) found that sedimentation rates notably declined after the construction of a dam, decreasing from 1.08 grams per square centimeter per year to 0.50 grams per square centimeter per year, signifying a 50% reduction (Nyarko et al., 2016). The coastal zone of the Volta delta is susceptible to erosion, historically experiencing high rates of up to 8 meters per year. To combat erosion, various initiatives like the Keta Sea Defense Project, Dzita-Atorkor sea defense, and the recent Ada sea defense have been implemented. Despite these efforts stabilizing local shorelines, erosion continues to persist, particularly downstream of these structures.

Conclusion

Previous studies have extensively evaluated the coastal flooding and erosion rates of Volta delta in terms of temporal and spatial coverage. These assessments focused on evaluating the susceptibility of the coastal zone to coastal hazards. Multiple studies conducted in Ghana have linked coastal hazards to climate change, investigating its effects on various aspects such as morphological changes, flooding, the degradation of wetlands and aquatic ecosystems, and other associated consequences. These studies have identified several key drivers that contribute to both biophysical and socio-economic transformations within the Volta delta. These drivers encompass practices related to upstream catchment management, the rising sea levels, the impact of energetic swell waves, strategies for managing coastal erosion, groundwater extraction, population dynamics, and land subsidence. On the other hand the use of remote sensing approaches has been limited to shoreline and sediment volume changes in the Volta delta, however coastal processes such as land subsidence and coastal flooding has not been fully explored for the entire delta. To address this gap, this study focuses on assessing the importance of relative sea level rise with land subsidence rates and the impact of coastal flooding in the Volta delta. This is done by utilizing remote sensing approach such as InSAR (Interferometric Synthetic Aperture Radar) techniques. This study utilizes high-resolution satellite imagery to estimate the extent of coastal flooding as well as the major factors that affect flooding in the Volta delta. This study fills this gap by assessing the relative sea level rise and coastal flooding using high-resolution DEMs constructed from satellite.

CHAPTER THREE

FUTURE FLOODING OF THE VOLTA DELTA CAUSED BY
SEA LEVEL RISE AND LAND SUBSIDENCE

Brempong E.K.^{1,2,3}, Almar R.³, Angnuureng D.B¹, Mattah P.A.D.¹⁴, Jayson-
Quashigah P.N.⁵, Appeaning Addo K.⁵, Minderhoud P.⁶, Teatini P⁷

¹ Africa Centre of Excellence in Coastal Resilience, Centre for Coastal
Management,
SBS, University of Cape Coast.

²Department of Fisheries and Aquatic Sciences (DFAS), University of Cape
Coast, Ghana

³LEGOS (University of Toulouse/CNRS/IRD/CNES), Toulouse, France.

⁴Department of Marine and Fisheries Sciences, University of Ghana, P. O. Box
LG 99, Accra, Ghana.

⁵IESS, University of Ghana, Legon.

⁶University of Wageningen, Soil Geography and Landscape Group, The
Netherlands.

⁷Dept. of Civil, Environmental and Architectural Engineering, University of
Padova, Via Marzolo 9, 35131 Padova – Italy.

Published: Springer, Journal Coastal Conservation 27, 24 (2023).
<https://doi.org/10.1007/s11852-023-00952-0>

Statement of Contributions of Joint Authorship

For this research article the contribution of the authors is as follows:

Conceptualization of the paper was done by; Brempong Emmanuel Kwadzo
and Rafael Almar.

Methodology was developed by; Brempong Emmanuel Kwadzo, Rafael Almar, Avornyo Selasi Yao.

Validation of results was carried by; Donatus B. Angnuureng and Rafael Alamar;

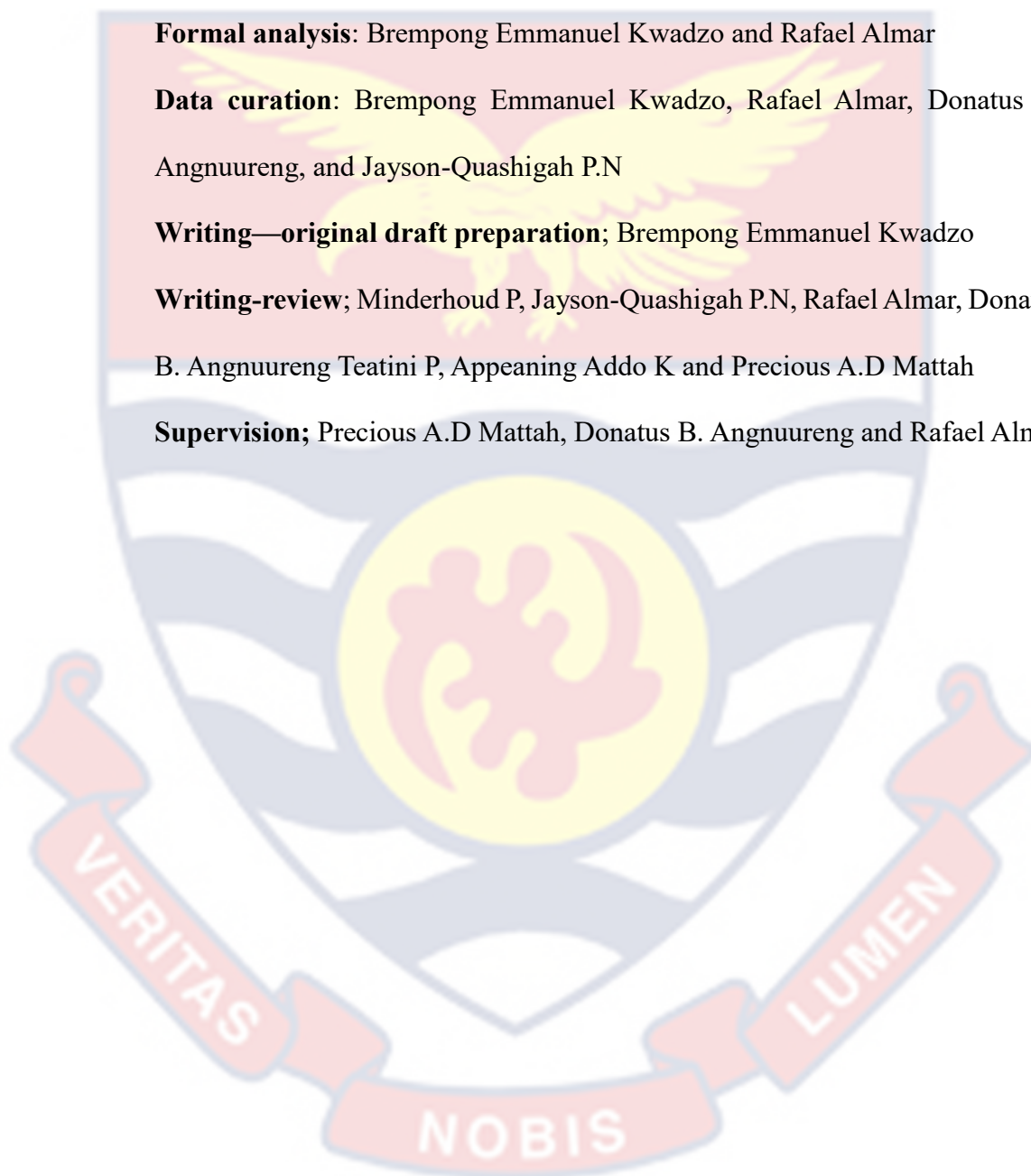
Formal analysis: Brempong Emmanuel Kwadzo and Rafael Almar

Data curation: Brempong Emmanuel Kwadzo, Rafael Almar, Donatus B. Angnuureng, and Jayson-Quashigah P.N

Writing—original draft preparation; Brempong Emmanuel Kwadzo

Writing-review; Minderhoud P, Jayson-Quashigah P.N, Rafael Almar, Donatus B. Angnuureng Teatini P, Appeaning Addo K and Precious A.D Mattah

Supervision; Precious A.D Mattah, Donatus B. Angnuureng and Rafael Almar



Abstract

The Volta Delta (Ghana, West Africa) is increasingly impacted by Sea Level Rise (SLR). SLR makes the Volta Delta mostly vulnerable to flooding, salinization of water resources and agriculture fields, and permanent loss of lands. This would potentially threaten and present a growing risk to its population, infrastructure and economy, and even worsen due to land subsidence (LS). Relative Sea Level Rise (RSLR) in this study is the rate of LS with respect to SLR. It is thus very important to precisely quantify LS rates together with SLR and plan and assess countermeasures. This study presents and discusses recent LS rates in the Volta Delta derived from satellite-based SAR-Interferometry and their impact on relative SLR. Sentinel-1 scenes acquired between 2015 and 2021 were used to quantify recent LS in the study area. The Persistent Scatter Interferometry (PS-InSAR) technique was applied, which allowed for estimating displacement rates of coherent backscatter targets with a mm/yr precision. Separate analyses of time series for the Keta lagoon and Songor lagoon areas give insight into the vertical land movements, with average rates of up to 4 mm/yr irregularly scattered in the coastland. LS in the Volta Delta is due to various causes, most prominently natural compaction of young deltaic sediments, but also aquifer overexploitation and salt mining. Furthermore, projection of future elevation projections by RSLR was assessed by combining the observed LS rates with three IPCC representative concentration pathways (RCP) scenarios. The RSLR impact assessments computed revealed that by 2100, more than 20% of the Volta Delta districts could potentially be elevated below MSL for all the addressed RCP scenarios including the fragile but key sand barriers surrounded by water bodies. The

study is, however, a preliminary investigation and recommends further analysis by local ground-based LS investigations to calibrate PS-InSAR outcome, thus improving our understanding of the areas driving critical present and future changes in the Volta Delta.

Keywords; Sea level Rise (SLR), Subsidence , Relative sea level rise (RSLR) , Flooding , Persistent Scatter Interferometry.



Introduction

Approximately 2% of the World's land is covered by deltas, where 10% of the World's population lives (McGranahan et al., 2007). Deltas are generally low-lying areas prone to flooding. Global sea level is rising at a rate of 3.3 ± 0.4 mm/year, causing deltas to be under threat of increasing flood frequency and severity (Sadat-Noori et al., 2021). The recent IPCC AR6 report shows the situation is expected to worsen by 2100 if nothing is done. Subsidence exacerbates the submergence of deltas resulting from global warming-induced sea level rise, as Nicholls et al. (2021) noted. Land Subsidence (LS) is vital, especially in coastal areas. It magnifies local SLR and puts the affected population and environment at a higher risk of coastal flooding, coastal erosion and saltwater intrusion. The severity of LS varies at local to regional scales. Space and time variability of LS vastly exceeds that of SLR in deltaic areas and also exceeds that of SLR over the 21st century, even for the projected worst-case scenarios (Becker et al., 2020). LS is a significant concern for coastal environments worldwide, with exemplificative cases such as the cities of Jakarta (Abidin et al., 2011) and Bangkok (Phien-wej et al., 2006) and the deltas of the Nile (Rateb & Abotalib, 2020); Mekong (Minderhoud et al., 2017); Po (Teatini et al., 2011) and Bangladesh (Steckler et al., 2021).

LS in deltas results from the superposition of various processes such as natural compaction of the Holocene deposits, compaction of reclaimed land loaded by high-rise infrastructure, and groundwater over-pumping from the aquifer systems (Da Lio et al., 2011; Minderhoud et al., 2018). Moreover, delta coastlines are affected by natural factors, which include SLR, alongside anthropogenic factors such as the construction of sea defence structures,

harbours and dams (Anthony et al., 2020; Marchesiello et al., 2019). Satellite Radar Interferometry – InSAR- to assess LS and flooding has proven very effective despite computational constraints. Contrary to other techniques that provide local estimates, this method allows large-scale investigation over time (Le Cozannet et al., 2015). Most studies have estimated the impacts of climate changes on coastal areas alongside SLR scenarios to predict flood inundation and coastal erosion (Di Paola et al., 2018). The Sentinel-1 (S1) mission, launched in 2014, stands out for its capacity to capture global observations every six days, providing a ground resolution of 20 m. This makes it particularly effective for maintaining consistent coherence and monitoring alterations to land.

On the other hand, SLR combined with LS; in other words, RSLR is one of the processes which pose severe threats to coastal ecosystems worldwide today (Tosi et al., 2020). Despite the continuous increase in SLR, land subsidence in many coastal areas globally has exceeded the SLR up to a factor of ten (6–100 mm yr⁻¹) (Erkens et al., 2015). However, there are no possible signs that either subsidence or SLR will decrease in the near future. Literally, LS would continue to rise. This is because population growth and ongoing urbanization in delta areas progressively drive socioeconomic development. Consequently, the impacts of RSLR in coastal areas would also increase by expected future climate change impacts such as; increased SLR, increased storm surges and changes in precipitation (Erkens et al., 2015).

Even though LS is threatening several countries worldwide (Herrera-García et al., 2021), the rate and extent of land subsidence are still largely unknown in most of Africa.

The Volta Delta, situated in the Gulf of Guinea in West Africa, is one of Africa's largest deltas and significantly impacts human livelihoods. It is vulnerable to subsidence, erosion, and flooding (Appeaning Addo et al., 2018; Duku et al., 2021). The status and trends report on the Volta Delta by the Delta Alliance (2019) identifies several research gaps that require attention. These gaps include an inadequate understanding of the complex interrelationship among various drivers of delta evolution, a lack of assessment of the impacts of SLR on wetlands, insufficient information on groundwater extraction, and a need for monitoring the compound effect of LS and SLR. Additionally, the report emphasises the importance of updated and quality data on socioeconomic and demographic characteristics in the delta, as well as research on multiple livelihoods and livelihood diversification mechanisms of delta populations (Appeaning Addo et al., 2019). Given these, many studies have been earmarked to assess LS in the area (Dealbera et al., 2021). This study is, therefore, a preliminary investigation for further studies on the validation of LS and flooding in the Volta Delta. The study's major limitation is that LS acquired from S1 needs to be validated with a reference point. However, this was a significant challenge since no continuous GPS base station exists. This paper aims to estimate the LS rates in the Volta Delta and potential areas that fall below sea level when LS is combined with SLR projected over the 21st Century. To achieve this, first and foremost, LS is estimated using S1 images from 2015 to 2021. Secondly, the Volta Delta is subjected to SLR with extreme coastal water levels and RLSR to identify areas viable to flooding based on IPCC scenarios by 2100. Finally, an assessment of the percentage of potential elevation of areas below both SLR and RSLR.

Material and Methods

Study Site.

The Volta Delta (Figure 15) is a low-lying area situated south of the lower parts of the Volta River basin, located in Ghana, the Gulf of Guinea (West Africa). The elevation of most of the delta is less than 5 m above mean sea level (msl) (see Figure 15). The Volta River basin is the ninth largest in sub-Saharan Africa, covering about 400,000 km² (van de Giesen et al., 2010). It spans six countries: Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Togo, and is home to nearly 19 million people. From 1970 to 2018, the river had an average annual discharge of 949.55 m³/s (Amenuvor et al., 2020). The basin is divided into four main sub-basins: Black Volta, White Volta, Oti, and Lower Volta, which includes the delta. The Volta Delta is essential because most of its inhabitants depend directly or indirectly on the resources of the Volta River. The delta areas, situated along the eastern coast of Ghana and covering an approximate area of 4562 km², have been divided into nine administrative districts crucial for resource management (Appeaning Addo et al., 2018).

Because the delta is wave-dominated (Roest et al., 2018), the drift-aligned beaches along the delta are mostly sandy (Anthony et al., 2019) and surround two major lagoons, the Keta Lagoon and the Songor Lagoon on the eastern and western part, respectively, of the Volta estuary. They serve as RAMSAR sites. The Volta Delta forms one of the most prominent geomorphic and coastal features along the eastern coast of Ghana.

The National Disaster Management Organisation (NADMO) recently reported frequent flooding in places such as Fuveme, Keta, Agaverdzi, Blekusu and

Salakope. Waves are characterised by moderate to high energy and lengthy periods. The significant wave height is about 1 m, with periods of about 11 s from the S-SW direction (Angnuureng et al., 2017; Almar et al., 2015; Roest et al., 2018). Tide is semidiurnal and is not more than 1.4 m (Appeaning Addo et al., 2008) with a limited effect on the morphology (Wellens-Mensah, 2002). Studies within the delta show that sections of the shoreline have been eroded since the mid-1890s, but the situation has worsened due to damming of the river, among other factors (Appeaning Addo et al., 2020; Anthony, 2015a; Ly, 1980), which has negatively affected the sediment budget (Anthony et al., 2016; Anthony, 2015b). According to studies conducted by Appeaning Addo et al. (2011) and Jayson-Quashigah et al. (2013), the Keta Sea Defence Project has downstream "knock-on effects". The reduction of sediment supply from the river to the delta system due to the presence of dams is being counterbalanced by the erosion of Holocene barrier deposits downstream of the Volta spit. This erosion is effectively making up for the loss of sediment and enabling the solid longshore drift potential towards the east to persist. The delta is exposed to various threats such as SLR, flooding, storm surge, salinization, coastal erosion, and LS, as noted by Appeaning Addo et al. (2018) and Tessler et al. (2015).

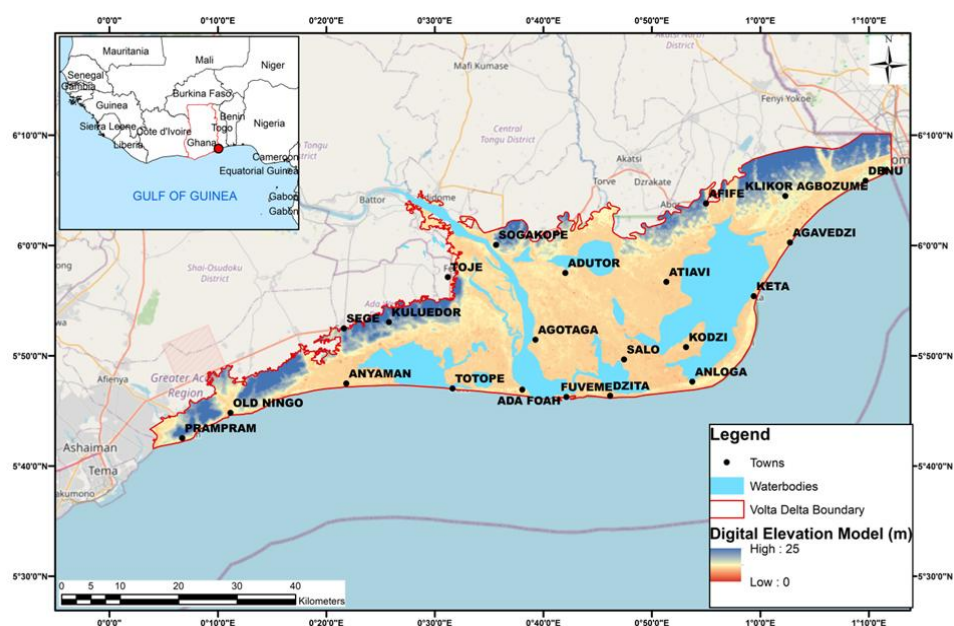


Figure 15: DEM of the Volta Delta in the eastern coast of Ghana, Gulf of Guinea

Vertical land motion

The study used satellite remote sensing and GIS approaches, specifically Sentinel-1A (S1) images acquired every six days with a steady acquisition geometry. The Level-1 Interferometric Wide Swaths Single Look Complex (SLC) products data are complex magnitude values and contain amplitude and phase information (Grandin, 2015). They are freely downloaded through the Copernicus Science Hub. S1 images are acquired with a steady geometry, which is most often at the same angle of incidence to the earth, making it easy to detect changes in the land surface. With its 250 by 170 km coverage, a typical S1 image facilitates monitoring large regions. The SAR sensor measures phase differences among various images acquired with the same geometry of observation (also known as interferograms). These data's interferometric processing (InSAR) allows for measuring land surface displacements of mm-

level precision and a meter spatial resolution over large areas (Hooper et al., 2012; Simons & Rosen, 2007). Two images were downloaded in the ascending orbit and VV polarisation for each month from May 2015 to June 2021, except for some months with only one image. In total, 138 images for each sub-swath are used for our analysis. This study used interferometric processing for vertical land movement following the workflow by Mancini et al. (2021). Sentinel Application Platform (SNAP) was used for processing and generating interferograms, Stanford Method for Persistent Scatterers (StaMPS) for processing of persistent scatter time series, and finally, Toolbox for Reducing Atmospheric InSAR Noise (TRAIN) for reduction of atmospheric noise. SNAP software is a Sentinel-based application platform equipped with inbuilt tools to help visualise S1 data. Specifically, SNAP TOPSAR can permit InSAR processing by incorporating STAMPS packages, providing a full PSI time series analysis (Bekaert et al., 2015a,b; Fomelis et al., 2018; Hooper et al., 2012; Zuhlke et al., 2015). More specifically, the InSAR technique uses phase data acquired from both the master and slave images to form the interferogram by contrasting their phase inconsistencies (Husnayaen et al., 2018). The overall phase difference or interferometric phase (ϕ) between the corresponding complex pixel can be represented using Equation 3, according to Rocca et al. (2000).

$$\phi = \phi^{flat} + \phi^{topo} + \phi^{disp} + \phi^{atm} + \phi^{orbit} + \phi^{noise}$$

Equation 3

Where ϕ^{flat} = the flat earth phase, ϕ^{topo} = the topographic phase or surface elevation, ϕ^{disp} = the displacement between two images, ϕ^{atm} = the phase

signal contribution from the atmosphere, ϕ^{orbit} = the changes in the platform's orbit, ϕ^{noise} = the phase noise, respectively.

In InSAR, the ϕ^{disp} component is the primary focus, and detecting differences at a sub-wavelength magnitude requires removing or reducing the other phase components. The StaMPS methodology (Hooper et al., 2012), summarised in Figure 2, was used to accomplish this in the study. The range variation between two passes, affected by satellite orbits and terrain, comprises ϕ^{orbit} , ϕ^{flat} , and ϕ^{topo} (Osmanoğlu et al., 2016), which can be corrected or removed with the SNAP software. The "Correction of Orbital" or Apply Orbit File function (Figure 2) updates the initial inaccurate orbit state vectors of each product to accurate satellite information on velocity and position (SNAP, 2020), thereby accounting for ϕ^{orbit} . The interferogram flattening method (Ferretti et al., 2015) is used to remove the phase component corresponding to the curvature of the Earth's surface (ϕ^{flat}), and the ϕ^{topo} the component is removed by using a digital elevation model (DEM). These phase components are eliminated automatically during the "Interferogram Formation" process in SNAP (Figure 16). This results in a reduction of Equation 3 to Equation 4.

$$\phi = \phi^{disp} + \phi^{atm} + \phi^{noise} \quad \text{Equation 4}$$

Using the adaptive filtering method embedded in the StaMPS toolbox in MATLAB, ϕ^{noise} is condensed.

In order to remove atmospheric phase ϕ^{atm} as a result of the influence of ionospheric and tropospheric, the Toolbox for Reducing Atmospheric InSAR Noise (TRAIN) by Bekaert et al. (2015) is used (Figure 16) in MATLAB.

This results in equation (4) where the interferometric phase corresponds directly to the displacement between two images:

$$\phi = \phi^{disp} \quad \text{Equation 5}$$

A summary of the processing workflow is shown in Figure 2. This includes all the various stages of preparation of products for persistent scatter preprocessing in StaMPS, i.e.:

- i. **Splitting of S1 images product:** All images of the same sub-swath (IW1) and bursts (3) (see figure 17.0) were selected, to help with the co-registration process;
- ii. **Correction of spatial orbits:** The spatial orbits were automatically downloaded and applied for a particular product;
- iii. **Coregistration:** All images are georeferenced with the help of the back-geocoding operator;
- iv. **Master image selection:** A master data (03-Feb-2018) is based on scientific concept (Coherence) is selected;
- v. **Deburst:** The azimuth direction was used by the S1 TOPS deburst operator, with VV polarization chosen, to merge all the bursts;
- vi. **Interferogram formation:** Interferograms were computed for the various data sets;
- vii. **Topographic phase removal:** In order to estimate changes in topography, the software computes the topographic phase and subtracts it from the interferograms. This process is accomplished using the 3-arc-seconds DEM from the Shuttle Radar Topography Mission (SRTM). After completion, the software produces an output file that contains the topographic phase band, elevation band, and ortho-rectified positions specified in latitude/longitude;
- viii. **StaMPS export;** In a particular format, SNAP makes it easy to export StaMPS data that consists of a stack of co-registered and corrected products

along with interferograms that have been modified to eliminate the influence of topographic phase.

To export the data, the PSI interferometric tool and the `mt_prep_snap` script from the StaMPS manual are employed, utilizing default values for parameters such as amplitude dispersion (D_a), as well as the number of overlapping pixels in both the azimuth (n_a) and range (n_r) directions. The number of patches used is determined based on the computer's computational capacity. The resulting stack of interferograms is then processed using StaMPS in MATLAB, and augmented with TRAIN (Mancini et al., 2021; Blasco et al., 2019; Hooper et al., 2012). Following this, the vertical displacement outcomes are exported and visualized using MATLAB and ArcGIS..

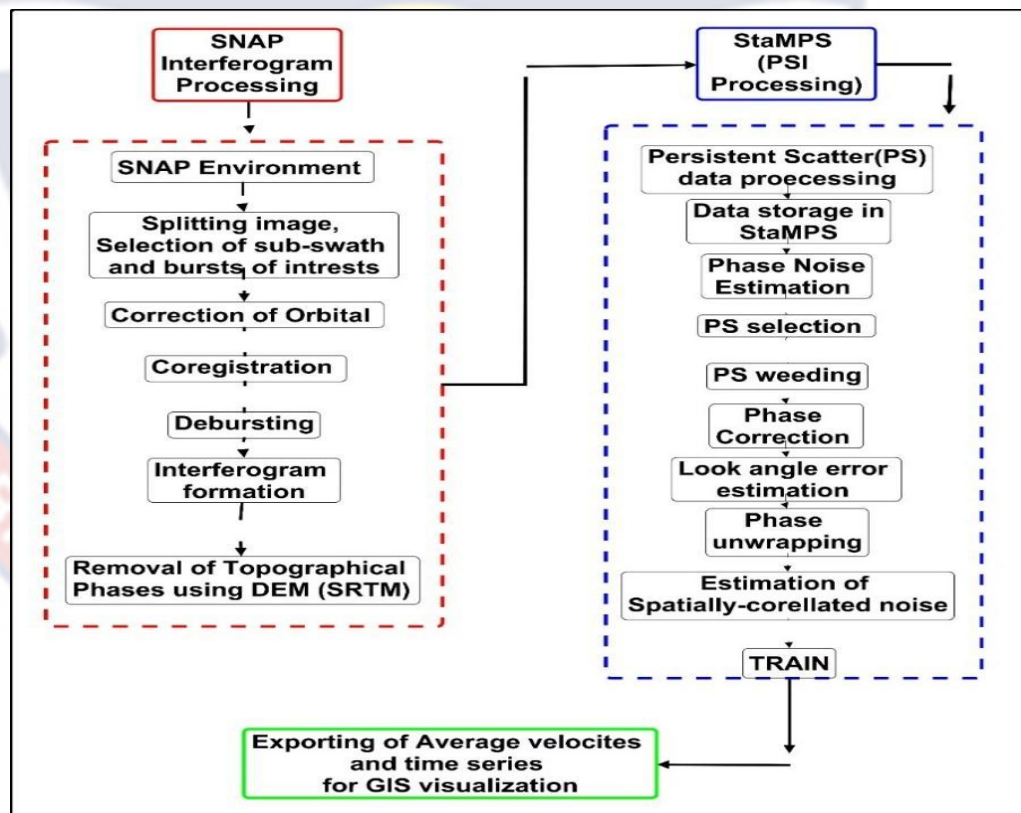


Figure 16: Flow chart of the combined workflow of SNAP-StaMPS adopted in this study to process S1 images

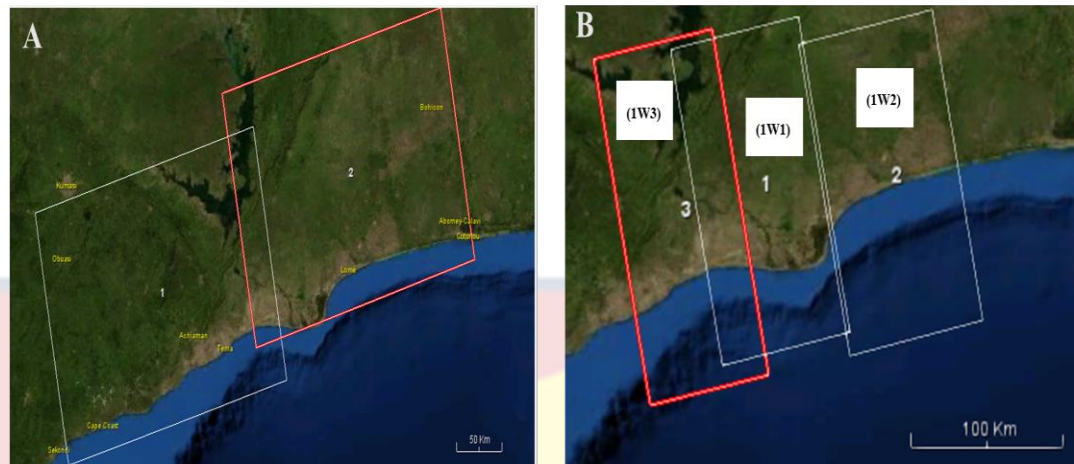


Figure 17: Swaths covering study area A) IW swath scenes covering study area extent B) Three overlapping sub-swaths covering the study area

Digital Elevation Model (DEM)

To assess and simulate flooding, Digital Elevation Model (DEM) was downloaded from the website of the Data Center in NASA's Earth Observing System Data and Information System (EOSDIS). This data is version 2 of the Global Digital Elevation Model created using Satellite Radar Altimetry with the Shuttle Radar Topography Mission (SRTM). The Altimeter Corrected Elevations Version 2 (ACE2) data is an improved version of Version 1, created by merging SRTM with Satellite Radar Altimetry. Data sources used in correction includes; Global Observations to Benefit the Environment (GLOBE), the original Altimeter Corrected Elevations (ACE) Digital Elevation Model (DEM), together with new matrices obtained from reprocessing European Remote Sensing (ERS-1) images. For this study, three arc seconds data (90 m) was downloaded for the Volta Delta, representing the best available resolution (See Figure 15).

Extreme Coastal Water Level (ECWL)

As per Almar et al. (2021), hydrodynamic, meteorological, and tidal parameters are required to compute ECWL. In this study, the following parameters were utilised: Sea Level Anomaly (SLA), Wave run-up (R), tide (T), and other atmospheric conditions (DAC), all of which were extracted at a grid point with a latitude of 6.047366° and longitude of 1.080522° , and referenced to the WGS84 datum. Hourly tidal data was obtained from the nearest grid point in the FES (Finite Element Solution) 2014 global tide model, which was provided by the Laboratory of Geophysical and Oceanographic Spatial Studies of Toulouse (LEGOS) (Carrere et al., 2015). The data for the atmospheric pressure and winds component (DAC) was generated by the MOG2D model from LEGOS of the Collecte Localisation Satellites (CLS) Space Oceanography Division, and was made available by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic) with assistance from the Centre National d'Etudes Spatiales (CNES) (Soudarin et al., 2018). Additional information on this data can be found at <http://www.aviso.altimetry.fr/>. The Altimetric-derived SLA, which includes Global Mean Sea Level Rise (GMSLR), was obtained from the nearest gridded data point of the altimetry data provided by AVISO (Marti et al., 2021). The Wave run-up data was obtained from the ERA-Interim reanalysis, a dataset that contains global climate and weather information from 1979 onwards at a resolution of $0.5^{\circ} \times 0.5^{\circ}$. The Wave run-up (R) was calculated using the dissipative beach equation proposed by Stockdon (2006), based on wave data at a 6-hourly resolution generated using the ECMWF (European Centre for Medium-Range Weather Forecasts) model (Almar et al., 2021).

$$R = \sqrt{H_s L_o} \quad \text{Equation 6}$$

The parameters, including H_s , which refers to the offshore significant wave height, and L_o , representing the wavelength, were resampled hourly from 1993 to 2015. All hydrodynamic data utilised in this research were readily accessible and extracted for the Volta Delta. The Extreme coastal water level (ECWL) outcomes are the product of various coastal phenomena (as per Eq. 7), including the regional sea level anomaly (referred to as SLA), which results from steric effects, oceanic circulation, and the transfer of mass from continents such as ice sheets, glaciers, and land water to the ocean. Other contributing factors include storm surge (DAC) caused by atmospheric pressure and winds, astronomical tide (T), and wave effects, specifically set up (R, as defined in Melet et al., 2018):

$$ECWL = SLA + DAC + T + R \quad \text{Equation 7}$$

In order to demonstrate the potential impact of sea-level rise on coastal flooding throughout the 21st century, various trajectories of global mean sea level rise (GMSLR) were examined in this study. These projections are based on different climate change scenarios, including RCP 8.5 (high-emission, low-mitigation), RCP 2.6 (low-emission, high-mitigation), and RCP 4.5 (middle of the road). Using different sea-level rise scenarios projected for the 21st century, such as RCP 8.5 (high-emissions, low-mitigation), RCP 2.6 (low-emissions, high-mitigation), and RCP 4.5 (moderate), we computed future time series for Extreme Coastal Water Level (ECWL) while keeping other contributing factors (S, T, and DAC) constant, as they were during the 1993-2015 period. Moreover, we computed future relative sea-level rise (RSLR) scenarios (depicted in Figure

18) by adding ECWL and the average LS rate derived from S1, using the different climate scenarios (Eq. 8). The reference datum for both ECWL and land topography was WGS

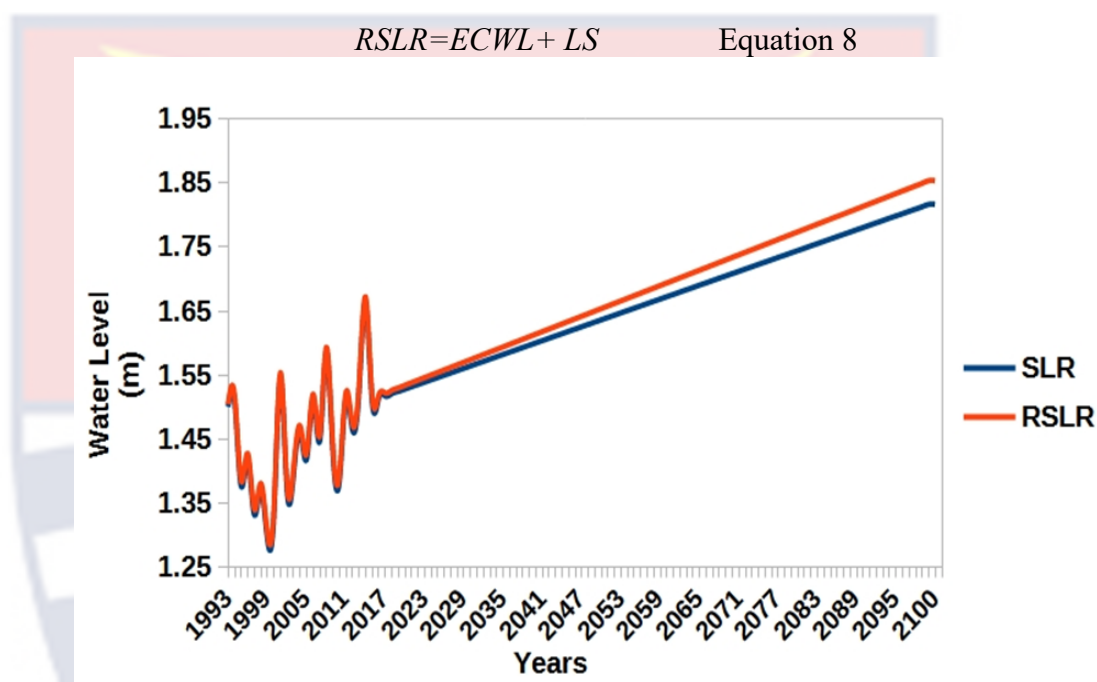


Figure 18: Example of extreme coastal water level and relative SLR trends from 1993 to 2100 as obtained by considering ECWL rate of 3.3 mm/yr from Almar et al., 2021 and LS rate of 4 mm/yr from S1 assuming LS rate is constant based on RCP 8.5 scenario

Elevation projection with respect to MSL under RSLR scenarios analysis

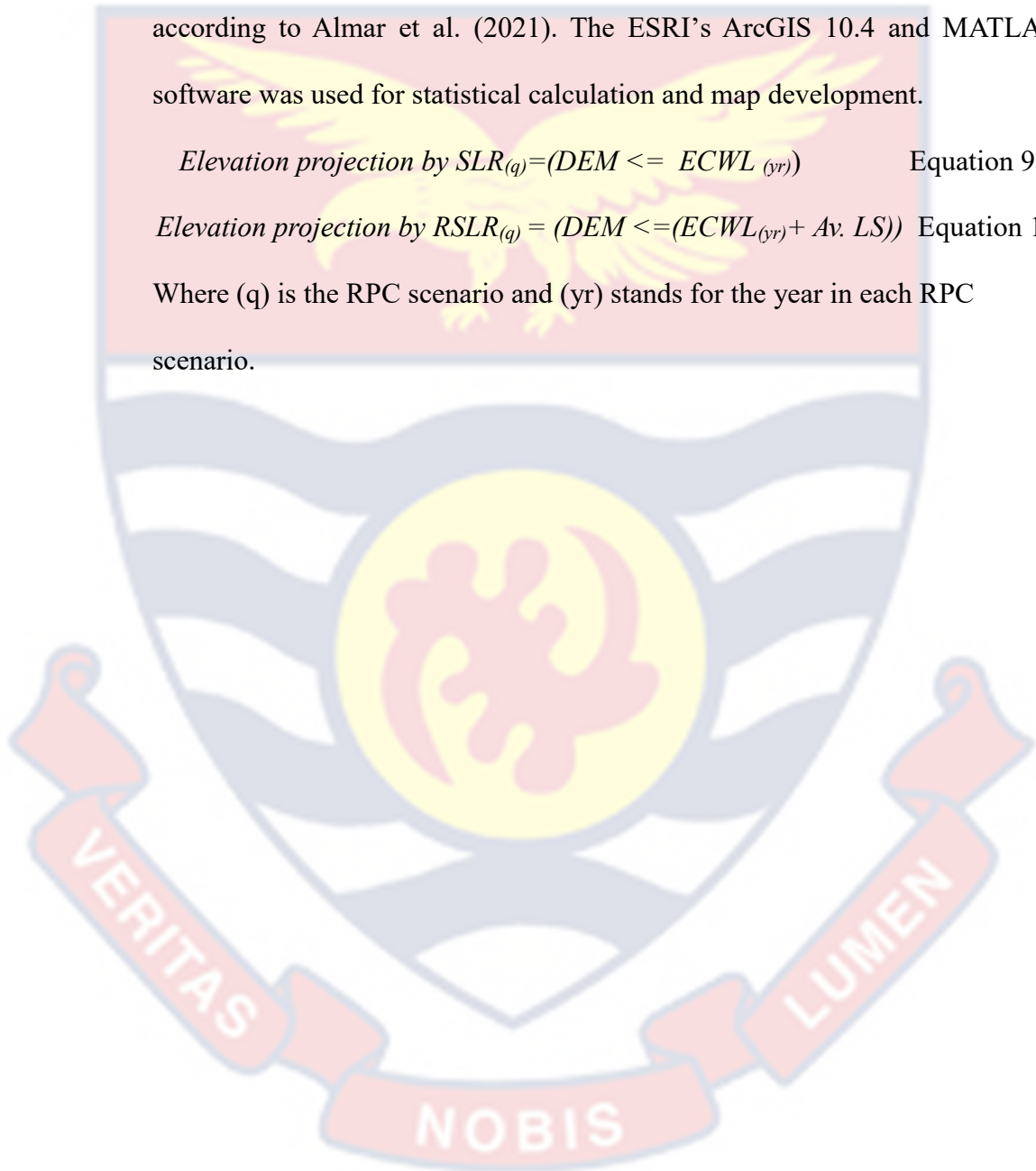
Using the raster calculator tool in ArcGIS 10.4, various relative SLR scenarios were processed to assess areas with low elevation projection of the Volta Delta alongside the ACE 2 DEM. All three RCP scenarios were considered for the bathtub analysis, which is an approach frequently used for this type of analysis (Leal-Alves et al., 2020; Didier et al., 2019; Aucelli et al., 2018; Di Paola et al., 2017; Snoussi et al., 2008). The principle was adapted (equations 9 and 10) because it is based on a simple arithmetic calculation that compares various water levels with the DEM to expose areas liable to flooding based on the area's

elevation. The precision of this method is highly reliant on the quality of the DEM data and yields information on both the depth and extent of flooding as water fills the relevant morphometric areas (Yunus et al., 2016; Poppenga & Worstell, 2016). For the sea-level rise scenarios simulation, this was applied according to Almar et al. (2021). The ESRI's ArcGIS 10.4 and MATLAB software was used for statistical calculation and map development.

$$\text{Elevation projection by } SLR_{(q)} = (DEM \leq ECWL_{(yr)}) \quad \text{Equation 9}$$

$$\text{Elevation projection by } RSLR_{(q)} = (DEM \leq (ECWL_{(yr)} + Av. LS)) \quad \text{Equation 10}$$

Where (q) is the RPC scenario and (yr) stands for the year in each RPC scenario.



Results

Vertical land displacement

The rates of vertical displacement obtained through PS-InSAR show that the coastal sector of the Volta Delta has experienced vertical land displacement rates mainly between -4 mm/yr and 4 mm/yr (subsidence or uplift, respectively) from 2015 to 2021. In Figure 18, the extreme western and eastern portions of the Volta River are dominated by average subsidence rates ranging between 1 and 4 mm/yr, with the middle portion showing an average uplift from 1 to 4 mm/yr.

In general, the upper western and eastern parts of the Volta River demonstrate uplift rates, while subsidence is limited to only a few areas (i.e., 1-4 mm/year). Approximately 48% of the delta experiences some subsidence. Uplift occurs along the main river shores, while subsidence occurs on extreme ends. Examples of average displacement time series for Keta township and Songor lagoon areas, where fluctuations of the PS-InSAR outcomes peak at an average of -20 to -40 mm (Figures 20c and 20d).

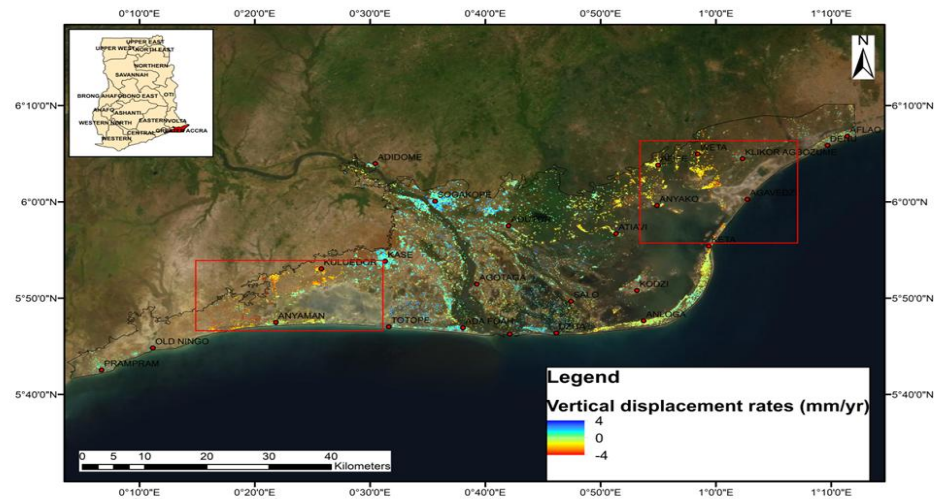


Figure 19: Map showing vertical displacement rates in the Volta Delta from 2015 to 2021

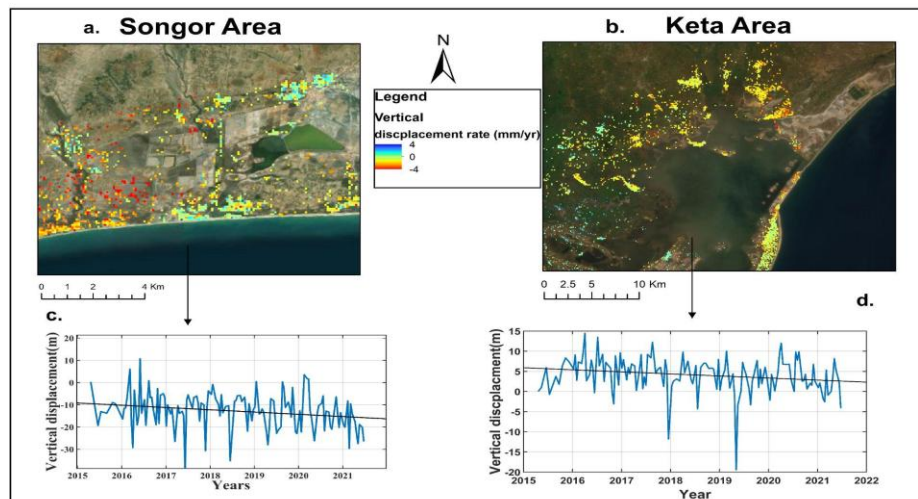


Figure 20: (a) Vertical displacement rate for Songor area; (b) Vertical displacement rate for Keta area; Average time series of the vertical displacement for (c) the Songor area and (d) the Keta lagoon area from 2015 to 2021.

Elevation projection with respect to MSL under RSLR scenarios

The bathtub model was applied using the IPCC RCP scenarios 2.6, 4.5 and 8.5, with modified extreme coastal water levels according to Almar et al. (2021), together with a regionally-averaged LS rate of 4 mm/yr (current altimetry-based regional sea level rise is of 3.3 mm/year, c.f. Marti et al., 2021).

The extent of flooding for RCP 8.5 is shown in Figure 21. The analysis reveals a significant erosion of the beaches, which, in multiple instances, has resulted in the partial or complete elimination of the bodies of water. The projection map shows the delta is vulnerable to inundation with even the lowest-relative SLR (0.1 m), with about 27% of the delta being flooded, as it is already regularly flooded with ECWL events. The flooded area gradually increases till 2100, when most of the delta can be potentially flooded. According to Figure 21, there is a possibility of permanent inundation in the near future for the sandy beaches and low-lying areas located behind the dunes and around the water bodies such as Keta and Songor lagoons. These areas have a mean elevation ranging from 0.15 to 2 m only.

Figure 21 shows the increase in flooding for all the projections due to SLR (ECWL) and RSLR, as well as the percentage of inundation area compared to the total area of the delta districts (about 4562 km²). The highest increase in percentage is computed for a 0.8 m (2100) rise, with a percentage of 5 and 12% for SLR and RSLR, respectively. The increase in flooded areas is gradual, with an increase in SLR and RSLR.

Figure 22 shows RSLR increases flooding by SLR with a maximum increase of 12 % and the area of the Volta Delta districts flooded by a maximum increase of 31%. When compared with the impact of SLR alone, LS increases the extent (and percentage) of the area being flooded with time. Our results indicate that in the absence of mitigation measures, the delta would be inundated by RSLR scenarios by 2100.

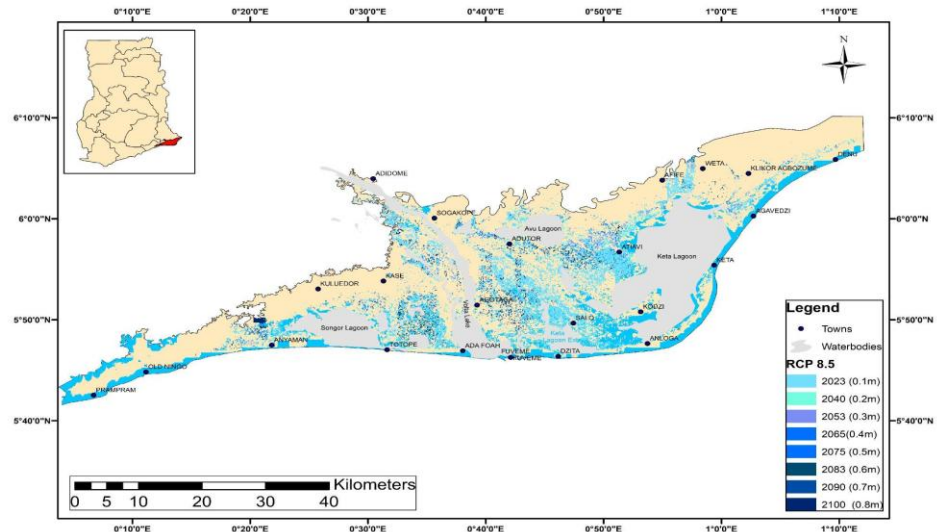


Figure 21: Elevation projection map of the Volta Delta using SLR for RCP 8.5

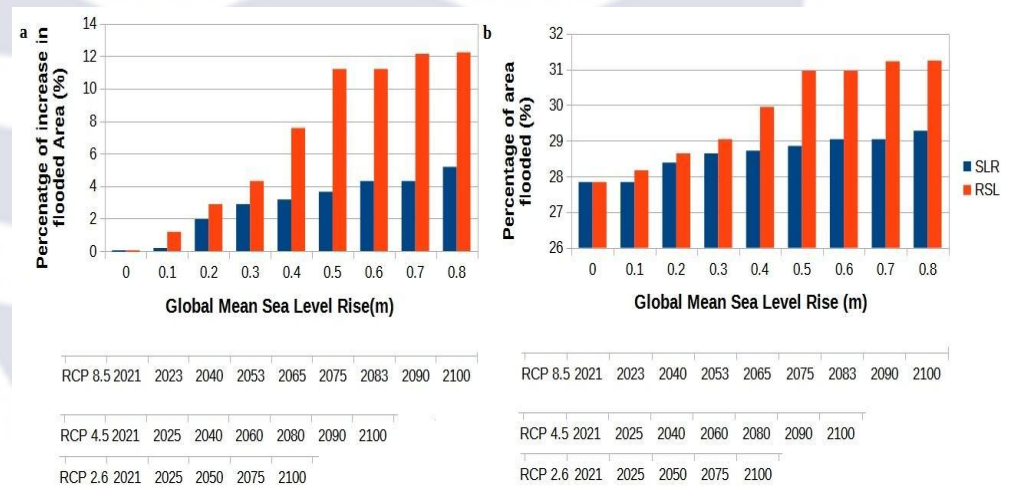


Figure 22: A graph of; a) Coastal inundation changes and b) area flooded during ECWL for all sea level rise scenarios where Sea Level Rise (SLR) is blue, and Relative Sea Level rise (RSL) is red

Discussion

As highlighted by the Delta Alliance report (2019) on the status and trend of the Volta Delta, one key gap in the region is the lack of estimates of the effects of relative SLR (Appeaning Addo et al., 2019). To understand the impact of relative sea level rise, a bathtub analysis was carried out, accounting for both SLR and relative SLR.

In this latter case, a constant subsidence rate has been considered, which is subject to caution regarding long-term trends. Our study quantifies for the first time the recent vertical land displacement rates in the Volta Delta of Ghana. In our satellite-based study, we find an average of 4 mm/yr, which is close to regional mean sea level rise (3.3 mm/yr, Marti et al., 2021). Currently, there are no ground-based measurements, such as continuous GPS, leveling, or tide gauge stations, in the Volta Delta. As a result, the estimated average land subsidence rate of 4 mm/year, which is higher than the previously estimated maximum of 2 mm/year (Appeaning Addo et al., 2018; Syvitski, 2008), should be treated with caution. To monitor changes in the delta's elevation over the coming decades, it is essential to establish continuous GPS and tide gauge stations in the region.

Overall, our study shows that coastal inundation could become more frequent and higher than the present-day conditions, particularly for the Volta Delta since it is a low-lying area. A similar concern is arising in various coastlands worldwide. For example, Paprotny and Terefenko (2017) highlighted that the Polish coastal zone is thought to be one of the most exposed to sea level rise in Europe.

RSLR will increase saltwater contamination of land and aquifers in the delta,

making it difficult to access drinking water. This is already evident in the Volta Delta and has been confirmed by FitzGibbon and Mensah (2012) for areas such as Ada. All the factors (natural, local and global human activities contributing to RSLR) presented here play essential roles in the Volta Delta and highlight the need to intensively monitor and manage their causes and the mitigation of their impacts.

In addition, RSLR has a compounding effect of morphological changes on the delta as well as on the socioeconomic and cultural dynamics of people in the vulnerable coastal communities (Appeaning Addo, 2018; Brempong et al., 2021; Boateng, 2009; Jayson-Quashigah et al., 2019; Ly, 1980). The delta is made up of diverse economies, which include; agriculture (including livestock rearing and fisheries), salt and sand mining, construction, trade, transport and tourism. Coastal flooding is playing a major role in the socio-ecosystems of the delta coastal area, destroying properties and displacing households (Appeaning Addo et al., 2018; Codjoe et al., 2020).

Within the study period, the overall average subsidence rates are generally less than 4 mm/yr. Similar to other case studies (Amelung et al., 1999; Chaussard et al., 2017; Steckler et al., 2022), the InSAR-based vertical displacements we obtained for the Volta Delta shows that vertical land motion is highly variable. Several natural and anthropogenic factors cause changes in vertical land movement. Areas of uplift are seen close to the Volta River banks. This could result from the gradual recharge of the groundwater aquifer system of the delta. Naturally, the Volta Delta falls in the Volta River Basin. The Keta basin is one of the many sedimentary basins in West Africa controlled by faults, as observed by Jørgensen and Banoeng-Yakubo (2001). The geology in the region primarily

consists of unconsolidated sediments and Quaternary rocks, including deposits of clay, loose sand, and gravel (Roest et al., 2018; Appeaning Addo et al., 2018). The basin's geology is primarily composed of acid and basic gneisses and schists from the Dahomeyan system, which serves as a source of drinking water for the central and southern parts of the basin (Nerquaye-Tetteh, 1993). These rock formations also constitute the main deeper aquifer in the Keta basin (Jørgensen & Banoeng-Yakubo, 2001). Although not detected in the current study, these factors may cause subsidence in the Volta Delta due to compaction. Additionally, Shirzaei et al. (2021) suggest that normal faulting, especially in large depocenters along passive margins, can significantly contribute to coastal subsidence. These normal faults, commonly growth faults, represent seaward failure under the gravity of thick, unconsolidated deposits (Shirzaei et al., 2021). This is confirmed in the Delta Alliance report (2019), which indicates that tectonic activity is one source of subsidence in the Volta Delta.

On the other hand, anthropogenic factors equally play a role in subsidence. Various factors, including the extraction of groundwater, oil and gas, mining of coal and salt, artificial drainage of compressible and organic soils, and overloading, can result in subsidence. However, as per Herrera-García et al. (2021), worldwide, the primary cause of subsidence is groundwater extraction. Withdrawal of water from permeable subsurface layers that store water, or aquifers, reduces the pore water pressure and can result in soil consolidation. In the Volta Delta, there are no reliable statistics on the number of irrigation farms, boreholes and wells in the delta. Almost 80% of people use irrigation farms, especially in the dry season. In general, the locations of hand-dug wells are present in every house (Martin & van de Giesenm, 2005). Tube wells are a

popular choice for vegetable farms and irrigation along the Keta Lagoon, and their use is gradually increasing among smallholder farms in the delta. Despite this, irrigation farming in the delta is still in the early stages of development, and smallholder farms in major towns like Keta and Ada utilize various irrigation methods. Furthermore, Appeaning Addo et al. (2018) indicated that subsidence might be accelerated as there are plans for oil and gas production from deep reservoirs in the deltaic area. This may increase fluid withdrawal from the delta subsurface, further contribute to local LS, and enlarge the impacts of RSLR (Ericson et al., 2006). Ericson et al. (2006) and Syvitski and Saito (2007) cite several other deltas that have experienced significant oil and gas accumulation and extraction, including the Niger, Magdalena, Mahakam, MacKenzie, and Mississippi deltas, as well as the Yellow River, as examples of this phenomenon. Abam (2001) also reported that the subsidence rates in the Niger Delta may range from 25 to 125 mm/yr, which is caused by oil and gas extraction activities. According to Morton et al. (2005), the Mississippi Delta is another example where coastal wetlands reduced 11,114 ha/yr from 1955 to 1978, followed by a decline of 2,591 ha/yr from 1990 to 2000. Moreover, along fringes of Lagoons and depressions in the Keta district, a report from the Ghana Ministry of Food and Agriculture states that irrigation farms cover an area of 1052 hectares of land with 34,263 wells. Amid limited data for the Volta Delta, the report also indicates that the Ketu south, Keta, and Ada west districts of the Volta Delta have 5, 11 and 16 dug-outs, respectively (MOFA, 2017). These could contribute to groundwater extraction in the Volta Delta. In terms of groundwater extraction, Martin and Van de Giesen (2005) estimates that 29.4 million cubic meters of groundwater were abstracted in 2001 from 7,285

boreholes in the Volta River basin.

Another important contributing factor to subsidence is salt mining (Mancini et al., 2009; Parwata et al., 2020). The Volta Delta has three available salt mining techniques: traditional, stoved or three-stage crystallisation. The traditional method is also known as the “Ada (location of Songor lagoon) technique”, where salt is produced using saltpans by digging huge trenches and pits and then allowing the brine to seep into them. As the brine evaporates and salt crystallises with the help of solar energy, it is then scraped and harvested by Artisanal and Small-Scale Mining (ASM) operators. This traditional technique usually produces large crystals of salt with low purity (Tychsen et al., 2017). On the other hand, during salt solution mining, salt water is obtained through dissolution that may create a brine-filled downhole, which deforms due to the loads exerted by the overburden. This resulting volume reduction causes surface subsidence (Muntendam-Bos, 2014). Ghana’s major salt mining sites are in the Volta Delta: Ada Songor Lagoon and Keta Lagoon salt production areas (Figure 23).

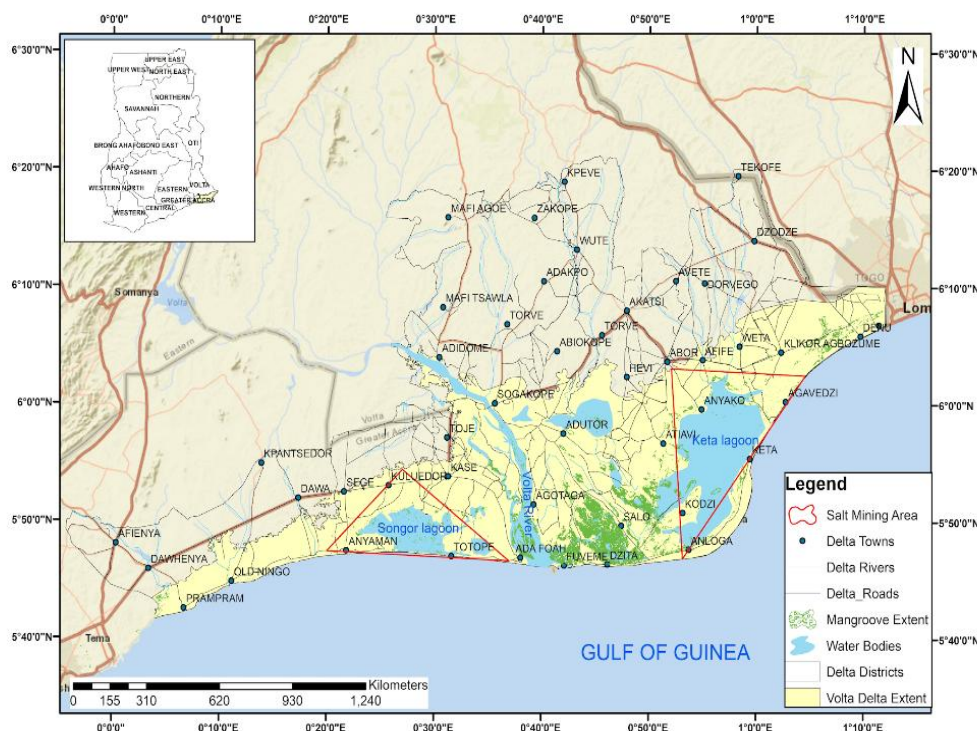


Figure 23: A map showing the general ecosystem of the Volta Delta with salt mining locations

The Third World Network-Africa (2018) report indicates some evidence of extraction of underground brine in Ketu south even though this approach is more expensive. It has more brine concentration, making it more productive (Alhassan, 2018). This is to the extent that Ketu South communities complain of increased salinity and water shortages in their localities (Alhassan, 2018). As of January 2017, there were 5 major salt mining companies in and around the Keta lagoon area. These companies were located in Fiahor, Adina, Afife, Blekusu and Adafienu which are all located in the Keta and Ketu south district (Alhassan, 2018). On the other hand, concerning Figure 19, the spatial distribution of subsidence shows subsidence dominating around the Keta and Songor lagoon. It is very interesting that the Third World Network-Africa (2018) report on “Towards Optimal Exploitation of Salt from the Keta Lagoon

Basin in Ghana” indicates that the Ada Songor area is understood to be the most productive salt mining area with production potential greater than the other salt mining sites in Ghana (Alhassan, 2018). Overall, our study stresses the fact that there could be more displacements of people in the Volta Delta as well as an increase in saltwater intrusion. This study highlights that the Volta Delta is very dynamic and brings to attention the importance of incorporating local LS to the potential effects of RSLR. The RSLR assessment presented here could help the government to create strategies that help reduce the risk of flooding and enhance the Volta Delta in order to adjust and adapt to future flooding events. Furthermore, it should be noted that this simulation of RSLR projection and mapping in areas in the Volta Delta is purely based on a bathtub approach. Therefore, other factors such as wave variations and sediment morphodynamics may contribute to flooding and erosion (an example in Figure 10). This is very important because the study assumes the DEM would most likely be the same throughout till 2100. Additional analysis ought to be conducted while considering calibrated LS measurements and in-situ wave activities from storm surges since they intensify flooding and beach erosion significantly in areas where subsidence has been identified.



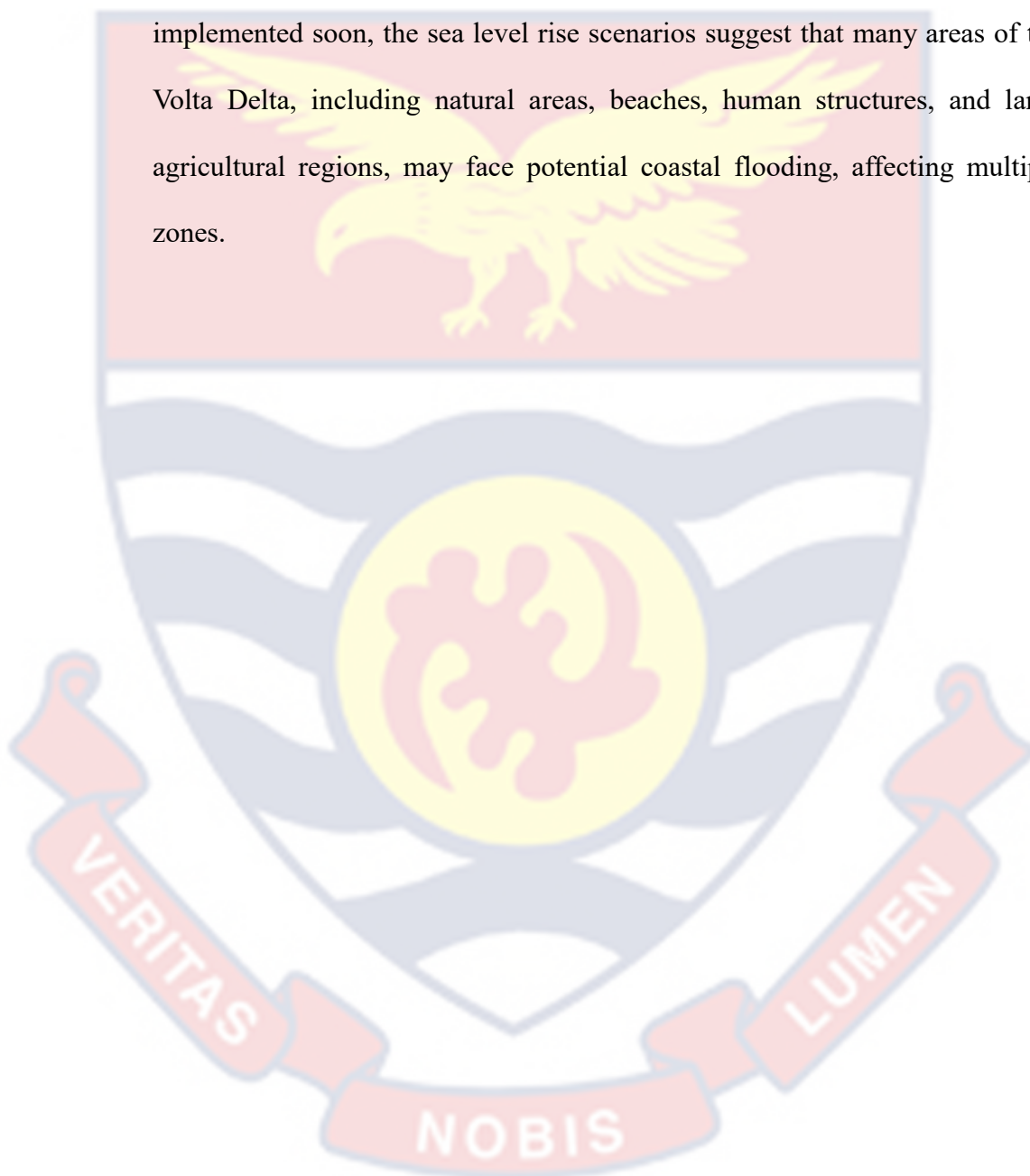
Figure 24: Coastal flooding at Ketu South in the Volta Delta.

Source; <https://newsghana.com.gh/relocation-is-essential-for-tidal-wave-victims-coda-ceo/>

Conclusion

The study estimated the extent of coastal land subsidence resulting from different scenarios of sea level rise and utilized this data to evaluate the projected elevations at risk in the Volta Delta and potential elevations affected by coastal sea level rise. The study assessed for the first-time vertical land movements from 2015 to 2021 using the PSI approach on Sentinel-1 images with the help of SNAP. Averagely subsidence occurs at a rate of 4 mm/yr (similar order of current local mean sea level rise of 3.3 mm/yr), mainly dominated in the Keta and Songor lagoons area, and can be attributed to three major sources: natural processes, groundwater extraction and salt mining. The impact of SLR and RSLR are assessed based on projections according to the scenarios of IPCC reports over the 21st century. In the near future, the increase in global mean sea level will further aggravate flooding events, already

occurring during extreme coastal water levels due to wave events. Despite lower emissions causing relatively moderate projections of sea level rise (RCP 2.6), the study shows that coastal flooding will still be exacerbated by local land subsidence, especially in the Keta area. If no preventive measures are implemented soon, the sea level rise scenarios suggest that many areas of the Volta Delta, including natural areas, beaches, human structures, and large agricultural regions, may face potential coastal flooding, affecting multiple zones.



CHAPTER FOUR

COASTAL FLOODING CAUSED BY EXTREME COASTAL WATER

LEVEL AT THE WORLD HERITAGE HISTORIC KETA CITY

(GHANA, WEST AFRICA)

Emmanuel K. Brempong^{1,2,3*}, Rafael Almar², Donatus Bapentire Angnuureng¹, Precious Agbeko Dzorgbe Mattah¹, Philip-Neri Jayson-Quashigah⁴, Kwesi Twum Antwi-Agyakwa^{1,2}, Blessing Charuka^{1,2}

¹ Africa Centre of Excellence in Coastal Resilience (ACECoR), University of Cape Coast, Cape Coast 00223, Ghana;

² LEGOS, Université de Toulouse, CNES, CNRS, IRD, UPS, Observatoire Midi Pyrénées, 14 Avenue Edouard Belin, 31400 Toulouse, France;

³ Department of Fisheries and Aquatic Sciences, School of Biological Sciences, University of Cape Coast, Cape Coast 00233, Ghana

⁴ Institute for Environment and Sanitation Studies, University of Ghana, Legon;

Author Contributions:

Conceptualization, Methodology, Formal analysis ,Validation: Emmanuel K. Brempong and Rafael Almar.

Investigation and data curation : Emmanuel K. Brempong, Rafael Almar and Donatus Bapentire Angnuureng .

Writing—original draft preparation : Emmanuel K. Brempong

Writing—review and editing : Emmanuel K. Brempong, Rafael Almar and Donatus Bapentire Angnuureng, Precious Agbeko Dzorgbe Mattah, Philip-Neri Jayson-Quashigah, Kwesi Twum Antwi-Agyakwa¹, Blessing Charuka:

Supervision; Precious Mattah, Rafael Almar , Donatus Bapentire

Angnuureng,

Published : MDPI, Journal of Marine Science and Engineering, 11(6), 1144.

<https://doi.org/10.3390/jmse11061144>.

Abstract

Like low-lying sandy coasts around the world, the Ghanaian coast is experiencing increasingly frequent coastal flooding due to climate change, putting important socio-economic infrastructure and people at risk. Our study assesses the major factors contributing to Extreme Coastal Water Levels (ECWL) from 1994 to 2015. ECWL are categorized into low, moderate and severe levels corresponding to the 30th, 60th and 98th percentiles, respectively. Using these 3 levels over Pleiades satellite-derived Digital Elevation Model topography, potential flood extent zones are mapped. ECWL has the potential to flood more than 40% of the study area, including socio-economically important sites such as touristic beach resorts, Cape St. Paul lighthouse and Fort Prinzenstein. In this study, all coastal flooding events recorded by the municipality of Keta fall within the 98th percentile category. Our results show a gradual increase in the frequency of flooding over the years. Flooding events are caused by a compound effect of tide, sea level anomaly, wave and atmospheric conditions. Finally, while wave run-up is the major contributor to coastal flooding, tide is the one varying most, which facilitates a simple early warning system based on waves and tide but adds uncertainty and complicates long-term predictability.

Keywords: Gulf of Guinea; Wave run-up; Sea level rise; Coastal flooding

Introduction

Globally, coastal flooding affects coastal areas due to sea-level rise (SLR). Coastal areas serve as homes for about 2.4 billion people (40% of the world's population) (Braun, 2021), as well as provide high economic value to coastal countries (McGranahan et al., 2007). Over the 21st century, projections have shown that SLR would increase the rate of coastal flooding globally (Peter Sheng et al., 2022). This would possibly displace most people living in low-lying coastal zones and impact socio-economic and ecological systems of high importance, particularly in Africa (Dada et al., 2021; Vousdoukas et al., 2022). Generally, the main cause of coastal flooding is high water levels due to several factors. Coastal flooding is instigated by an amalgamation of numerous factors from the ocean and atmosphere, such as mean sea level changes, tides, storm surges, waves, river discharge, and rainfall (Marcos et al., 2019). When two or more of these factors occur simultaneously, the severity of flooding can worsen, leading to an amplified risk of coastal flooding. Examples of compound flooding events include a combination of river discharge and storm surges (Olbert et al., 2023), rainfall and surges along the U.S. coast (Wahl et al., 2012), and the interaction of rainfall, surges, and waves (Bilskie & Hagen, 2018; Paprotny et al., 2018). If these events are statistically dependent, meaning they share a mutual driving force, the likelihood of them occurring together is higher than expected when considering each variable separately. This increased likelihood of compound flooding events can lead to a higher chance of coastal flooding (Almar et al., 2021; Marcos et al., 2019).

All these together would eventually lead to overtopping and inundating coastal defenses in low-lying areas, which potentially cause damage to life and

property. Coastal flooding continues to pose a huge threat to coastal inhabitants. It is known to be one of the most dangerous and costly of all natural disasters (Church et al., 2013; Nerem et al., 2018). Therefore, it is essential to create awareness of the need to plan, mitigate and consider alternatives to reduce the effects of coastal flooding. Understanding the occurrence of Extreme Coastal Water Levels (ECWL) (Almar et al., 2021; Gregory et al., 2019) can help support decision-making in coastal zone management. This would help identify regions affected by a strong increase in flood risk and prioritize mitigation and adaptation efforts (de Moel et al., 2015). During ECWL, overtopping is the main cause of coastal flooding, with much water surpassing the maximum coastal elevation (dunes, dykes, cliffs) (van der Meer et al., 2019). Despite this, when overtopping occurs, all areas with low elevation do not submerge though this phenomenon mainly drives localized coastal flooding and damage to infrastructures.

Furthermore, overtopping due to ECWL is even more catastrophic when there is a failure or absence of coastal protection, such as groins and revetments (Bertin et al., 2014). According to Melet et al., (2018), the principal components of ECWL are Sea Level Anomaly (SLA), Dynamic Atmospheric Conditions (DAC), Tide (T) and Wave Run-up (R). On Jamestown Beach in Accra, Angnuureng et al., (2018) noted that shoreline change responds in decreasing order to sea level variations (86%), waves (9%), and tidal cycles (5%) on daily bases. Wind-induced setup has limited effect on the shoreline, while the observed most important component of SLA at that coast was the influence from the inverse barometer. SLA is due to the steric effect, ocean circulation, and transfer of mass from the continents (ice sheets, glaciers, land water) to the

ocean, DAC due to atmospheric pressure and winds, astronomical tide (T), and wave effects here referred to collectively as run-up (R), which includes a time-averaged component (setup) and an oscillatory component (swash) (Melet et al., 2018). Quantifying these local contributions during flooding events is key, as their relative contribution varies spatiotemporally. One key factor to consider when assessing flooding and overtopping is a good and higher DEM resolution. A higher resolution DEM tends to preserve the topographical terrain features thus determining where floods are most likely to cause problems for people and property and estimating how water interacts with the environment depending on high-quality DEM data. The precision and spatial resolution of the DEM affect the accuracy of forecasts of flood depths (Vaze et al., 2010). Numerous publications have extensively examined the justification for utilizing coarse DEM resolutions. They concluded that, despite their lack of precision, their model simulations offer a good trade-off between readily accessible (free) data, minimal computational requirements, and an appropriate depiction of hydrological processes and catchment responses. However, even while increased spatial resolution and accuracy frequently lead to better outcomes, it is rarely available since these are commercial and not freely available. Recently, the high-resolution DEMs from sources such as Pleiades stereo imagery have played a significant role in coastal morphology changes, making them a great tool to explore and use (Almeida et al., 2019; Taveneau et al., 2021).

The eastern coast of Ghana is known to be the most vulnerable coast in Ghana. It experiences coastal flooding not less than twice every year (Appeaning Addo et al., 2018). In addition, the frequency and intensity of coastal flooding and erosion have increased. Over the past decade, the Volta Delta has significantly

increased coastal flooding events and duration (Bokpe, 2010; Matteo, 2016). Some studies have attributed this to intensive rainfall, oceanographic conditions (waves, sea level rise and tides) and human activities (watershed management) (Appeaning Addo et al., 2018).

On the other hand, the construction of the Akosombo dam on the Volta River has been identified as a major cause of erosion and flooding problems in the Volta Delta region (Anthony, 2015; Appeaning Addo et al., 2020; Ly, 1980). In particular, the Keta district has been affected by coastal erosion and flooding. For this reason, one of Ghana's largest sea defences was constructed from 2000 to 2004 to control coastal erosion and flooding. Therefore, it is very important to understand hydrodynamic factors dominating coastal flooding in Keta and Volta Delta at large.

Our study uses Pleiades stereo images to develop the Digital Elevation Model (DEM) and wave, tide and sea level anomaly data from satellite and globally freely available reanalysis. The main aim of this study is to assess the predominant factors of coastal flooding in the Keta municipality. To achieve this, ECWL were first categorized into three main percentiles (30th, 60th, 98th); secondly, the spatial extent of flooding at each percentile was assessed; and finally, the dominant and most varying factors were assessed in the 98th percentile scenario. The importance of this study is that it explores the most dominant factors and thus provides reasons to consider these factors in implementing coastal flooding decisions.

Materials and Methods

Study area

Keta Municipality and its neighboring towns are located in a large wetland-protected area of 1200 km². Keta lies on the eastern coast of Ghana and is located precisely at the extreme east of the Volta Estuary. This study used Pleiades satellite imagery (Figure 25) covering major towns such as Woe, Tegbi and Keta. The largest lagoon in Ghana, the Keta Lagoon complex, is located in this municipality. The Keta Lagoon facilitates water transportation to surrounding communities and has the potential for large-scale commercial aquaculture. Generally, the municipality serves as a breeding ground for many sea turtles and a temporary passage point for migratory birds. The town is separated by a narrow sand strip separating the Keta lagoon from the sea. Keta is in the Keta Basin, and its geology largely includes mud, wobbly sand, and gravel (Akpati, 1978). Studies by Kabo-bah & Diji (2018) indicate the presence of numerous canyons(valleys) in the deep waters, which also signify active erosion. In the past, rampant coastal flood and erosion cases were recorded, precisely in 1907 when the first coastal erosion occurred, then in 1924, 1949, 1986, 1996, and 1997 (GARR, 2010). This has led to constructing sea defence structures along the Keta municipality stretch.

The climate conditions are dry equatorial, with a mean rainfall below 1000 mm in May and July and sometimes late August and October. Generally, wind conditions are weak, with speeds less than 2.6 m/s (Addo et al., 2018a; Roest, n.d.-b). Wave conditions are generally less than 3 m and a maximum period of 19.68s in the direction south and southwest with an average period of 10.91s. The tide condition is micro-tidal and estimated to be 1 m on average. The

beaches are generally sandy with a median grain size of 0.6 mm, and most inhabitants survive by fishing and farming (Duku et al., 2022). The inhabitants of Keta district are involved in various economic activities. These include agriculture, fisheries, salt harvesting, sand mining, and tourism. The agricultural and fishing sectors are more dominant than the other sectors. Fort Prizenstein and Woe Lighthouse are two major tourist sites in the Keta District. The Keta district is very important to the Volta Delta; therefore, it is imperative to assess and understand the factors that influence coastal flooding in this area and for the Volta Delta as a whole.

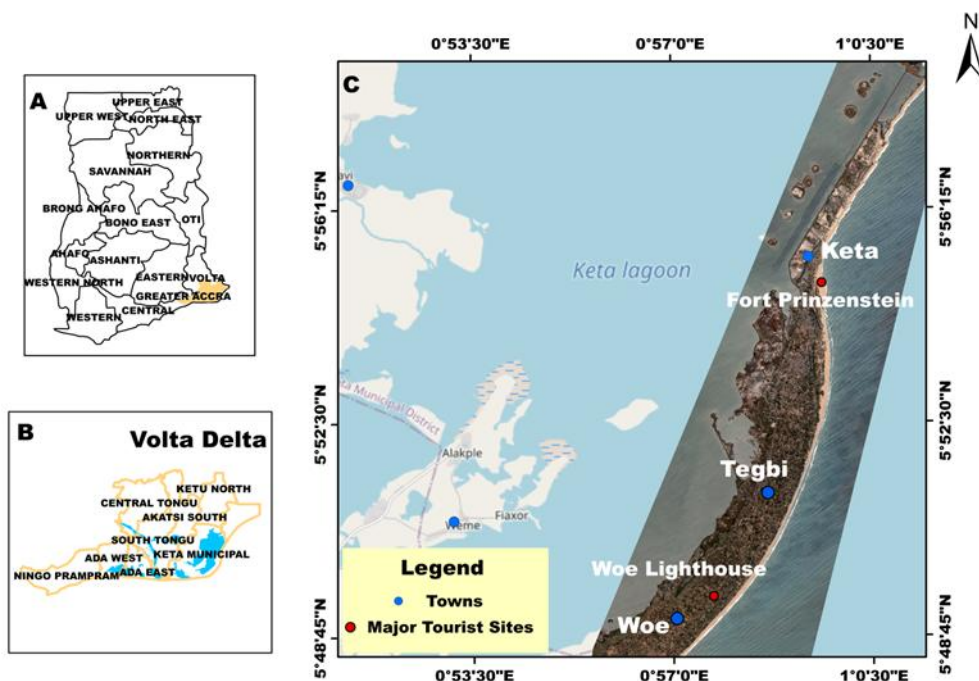


Figure 25: A map of the study area showing; A) an image of Ghana with all regions and the Volta Delta shaded in yellow; B) an image of the Volta Delta showing all the districts, and C) an image of Keta District with Pleiades multi-spectral satellite image superimposed showing the major towns and tourist sites in the Keta District of the Volta Delta, Ghana (Gulf of Guinea, West Africa)

Datasets

This section describes the data used for this study. This study uses satellite imagery and hydrodynamic data. for the Keta area.

Pleiades Satellite Imagery and Acquisition

Satellite data provide key missing information for coastal management (Turner et al., 2021), including ocean drivers, land use and vulnerability assessment (Almar et al., 2019; Melet et al., 2018). It turns out that in West Africa, there are several gaps in coastal management. Also, there is limited use of high-resolution satellites, thereby preventing any efficient mitigation measure on a broad scale.

The Pleiades satellites 1A and 1B were launched in 2011 and 2012, respectively, at an altitude of 694 km and can obtain a burst of up to 12 images during a single pass (Almar et al., 2023). The Pleiades imagery comes in single or (tri)stereo images with Panchromatic and multi-spectral images of respective ground pixel resolutions of 0.5 m and 2 m. Thus, the sensors of the Pleiades satellites work in the near-infrared and visible spectrum. However, the Pleiades imagery was first established in line with the French–Italian Optical and Radar Federated Earth Observation program (ORFEO). In recent years other partners in Europe and other countries have used it in their studies. The major features of the Pleiades collection are explained in detail in the user guide of Pleiades Imagery (Gleyzes et al., 2012). For this study, tri-stereo imagery was acquired from the Centre National D'études Spatiales (CNES).

At Keta, such burst and tri-stereo images (Figure 26) were acquired on the 20th of October 2020 and constituted the data used in this study. The time difference between the individual images is set for each acquisition to $dT = 6$ s. This gives

a base-to-height (B-H) ratio for the two data sets of $B/H = 0.12$. Generally, for flat areas, a low B/H value gives a better height accuracy of the stereoscopy (Jacobsen & Topan, 2015). The Pleiades images were acquired at an approximately equal tidal elevation of +0.8 m. These images were finally downloaded from Centre National D'études Spatiales (CNES) website. Unfortunately, this data is not freely available but was acquired with the help of LEGOS.

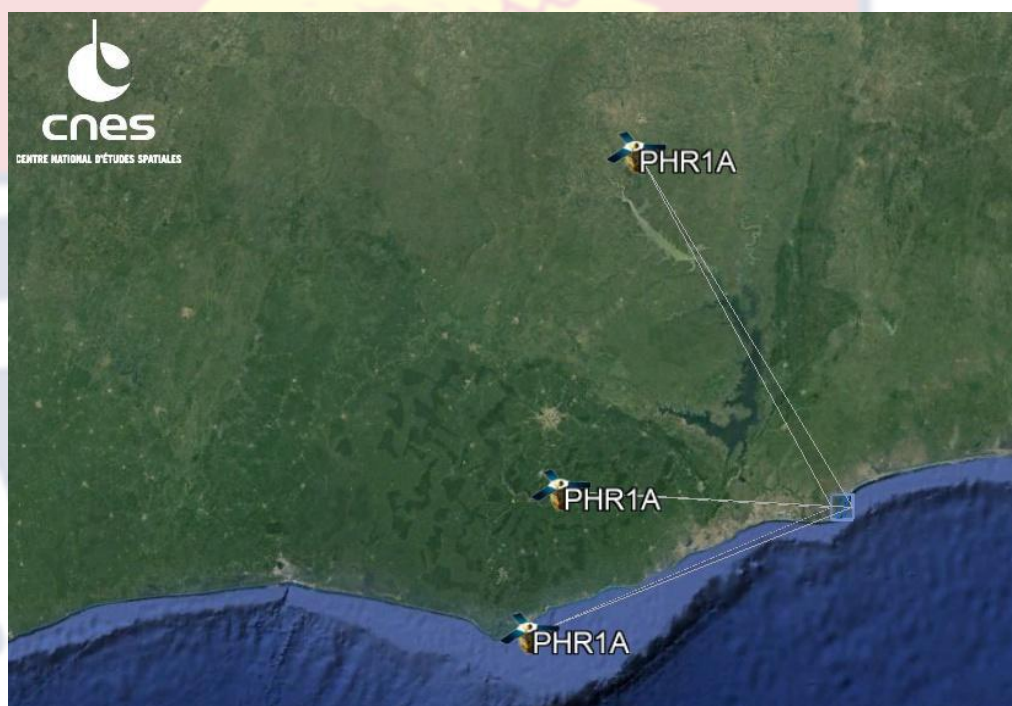


Figure 26: An image of the tri-stereo images (PHR1A) acquired on the 20th of October 2020 for the Keta study area (made using google earth)

Hydrodynamic data

To compute ECWL, it is required to use hydrodynamic, meteorological and tidal parameters (Almar et al., 2021). For this study, the parameters used include; Sea Level Anomaly (SLA), Wave run-up (R), tide (T) and other atmospheric conditions (DAC). All parameters were referenced to the WGS84

datum and extracted at a grid point of latitude of 6.047366° and longitude of 1.080522° .

Tide data was extracted on the hourly resolution at the nearest grid point from the global tide FES (Finite Element Solution) 2014 model (Carrere et al., 2015).

This data is produced by the Laboratory of Geophysical and Oceanographic Spatial Studies of Toulouse (LEGOS). AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic) data, with the support of the Centre National d'Etudes Spatiales (CNES), distributes the Atmospheric pressure and winds component (DAC) generated by the MOG2D model from LEGOS of the Collecte Localisation Satellites (CLS) Space Oceanography Division (Soudarin et al., 2018). More information can be found at <http://www.aviso.altimetry.fr/>.

Altimetric-derived SLA, including global mean level rise (GMSLR), was extracted from AVISO's nearest gridded data point of the altimetry data point (Marti et al., 2021).

All Wave run-up data were obtained from ERA-Interim reanalysis (global climate and weather data available from 1979 onward at a $0.5^\circ \times 0.5^\circ$ resolution).

This data was produced by the European Center for Medium-Range Weather Forecasting (ECMWF) model, which used wave data at 6-hourly resolution.

The calculation of Wave run-up (R) was done using the dissipative beach equation proposed by (Stockdon et al., 2006) (see (Almar et al., 2021);

Refer to equation 6

H_s is the offshore significant wave height, and L_o is the wavelength. All the parameters mentioned above are resampled hourly from 1994-2015. All hydrodynamic data used in this study were freely available and extracted for the Keta area within its conforming grids.

Workflow and Methodology

This section describes all methods used in this study; this includes DEMs derived from the Pleiades, Computing Extreme Coastal Water level (ECWL) and flood extent mapping.

Pleiades-derived topography

Digital Elevation Models (DEMs) were generated from the Pleiades stereo imagery using the NASA AMES Stereo Pipeline (ASP) software to obtain the topographic variation of the beach. The ASP software uses the tri-stereogrammetry method, where DEMs are derived from the sensor level. For the tri-stereo methodology approach of ASP, three panchromatic images are taken as input (0.5 m resolution) (Rupnik et al., 2018). These are then correlated pair by pair, and a final correlation between the two correlated pairs gives the output DEM. This method uses the Rational Polynomial Coefficient (RPC), which accompanies the imagery and further provides a relationship between the satellite image and ground coordinates. The DEM was then orthorectified by referencing them to planimetric coordinates. This was done using AMES Stereo Pipeline software. It has a feature that ortho-rectifies a sensor-level satellite image using its geometry by the accompanied RPC file and, in the process, creates a DEM at a set resolution (see also (Almeida et al., 2019; Taveneau et al., 2021)). This DEM is automatically ortho-rectified, after which the satellite images at the sensor are projected onto the DEM so that the output images are fully ortho-rectified and corrected using ground control points (Gleyzes et al., 2012). The Pleiades panchromatic images (0.5 m resolution) produced a 2 m

resolution DEM. The various steps involved in Pleiades imagery processing are summarized in Figure 27.

Pleiades Imagery Pre-processing

This is the preliminary stage of Pleiades data processing. In this stage, data is selected and organized by matching similar features. The pairs of Pleiades images called 1&2 and 2&3 are selected and processed. After this, the stereo image pairs are selected, and band one is selected from each image and aligned using the affine-epipolar algorithm of ASP (Palaseanu-Lovejoy et al., 2019). Images are pre-aligned. This process is carried out by identifying tie-points between them, which are then used to alternate the sensor spot to guarantee that pairs of conjugate epipolar lines are both col-linear and analogous to one of the image axes (Shean et al., 2016). Due to the incompatibility of the ASP software with multi-band imagery, this study opted for a panchromatic image (band 1) as it offers a wide range of radiance data and good graphic and visual contrast, which aids in distinguishing image features from their respective shadows.

Corresponding features

In the ASP, features are matched with each other after the images are prepared for feature matching (Figure 27). The search window algorithms (SW) in ASP approximate the superficial motion of each scene point by linking the search windows of each local window with each pixel in the stereo pair (Facciolo et al., 2015). For each stereo pair, a relative disparity map is produced with a search window algorithm (Palaseanu-Lovejoy et al., 2019)

Reconstruction of topography from Pleiades (3D reconstruction)

After data is processed and corresponding features are identified, ASP uses the stereo triangulation algorithm method (Figure 27) to merge features to obtain a 3D location (x, y, z) of the nearby intersection between lines that link the sensor orbital location to all matched pixels in both the left and right images. This approach combines all the information on altitudes, the model of each sensor, and the disparity map. The result of the process is a raster format consisting of four bands containing triangulated coordinates for x, y, and z, as well as a triangulation error metric stored in the fourth band. This metric is useful in evaluating the quality of the sensor model, ephemeris/attitude data, and the disparity matches (Soudarin et al., 2018). Next, the output is transformed into a 3D point cloud, which is geocoded using the WGS84 UTM 31N coordinate system and ellipsoid heights. The post-processing stage of the ASP involves determining the orthometric heights of the 3D point cloud using ground control points (GCPs) with known orthometric heights to calculate a height correction factor for the 3D point cloud (Knuth et al., 2023). Ground Control Points (GCPs) in the form of concrete pillars buried at ground level and marked for identification purposes were used for the study. These GCPs were obtained from (Jayson-Quashigah et al., 2019) for the Keta area. The GCPs obtained were in the form of X, Y, and Zs of ground pillars. They were connected to the Ghana Metre grid system to establish and coordinate the concrete pillars as Ground Control Points (GCPs). This process followed the standards set by the Ghana Survey Department, ensuring consistency and conformity. The static Differential GPS (D-GPS) method was employed to observe each control point, with an average observation time of not more than 30 minutes. These

observations were referenced to the established Ghana National coordinated pillars (Jayson-Quashigah et al., 2019). Finally, the 3D point cloud is utilized to generate DEMs and orthophotos. The final DEM and orthophotos are exported and saved for further analysis using the ASP stereo-RPC algorithms.

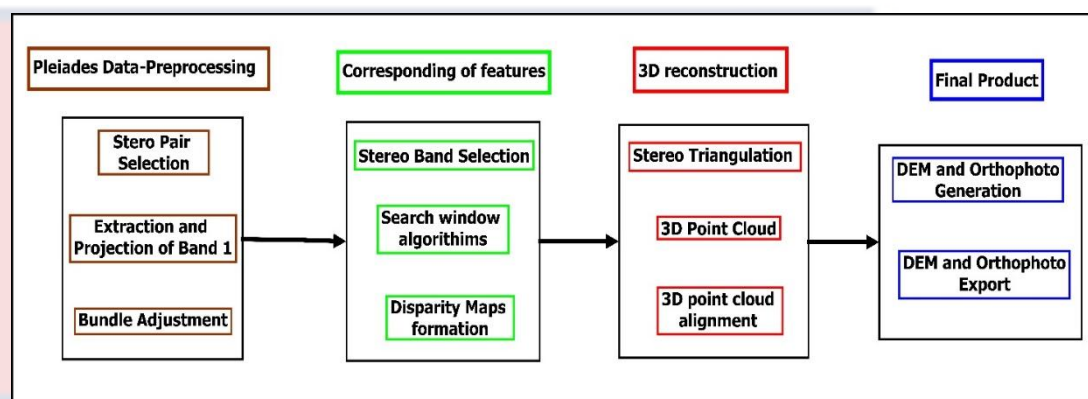


Figure 27: A summary of the methodology for NASA's Ames Stereo Pipeline software (ASP) for Structure from Motion procedure workflow implemented in this study. This approach derives DEMs and orthophotos from satellite imagery

The Altimeter Corrected Elevations Version 2 (ACE2)

To assess the quality of DEMs for coastal flooding studies, DEM was downloaded from the website of the Data Center in NASA's Earth Observing System Data and Information System (EOSDIS). ACE2 is the second iteration of the Global Digital Elevation Model that the Shuttle Radar Topography Mission produced using satellite radar altimetry (SRTM). Version 1 data has been upgraded with the release of the Altimeter Corrected Elevations Version 2 (ACE2) generated by combining Satellite Radar Altimetry with SRTM. Global Observations to Benefit the Environment (GLOBE), the original Altimeter Corrected Elevations (ACE) Digital Elevation Model (DEM), and additional matrices produced by reprocessing European Remote Sensing (ERS-1) images are among the data sources used in the adjustment. The three arc seconds data

(90 m) was downloaded with the same datum for this study to compare with Pleiades-derived DEM (Mesa-Mingorance & Ariza-López, 2020).

Computing Extreme Coastal Water Level (ECWL)

Using the hourly datasets described earlier, ECWLs were calculated hourly from 1994–2015. This approach followed the formula.

Refer to equation 7

Three major percentiles were used to show how severe ECWL goes; the 30th, 60th and 98th percentiles were obtained and further confirmed with in-situ flood occurrence dates from 2000 to 2015 from the National Disaster Management Organization of the Keta district. In Keta, Extreme Coastal Water Levels (ECWL) are determined using an approach that combines several parameters such as Sea Level Anomaly (SLA), storm surge height caused by atmospheric pressure and winds (DAC), astronomical tide level (T), and height of wave breaking (R). The worst scenario of water levels is defined as the top 2% or 98th percentile to determine the physical impact of ECWL in the area. The cumulative annual occurrence of the time spent over this threshold is computed over the study period. Topographic data is set to a geoidal coordinate system to assess the potential for overtopping and flooding. ECWL is converted to geodetic data using the vertical datum value of Collilieux & Wöppelmann (2011) to superimpose with the topographic data. Finally, MATLAB software's linear regression is used to analyze the trend of ECWL in the Keta area based on annualized data.

Flood extent mapping

Potential flood extent zones were mapped using the bathtub inundation model. This approach assumes that areas would be flooded with elevations lower than the ECWL for all percentiles. Flooded areas are mapped in the Geographic Information System (GIS) environment using a simple calculation (equation 3). All elevations in each cell of the Pleiades DEM are equated against a predicted ECWL, and all cells that fall below the ECWL are considered flooded. Since only data on the elevation is needed for its application, the approach allows for estimates without detailed hydrological data (Yunus et al., 2016).

Using the raster calculator tool in ArcGIS 10.4, ECWL for the different percentiles were computed to assess areas which fall below ECWL along Keta city. All ECWL for the three percentiles were considered for a bathtub analysis. This approach is frequently used for this type of analysis (Didier et al., 2019; Leal-Alves et al., 2020; Rizzo et al., 2022; Snoussi et al., 2008). The ESRI's ArcGIS 10.4 and MATLAB software was used for statistical calculation and map development.

$$\text{Elevation projection by } ECWL_{(p)} = (DEM \leq ECWL_{(p)}) \quad \text{Equation 11}$$

where (p) are percentiles (30th, 60th or 98th percentile).

Results

Percentile of Coastal flood occurrences

All ECWL was ranked 30th, 60th and 98th percentiles, corresponding to 0.54 m, 0.97 m and 1.62 m, respectively. For example, from Figure 28, flood events obtained from the National Disaster Management Organization (NADMO) in the Keta district occurred around the 98th percentile (1.62 m).

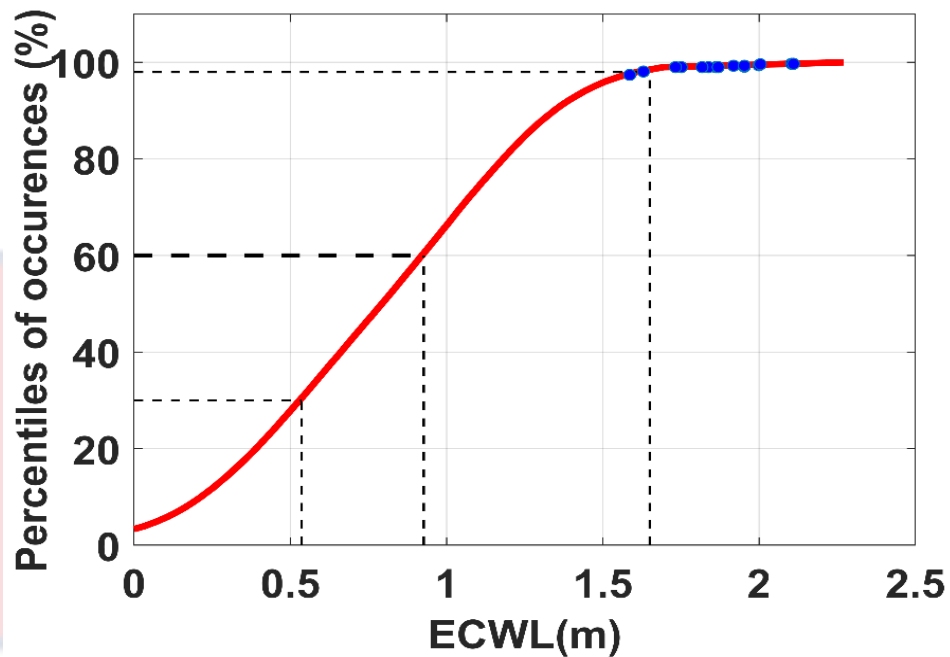


Figure 28: A percentile distribution plot of extreme coastal water levels from 1994 to 2015 showing the 30th, 60th and 98th percentile with occurrences of coastal flooding obtained from NADMO in blue dots

Time spent in the 98th percentile

Generally, for the 98th percentile, the maximum time spent on coastal flooding is 200 hours per year. However, there is an increase in time spent from 1994 to 2015. Figure 29 shows a gradual increase in hours spent every year.

Table 1; The occurrence of coastal flooding was obtained from NADMO from 2002 to 2015. Generally, all data obtained from NADMO ranges between 2002 to 2015. There is no data available from 1994 to 2002. All data sets were collected by observing flooding.

Generally, all data obtained from NADMO ranges between 2002 to 2015. There is no data available from 1994 to 2002. All data sets were collected by observing flooding and reporting by the NADMO office in Keta, Ghana.

Table 1. The occurrence of coastal flooding was obtained from NADMO from 2002 to 2015

Year of occurrence	Month of Occurrence
2002	August
2003	September
2004	July
2005	July
2006	September
2007	July
2008	August
2009	September
2010	August
2011	July
2012	June
2013	July
2014	August
2015	September

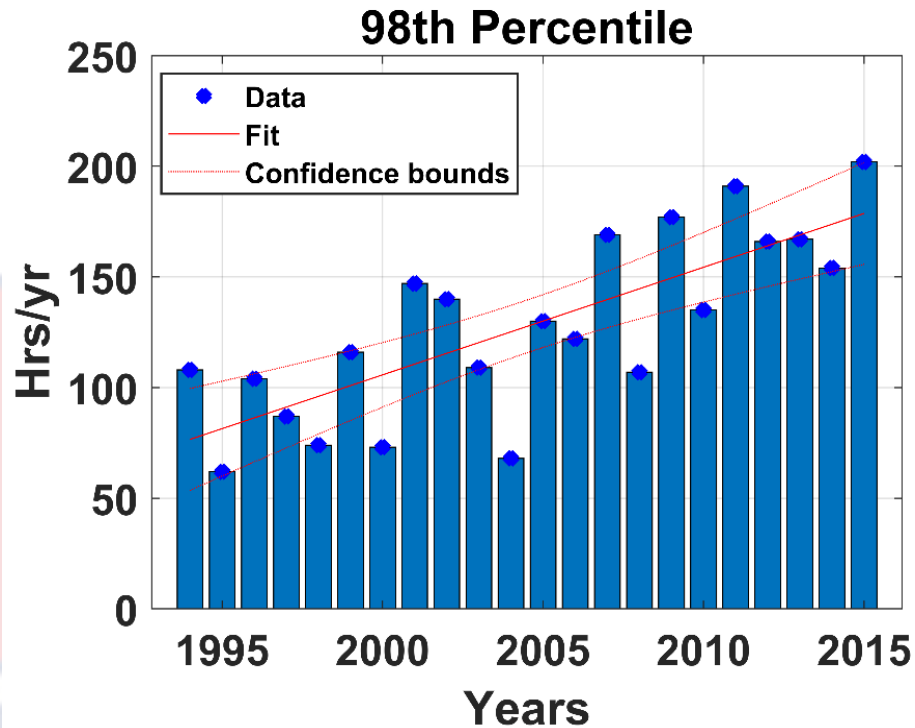


Figure 29: Time spent by an occurrence at the 98th percentile in hours per year from 1994 to 2015, showing blue dots of maximum annual ECWL data and red trend line from 1994 to 2015

Flood extent mapping concerning percentiles

Figure 30 shows the extent and percentage of potentially flooded areas for all percentiles. The highest percentage of the area flooded was recorded in the 98th percentile. The figure shows that 43% of the area would potentially flood. The 30th and 60th percentiles showed that 19% and 29% of the area would potentially be flooded, respectively. However, the most severe flooding is observed in the 98th percentile scenario.

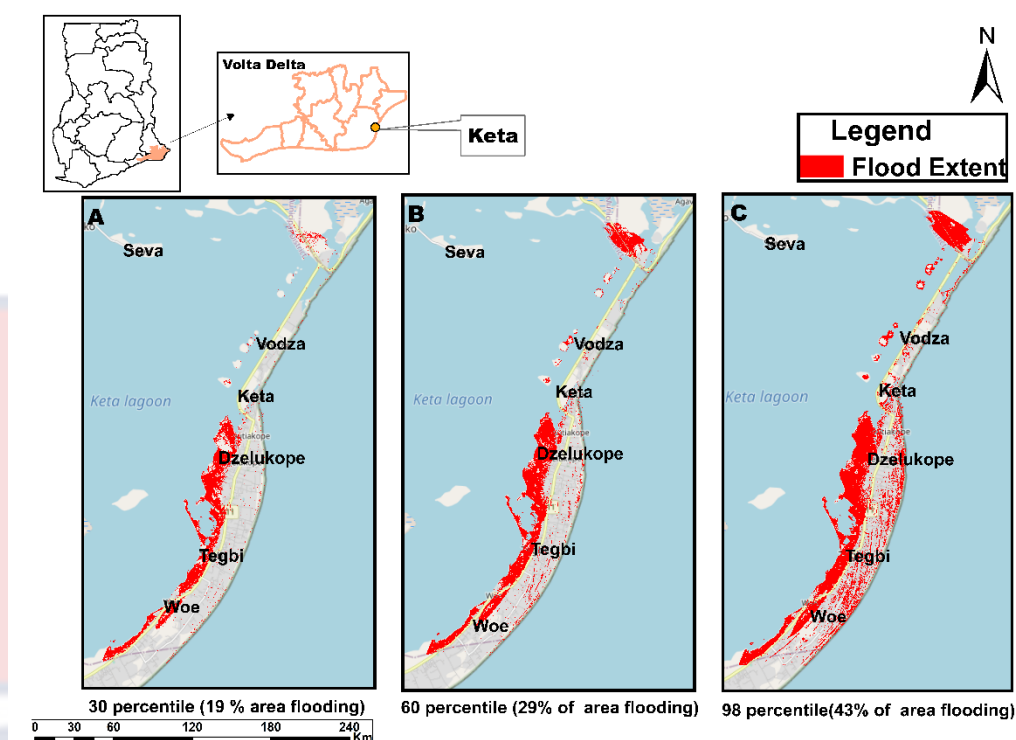


Figure 30: Flood extent mapping for each scenario of ECWL where; A) 30th percentile of ECWL with 19 % of the area being potentially flooded, B) 60th percentile of ECWL with 29 % of the area being potentially flooded, C) 98th percentile of the area being potentially flooded

Comparison of Pleiades DEM and ACE2 DEM

A simple comparison between the two DEMs was assessed to show the ability of Pleiades DEMs to capture beach evolution and coastal flooding. Figure 31A and 31B shows the location of the transect (red line) from which elevation profiles were extracted for both Pleiades and ACE2 DEMs. Figure 31C exhibits profile variations extracted for a distance of about 600 m, and this further shows a maximum elevation of 11 m high for Pleiades DEM and 2 m high for ACE2 DEM. This shows a very good representation and variation in the beach's topography. Figure 31 D is a box plot showing the variation and distribution of elevation along the transect. While Pleiades DEM shows a good elevation distribution and variation, ACE 2 DEM barely shows any variation distribution in elevation within the same transect.

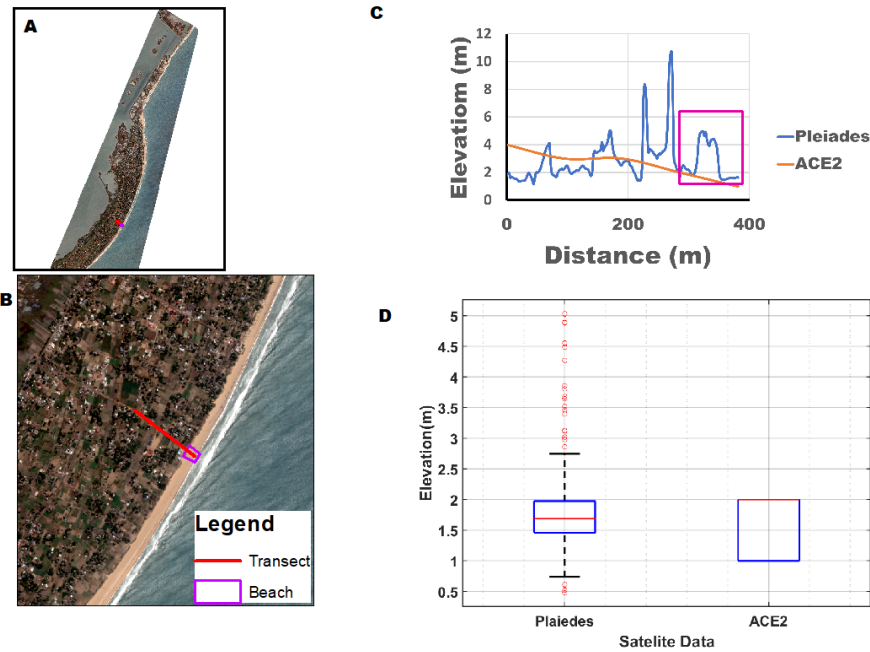


Figure 31: A) An orthophoto of the Pleiades imagery for the Keta municipality with a red line B) The zoomed-in orthophoto of the selected transect and a purple box showing the beach area. C) Elevation variation for Pleiades and ACE2 with a purple box showing the beach area of the transect. D) A box plot of elevation along the transect shows the distribution of Pleiades and ACE2 imagery elevation values

Hydrodynamic contributors of coastal flooding

The major factors contributing to coastal flooding in the 98th percentile were evaluated from 1994 to 2015. Figure 32 shows the distribution of dominant factors in the ECWL. Waves have the highest contribution of 1.2 m compared to all other factors. Tide is the second highest contributor with 0.6 m, followed by SLA and DAC. Figure 32 shows that Wave Run-up dominates 98% of ECWL to coastal flooding, followed by the Tides, SLA and DAC.

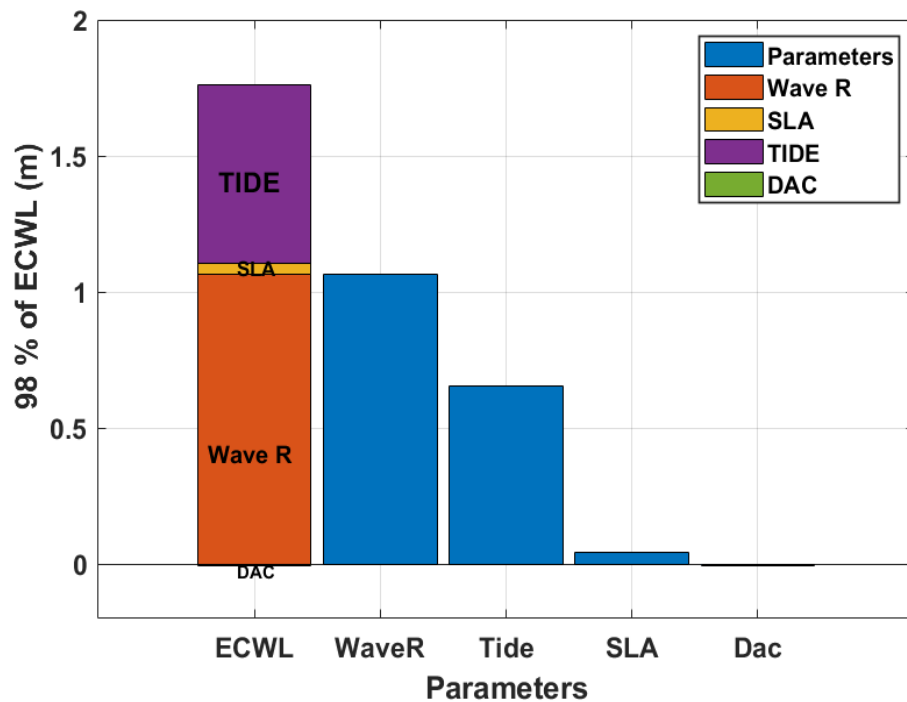


Figure 32: Hydrodynamic contributors to coastal flooding at 98 %, showing the contribution of all parameters in ECWL at 98 % of ECWL. The extreme left shows a stacked bar plot of all parameters, with Wave R, Tide, SLA and DAC showing the dominance hierarchy

Variability of ECWL parameters

Figure 33 shows the variability of parameters in 98% of ECWL. A mean deviation plot was plotted to assess the variability between each parameter. From Figure 33, tide shows the highest variability amongst all the parameters, with about 0.75 m of variation. Though waves dominate from Figure 33, tides vary greatly during coastal flooding of 98% of ECWL. On the other hand, parameters such as SLA and DAC exhibit very low variability between -0.05 and 0.05 m.

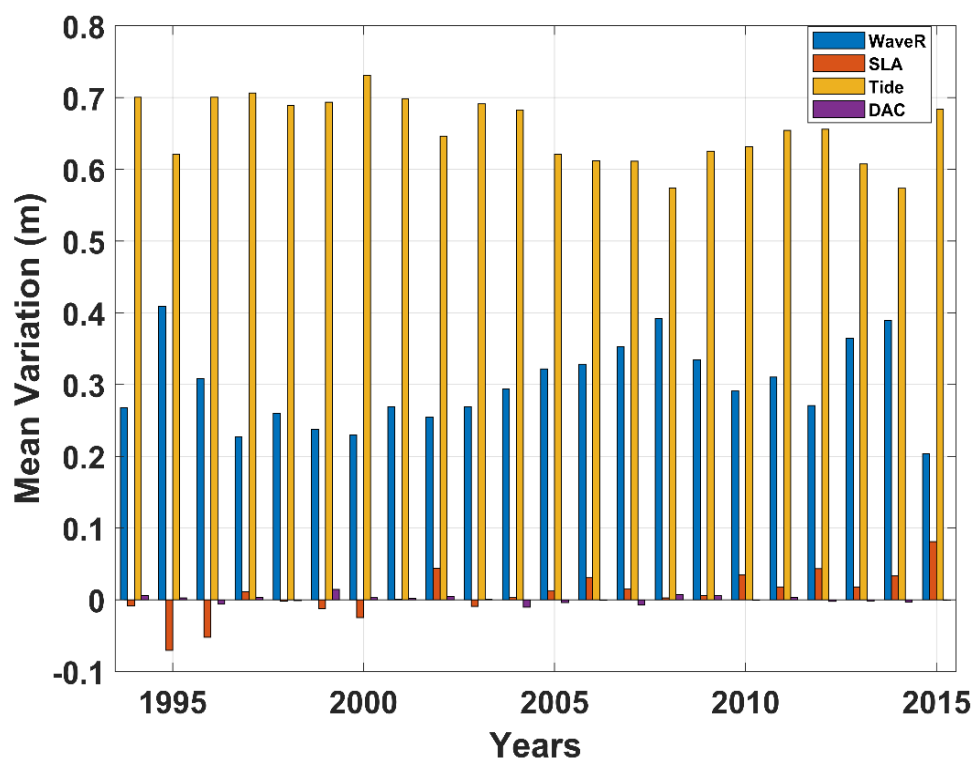


Figure 33: Variation in contributors of ECWL from 1994 to 2015 using the yearly mean deviation of all parameters for 98 % of ECWL from 1994 to 2015

Discussion

Generally, low-lying regions experience coastal flooding. The findings of this study indicate that even with the smallest level of extreme coastal water levels (ECWL), coastal flooding occurs. This phenomenon is common in low-lying areas like deltas. Coastal flooding due to ECWL can result from a single factor or a compound effect from several factors. On average, the Volta Delta experiences frequent flooding events (Figure 30) (Addo et al., 2018a). Most of these events have been attributed to "tidal waves". However, as global warming increases extreme sea levels in the coming decades, coastal flooding is expected to become more frequent (Walsh et al., 2012). To understand which parameter contributes the most to extreme coastal events, all ECWLs were aggregated into severity ranks where the 98th percentile is the most severe, the 60th percentile is

severe, and the 30th percentile is less severe. This study shows that all coastal flooding events in Keta District are in the 98th percentile of coastal flooding. This further indicates that coastal flooding in the Keta area was reported as a severe event from 2002 to 2015. ECWL can result from a single ocean factor such as high tide, wave, or SLA. However, combining all these factors makes the scenario worse and more extreme. Coastal flooding at a given location occurs at varying temporal and spatial scales. This study shows that over the years, there has generally increased in the time spent by ECWL. From Figure 29, the time spent by ECWL reaches values as high as 200 hours/year. This is consistent with the general sentiment of coastal flooding in the Volta Delta of Ghana over the past decade. In addition, global warming is still on the rise and thus accounts for the increase in flooding events and time spent per year during the most extreme events.

The spatial extent of coastal flooding by ECWL shows that most of the area is potentially flooded in the 98th percentile of coastal flooding. Interestingly, in the 98th percentile case, parts of the main road and houses would potentially flood in the most extreme case. This is because the area is generally low-lying, and any minute increase in ECWL would result in coastal flooding. The annual number of hours shows a positive (i.e., increasing) trend (calculated using the hourly ECWL time series for all years) (Figure 29). The highest increase rates were observed in the 98th percentile and 2015. This is possible because coastal areas generally have low ECWL variability (time series variance). Thus, even a small increase in regional sea level can greatly impact coastal flooding (Taherkhani et al., 2020). ECWL at the coast results from various, sometimes unrelated contributions, i.e. both natural and anthropogenic (Woodworth et al.,

2019). These include tides, meteorological processes, wave conditions, and sea level anomalies. Assessing the combination of these factors helps reduce the risk posed by coastal flooding (Imani et al., 2021).

For this reason, many global studies have attributed the cause of coastal flooding to sea level rise without considering the role of other factors along the coast (Amores et al., 2021; Mimura, 2013; Nicholls, 2002; Nicholls & Tol, 2006). This factor is equally important, as knowing about it would reduce the magnitude and exposure of physical damage. Appropriate planning and mitigation measures can be implemented with proper forecasting of extreme coastal events and a better understanding of the major contributors to coastal flooding at the local scale (Anthony and Orford, 2002; Ciavola et al., 2011). It is, however, worth knowing that, from Figure 31, Pleiades DEM can capture enough beach variations, such as the back beach, berm and nearshore topography, compared to global DEM. This is relevant for coastal flooding studies since beach topography is very important for coastal flood prediction and how coastal structures impact and protect beaches.

Furthermore, in this study, wave run-up is the primary contributor to ECWL for the Keta area. This confirms studies indicating that the Volta Delta is primarily wave-dominated, and thus all beaches are primarily formed and affected by wave activity (Anthony & Orford, 2002; Jayson-Quashigah et al., 2021). In this study, the ECWL at the 98th percentile has the wave run-up contributing as much as 70% to them (see Figure 32). In general, in the swash zone, single waves propagate beyond the slope of the beach and shoreline (Chen et al., 2023; Deng et al., 2022). This area experiences significant erosion and wave overtopping during storms, as seen in Figure 34 C. Water continuously covers and uncovers

this area (Figure 34 B). In particular, during a strong storm surge, waves affect the barrier beach or foredune more (Mehrtens et al., 2023). This also confirms the study by (Melet et al., 2018), which indicates that coastal flooding occurrences are expected to increase significantly in the coming decades.

For this reason, as the sea level rises, the study results show that considering wave contributions to long-term changes in total water level at the coast would lead to more accurate decadal forecasts and longer-term projections of total water level at the coast. Figure 33 shows the variability of the contributors in the ECWL. The tide is more variable on all time scales. Normally, the tide varies, including diurnal, biweekly with spring and neap tides, and seasonal and interannual scales. This explains why the tide is the most variable parameter among all parameters despite the predominance of waves in Figure 32. However, it is impossible to predict the phase between the tide and the wave run-up, which depend on independent factors. Overall, this increases the uncertainty of both short-term deterministic forecasts (Bertin et al., 2014), while the probabilistic approach is more suitable for long-term prediction of overtopping and flooding (Vousdoukas et al., 2018). Other factors, such as SLA and DAC, contribute to ECWL, but their effects are rarely seen in the ECWL. Using the Pleiades' derived DEM has proven to show how promising the Pleiades would contribute to studies in the coastal environment compared to global DEMs. This would be very helpful locally, particularly for coastal managers and engineers. Although operational accuracy without a ground control point is not yet possible for coastal studies at this stage (as stated by (Cisse et al., 2022; Taveneau et al., 2021; Turner et al., 2021) the limitations in accuracy encountered suggest that satellite-based topography monitoring can

be a significant advancement in overcoming long-standing technological barriers in monitoring, thereby supporting local coastal engineering and coastal monitoring. By offering local perspectives, this study offers valuable insights for developing evidence-based measures to minimize damage and injury. As a result, using ECWL will attract considerable attention from diverse audiences in West Africa, including researchers, practitioners, decision-makers, and policymakers from various fields such as catchment management, engineering, economics, disaster management, and science-informed policy planning.



Figure 34: The imagery of beach resorts affected by ECWL; A) An aerial view of two major beach resorts (Aborigines beach resort and Agblor Lodge) in Keta without flooding. B) Gradual flooding of the Agblor Lodge and Aborigines beach resort being affected by ECWL; C) An aerial view of wave overtopping in the Keta area due to ECWL

(Photo A obtained from https://www.agblorlodge.com/gallery_cat/aerial-photograph/; Photo credit of B and C: Brempong Emmanuel; Date: 21/04/2023)

Conclusions

This study quantified coastal flooding from 1994 to 2015 in the historical city of Keta in the Volta Delta, Ghana. High-resolution coastal topography derived from Pleiades satellites and extreme coastal water levels (ECWL), including wave contribution, were used to map potential flood areas. During the most severe situation (98% percentile of ECWL), 43 % of the Keta area was potentially flooded, including roads and inhabitants' houses. The primary hydrodynamic factor contributing to coastal flooding is wave run-up, unlike in Senegal, where tides are the dominant factor. On the other hand, while wave run-up dominates, the tide is more variable, indicating the key role of the phasing between components. The time spent (hr/yr) with potential severe flooding from 1994 to 2015 is increasing due to global mean sea level rise, as observed by satellite altimetry. It will most likely accelerate over the twentieth century with more and more people being displaced. Our local findings can help decrease exposure to damage and injury by developing pertinent science-based protection and mitigation solutions.

CHAPTER FIVE

APPLICATION OF INSAR-DERIVED DEM; A PILOT STUDY FOR BEACH EVOLUTION

Emmanuel K. Brempong^{1,2,3*}, Rafael Almar², Donatus Bapentire Angnuureng¹, Precious Agbeko Dzorgbe Mattah¹, Andreas Braun⁴

¹Africa Centre of Excellence in Coastal Resilience (ACECoR), University of Cape Coast, Cape Coast 00223, Ghana.

²LEGOS, Université de Toulouse, CNES, CNRS, IRD, UPS, Observatoire Midi Pyrénées, 14 Avenue Edouard Belin, 31400 Toulouse, France.

³Department of Fisheries and Aquatic Sciences, School of Biological Sciences, University of Cape Coast, Cape Coast 00233, Ghana.

⁴Department of Geosciences, University of Tübingen, Rümelinstraße 19-23, Tübingen, 72070, Germany.

Submitted and under review: Science of Remote Sensing

Statement of Contributions of Joint Authorship

Brempong Emmanuel K:

Candidate

Conceptualization, Methodology, Data Analysis, Writing-original draft,

Manuscript review, and editing

Precious Agbeko Dzorgbe Mattah:

Principal Supervisor

Donatus Bapentire Angnuureng

Co-Supervisor

Rafael Almar:

Co-Supervisor

Andreas Braun:

Co-Author

Abstract

Beaches are highly vulnerable to hazards, especially with the increasing threat of relative sea level rise. Precise elevation data is essential for evaluating flood hazards, particularly in densely inhabited areas like the Volta Delta of Ghana. When choosing a Digital Elevation Model (DEM) for assessing coastal flooding, sea-level rise, or erosion risk, elevation accuracy and spatial resolution are usually key considerations. However, it is important to consider the limitations of DEMs resulting from their original data source during the selection process. Although global elevation data provided are free, most are one-time data with low spatial resolutions. Therefore, evaluating the potential of using Sentinel-1 DEM for beach evolution through acquiring favourable DEMs is very important. Using the In-SAR approach, the resulting DEMs were assessed through comparison and correction with FABDEM. With the Volta Delta of Ghana as a case study, all Sentinel-1 DEMs were corrected with FABDEM. The study revealed that using a known DEM such as FABDEM, the quality of DEM from sentinel-1 is improved. However, it is difficult to identify features for beach evolution since Sentinel-1 DEMs strongly depend on a good perpendicular baseline. The study suggests that using openly obtainable DEMs, such as FABDEM, would be preferable over creating DEMs from Sentinel-1. Alternative options like LiDAR data can be considered if a higher spatial and temporal resolution is needed. However, the study serves as a starting point for exploring the potential of InSAR-derived DEMs in analyzing changes in beach profiles and variations in DEM in coastal regions.

Keywords: Digital Elevation Model; Sentinel 1; InSAR ;FABDEM

Introduction

Coastal environments, particularly beaches, are rapidly evolving systems driven by the continuous interaction of the topography and sediment transport processes with wind, wave and tidal forcing (Laignel et al., 2023). To understand and quantify coastal morphodynamics, acquiring high-resolution data on beach topographic changes is necessary. The common in-situ monitoring method for the measurement of beach topography (especially at small scales, up to a few hundred meters of coastline) is cross-shore GNSS-RTK (Global Navigation Satellite System–Realtime Kinematic) surveys, which can result in highly accurate information along the measured transects (Casella et al., 2020). Digital elevation models (DEMs) provide a physical and visible 3D illustration of the earth's surface topography. When these models have a high spatial resolution, accuracy, and precision in terms of elevation data, they can be applied in various fields, including natural resource management, engineering, infrastructure projects, crisis management, risk analysis, archaeology, security, aviation, forestry, energy management, surveying, topography, landslide monitoring, subsidence analysis, and spatial information systems (Makineci and Karabörk, 2016; Polidori & El Hage, 2020). Different techniques, such as stereo imaging, LiDAR, and synthetic-aperture radar (SAR), can be used to obtain DEMs, making them useful tools for creating models of the earth's surface (Rui et al., 2016). Digital elevation models can be created using optical and radar satellite images, which are available in various weather conditions and at night (Mahmoud et al., 2022). However, DEMs generated from global sources may contain artefacts that must be detected, and multi-source DEM fusion can improve accuracy. These include, SRTM,

ASTER and TanDEM-X (Arefi & Reinartz, 2011; Baugh et al., 2013; Mason et al., 2016). On a regional scale, these DEMs have also been studied to improve accuracy (Apeh et al., 2019). Higher-resolution satellite images can be used to create more detailed DEMs. Two methods for producing DEMs from satellite images are SAR interferometry and radar grammetry (Palama et al., 2023). However, cloud cover is a significant challenge for optical imagery in tropical regions like Ghana, hindering the observation of the earth's surface from space (Ferretti et al., 2001). In contrast, InSAR (Interferometric Synthetic Aperture Radar) has emerged as a cost-effective, accurate, and efficient technique for measuring dense points in a region without being affected by cloud cover, making it the preferred method for this purpose (Cigna et al., 2017; Dering et al., 2019; Ferretti et al., 2001).

The Sentinel-1 mission is an openly available source of radar imaging data for DEM creation. Its first satellite, Sentinel-1A, was launched in 2014, and its data has been publicly available since then. In recent years, there has been a surge in space missions to gather data from the Earth's surface. One of the most notable and recent initiatives in this area is the Sentinel mission, which features the advanced Sentinel-1 radar imaging component (Proceedings of EUSAR 2016, 2016). This mission is a joint effort between the European Union and the European Space Agency, and the first satellite, Sentinel-1A, was launched on April 3, 2014, with its data becoming available to the public on October 3, 2014. The Sentinel mission comprises two platforms, Sentinel-1A and Sentinel-1B, which orbit with a phase difference of 180 degrees. Even though Sentinel-1 B has failed, Sentinel 1 C is expected to be out soon. The Sentinel-1 satellite has an advanced synthetic aperture radar (SAR) that operates at a center frequency

of 5.405 GHz and can capture SAR images in HH, HV, VV, and VH polarization. The revisiting time for the satellite is 6 days, and its incidence angle ranges from 29.1 to 46 degrees. The IW mode is the primary imaging setting for interferometry applications, offering a swath width of 250 km and spatial resolution of 5 m by 20 m (Attema et al., 2009; Yague-Martinez et al., 2016). In ideal settings, this potentially allows for the derivation of DEMs at higher spatial detail compared to the currently openly available ones (Braun, 2021). Generally, all DEM data derived from remote sensing are susceptible to outliers from different factors, including sensor limitations, low terrain texture contrast, and interferogram phase error (Li et al., 2022). Moreover, elevation errors and outliers are expected in DEM data obtained from SAR interferometry (Li et al., 2022). Therefore, it is essential to modify SAR-derived DEM data to ensure accuracy. Among other methods, outlier removal is a technique for improving the quality of DEM data, but also interpolation-based methods like multiquadric interpolation and their advanced algorithms have shown remarkable effectiveness in mitigating the impact of outliers on the generated DEMs (Zeybek & Şanlıoğlu, 2020). Other approaches include; using a single-baseline and multi-baseline InSAR techniques for reconstructing Digital Elevation Models (DEMs) using TerraSAR-X SAR images. Thus, for a single-baseline InSAR, different sets of interferograms are examined, and the accuracy of the resulting DEM was assessed under conditions of low height ambiguity and significant coherence magnitude. A new method for merging single-baseline InSAR DEMs based on coherence magnitudes was proposed. Multi-baseline InSAR was explored using unconstrained and constrained Maximum Likelihood Estimation algorithms, and results indicated that the suggested

weighted fusion of single-baseline InSAR DEMs outperformed the constrained multi-baseline method. Both techniques demonstrated improved accuracy compared to single-baseline InSAR, highlighting the value of leveraging multiple observations for enhancing DEM quality, others also include creating composite DEM mosaics from diverse sources, with a primary emphasis on interferometric SAR techniques. It briefly discusses the variables affecting the accuracy of height determination and introduces the notion of height error maps, which indicate the precision of the resultant DEMs. The procedure of combining DEMs from different sources, particularly ERS tandem data gathered from ascending and descending orbits, is very helpful (Choussiafis et al., 2012; Zhang et al., 2022). However, all these approaches have not succeeded in capturing temporal changes in DEM.

Recent research has demonstrated the potential of interferometry to produce high-resolution topographic maps with relative height errors of 5 meters or less, as evidenced by the work of Huang et al. (2015) and (Ferreira, 2014). The process of handling interferometric synthetic aperture radar (InSAR) data for surface monitoring remains a demanding computational task. This challenge stems from factors like the substantial data volume, high computational costs associated with data acquisition, and uncertainties surrounding data quality. Pre-processing steps such as co-registration, interferogram generation, and flat earth removal require high-performance computers. A single scene of Sentinel-1 data can consume up to 4 Gigabytes of computer storage. To achieve accurate and very good results in InSAR pre-processing, image pairs should have perpendicular baselines above 150 m and minimized temporal baselines, in the case of Sentinel-1 this refers to 6 to 12 days (Ferretti et al., 2007). Even though

DEM generation from other sources such as LIDAR is very useful for smaller areas, on a large scale this would be very expensive as compared to the use of freely available S1 images. Moreover, the application InSAR derived DEM for temporal beach topographic changes has never been assessed along the coast of West Africa. Therefore, for the first time this study seeks to test Sentinel-1 data for beach shores in Ghana. This study attempts to explore the use of SAR-derived DEM for temporal beach changes. This is achieved, first and foremost, through the acquisition of favourable S1 images and producing DEMs using the InSAR approach, secondly through comparison and correcting of composite S1 DEMs with a reference DEM, and finally, assessing the temporal changes with corrected DEM using the Volta Delta of Ghana as a case study.

Materials and Methods

Study area

The Volta Delta is a diverse and ever-changing coastal region in Ghana, West Africa, which the Volta River creates as it flows into the Gulf of Guinea. This area features an array of habitats, including wetlands, mangroves, and sandy beaches, and is recognised for its critical role in the conservation of plant and animal species, including endangered ones. Moreover, the region is economically vital to Ghana, providing resources like fish and timber, as well as serving as a transportation hub for goods and people. However, the environmental challenges facing the Volta Delta are extensive, as stated by Addo et al. (2018), the delta is threatened by coastal erosion, flooding, and sedimentation, caused mainly by human activities such as sand mining and construction of sea defence. Furthermore, climate change is exacerbating these

issues by causing sea level rise and changing weather patterns (Brempong et al., 2023). Various organisations and the Ghanaian government have tried to address these environmental challenges through shoreline protection, reforestation, and sustainable fishing practices (Appeaning Addo et al., 2018).

The Volta Delta has soft quaternary rocks and unconsolidated sediments, including clay, sand, and gravel. It also contains several water bodies, such as the Keta Lagoon complex, Songor Lagoon, creeks, and marshy areas, which have been designated a Ramsar site. The area experiences two types of waves and semi-diurnal tides with weak tidal currents. The climate is dry equatorial, and the vegetation is coastal strands and mangroves. There are two rainy seasons, and the monthly average wind speed ranges from 1.7 to 2.6 meters per second (Roest, 2018). In addition, the Volta Delta experiences swell waves from the S-SW direction, with a significant wave height of approximately 1.4 m and a period of 11 seconds (Roest, 2018). These waves generate longshore currents that transport sediment eastward, causing high rates of annual net longshore sand drift. Tides are semidiurnal with weak tidal currents, but they can affect the shoreline morphology in the short term. The strong longshore drift potential eastward is satisfied by the reworking of the Holocene barrier deposits within the delta downdrift of the Volta spit. Mainly for this study, 4 pilot study areas were selected to be used for comparison and experimenting with the potential of S1 DEM for beach topography evolution.

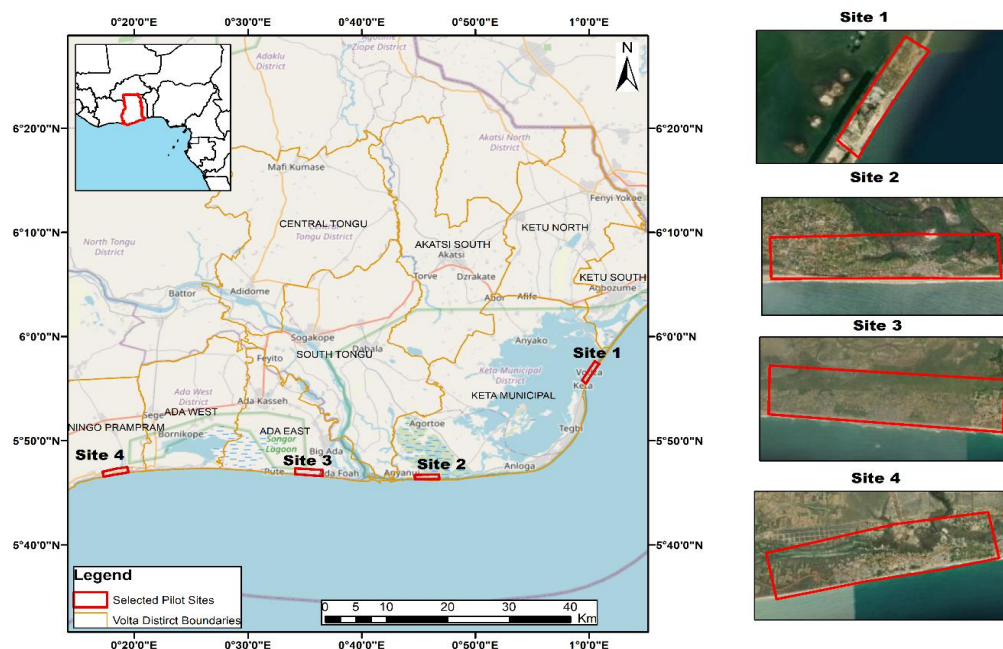


*Figure 35;*A map of the study site with selected study sites for further study and analysis

Sentinel 1 data and processing

To derive DEMs from Sentinel 1, several steps are involved, the first step is to obtain the satellite data from the European Space Agency's (ESA) Sentinel Data Hub, which is available for free. Level 1 SLC data is required because it contains complex phase information. Sentinel-1 data must be preprocessed to correct for any errors or anomalies. After preprocessing, the interferometry process is applied, which involves co-registration, interferogram generation, and phase unwrapping. The final step is to convert the unwrapped phase into absolute height information of the DEM, which may involve applying filters and corrections, resampling and interpolation, and exporting the DEM in various formats. After generating the DEM, it can be analysed and interpreted to gain insights into detailed topographic features and changes in the Earth's surface over time. This may involve comparing multiple DEMs or studying

specific features in the DEM, and the results can be visualised using GIS software to create maps and other visualisations. This was generated for all 15 images used for this study (Table 2).

A detailed set-up is seen in the flowchart below.

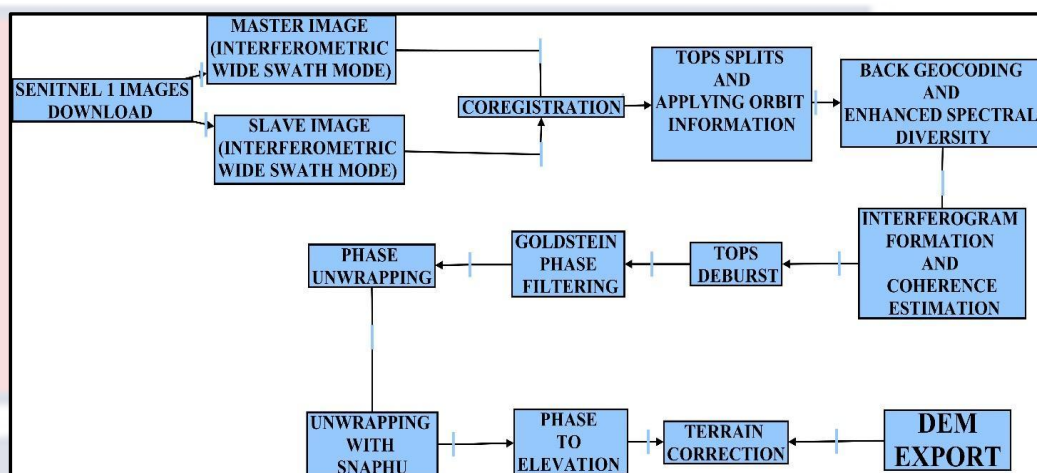


Figure 36: Detailed flow chart of S1 Dem processing (Adopted from Braun (2021))

Table 2: All Sentinel-1 data selected for study with perpendicular baseline distance and temporary baseline

Primary	Secondary	Perpendicular Baseline(m)	Temporary Baseline(days)
29/12/17	4/01/18	120	6
23/03/18	3/02/18	103	48
4/02/19	10/02/19	81	6
23/02/21	11/02/21	86	12
5/03/18	23/03/18	82	18
22/04/18	16/04/18	63	6
24/10/17	30/10/17	18	6
22/09/22	4/10/22	323	12
29/12/17	23/11/17	147	36
24/10/17	5/11/17	59	12
7/11/19	1/11/19	78	6
25/11/20	19/11/20	102	6
9/11/22	21/11/22	249	12
23/12/17	29/12/17	141	6
12/12/18	6/12/18	105	6

FABDEM DEM description and usage

FABDEM, denoted as the Forest And Buildings removed Copernicus Digital Elevation Model (DEM), represents a pioneering global DEM characterized by the removal of forested areas and built structures, at a resolution of 30 meters.

This dataset is constructed utilizing a correction algorithm, which effectively counteracts biases present in the Copernicus GLO 30 Digital Surface Model (DSM), induced by the presence of various objects on the Earth's surface. This DSM is used in this study because all buildings and forests at 1 arc-second (~30 m) grid spacing have been removed using machine learning. Already some studies have shown that FABDEM is more accurate than existing global elevation maps and has the potential to provide high-quality global terrain information (Hawker et al., 2022; Seeger et al., 2023). Particularly for coastal flooding scenarios, FABDEM can be used showing flood exposed areas. This data was then clipped to the Volta Delta for data analysis.

Correction of S1 DEM with FABDEM

All S1 generated DEMs were corrected using the regression coefficient values between FABDEM and S1 DEMs for each study area. This was done using the entire DEM instead of a specific ground control point. This is because the distribution of S1 points is not uniform. Therefore, using selected points alone can make it biased.

Drone Data

Using Agisoft PhotoScan and the Structure from Motion (SfM) approach, an average of 300 images were processed for the flight (Study Site 2), enabling the

creation of three-dimensional coastal topography from two-dimensional images. The SfM and multiview stereo (MVS) algorithms handle overlapping images captured from different positions and camera orientations. The software workflow involves uploading drone-captured photos, aligning them to form a sparse cloud, processing dense clouds using Ground Control Points (GCPs), and generating Digital Elevation Models (DEMs) and orthophotos. The entire SfM and MVS process for each flight took a maximum of 10 hours, producing images with an average spatial resolution of 2 cm/pixel or less. The DEM data from the drone was compared to DEMs obtained from FABDEM and Sentinel 1. All DEMs obtained were exported and analysed using ArcGIS and MATLAB.

Results

DEMs obtained from Sentinel 1 for the Volta Delta

The DEMs derived from Sentinel-1 data revealed a wide range of elevations across the Volta Delta, with a maximum elevation of 270 metres. The DEM (Figure 37) shows inconsistent variations in elevation in the Volta Delta. All Sentinel-1 DEMs are generally of higher and very coarse elevations compared to freely available DEMs such as SRTM and the rest.

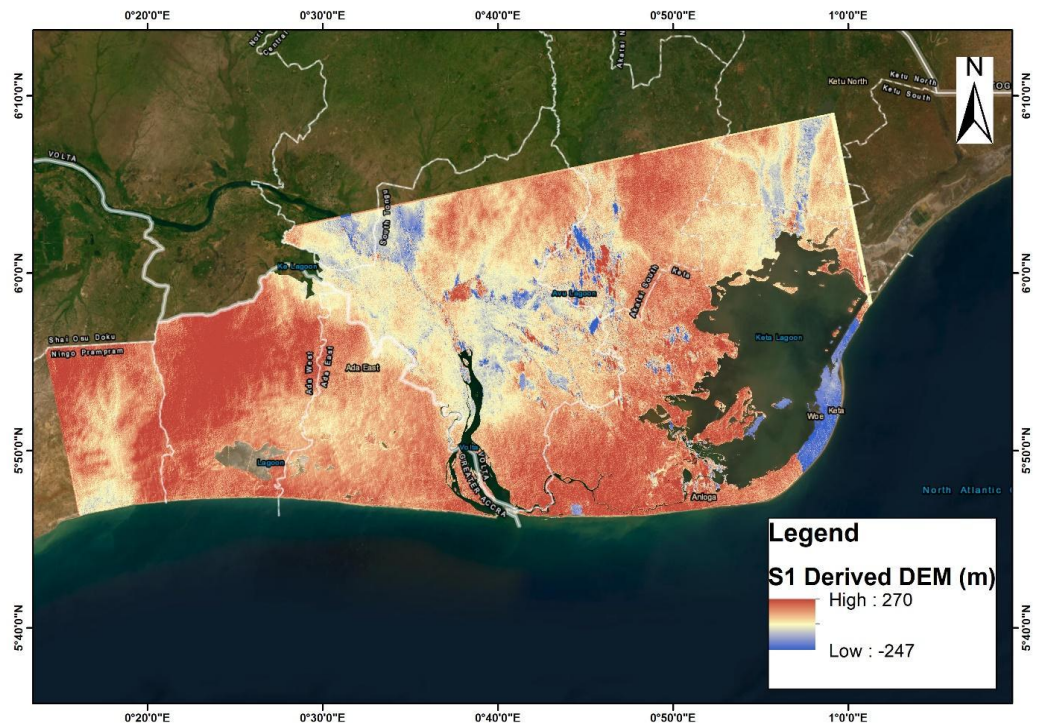


Figure 37: Sample of Sentinel-1 derived DEM of Volta Delta for pilot study

Comparison of corrected DEMs of Sentinel 1 and FABDEM

Correcting Sentinel 1 DEMs with FABDEM showed great improvement with elevations reducing from as high as 150 m to 10 m. This was observed for all pilot study sites (Figure 38). For all the selected pilot sites the S1 corrected DEMs showed variation within the same range with FABDEM.

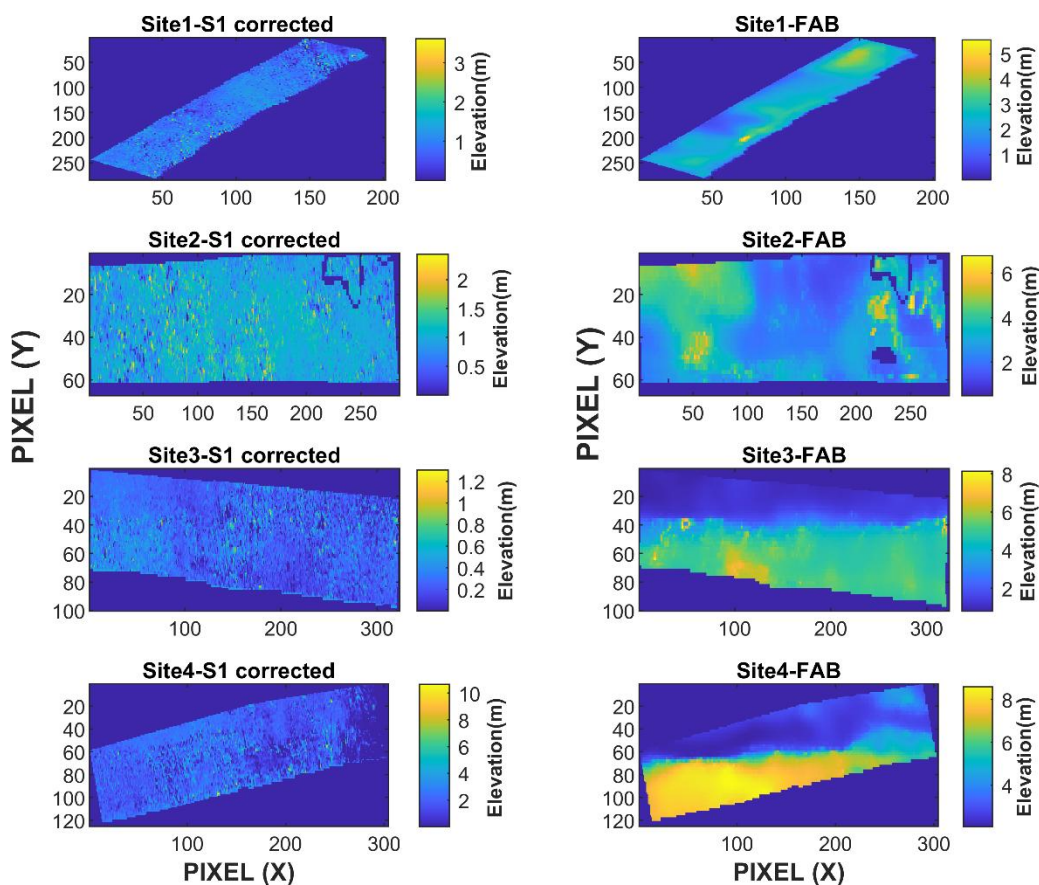


Figure 38: A representation of corrected selected areas with FABDEM of Volta Delta for the pilot study and FAB DEM for the selected study areas

Correlation between Sentinel 1 DEM and other DEMs for all pilot sites

In order to assess the quality of Sentinel-1, correlation coefficient was estimated and plotted (Figure 39). Largely, all Sentinel-1 derived DEMs showed a lot of discrepancies with 3 main dates showing a positive correlation at all sites. As seen in Figure 39, site 1 shows the highest and the lowest correlation of 0.7 and 0.4 on other dates. In general Sentinel 1 Derived DEMs are not consistent for all sites and dates.

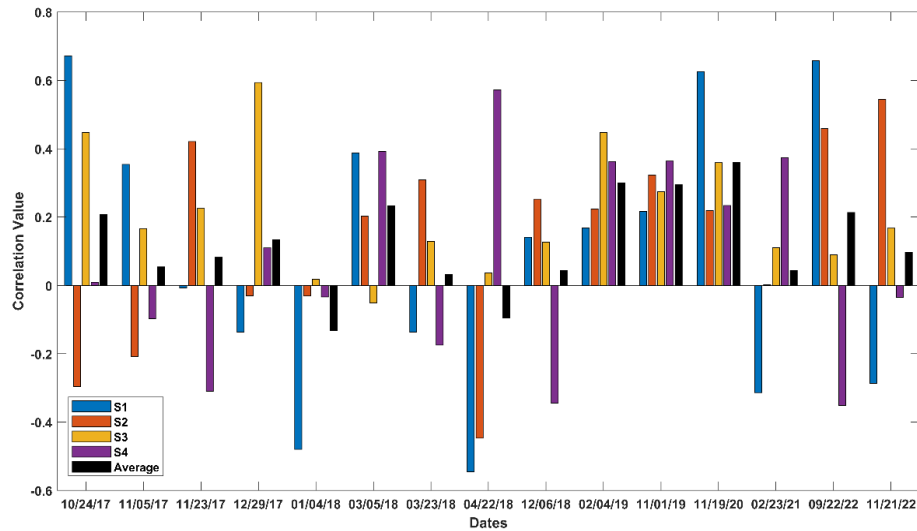


*Figure 39:*A correlation of selected areas of Volta Delta for the pilot study and FAB DEM for the selected study areas

Correlation of Corrected Sentinel-1 DEM and FABDEM for all pilot study sites

To assess the quality of Sentinel-1 all correlation coefficients of corrected Sentinel 1 DEMs were corrected with FABDEM. The Sentinel-1 derived DEMs exhibited significant uniformity, showing a positive correlation as high as 0.7 for Site 1 and as low as -0.36 for Site 2 across two different dates. Generally correcting Sentinel 1 DEM with FABDEM improved the correlation between FABDEM and Sentinel 1 derived DEMs.

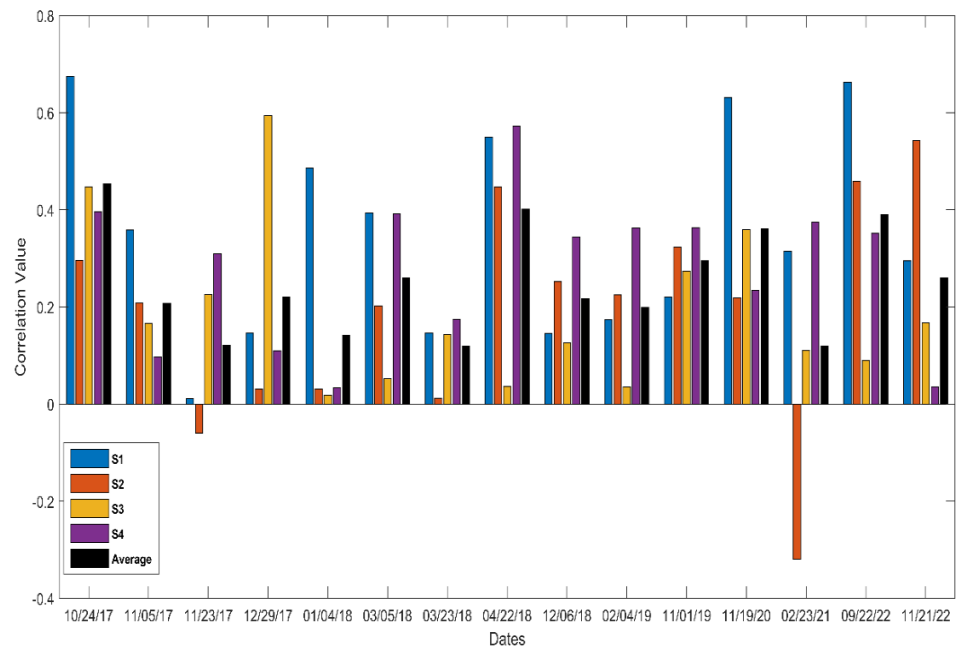


Figure 40:. A correlation between selected sites of Volta Delta for the pilot study and FABDEM data

Correlation of Sentinel-1 DEM and another Sentinel 1 DEM for all pilot study sites

In general Sentinel-1 DEMs showed inconsistency with DEMs obtained from 22/09/22 with all. From Figure 41, Site 1 exhibited the highest correlation as well the lowest correlation with three dates showing uniformity at all 4 selected pilot sites. Overall, even within Sentinel 1 DEMs there are a lot of inconsistencies with Sentinel 1 DEMS.

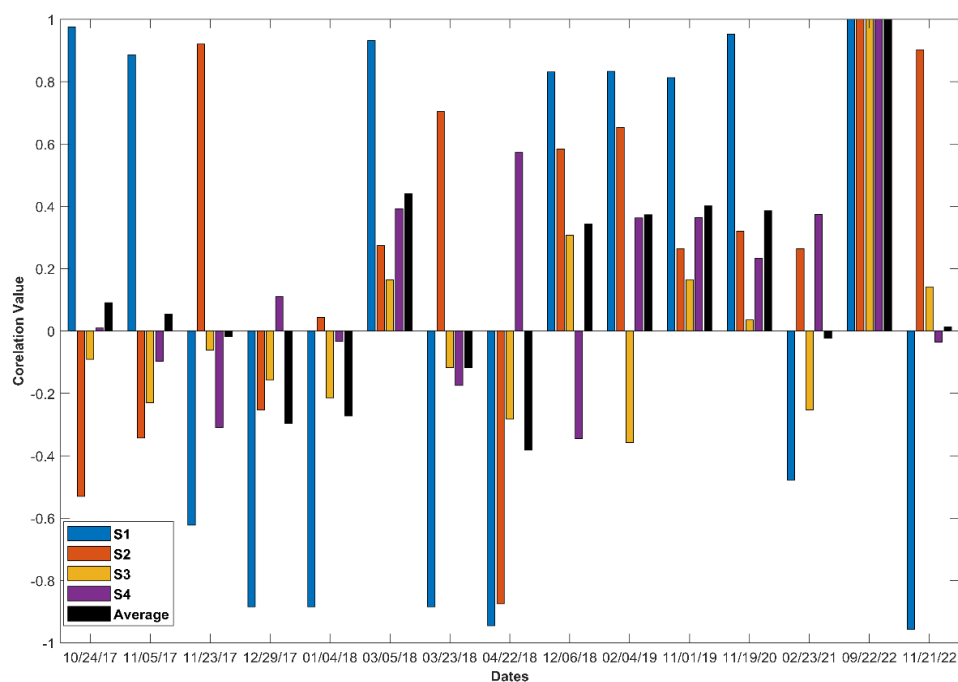


Figure 41: A correlation between selected sites of Volta Delta for pilot study and selected S1 data

Correlation of Composite Sentinel 1 DEM and FABDEM for all pilot study sites

In order to assess the quality of Sentinel-1 derived DEMs when they are composited. Generally, when DEMs from Sentinel-1 are composited, there is improvement with correlation coefficients even when DEMs are not corrected. The highest correlation (0.58) is observed when DEMs are smoothed and corrected with FABDEM. Sites 4 consistently shows very low correlation coefficient in all three scenarios.

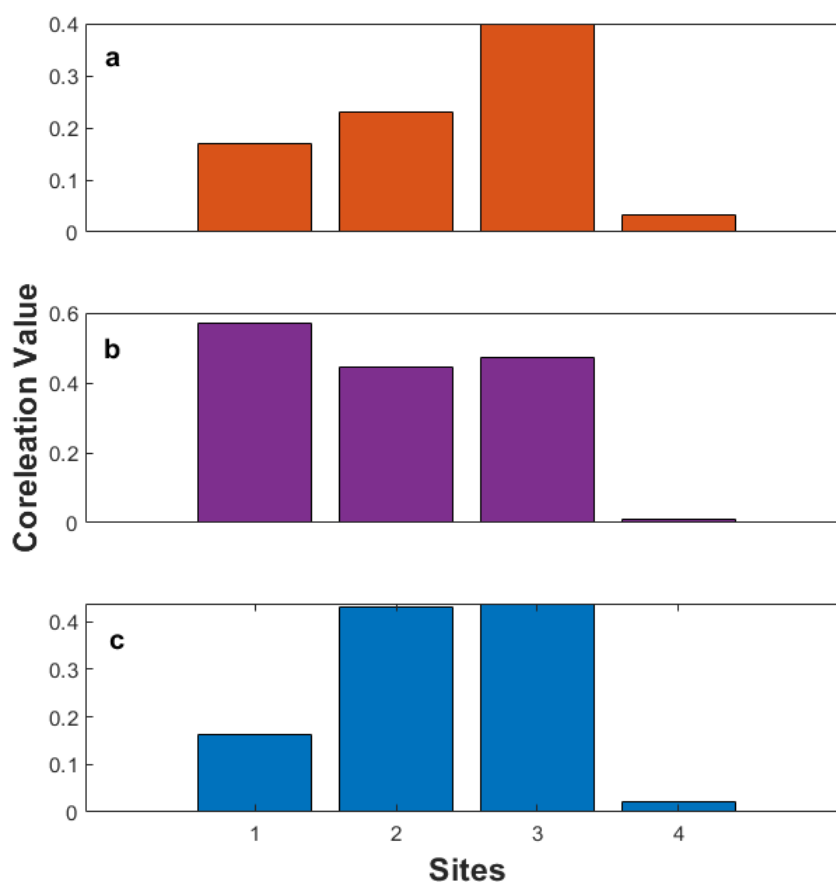


Figure 42: A correlation between composite of Sentinel 1 for all sites of Volta Delta and FAB DEM for the selected study areas. Where a) a plot of correlation coefficient when composited DEM are corrected with FABDEM b) a plot of correlation coefficient when composite DEMs are corrected and smoothed with FABDEM c) a plot of correlation coefficient when composite DEMs are not corrected and smoothed with FABDEM

Root Mean Square Errors composites of all pilot study sites

Table 3: RMSEs for all composite S1 derived DEMS acquired for all selected sites

Sites	RMSE(m)
1	0.956
2	4.4197
3	1.624
4	4.7069

Table 3 shows that all S1 composite DEMs for selected sites show a varying range of RMSEs. The highest RMSE is observed in Site 4, followed by Site 2 and Site 3 and Site 1 consecutively. Site 1 has RMSE of 0.956, this shows that after correcting, all DEMs from sentinel Site 1 have very close elevations to the true elevation values on FABDEM.

Vertical profiles along Study site 2

A simple comparison between the two DEMs was assessed to show the ability of composite Sentinel 1 DEM to capture beach evolution. Figure 43 exhibits profile variations extracted for a distance of about 250 m.

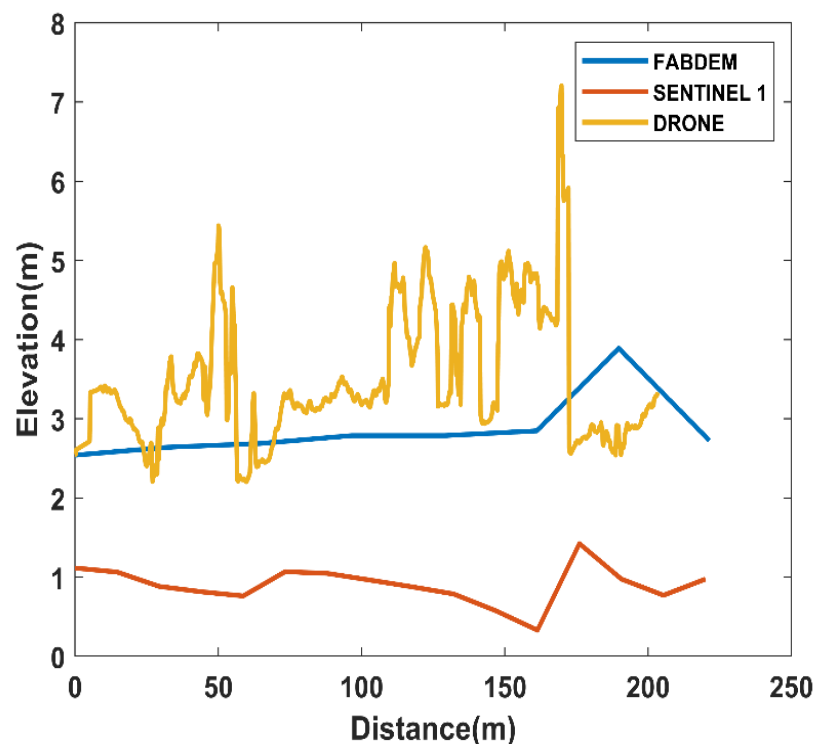


Figure 43: Shows the general evolution of the DEM profile in study Site 2. In general, S1 composited DEM, has a maximum height of 1.8m whiles the UAV and FABDEM have a maximum height of 7 m and 3.9 m, respectively. The profiles show a general beach shape which could include beach berms

Composite DEMS

In order to further improve S1 derived DEMs, a composite DEM was derived from all selected sites. In general composite DEMs showed a very good range of DEMs compared to individual DEMs. However, these were not able to capture visible features as expected for the study areas. Apart from Site one which showed very minute patterns all other sites (Site 2,3,4) showed noisy and inconsistent patterns.

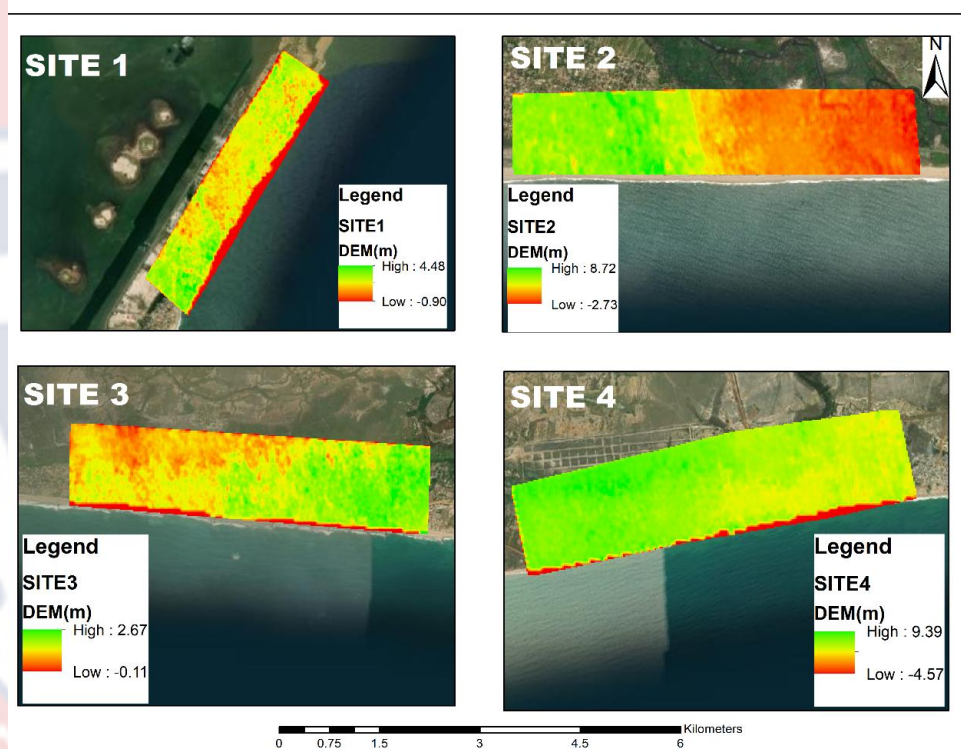


Figure 44: A spatial plot of the DEMs after they are composited for each site

Discussion

The use of temporal DEM is essential in the coastal field. This is important for modelling and provides a better understanding of short-term beach evolution. DEMs are significant in research applications on a global and regional scale, such as flood risk mapping and disaster risk management (Tralli et al., 2005).

However, over the years, DEMs provided have been produced on a global scale, making it difficult for users on local or regional scales. Using InSaR-derived DEM from Sentinel 1 could be a promising and innovative temporal beach evolution assessment tool. However, this approach is very complex, with many requirements. This study explores InSaR-derived DEM from Sentinel 1 for beach evolution. For this study, Sentinel 1 images were selected based on requirements defined by Ferretti et al. (2007). In contrast, since images within the Volta delta didn't meet the strict requirement by Braun, 2021 sample images were selected within the requirement and other data sets to show variation and allow for enough compositing.

All DEMs generated from Sentinel 1 showed elevations of extremely high ranges. This is expected since InSAR DEMs through repeat-pass interferometry is a difficult task, particularly in areas with vegetation, because of the short perpendicular baselines and changes of C-band SAR data. Thus, there is a reduction or weakening of coherence evident in radar images. Heightened coherence between the paired radar images indicates a situation where radar waves have followed similar paths and interacted with the same scattering locations on the Earth's surface. This significant increase in coherence greatly aids in generating accurate interferograms and analyzing subsequent ground deformations. It is essential to understand that although a higher spatial resolution can be achieved, phase decorrelation can lead to inaccuracies. The resulting elevation data is typically inferior to freely accessible DEMs like SRTM or AW3D30 (Braun, 2021). Our studies confirmed that the DEMs generated by Sentinel 1 are not always better than already existing DEMs, as Braun (2021) stated. Furthermore, decorrelation in InSAR involves reduced

coherence between radar signals passing through different materials like vegetation or moisture. Radar waves interact with these elements, undergoing scattering, reflection, and absorption, causing phase changes. In areas rich in vegetation or moisture, such as coastal plains, this interaction becomes complex, resulting in decreased coherence between radar signals acquired from the same ground location in different acquisitions. In regions characterized by coastal plains and abundant vegetation and moisture, the influence of volume decorrelation is markedly evident. This leads to a situation where, during the process of InSAR analysis in these areas, the coherence between radar images captured over such terrain is noticeably diminished compared to regions with less vegetation or lower levels of moisture. Nonetheless, the heightened volume decorrelation observed in areas with abundant vegetation or moisture along coastal plains results in interferograms displaying more complex and noisy fringe patterns. These fringes cease to solely represent deformation; they now encompass the intricate interplay between radar waves and vegetation or moisture. This increased intricacy introduces challenges to accurately interpreting the interferograms and extracting meaningful information about ground elevation. During interferogram "unwrapping," where phase differences are transformed into elevation data, the impact of volume decorrelation becomes more noticeable. This unwrapping process involves calculating the total radar signal wavelengths added or subtracted between data acquisitions. In regions with significant decorrelation, this procedure becomes more complex, resulting in unwrapped interferograms that may not faithfully represent the genuine characteristics of the terrain. Consequently, the DEMs

deduced from unwrapping such interferograms frequently lack dependability and may inadequately present precise topographic details.

With this established, the study continues to probe into details by correcting the Sentinel 1 derived DEMs to assess the ability of Sentinel 1 derived DEMs for beach evolution studies and show some features. Four areas were selected along the beaches of the Volta Delta (Figure 35.0).

All correlation coefficients for the month of 02/04/18, 11/01/19/ and 11/19/20 showed that elevation values in the FAB DEM and S1 DEM tend to increase or decrease together. Thus, even without correcting these DEMs for all 4 study sites showed a good distribution of elevation values with respect to FABDEM. This indicates that at least S1 derived DEM from these three days received good signals from the satellite, but due to phase decorations which introduce a lot of errors, it is however very difficult to obtain smooth DEM distributions for the study areas. Also, there is a possibility that, due to the temporal baseline of 6 days for the dates there is a consistent positive correlation for all selected sites. Conversely, very high correlation values of 0.7 and -0.58 were recorded in Site 1. This is likely due to Site 1 having less vegetation cover compared to the other study site, which can significantly influence the accuracy and consistency of remote sensing measurements.

Nevertheless, after applying the linear regression correlation between FABDEM and S1 derived DEMs, a consentient correlation value is obtained thus, this improved correlation significantly, with as high correlations with FABDEM, because it was corrected with FABDEM. The DEM from Sentinel 1 can be improved by this approach, which makes it possible to use Sentinel 1 DEMs for other studies. Although specific features could not yet be identified

on the DEM, the approach demonstrates potential for the corrected DEM to be valuable in future research applications.

Furthermore, the study continued to explore the correlation between a selected S1 DEM Sentinel 1 and all the other S1 DEMs. This was done to further understand sentinel-derived DEM, a correlation between sentinel 1 DEM and another Sentinel 1 DEM was done. This is to establish the internal consistencies within Sentinel 1-derived DEM. However, some consistent correlations between different dates DEM derived from 03/05/18, 11/01/19 and 11/19/20 showed consistent correlation with the selected sentinel 1 derived DEM (09/22/22). This shows that all DEMs do not consistently correlate with the selected DEM. This is mainly because DEMs are not of the exact date and have a different configuration of baseline and perpendicular distance.

In addition to this correlation between composite Sentinel 1 DEMS and FABDEM. All DEMs were composited to observe if that improves the correlation with FABDEM. S1 DEMS smoothened and corrected with FABDEM for all their correction scenarios showed the highest correlation.

To further understand the variation in DEMs. The Root Mean Square Errors were calculated. By comparing RMSE values of the different composite sites, the site 1 and site 3 have low magnitudes of RMSE, this Site 1 and 3 predictions are closer to FABDEM values compared to site 2 and 4. This is primarily because site 1 and 3 are less vegetated compared to the other sites. Based on table 2, Site 1 and Site 2 provide more accurate elevation measurements in their regions. This implies that for such areas the DEM has the ability to reproduce elevation measurements that are consistent with FABDEM. Furthermore, these areas with low RMSE after correction show a potential of using them for studies

such as temporal beach morphodynamics and if possible, modelling beach changes. This study also indicates inconsistencies based on both baseline and perpendicular distance, which determines the accuracy of Sentinel-1 DEMs. Larger baselines improve accuracy but reduce spatial resolution, while larger perpendicular distances reduce accuracy due to lower SNR. Thus, finding an optimal balance between these two factors is necessary to generate the most accurate Sentinel-1 DEMs for a given application.

Generating S1 DEMs is challenging due to SAR complexity however obtaining elevation data from radar imagery is a rewarding endeavour. The use of S1 temporal DEM for beach profile is however very difficult because the qualities of S1 DEMs are very poor along the nearshore and generally the land and sea masks removes most of the nearshore beach features such as berms and foreshore. A typical comparison between the DEM derived with UAV, FABDEM and S1 shows S1 has the potential to capture the beach area with the beach shapes however this is not close to the nearshore environment. Therefore, this has to be done with caution because the beach area is very dynamic and is constantly changing over time. Finally finding S1 imagery within the requirement is very hectic therefore applying this approach would be very difficult depending on the study location.

Conclusion

Creating Digital Elevation Models over time is critical for extracting important coastal geomorphology attributes such as beach profile, beach slope, and berm elevation. This is typically achieved using satellite imagery, with Synthetic Aperture Radar interferometry commonly used. The recent Sentinel-1 mission provides high-resolution images with global coverage every 6 days, making it an attractive option for generating DEMs. Yet, the study comparing InSAR-generated DEMs from Sentinel-1 imagery with existing DEMs like FABDEM found that the accuracy was lower. The study attributed this to two reasons: the inability of C-band signals to penetrate dense vegetation areas such as canopies and trees and the small perpendicular baseline of Sentinel-1 data, which should ideally be between 150 to 300 m for DEM creation. Therefore, the study suggests, before using S1 DEMs, to correct these DEMs with a known one efficiently. This study suggests the use of freely available DEMs like FABDEM instead of creating DEMs from Sentinel-1. Other products like LiDAR data can be used for those requiring higher spatial and temporal resolution. Nevertheless, this study serves as a baseline to explore using DEMs from InSAR for beach profile evolution and changes in DEM along coastal zones.

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This thesis aimed to assess some morphological changes in the Volta Delta of Ghana using a remote-sensing approach. The first objective was to estimate the Land subsidence rates in the Volta Delta and potential areas that fall below sea level when Land subsidence rates are combined with SLR projected over the 21st Century. Secondly, to determine the predominant oceanographic factors affecting the Volta Delta using Keta as a case study. Finally, to explore for the first time the use of SAR-derived DEM for temporal beach changes using the Volta Delta as a case study. The following sections summarise the outcomes of this research and demonstrate how these outcomes fulfil the study's objectives and the overall aim.

a. To estimate the Land Subsidence rates in the Volta Delta and potential areas that fall below sea level when Land Subsidence rates are combined with SLR projected over the 21st Century:

This objective examines land subsidence rates in the Volta Delta using satellite-based SAR-Interferometry and investigates their impact on relative sea level rise. By analyzing Sentinel-1 scenes captured between 2015 and 2021, this objective employed the PS-InSAR technique to precisely estimate displacement rates of coherent backscatter targets at a millimetre scale per year. It was found that the average rates of land subsidence in these regions were irregularly distributed, reaching up to 4 mm per year. The primary causes of land subsidence in the Volta Delta likely include the natural compaction of young deltaic sediments, over extraction of groundwater from aquifers, salt mining activities, and a possible reduction in sediment supply resulting from dam

construction. Furthermore, the study projected future elevation changes by combining the observed land subsidence rates with three IPCC representative concentration pathways scenarios. The assessment of relative sea level rise impact revealed that by the year 2100, more than 20% of the districts in the Volta Delta, including the vulnerable sand barriers surrounded by water bodies, could be below mean sea level for all the considered scenarios.

b. To determine the predominant oceanographic factors affecting the Volta Delta using Keta as a case study:

Objective two of the study examined the factors contributing to extreme coastal water levels (ECWLs) from 1994 to 2015. Based on percentiles, the study categorized ECWLs into low, moderate, and severe levels and used satellite data to map potential flood zones. The results showed that more than 40% of the study area, including important locations such as tourist beach resorts and historical landmarks, could be affected by ECWLs. Notably, all recorded coastal flooding events in the municipality of Keta fell within the highest percentile category. The study identified a gradual increase in the frequency of flooding over time, primarily caused by a combination of tides, sea level anomalies, waves, and atmospheric conditions. While wave run-up and tides were significant factors in coastal flooding, the variability of tides allowed for developing a simple, early warning system, despite some uncertainty in long-term predictability.

c. To explore for the first time the use of SAR-derived DEM for temporal beach changes using the Volta Delta as a case study:

Accurate elevation data is crucial for assessing flood hazards, especially in densely populated coastal areas. While global elevation data is often freely

available, most have low spatial resolutions and may not provide sufficient detail for accurate assessments. Therefore, exploring the potential of using Sentinel-1 DEMs for analyzing beach evolution becomes crucial. In this objective the study used the In-SAR approach and compared the resulting Sentinel-1 DEMs with a known DEM called FABDEM, which was used for correction purposes. The study focused on the Volta Delta of Ghana as a case study. The findings revealed that using a known DEM like FABDEM improved the quality of the Sentinel-1 DEMs. However, it was challenging to identify features related to beach evolution since the quality of Sentinel-1 DEMs strongly depended on a good perpendicular baseline. The study suggests that using openly available DEMs like FABDEM would be preferable over creating DEMs solely from Sentinel-1 data. Alternative options such as LiDAR data can be considered if higher spatial resolution is needed. Overall, this objective serves as an initial exploration of the potential of InSAR-derived DEMs in analyzing changes in beach profiles and variations in DEM in coastal regions.

Conclusions

This research employed a remote sensing approach to thoroughly investigate the intricate elements connected to the recurring flooding occurrences in the Volta delta of Ghana. Furthermore, the study showcased the utilizing remote sensing approaches such SAR and Pleiades to conduct high-resolution evaluations of subsidence and coastal flooding along the coast of the Volta delta and the Gulf of Guinea.

The objective one of the studies was to estimate how coastal land subsidence caused by sea level rise would affect the Volta Delta. By employing the

Persistent Scattered Interferometry (PSI) technique on Sentinel-1 images, the study examined the vertical land movements occurring between 2015 and 2021. The findings revealed an average subsidence rate of 4 mm per year, aligning with the local mean sea level rise of 4 mm per year. The Keta and Songor lagoons area exhibited the most notable subsidence, which could be attributed to natural processes, groundwater extraction, and salt mining. In addition, the study evaluated the potential consequences of sea level rise by analyzing projections from the Intergovernmental Panel on Climate Change (IPCC) reports. Even in scenarios characterized by moderate sea level rise and reduced emissions (RCP 2.6), the situation would be aggravated due to the combined effects of coastal flooding and local land subsidence, particularly in the Keta area. The study emphasized the urgency of adopting proactive strategies to mitigate the potential risks of flooding and safeguard the vulnerable areas in the region.

The second objective of the study was to determine the key factors driving coastal flooding during Extreme Coastal Water Level (ECWL) events from 1993 to 2015. Using high-resolution coastal topography data from advanced satellites, the study mapped the potential flood areas during ECWL, taking wave contributions into account. The results indicated that under the most severe ECWL scenario, approximately 43% of the Keta area, including residential areas and roads, would be submerged. Additionally, the study found that wave run-up played a significant role in causing coastal flooding. This was primarily due to wave run-up considering the elevation and slope of the beach. On the other hand, tides exhibited greater variability, fluctuating significantly between high and low tides within a single day. The research also revealed an

increase in the duration of ECWL events from 1993 to 2015, indicating a more frequent occurrence of coastal flooding over time.

The study's final objective was to utilize remote sensing techniques, specifically Synthetic Aperture Radar (SAR) interferometry, to create Digital Elevation Models (DEMs) essential for extracting vital coastal information like beach profile, beach slope, and berm elevation over time. The study made use of satellite imagery, particularly from the Sentinel-1 mission, known for its high-resolution global coverage every six days, which is commonly employed for DEM generation. However, when comparing the DEMs generated from Sentinel-1 imagery using SAR interferometry with existing DEMs like FABDEM, the study discovered that the accuracy of the Sentinel-1 DEMs was lower. The study identified two primary factors contributing to this disparity. Firstly, the C-band signals used by Sentinel-1 encounter limitations in penetrating dense vegetation areas, such as canopies and trees, resulting in incomplete data. Secondly, the small perpendicular baseline of the Sentinel-1 data, ideally ranging between 150 to 300 meters for accurate DEM creation, further contributed to the reduced precision. To address these challenges, the study suggests a correction process for the Sentinel-1 DEMs by comparing them with a known and accurate DEM.

Recommendations

Based on the research findings and conclusions, the following recommendations are proposed to mitigate the current impacts and reduce the future risks of catastrophic coastal flooding, with a particular focus on protecting the well-being and livelihoods of affected individuals:

In order to adequately curb coastal flooding in the Volta Delta, the study suggests an alternative solution of extracting water from the Volta River and treating it as a viable alternative to freshwater. This would reduce the impact of land subsidence. By adopting this approach, the dependence on groundwater extraction can be minimized, leading to a reduction in its overexploitation. This initiative can be spearheaded by the Ghana Water Company Limited (GWCL) and the Water Resources Commission (WRC). These agencies can also promote the use of treated wastewater to supplement freshwater needs and decrease pressure on groundwater resources, drawing inspiration from similar practices in the Netherlands and California in the United States.

Additionally, a baseline survey to establish a subsurface image of the area and continuous monitoring to detect subsurface changes over time is recommended.

The Ghana Geological Survey Authority (GGSA), in collaboration with scientific research agencies, should process and analyze data to identify potential causes of subsidence, enabling the creation of predictive models to forecast future subsidence patterns. Validation or ground-truthing of deformation rates obtained from remote-sensed InSAR data is also of utmost importance. It is strongly recommended to establish an ongoing GPS monitoring system led by the GGSA and academic institutions such as the

University of Ghana to calibrate InSAR measurements across different acquisition timelines.

The study also suggests timely preventive measures to mitigate the potential risks of coastal flooding in various regions of the Volta Delta. This includes protecting natural habitats, beaches, human infrastructure, and crucial agricultural areas. The Forestry Commission of Ghana and the Environmental Protection Agency (EPA) are recommended to lead efforts in establishing buffer zones, following international practices such as the Mediterranean Protocol's 100-meter guideline, and relocating residents living in close proximity to the sea. The National Disaster Management Organization (NADMO) and the Ministry of Works and Housing should oversee the planning and implementation of relocation strategies, ensuring the provision of necessary infrastructure for affected communities.

The study underscored considering wave run-up when developing strategies for coastal flooding and implementing early warning systems. Such measures can reduce the potential for damage and injuries, while also facilitating the implementation of effective strategies to enhance the resilience of coastal communities. This task could be coordinated by the Hydrological Services Department and the Meteorological Agency, in collaboration with international partners such as UNEP.

In order to generate accurate Digital Elevation Models (DEMs), the study recommends utilizing freely available options like FABDEM instead of relying exclusively on DEMs derived from Sentinel-1 data. For projects requiring higher spatial and temporal resolution, alternative products such as LiDAR or UAV data can be employed as suitable alternatives. Academic institutions and

technical agencies could lead the acquisition and application of these advanced tools.

Additionally, employing Digital Elevation Models (DEMs) with higher resolutions is crucial to effectively capture and map changes in the topography.

The Hydrological Services Department and academic collaborators should ensure that future Bathtub Relative Sea Level Rise (RSLR) projections are based on higher-resolution DEMs to reduce uncertainties and improve precision.

The study acknowledges that some data used, specifically for estimating Extreme Coastal Water Level (ECWL), were sourced from regional or global datasets. This could potentially introduce inaccuracies in the findings due to the need to scale up or down the actual values. To address this issue, the study recommends incorporating high-resolution in situ data, if accessible. This approach would help mitigate and minimize inaccuracies, improving the calibration and performance of the models, and ultimately yielding more accurate results.

On a regional scale, the study recommends strengthening the enforcement of conservation laws and conventions that Ghana has ratified to safeguard cultural heritage sites, Ramsar sites, and other protected areas in the Volta Delta. The Forestry Commission of Ghana and the EPA should prioritize enforcement and monitoring activities to ensure compliance and protection of these critical areas for future generations.

To summarize, the study suggests creating a robust monitoring framework to actively monitor the coastal conditions in the Volta Delta and West Africa. Regular mapping and monitoring activities led by the Hydrological Services

Department, Meteorological Agency, and UNEP will enhance the understanding of the delta system, identify the main drivers of changes, and generate valuable data for future studies, trend analysis, and the implementation of early warning systems. These measures are crucial for effectively addressing coastal hazards and ensuring the long-term resilience of the Volta Delta.



REFERENCES

- Abam, T. K. S. (2001). Regional hydrological research perspectives in the Niger Delta. *Hydrological Sciences Journal*, 46(1), 13-25
<https://doi.org/10.1080/02626660109492797> .
- Abd-Elaty, I., Straface, S., & Kuriqi, A. (2021). Sustainable saltwater intrusion management in coastal aquifers under climatic changes for humid and hyper-arid regions. *Ecological Engineering*, 171, 106382.
<https://doi.org/10.1016/j.ecoleng.2021.106382>
- Abidin, H. Z., Andreas, H., Gumilar, I., & Brinkman, J. J. (2015). Study on the risk and impacts of land subsidence in Jakarta. *Proceedings of the International Association of Hydrological Sciences*, 372, 115–120.
<https://doi.org/10.5194/piahs-372-115-2015>.
- Abidin, H. Z., Andreas, H., Gumilar, I., Fukuda, Y., Pohan, Y. E., & Deguchi, T. (2011). Land subsidence of Jakarta (Indonesia) and its relation with urban development. *Natural Hazards*, 59(3), 1753–1771.
<https://doi.org/10.1007/s11069-011-9866-9>
- Abidin, H. Z., Andreas, H., Gumilar, I., Fukuda, Y., Pohan, Y., Deguchi, T. (2011). Land subsidence of Jakarta (Indonesia) and its relation with urban development. *Natural Hazards*. 59. [10.1007/s11069-011-9866-9](https://doi.org/10.1007/s11069-011-9866-9).
- Aboudou Ango, T., Yannah, M., Hamdouni, R. E., Njom, B., & Ondo, J. M. (2023). Evaluation of tectonic activity in the Kopongo area, southwestern Cameroon: Insights from geomorphic indices, remote sensing, and GIS. *Arabian Journal of Geosciences*, 16(3), 175.
<https://doi.org/10.1007/s12517-023-11242-2>

- Addo, K. A., Nicholls, R. J., Codjoe, S. N. A., & Abu, M. (2018a). A Biophysical and Socioeconomic Review of the Volta Delta, Ghana. *Journal of Coastal Research*, 345, 1216–1226.
<https://doi.org/10.2112/JCOASTRES-D-17-00129.1>
- Addo, K. A., Nicholls, R. J., Codjoe, S. N. A., & Abu, M. (2018b). A Biophysical and Socioeconomic Review of the Volta Delta, Ghana. *Journal of Coastal Research*, 345, 1216–1226.
<https://doi.org/10.2112/JCOASTRES-D-17-00129.1>
- Akpati, B. N. (1978). Geologic structure and evolution of the Keta basin, Ghana, West Africa. *Geological Society of America Bulletin*, 89(1), 124.
[https://doi.org/10.1130/0016-7606\(1978\)89<124:GSAEOT>2.0.CO;2](https://doi.org/10.1130/0016-7606(1978)89<124:GSAEOT>2.0.CO;2)
- Alfarrah, N., & Walraevens, K. (2018). Groundwater Overexploitation and Seawater Intrusion in Coastal Areas of Arid and Semi-Arid Regions. *Water*, 10(2), 143. <https://doi.org/10.3390/w10020143>
- Almar, R., Bergsma, E. W. J., Maisongrande, P., & de Almeida, L. P. M. (2019). Wave-derived coastal bathymetry from satellite video imagery: A showcase with Pleiades persistent mode. *Remote Sensing of Environment*, 231, 111263. <https://doi.org/10.1016/j.rse.2019.111263>
- Almar, R., Kestenare, E., Reyns, J., Jouanno, J., Anthony, E. J., Laibi, R., & Ranasinghe, R. (2015). Response of the Bight of Benin (Gulf of Guinea, West Africa) coastline to anthropogenic and natural forcing, Part1: Wave climate variability and impacts on the longshore sediment transport. *Continental Shelf Research*, 110, 48-59.
<https://doi.org/10.1016/j.csr.2015.09.020>

- Almar, R., Ranasinghe, R., Bergsma, E. W. J., Diaz, H., Melet, A., Papa, F., Vousdoukas, M., Athanasiou, P., Dada, O., Almeida, L. P., & Kestenare, E. (2021). A global analysis of extreme coastal water levels with implications for potential coastal overtopping. *Nature Communications*, 12(1), 3775. <https://doi.org/10.1038/s41467-021-24008-9>
- Almar, R., Stieglitz, T., Addo, K. A., Ba, K., Ondo, G. A., Bergsma, E. W. J., Bonou, F., Dada, O., Angnuureng, D., & Arino, O. (2023). Coastal Zone Changes in West Africa: Challenges and Opportunities for Satellite Earth Observations. *Surveys in Geophysics*, 44(1), 249–275. <https://doi.org/10.1007/s10712-022-09721-4>
- Almeida, L., Almar, R., Bergsma, E., Berthier, E., Baptista, P., Garel, E., Dada, O., & Alves, B. (2019). Deriving High Spatial-Resolution Coastal Topography From Sub-meter Satellite Stereo Imagery. *Remote Sensing*, 11(5), 590. <https://doi.org/10.3390/rs11050590>
- Altimeter Corrected Elevations (ACE2), v2: Digital Elevation Data Collection (DEDC) | SEDAC. (2022). Retrieved 17 March 2022, from <https://sedac.ciesin.columbia.edu/data/set/dedc-ace-v2>.
- Amelung, F., Galloway, D. L., Bell, J. W., Zebker, H. A., & Lacznia, R. J. (1999). Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation. *Geology*, 27(6), 483-486.
- Amenuvor, M., Gao, W., Li, D., & Shao, D. (2020). Effects of Dam Regulation on the Hydrological Alteration and Morphological Evolution of the Volta River Delta. *Water*, 12(3), 646. <https://doi.org/10.3390/w12030646>

Amores, A., Marcos, M., Pedreros, R., Le Cozannet, G., Lecacheux, S., Rohmer, J., Hinkel, J., Gussmann, G., Van Der Pol, T., Shareef, A., & Khaleel, Z. (2021). Coastal Flooding in the Maldives Induced by Mean Sea-Level Rise and Wind-Waves: From Global to Local Coastal Modelling. *Frontiers in Marine Science*, 8, 665672. <https://doi.org/10.3389/fmars.2021.665672>.

Angnuureng, D. B., Almar, R., Senechal, N., Castelle, B., Addo, K. A., Marieu, V., & Ranasinghe, R. (2017). Shoreline resilience to individual storms and storm clusters on a meso-macrotidal barred beach. *Geomorphology*, 290, 265-276. <https://doi.org/10.1016/j.geomorph.2017.04.007>

Angnuureng, D. B., Appeaning Addo, K., Almar, R., & Dieng, H. (2018). Influence of sea level variability on a micro-tidal beach. *Natural Hazards*, 93(3), 1611–1628. <https://doi.org/10.1007/s11069-018-3370-4>

Anthony, E. J. (2015). Patterns of Sand Spit Development and Their Management Implications on Deltaic, Drift-Aligned Coasts: The Cases of the Senegal and Volta River Delta Spits, West Africa. In G. Randazzo, D. W. T. Jackson, & J. A. G. Cooper (Eds.). *Sand and Gravel Spits* (Vol. 12, pp. 21–36). Springer International Publishing. https://doi.org/10.1007/978-3-319-13716-2_2

Anthony, E. J., & Aagaard, T. (2020). The lower shoreface: Morphodynamics and sediment connectivity with the upper shoreface and beach. *Earth-Science Reviews*, 210, 103334. <https://doi.org/10.1016/j.geomorph.2017.04.007>

Anthony, E. J., & Orford, J. D. (2002). Between Wave- and Tide-Dominated Coasts: The Middle Ground Revisited. *Journal of Coastal Research*, 36, 8–15. <https://doi.org/10.2112/1551-5036-36.sp1.8>

Anthony, E. J., 2015a. Patterns of Sand Spit Development and Their Management Implications on Deltaic, Drift-Aligned Coasts: The Cases of the Senegal and Volta River Delta Spits, West Africa. In G. Randazzo, D. W. Jackson, J.A.G. Cooper (Eds.), *Sand and Gravel Spits*, pp. 21-36, Springer International Publishing.

Anthony, E. J., 2015b. Wave influence in the construction, shaping and destruction of river deltas: A review. *Marine Geology*, 361, 53-78.

Anthony, E. J., Almar, R., & Aagaard, T. (2016). Recent shoreline changes in the Volta River delta, West Africa: The roles of natural processes and human impacts. *African Journal of Aquatic Science*, 41(1), 81-87.

Anthony, E. J., Almar, R., Besset, M., Reyns, J., Laibi, R., Ranasinghe, R., & Vacchi, M. (2019). Response of the Bight of Benin (Gulf of Guinea, West Africa) coastline to anthropogenic and natural forcing, Part 2: Sources and patterns of sediment supply, sediment cells, and recent shoreline change. *Continental Shelf Research*, 173, 93-103.

Anthony, E. J., Brunier, G., Besset, M., Goichot, M., Dussouillez, P., & Nguyen, V. L. (2015). Linking rapid erosion of the Mekong River delta to human activities. *Scientific reports*, 5(1), 1-12.

- Apeh, O. I., Uzodinma, V. N., Ebinne, E. S., Moka, E. C., & Onah, E. U. (2019). Accuracy Assessment of Alos W3d30, Aster Gdem and Srtm30 Dem: A Case Study of Nigeria, West Africa. *Journal of Geographic Information System*, 11(02), 111–123. <https://doi.org/10.4236/jgis.2019.112009>
- Appeaning Addo, K., Brempong, E. K., & Jayson-Quashigah, P. N. (2020). Assessment of the dynamics of the Volta river estuary shorelines in Ghana. *Geoenvironmental Disasters*, 7(1), 19. <https://doi.org/10.1186/s40677-020-00151-1>
- Appeaning Addo, K., Jayson-Quashigah, P.-N., Codjoe, S. N. A., & Martey, F. (2018). Drone as a tool for coastal flood monitoring in the Volta Delta, Ghana. *Geoenvironmental Disasters*, 5(1), 17. <https://doi.org/10.1186/s40677-018-0108-2>
- Appeaning Addo, K., Kinney, K., Yao, A., Jayson-Quashigah, P. N., Langenberg, V. T. (2019). *Report of the Volta delta Status and trends*, An assessment by the Ghana Wing; Commissioned by the Delta Alliance Secretariat, The Netherlands. <http://www.delta-alliance.org/wings/ghana-wing>.
- Appeaning Addo, K., Larbi, L., Amisigo, B., & Ofori-Danson, P. K. (2011). Impacts of Coastal Inundation Due to Climate Change in a CLUSTER of Urban Coastal Communities in Ghana, West Africa. *Remote Sensing*, 3(9), 2029–2050. <https://doi.org/10.3390/rs3092029>
- Appeaning Addo, K., Nicholls, R. J., Codjoe, S. N. A., & Abu, M. (2018). A biophysical and socioeconomic review of the Volta delta, Ghana. *Journal of Coastal Research*, 34(5), 1216-1226.
- Appeaning Addo, K., Walkden, M., & Mills, J. T. (2008). Detection, measurement and prediction of shoreline recession in Accra,

Ghana. *ISPRS Journal of Photogrammetry and Remote Sensing*, 63(5), 543-558.

Arefi, H., & Reinartz, P. (2011). Accuracy Enhancement of ASTER Global Digital Elevation Models Using ICESat Data. *Remote Sensing*, 3(7), 1323–1343. <https://doi.org/10.3390/rs3071323>

Attema, E., Davidson, M., Snoeij, P., Rommen, B., & Floury, N. (2009). Sentinel-1 mission overview, 2009, *IEEE International Geoscience and Remote Sensing Symposium*, I-36-I-39. <https://doi.org/10.1109/IGARSS.2009.5416921>

Aucelli, P. P., Di Paola, G., Rizzo, A., & Roskopf, C. M. (2018). Present day and future scenarios of coastal erosion and flooding processes along the Italian Adriatic coast: the case of Molise region. *Environmental Earth Sciences*, 77(10), 1-19.

Babae, S., Mousavi, Z., Masoumi, Z., Malekshah, A. H., Roostaei, M., & Aflaki, M. (2020). Land subsidence from interferometric SAR and groundwater patterns in the Qazvin plain, Iran. *International Journal of Remote Sensing*, 41(12), 4780–4798. <https://doi.org/10.1080/01431161.2020.1724345>

Bateson, L., Cigna, F., Boon, D., & Sowter, A. (2015). The application of the Intermittent SBAS (ISBAS) InSAR method to the South Wales Coalfield, UK. *International Journal of Applied Earth Observation and Geoinformation*, 34, 249-257.

Baugh, C. A., Bates, P. D., Schumann, G., & Trigg, M. A. (2013). SRTM vegetation removal and hydrodynamic modeling accuracy: Srtm

Vegetation Error Removal. *Water Resources Research*, 49(9), 5276–5289. <https://doi.org/10.1002/wrcr.20412>

Becker, M., Papa, F., Karpytchev, M., Delebecque, C., Krien, Y., Khan, J. U., Ballu, V., Durand, F., Le Cozannet, G., Islam, A. K. M. S., Calmant, S., & Shum, C. K. (2020). Water level changes, subsidence, and sea level rise in the Ganges–Brahmaputra–Meghna delta. *Proceedings of the National Academy of Sciences*, 117(4), 1867–1876. <https://doi.org/10.1073/pnas.1912921117>

Bekaert, D., A. Hooper, and T. Wright, A spatially-variable power-law tropospheric correction technique for InSAR data, *Journal of Geophysical Research: Solid Earth*, 120 (2), 1345-1356.

Bekaert, D., R. Walters, T. Wright, A. Hooper, and D. Parker, Statistical comparison of insar tropospheric correction techniques, *Remote Sensing of Environment*, 170, 40 – 47, 2015b. 1, 2.3.2

Bertin, X. (2016). Storm surges and coastal flooding: Status and challenges. *La Houille Blanche*, 102(2), 64–70. <https://doi.org/10.1051/lhb/2016020>

Bertin, X., Li, K., Roland, A., & Bidlot, J.-R. (2015). The contribution of short-waves in storm surges: Two case studies in the Bay of Biscay. *Continental Shelf Research*, 96, 1–15. <https://doi.org/10.1016/j.csr.2015.01.005>

- Bertin, X., Li, K., Roland, A., Zhang, Y. J., Breilh, J. F., & Chaumillon, E. (2014). A modeling-based analysis of the flooding associated with Xynthia, central Bay of Biscay. *Coastal Engineering*, 94, 80–89. <https://doi.org/10.1016/j.coastaleng.2014.08.013>
- Bianchi, T. S., & Allison, M. A. (2009). Large-river delta-front estuaries as natural “recorders” of global environmental change. *Proceedings of the National Academy of Sciences*, 106(20), 8085–8092. <https://doi.org/10.1073/pnas.0812878106>
- Bilskie, M. V., & Hagen, S. C. (2018). Defining Flood Zone Transitions in Low-Gradient Coastal Regions. *Geophysical Research Letters*, 45(6), 2761–2770. <https://doi.org/10.1002/2018GL077524>
- Blasco, J.M.D., Foumelis, M., Stewart, C., Hooper, A., 2019. Measuring urban subsidence in the Rome Metropolitan Area (Italy) with Sentinel-1 SNAP-StaMPS Persistent Scatterer Interferometry. *Remote Sensing* 11, 129. <https://doi.org/10.3390/rs11020129>.
- Boateng, I. (2009, May). Development of integrated shoreline management planning: A case study of Keta, Ghana. In *Proceedings of the Federation of International Surveyors Working Week 2009-Surveyors Key Role in Accelerated Development, TS 4E, Eilat, Israel, 3-8 May*.
- Bokpe, S. (2010, August 20). *Azizanya is drowning*. <http://sethbnews09.blogspot.com/2010/08/helpazizanya-is-drowning-friday-august.html>
- Braun, A. (2021). Retrieval of digital elevation models from Sentinel-1 radar data – open applications, techniques, and limitations. *Open Geosciences*, 13(1), 532–569. <https://doi.org/10.1515/geo-2020-0246>

Braun, A., Höser, T., & Delgado Blasco, J. M. (2021). Elevation change of Bhasan Char measured by persistent scatterer interferometry using Sentinel-1 data in a humanitarian context. *European Journal of Remote Sensing*, 54(sup1), 109–126.

<https://doi.org/10.1080/22797254.2020.1789507>

Brempong, E. K., Almar, R., Angnuureng, D. B., Mattah, P. A. D., Jayson-Quashigah, P.-N., Antwi-Agyakwa, K. T., & Charuka, B. (2023). Coastal Flooding Caused by Extreme Coastal Water Level at the World Heritage Historic Keta City (Ghana, West Africa). *Journal of Marine Science and Engineering*, 11(6), 1144. <https://doi.org/10.3390/jmse11061144>

Brempong, E. K., Angnuureng, D. B., Appeaning Addo, K., & Jayson-Quashigah, P. N. (2021). Short-term seasonal changes of the Dzita beach of Ghana using geographic information system and photogrammetry. *Interpretation*, 9(4), SH87-SH97.

Brown, S., & Nicholls, R. J. (2015). Subsidence and human influences in mega deltas: The case of the Ganges–Brahmaputra–Meghna. *Science of The Total Environment*, 527–528, 362–374. <https://doi.org/10.1016/j.scitotenv.2015.04.124>

Buiter, S. J. H., Brune, S., Keir, D., & Peron-Pinvidic, G. (2023). Rifting Continents. In *Dynamics of Plate Tectonics and Mantle Convection* (pp. 459–481). Elsevier. <https://doi.org/10.1016/B978-0-323-85733-8.00016-0>

- Caldwell, R. L., Edmonds, D. A., Baumgardner, S., Paola, C., Roy, S., & Nienhuis, J. H. (2019). A global delta dataset and the environmental variables that predict delta formation on marine coastlines. *Earth Surface Dynamics*, 7(3), 773–787. <https://doi.org/10.5194/esurf-7-773-2019>
- Canova, F., Tolomei, C., Salvi, S., Toscani, G., & Seno, S. (2012). Land subsidence along the Ionian coast of SE Sicily (Italy), detection and analysis via Small Baseline Subset (SBAS) multitemporal differential SAR interferometry: land subsidence along the ionian coast of se sicily (italy). *Earth Surface Processes and Landforms*, 37(3), 273–286. <https://doi.org/10.1002/esp.2238>
- Carnero-Bravo, V., Sanchez-Cabeza, J.-A., Ruiz-Fernández, A. C., Merino-Ibarra, M., Corcho-Alvarado, J. A., Sahli, H., Hélie, J.-F., Preda, M., Zavala-Hidalgo, J., Díaz-Asencio, M., & Hillaire-Marcel, C. (2018). Sea level rise sedimentary record and organic carbon fluxes in a low-lying tropical coastal ecosystem. *Catena*, 162, 421–430. <https://doi.org/10.1016/j.catena.2017.09.016>
- Carrere, L., Lyard, F., Cancet, M., & Guillot, A. (2015). *FES 2014, a new tidal model on the global ocean with enhanced accuracy in shallow seas and in the Arctic region*. 5481.
- Casella, E., Drechsel, J., Winter, C., Benninghoff, M., & Rovere, A. (2020). Accuracy of sand beach topography surveying by drones and photogrammetry. *Geo-Marine Letters*, 40(2), 255–268. <https://doi.org/10.1007/s00367-020-00638-8>

Chaussard, E., Amelung, F., Abidin, H., & Hong, S.-H. (2013). Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. *Remote Sensing of Environment*, 128, 150–161. <https://doi.org/10.1016/j.rse.2012.10.015>

Chaussard, E., Milillo, P., Bürgmann, R., Perissin, D., Fielding, E. J., & Baker, B. (2017). Remote sensing of ground deformation for monitoring groundwater management practices: Application to the Santa Clara Valley during the 2012–2015 California drought. *Journal of Geophysical Research: Solid Earth*, 122(10), 8566–8582.

Chen, W., Van Der Werf, J. J., & Hulscher, S. J. M. H. (2023). A review of practical models of sand transport in the swash zone. *Earth-Science Reviews*, 238, 104355. <https://doi.org/10.1016/j.earscirev.2023.104355>

Choudhury, A., Lahkar, J., Saikia, B. K., Singh, A. K. A., Chikkaputtaiah, C., & Boruah, H. P. D. (2021). Strategies to address coal mine-created environmental issues and their feasibility study on northeastern coalfields of Assam, India: A review. *Environment, Development and Sustainability*, 23(7), 9667–9709. <https://doi.org/10.1007/s10668-020-01091-4>

Choussiafis, C., Karathanassi, V., & Nikolakopoulos, K. (2012). Mosaic Methods for Improving the Accuracy of Interferometric Based Digital Elevation Models. *Advances in Geosciences*, 9.

- Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., & Unnikrishnan, A. S. (2013). Sea-Level Rise by 2100. *Science*, 342(6165), 1445–1445. <https://doi.org/10.1126/science.342.6165.1445-a>
- Cian, F., Blasco, J., & Carrera, L. (2019). Sentinel-1 for Monitoring Land Subsidence of Coastal Cities in Africa Using PSInSAR: A Methodology Based on the Integration of SNAP and StaMPS. *Geosciences*, 9(3), 124. <https://doi.org/10.3390/geosciences9030124>
- Ciavola, P., Ferreira, O., Haerens, P., Van Koningsveld, M., & Armaroli, C. (2011). Storm impacts along European coastlines. Part 2: Lessons learned from the MICORE project. *Environmental Science & Policy*, 14(7), 924–933. <https://doi.org/10.1016/j.envsci.2011.05.009>
- Cigna, F., Banks, V., Donald, A., Donohue, S., Graham, C., Hughes, D., McKinley, J., & Parker, K. (2017). Mapping Ground Instability in Areas of Geotechnical Infrastructure Using Satellite InSAR and Small UAV Surveying: A Case Study in Northern Ireland. *Geosciences*, 7(3), 51. <https://doi.org/10.3390/geosciences7030051>
- Cisse, C. O. T., Bremping, E. K., Taveneau, A., Almar, R., Sy, B. A., & Angnuureng, D. B. (2022). Extreme coastal water levels with potential flooding risk at the low-lying Saint Louis historic city, Senegal (West Africa). *Frontiers in Marine Science*, 9, 993644. <https://doi.org/10.3389/fmars.2022.993644>

- Codjoe, S. N. A., Addo, K. A., Tagoe, C. A., Nyarko, B. K., Martey, F., Nelson, W. A., & Abu, M. (2020). The Volta delta, Ghana: Challenges in an African Setting. In *Deltas in the Anthropocene* (pp. 79-102). Palgrave Macmillan, Cham. Coral Gables, Florida, USA. *Natural Hazards*, 1-30.
- Collilieux, X., & Wöppelmann, G. (2011). Global sea-level rise and its relation to the terrestrial reference frame. *Journal of Geodesy*, 85(1), 9–22.
<https://doi.org/10.1007/s00190-010-0412-4>
- Craik, A. D. D. (2004). The origins of water wave theory. *Annual Review of Fluid Mechanics*, 36(1), 1–28.
<https://doi.org/10.1146/annurev.fluid.36.050802.122118>
- Crosetto, M., & Crippa, B. (n.d.). Quality assessment of interferometric sar DEMs. *Part B*.
- Da Lio, C., & Tosi, L. (2018). Land subsidence in the Friuli Venezia Giulia coastal plain, Italy: 1992–2010 results from SAR-based interferometry. *Science of The Total Environment*, 633, 752–764.
<https://doi.org/10.1016/j.scitotenv.2018.03.244>
- Da Lio, C., Tosi, L., Zambon, G., Vianello, A., Baldin, G., Lorenzetti, G., & Teatini, P. (2013). Long-term groundwater dynamics in the coastal confined aquifers of Venice (Italy). *Estuarine, Coastal and Shelf Science*, 135, 248-259.
- Dada, O., Almar, R., Morand, P., & Menard, F. (2021). “Towards West African coastal social-ecosystems sustainability: Interdisciplinary approaches.” *Ocean & Coastal Management*, 211, 105746.
<https://doi.org/10.1016/j.ocecoaman.2021.105746>
- Dandekar, P., & Thakkar, H. (2014). *Shrinking and Sinking Deltas*

- Davidson-Arnott, R. G. D. (2005). Conceptual Model of the Effects of Sea Level Rise on Sandy Coasts. *Journal of Coastal Research*, 216, 1166–1172. <https://doi.org/10.2112/03-0051.1>
- De Boer, B., Stocchi, P., Whitehouse, P. L., & Van De Wal, R. S. W. (2017). Current state and future perspectives on coupled ice-sheet – sea-level modelling. *Quaternary Science Reviews*, 169, 13–28. <https://doi.org/10.1016/j.quascirev.2017.05.013>
- de Moel, H., Jongman, B., Kreibich, H., Merz, B., Penning-Rowsell, E., & Ward, P. J. (2015). Flood risk assessments at different spatial scales. *Mitigation and Adaptation Strategies for Global Change*, 20(6), 865–890. <https://doi.org/10.1007/s11027-015-9654-z>
- De Oliveira, A. D. O., & Bonetti, J. (2021). Dynamical descriptors of physical vulnerability to sea-level rise in sheltered coastal systems: A methodological framework. *Estuarine, Coastal and Shelf Science*, 249, 107118. <https://doi.org/10.1016/j.ecss.2020.107118>
- Dealbera, S., Almar, R., Papa, F., Becker, M., & Wöppelmann, G. (2021). Disentangling vertical land motion and waves from coastal sea level altimetry and tide gauges. *Continental Shelf Research*, 231, 104596.
- Deng, B., Zhang, W., Yao, Y., & Jiang, C. (2022). A laboratory study of the effect of varying beach slopes on bore-driven swash hydrodynamics. *Frontiers in Marine Science*, 9, 956379. <https://doi.org/10.3389/fmars.2022.956379>

- Dering, G. M., Micklethwaite, S., Thiele, S. T., Vollgger, S. A., & Cruden, A. R. (2019). Review of drones, photogrammetry and emerging sensor technology for the study of dykes: Best practises and future potential. *Journal of Volcanology and Geothermal Research*, 373, 148–166. <https://doi.org/10.1016/j.jvolgeores.2019.01.018>
- Di Paola, G., Alberico, I., Aucelli, P. P. C., Matano, F., Rizzo, A., & Vilardo, G. (2018). Coastal subsidence detected by Synthetic Aperture Radar interferometry and its effects coupled with future sea-level rise: the case of the Sele Plain (Southern Italy). *Journal of Flood Risk Management*, 11(2), 191-206.
- Didier, D., Baudry, J., Bernatchez, P., Dumont, D., Sadegh, M., Bismuth, E., Bandet, M., Dugas, S., & Sévigny, C. (2019). Multihazard simulation for coastal flood mapping: Bathtub versus numerical modelling in an open estuary, Eastern Canada. *Journal of Flood Risk Management*, 12(S1). <https://doi.org/10.1111/jfr3.12505>
- Didier, D., Baudry, J., Bernatchez, P., Dumont, D., Sadegh, M., Bismuth, E., & Sévigny, C. (2019). Multihazard simulation for coastal flood mapping: Bathtub versus numerical modelling in an open estuary, Eastern Canada. *Journal of Flood Risk Management*, 12, e12505.
- Duku, E., Dzorgbe Mattah, P. A., & Angnuureng, D. B. (2022). Assessment of wetland ecosystem services and human wellbeing nexus in sub-Saharan Africa: Empirical evidence from a socio-ecological landscape of Ghana. *Environmental and Sustainability Indicators*, 15, 100186. <https://doi.org/10.1016/j.indic.2022.100186>

- Duku, E., Mattah, P. A. D., & Angnuureng, D. B. (2021). Assessment of land use/land cover change and morphometric parameters in the Keta Lagoon complex Ramsar site, Ghana. *Water*, 13(18), 2537.
- Dulou, C., Belzons, M., & Rey, V. (2000). Laboratory study of wave bottom interaction in the bar formation on an erodible sloping bed. *Journal of Geophysical Research: Oceans*, 105(C8), 19745–19762.
<https://doi.org/10.1029/2000JC900082>
- Elgar, S., & Guza, R. T. (1985). Observations of bispectra of shoaling surface gravity waves. *Journal of Fluid Mechanics*, 161(1), 425.
<https://doi.org/10.1017/S0022112085003007>
- Erban, L. E., Gorelick, S. M., & Zebker, H. A. (2014). Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam. *Environmental Research Letters*, 9(8), 084010.
<https://doi.org/10.1088/1748-9326/9/8/084010>
- Erena, Domínguez, Aguado, Soria, & García-Galiano. (2019). Monitoring Coastal Lagoon Water Quality Through Remote Sensing: The Mar Menor as a Case Study. *Water*, 11(7), 1468. <https://doi.org/10.3390/w11071468>
- Ericson, J., Vorosmarty, C., Dingman, S., Ward, L., & Meybeck, M. (2006). Effective sea-level rise and deltas: Causes of change and human dimension implications. *Global and Planetary Change*, 50(1–2), 63–82.
<https://doi.org/10.1016/j.gloplacha.2005.07.004>
- Erkens, G., Bucx, T., Dam, R., De Lange, G., & Lambert, J. (2015). Sinking coastal cities. *Proceedings of the International Association of Hydrological Sciences*, 372, 189-198.

- Fabris, M., Achilli, V., & Menin, A. (2014). Estimation of subsidence in Po Delta area (Northern Italy) by integration of GPS data, high-precision leveling and archival orthometric elevations. *International Journal of Geosciences*, 05(06), 571–585. <https://doi.org/10.4236/ijg.2014.56052>
- Facciolo, G., Franchis, C. D., & Meinhardt, E. (2015). MGM: A Significantly More Global Matching for Stereovision. *Proceedings of the British Machine Vision Conference 2015*, 90.1-90.12. <https://doi.org/10.5244/C.29.90>
- Ferguson, K. C., Rucker, M. L., & Panda, B. B. (2015). Methods for monitoring land subsidence and earth fissures in the Western USA. *Proceedings of the International Association of Hydrological Sciences*, 372, 361–366. <https://doi.org/10.5194/piahs-372-361-2015>
- Ferreira, B. R. (2014). *High-resolution lidar mapping and analysis to quantify surface movement of Swift Creek landslide, Whatcom County, WA*. <https://doi.org/10.25710/V0XE-DM93>
- Ferretti, A., Colombo, D., Fumagalli, A., Novali, F., and Rucci, A. (2015). *InSAR data for monitoring land subsidence: time to think big*, Proc. IAHS, 372, 331–334, <https://doi.org/10.5194/piahs-372-331-2015>.
- Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent Scatterers in SAR Interferometry. *IEEE Transactions on geoscience and remote sensing*, 39(1).

Fiaschi, S., Fabris, M., Floris, M., & Achilli, V. (2018). Estimation of land subsidence in deltaic areas through differential SAR interferometry: The Po River Delta case study (Northeast Italy). *International Journal of Remote Sensing*, 39(23), 8724–8745.

<https://doi.org/10.1080/01431161.2018.1490977>

FitzGerald, D. M., Fenster, M. S., Argos, B. A., & Buynevich, I. V. (2008). Coastal Impacts Due to Sea-Level Rise. *Annual Review of Earth and Planetary Sciences*, 36(1), 601–647. <https://doi.org/10.1146/annurev.earth.35.031306.140139>

FitzGibbon, J., & Mensah, K. O. (2012). Climate change as a wicked problem: an evaluation of the institutional context for rural water management in Ghana. *Sage Open*, 2(2), 2158244012448487.

Foumelis, M., Blasco, J. M. D., Desnos, Y. L., Engdahl, M., Fernández, D., Veci, L., & Wong, C. (2018, July). ESA SNAP-StaMPS integrated processing for Sentinel-1 persistent scatterer interferometry. In *IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium* (pp. 1364-1367). IEEE.

Fredsøe, J., & Deigaard, R. (1992). *Mechanics of Coastal Sediment Transport* (Vol. 3). World Scientific. <https://doi.org/10.1142/1546>

GARR, E. (2010). *Infrastructure policy reforms and rural poverty reduction in Ghana: The case of the Keta Sea Defence Project* [University of the Western Cape]. <https://core.ac.uk/download/pdf/58913725.pdf>

- Gierszewski, P. J., Habel, M., Szmańda, J., & Luc, M. (2020). Evaluating effects of dam operation on flow regimes and riverbed adaptation to those changes. *Science of The Total Environment*, 710, 136202. <https://doi.org/10.1016/j.scitotenv.2019.136202>
- Gleyzes, M. A., Perret, L., & Kubik, P. (2012). PLEIADES SYSTEM ARCHITECTURE AND MAIN PERFORMANCES. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXIX-B1, 537–542. <https://doi.org/10.5194/isprsarchives-XXXIX-B1-537-2012>
- Goodbred, S. L., & Kuehl, S. A. (2000). The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges–Brahmaputra delta. *Sedimentary Geology*, 133(3–4), 227–248. [https://doi.org/10.1016/S0037-0738\(00\)00041-5](https://doi.org/10.1016/S0037-0738(00)00041-5)
- Grandin, R. (2015, March). Interferometric processing of SLC Sentinel-1 TOPS data. In *FRINGE'15: Advances in the Science and Applications of SAR Interferometry and Sentinel-1 InSAR Workshop, Frascati, Italy, 23-27 March 2015*.
- Grases, A., Gracia, V., García-León, M., Lin-Ye, J., & Sierra, J. P. (2020). Coastal Flooding and Erosion under a Changing Climate: Implications at a Low-Lying Coast (Ebro Delta). *Water*, 12(2), 346. <https://doi.org/10.3390/w12020346>

- Gray, K. A. (2021). Climate Action: The Feasibility of Climate Intervention on a Global Scale. In W. Burns, D. Dana, & S. J. Nicholson (Eds.), *Climate Geoengineering: Science, Law and Governance* (pp. 33–91). Springer International Publishing. https://doi.org/10.1007/978-3-030-72372-9_3
- Gregory, J. M., Griffies, S. M., Hughes, C. W., Lowe, J. A., Church, J. A., Fukimori, I., Gomez, N., Kopp, R. E., Landerer, F., Cozannet, G. L., Ponte, R. M., Stammer, D., Tamisiea, M. E., & Van De Wal, R. S. W. (2019). Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global. *Surveys in Geophysics*, 40(6), 1251–1289. <https://doi.org/10.1007/s10712-019-09525-z>
- Griggs, G., & Reguero, B. G. (2021). Coastal Adaptation to Climate Change and Sea-Level Rise. *Water*, 13(16), 2151. <https://doi.org/10.3390/w13162151>
- Hansom, J. D., Switzer, A. D., & Pile, J. (2015). Chapter 11 - Extreme Waves: Causes, Characteristics, and Impact on Coastal Environments and Society. In J. F. Shroder, J. T. Ellis, & D. J. Sherman (Eds.), *Coastal and Marine Hazards, Risks, and Disasters* (pp. 307–334). Elsevier. <https://doi.org/10.1016/B978-0-12-396483-0.00011-X>
- Hawker, L., Uhe, P., Paulo, L., Sosa, J., Savage, J., Sampson, C., & Neal, J. (2022). A 30 m global map of elevation with forests and buildings removed. *Environmental Research Letters*, 17(2), 024016. <https://doi.org/10.1088/1748-9326/ac4d4f>

- Heleno, S. I. N., Oliveira, L. G. S., Henriques, M. J., Falcão, A. P., Lima, J. N. P., Cooksley, G., Ferretti, A., Fonseca, A. M., Lobo-Ferreira, J. P., & Fonseca, J. F. B. D. (2011). Persistent Scatterers Interferometry detects and measures ground subsidence in Lisbon. *Remote Sensing of Environment*, 115(8), 2152–2167. <https://doi.org/10.1016/j.rse.2011.04.021>
- Herrera-García, G., Ezquerro, P., Tomás, R., Béjar-Pizarro, M., López-Vinielles, J., Rossi, M., & Ye, S. (2021). Mapping the global threat of land subsidence. *Science*, 371(6524), 34-36. DOI: 10.1126/science.abb8549
- Higgins, S. A. (2016a). Review: Advances in delta-subsidence research using satellite methods. *Hydrogeology Journal*, 24(3), 587–600. <https://doi.org/10.1007/s10040-015-1330-6>
- Higgins, S. A. (2016b). Review: Advances in delta-subsidence research using satellite methods. *Hydrogeology Journal*, 24(3), 587–600. <https://doi.org/10.1007/s10040-015-1330-6>
- Hooijer, A., Page, S., Jauhiainen, J., Lee, W. A., Lu, X. X., Idris, A., & Anshari, G. (2012). Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences*, 9(3), 1053–1071. <https://doi.org/10.5194/bg-9-1053-2012>
- Hooper A; Bekaert D; Spaans K; Arikan M (2012), Recent advances in SAR interferometry time series analysis for measuring crustal deformation, *Tectonophysics*, 514-517, pp.1-13. <https://doi:10.1016/j.tecto.2011.10.013>.

Hooper, A., Spaans, K., Bekaert, D., Cuenca, M. C., Arkan, M., & Oyen, A.

(2010). StaMPS/MTI manual. *Delft Institute of Earth Observation and Space Systems Delft University of Technology, Kluyverweg, 1*, 2629.

<https://mofa.gov.gh/site/publications/research-reports/91-survey-on-small-scale-irrigation-and-dugouts>

Huang, C., & Asner, G. (2009). Applications of Remote Sensing to Alien Invasive Plant Studies. *Sensors*, 9(6), 4869–4889.

<https://doi.org/10.3390/s90604869>

Huang, Y., Yu, M., Xu, Q., Sawada, K., Moriguchi, S., Yashima, A., Liu, C., & Xue, L. (2015). InSAR-derived digital elevation models for terrain change analysis of earthquake-triggered flow-like landslides based on ALOS/PALSAR imagery. *Environmental Earth Sciences*, 73(11), 7661–7668. <https://doi.org/10.1007/s12665-014-3939-5>

Hudson, P. F. (2021). *Flooding and Management of Large Fluvial Lowlands: A Global Environmental Perspective* (1st ed.). Cambridge University Press. <https://doi.org/10.1017/9781139015738>

Husnayaen, Rimba, A. B., Osawa, T., Parwata, I. N. S., As-syakur, A. R., Kasim, F., & Astarini, I. A. (2018). Physical assessment of coastal vulnerability under enhanced land subsidence in Semarang, Indonesia, using multi-sensor satellite data. *Advances in Space Research*, 61(8), 2159–2179. <https://doi.org/10.1016/j.asr.2018.01.026>

Imani, M., Kuo, C.-Y., Chen, P.-C., Tseng, K.-H., Kao, H.-C., Lee, C.-M., & Lan, W.-H. (2021). Risk Assessment of Coastal Flooding under Different Inundation Situations in Southwest of Taiwan (Tainan City). *Water*, 13(6), 880. <https://doi.org/10.3390/w13060880>

- IPCC. (2022). *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge University Press. <https://doi.org/10.1017/9781009157964>
- Irawan, A. M., Marfai, M. A., Munawar, Nugraheni, I. R., Gustono, S. T., Rejeki, H. A., Widodo, A., Mahmudiah, R. R., & Faridatunnisa, M. (2021). Comparison between averaged and localised subsidence measurements for coastal floods projection in 2050 Semarang, Indonesia. *Urban Climate*, 35, 100760. <https://doi.org/10.1016/j.uclim.2020.100760>
- Jacobsen, K., & Topan, H. (2015). Corrigendum to “DEM GENERATION WITH SHORT BASE LENGTH PLEIADES TRIPLET.” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-3/W2, 297–297. <https://doi.org/10.5194/isprsarchives-XL-3-W2-297-2015>
- Jayson-Quashigah, P. N., Addo, K. A., & Kodzo, K. S. (2013). Medium resolution satellite imagery as a tool for monitoring shoreline change. Case study of the Eastern coast of Ghana. *Journal of coastal Research*, (65 (10065)), 511-516. DOI: 10.2112/SI65-087.1
- Jayson-Quashigah, P.-N., Appeaning Addo, K., Amisigo, B., & Wiafe, G. (2019). Assessment of short-term beach sediment change in the Volta Delta coast in Ghana using data from Unmanned Aerial Vehicles (Drone). *Ocean & Coastal Management*, 182, 104952. <https://doi.org/10.1016/j.ocecoaman.2019.104952>

- Jayson-Quashigah, P.-N., Appeaning Addo, K., Wiafe, G., Amisigo, B. A., Brempong, E. K., Kay, S., & Angnuureng, D. B. (2021). Wave dynamics and shoreline evolution in deltas: A case study of sandy coasts in the Volta delta of Ghana. *Interpretation*, 9(4), SH99–SH113. <https://doi.org/10.1190/INT-2021-0028.1>
- Jørgensen, N. O., & Banoeng-Yakubo, B. K. (2001). Environmental isotopes (18 O, 2 H, and 87 Sr/86 Sr) as a tool in groundwater investigations in the Keta Basin, Ghana. *Hydrogeology Journal*, 9(2), 190-201. <https://doi.org/10.1007/s100400000122>
- Kabo-bah, A., & Diji, C. J. (Eds.). (2018). *Sustainable hydropower in West Africa: Planning, operation, and challenges*. Academic Press, an imprint of Elsevier.
- Klemas, V. (2013). Remote sensing of emergent and submerged wetlands: An overview. *International Journal of Remote Sensing*, 34(18), 6286–6320. <https://doi.org/10.1080/01431161.2013.800656>
- Klemas, V. V. (2009). The Role of Remote Sensing in Predicting and Determining Coastal Storm Impacts. *Journal of Coastal Research*, 256, 1264–1275. <https://doi.org/10.2112/08-1146.1>
- Knuth, F., Shean, D., Bhushan, S., Schwat, E., Alexandrov, O., McNeil, C., Dehecq, A., Florentine, C., & O’Neel, S. (2023). Historical Structure from Motion (HSfM): Automated processing of historical aerial photographs for long-term topographic change analysis. *Remote Sensing of Environment*, 285, 113379. <https://doi.org/10.1016/j.rse.2022.113379>

- Koster, K., Stafleu, J., Cohen, K. M., Stouthamer, E., Busschers, F. S., & Middelkoop, H. (2018). Three-dimensional distribution of organic matter in coastal-deltaic peat: Implications for subsidence and carbon dioxide emissions by human-induced peat oxidation. *Anthropocene*, 22, 1–9. <https://doi.org/10.1016/j.ancene.2018.03.001>
- Laignel, B., Vignudelli, S., Almar, R., Becker, M., Bentamy, A., Benveniste, J., Birol, F., Frappart, F., Idier, D., Salameh, E., Passaro, M., Menende, M., Simard, M., Turki, E. I., & Verpoorter, C. (2023). Observation of the Coastal Areas, Estuaries and Deltas from Space. *Surveys in Geophysics*. <https://doi.org/10.1007/s10712-022-09757-6>
- Le Cozannet, G., Rohmer, J., Cazenave, A., Idier, D., van De Wal, R., De Winter, R., & Oliveros, C. (2015). Evaluating uncertainties of future marine flooding occurrence as sea-level rises. *Environmental Modelling & Software*, 73, 44-56.
- Leal-Alves, D. C., Weschenfelder, J., Albuquerque, M. da G., Espinoza, J. M. de A., Ferreira-Cravo, M., & Almeida, L. P. M. de. (2020). Digital elevation model generation using UAV-SfM photogrammetry techniques to map sea-level rise scenarios at Cassino Beach, Brazil. *SN Applied Sciences*, 2(12), 2181. <https://doi.org/10.1007/s42452-020-03936-z>

- Leuven, J. R. F. W., Niesten, I., Huismans, Y., Cox, J. R., Hulsen, L., Van Der Kaaij, T., & Hoitink, A. J. F. (Ton). (2023). Peak Water Levels Rise Less Than Mean Sea Level in Tidal Channels Subject to Depth Convergence by Deepening. *Journal of Geophysical Research: Oceans*, 128(4), e2022JC019578. <https://doi.org/10.1029/2022JC019578>
- Lewis, J. A., & Ernstson, H. (2019). Contesting the coast: Ecosystems as infrastructure in the Mississippi River Delta. *Progress in Planning*, 129, 1–30. <https://doi.org/10.1016/j.progress.2017.10.003>
- Li, Y., Fu, H., Zhu, J., Wu, K., Yang, P., Wang, L., & Gao, S. (2022). A Method for SRTM DEM Elevation Error Correction in Forested Areas Using ICESat-2 Data and Vegetation Classification Data. *Remote Sensing*, 14(14), 3380. <https://doi.org/10.3390/rs14143380>
- Lincoln, S., Buckley, P., Howes, E. L., Maltby, K. M., Pinnegar, J. K., Ali, T. S., Alosairi, Y., Al-Ragum, A., Baglee, A., Balmes, C. O., Hamadou, R. B., Burt, J. A., Claereboudt, M., Glavan, J., Mamiit, R. J., Naser, H. A., Sedighi, O., Shokri, M. R., Shuhaibar, B., ... Le Quesne, W. J. F. (2021). A Regional Review of Marine and Coastal Impacts of Climate Change on the ROPME Sea Area. *Sustainability*, 13(24), 13810. <https://doi.org/10.3390/su132413810>
- Lloyd, E. A., Oreskes, N., Seneviratne, S. I., & Larson, E. J. (2021). Climate scientists set the bar of proof too high. *Climatic Change*, 165(3–4), 55. <https://doi.org/10.1007/s10584-021-03061-9>

Loucks, D. P. (2019). Developed river deltas: Are they sustainable, *Environmental Research Letters*, 14(11), 113004.

<https://doi.org/10.1088/1748-9326/ab4165>

Ly, C. K. (1980). The role of the Akosombo Dam on the Volta river in causing coastal erosion in central and eastern Ghana (West Africa). *Marine Geology*, 37(3–4), 323–332. [https://doi.org/10.1016/0025-3227\(80\)90108-5](https://doi.org/10.1016/0025-3227(80)90108-5)

Mahmoud, T. A., Saied, S. K., & Elshafey, M. A. (2022). Integrated Denoised Synthetic Aperture Radar Images for Enhanced Digital Elevation Model Generation. *Journal of Aerospace Information Systems*, 19(3), 194–202. <https://doi.org/10.2514/1.I010903>

Makineci, H. B., & Karabörk, H. (2016). Evaluation digital elevation model generated by synthetic aperture radar data. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B1, 57–62. <https://doi.org/10.5194/isprsarchives-XLI-B1-57-2016>

Mancini, F., Grassi, F., & Cenni, N. (2021). A Workflow Based on SNAP–StaMPS Open-Source Tools and GNSS Data for PSI-Based Ground Deformation Using Dual-Orbit Sentinel-1 Data: Accuracy Assessment with Error Propagation Analysis. *Remote Sensing*, 13(4), 753.

Mancini, F., Stecchi, F., & Gabbianelli, G. (2009). GIS-based risk assessment due to salt mining activities at Tuzla (Bosnia and Herzegovina). *Engineering Geology*, 109(3–4), 170–182.

- Marchesiello, P., Nguyen, N. M., Gratiot, N., Loisel, H., Anthony, E. J., San Dinh, C., & Kestenare, E. (2019). Erosion of the coastal Mekong delta: Assessing natural against man induced processes. *Continental Shelf Research*, 181, 72-89.
- Marcos, M., Rohmer, J., Vousdoukas, M. I., Mentaschi, L., Le Cozannet, G., & Amores, A. (2019). Increased Extreme Coastal Water Levels Due to the Combined Action of Storm Surges and Wind Waves. *Geophysical Research Letters*, 46(8), 4356–4364. <https://doi.org/10.1029/2019GL082599>
- Marti, F., Cazenave, A., Birol, F., Passaro, M., Léger, F., Niño, F., Almar, R., Benveniste, J., & Legeais, J. F. (2021). Altimetry-based sea level trends along the coasts of Western Africa. *Advances in Space Research*, 68(2), 504–522. <https://doi.org/10.1016/j.asr.2019.05.033>
- Martin, N., & Van De Giesen, N. (2005). Spatial distribution of groundwater production and development potential in the Volta River basin of Ghana and Burkina Faso. *Water international*, 30(2), 239-249.
- Martínez, M. L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., & Landgrave, R. (2007). The coasts of our world: Ecological, economic and social importance. *Ecological Economics*, 63(2–3), 254–272. <https://doi.org/10.1016/j.ecolecon.2006.10.022>
- Mason, D. C., Trigg, M., Garcia-Pintado, J., Cloke, H. L., Neal, J. C., & Bates, P. D. (2016). Improving the TanDEM-X Digital Elevation Model for flood modelling using flood extents from Synthetic Aperture Radar images. *Remote Sensing of Environment*, 173, 15–28. <https://doi.org/10.1016/j.rse.2015.11.018>

- Matteo, F. (2016). *West Africa is being swallowed by the sea*. <http://foreignpolicy.com/2016/10/21/west-africa-is-being-swallowed-by-the-seaclimate-change-ghana-benin/>
- Mazhar, S., Pellegrini, E., Contin, M., Bravo, C., & De Nobili, M. (2022). Impacts of salinization caused by sea level rise on the biological processes of coastal soils—A review. *Frontiers in Environmental Science*, 10, 909415. <https://doi.org/10.3389/fenvs.2022.909415>
- McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, 19(1), 17–37. <https://doi.org/10.1177/0956247807076960>.
- Mehrtens, B., Lojek, O., Kosmalla, V., Bölker, T., & Goseberg, N. (2023). Fore-dune growth and storm surge protection potential at the Eiderstedt Peninsula, Germany. *Frontiers in Marine Science*, 9, 1020351. <https://doi.org/10.3389/fmars.2022.1020351>
- Melet, A., Meyssignac, B., Almar, R., & Le Cozannet, G. (2018). Under-estimated wave contribution to coastal sea-level rise. *Nature Climate Change*, 8(3), 234–239. <https://doi.org/10.1038/s41558-018-0088-y>
- Mesa-Mingorance, J. L., & Ariza-López, F. J. (2020). Accuracy Assessment of Digital Elevation Models (DEMs): A Critical Review of Practices of the Past Three Decades. *Remote Sensing*, 12(16), 2630. <https://doi.org/10.3390/rs12162630>
- Mimura, N. (2013). Sea-level rise caused by climate change and its implications for society. *Proceedings of the Japan Academy, Series B*, 89(7), 281–301. <https://doi.org/10.2183/pjab.89.281>

Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., & Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environmental Research Letters*, 12(6), 064006. <https://doi.org/10.1088/1748-9326/aa7146>

Minderhoud, P., Erkens, G., Pham, H. B. V., Erban, L., Kooi, H. and Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environmental Research Letters*, doi:12. 064006. 10.1088/1748-9326/aa7146.

Ministry of Food and Agriculture (MOFA) (2017), *Survey on Small Scale Irrigation and Dugouts*

Mohseni, F., Saba, F., Mirmazloumi, S. M., Amani, M., Mokhtarzade, M., Jamali, S., & Mahdavi, S. (2022). Ocean water quality monitoring using remote sensing techniques: A review. *Marine Environmental Research*, 180, 105701. <https://doi.org/10.1016/j.marenvres.2022.105701>

Morton, R. A., Bernier, J. C., Barras, J. A., & Ferina, N. F. (2005). Historical subsidence and wetland loss in the Mississippi delta plain.

Muntendam-Bos, A.G., J.P.A. Roest, and J.A. De Waal, Managing Subsidence due to Salt Mining, *Proceedings of the Solution Mining Research Institute Fall 2014 Technical Conference, Groningen*, September 2014.

- Musa, Z. N., Popescu, I., & Mynett, A. (2015). A review of applications of satellite SAR, optical, altimetry and DEM data for surface water modelling, mapping and parameter estimation. *Hydrology and Earth System Sciences*, 19(9), 3755–3769. <https://doi.org/10.5194/hess-19-3755-2015>
- Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences*, 115(9), 2022–2025. <https://doi.org/10.1073/pnas.1717312115>
- Nerquaye-Tetteh, B. H. (1993, September). Water, sanitation, environment, and development: Water resources appraisal in the Keta Basin. In *Proceedings of the 19th WEDC Conference* (pp. 102-108).
- Newton, A., Icely, J., Cristina, S., Perillo, G. M. E., Turner, R. E., Ashan, D., Cragg, S., Luo, Y., Tu, C., Li, Y., Zhang, H., Ramesh, R., Forbes, D. L., Solidoro, C., Béjaoui, B., Gao, S., Pastres, R., Kelsey, H., Taillie, D., ... Kuenzer, C. (2020). Anthropogenic, Direct Pressures on Coastal Wetlands. *Frontiers in Ecology and Evolution*, 8, 144. <https://doi.org/10.3389/fevo.2020.00144>
- Nguyen, T. C., Schwarzer, K., & Ricklefs, K. (2023). Water-level changes and subsidence rates along the Saigon-Dong Nai River Estuary and the East Sea coastline of the Mekong Delta. *Estuarine, Coastal and Shelf Science*, 283, 108259. <https://doi.org/10.1016/j.ecss.2023.108259>

- Nicholls, R. J. (2002). Analysis of global impacts of sea-level rise: A case study of flooding. *Physics and Chemistry of the Earth, Parts A/B/C*, 27(32–34), 1455–1466. [https://doi.org/10.1016/S1474-7065\(02\)00090-6](https://doi.org/10.1016/S1474-7065(02)00090-6)
- Nicholls, R. J., & Tol, R. S. J. (2006). Impacts and responses to sea-level rise: A global analysis of the SRES scenarios over the twenty-first century. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 364(1841), 1073–1095. <https://doi.org/10.1098/rsta.2006.1754>
- Nicholls, R. J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A. T., Meyssignac, B., Hanson, S. E., Merkens, J.-L., & Fang, J. (2021). A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change*, 11(4), 338–342. <https://doi.org/10.1038/s41558-021-00993-z>
- Nicholls, R. J., Wong, P. P., Burkett, V., Codignotto, J., Hay, J., McLean, R., Ragoonaden, S., Woodroffe, C. D., Abuodha, P. A. O., Arblaster, J., Brown, B., Forbes, D., Hall, J., Kovats, S., Lowe, J., McInnes, K., Moser, S., Rupp-Armstrong, S., & Saito, Y. (2007). *Coastal systems and low-lying areas*.
- Noe, G. B., Cashman, M. J., Skalak, K., Gellis, A., Hopkins, K. G., Moyer, D., Webber, J., Benthem, A., Maloney, K., Brakebill, J., Sekellick, A., Langland, M., Zhang, Q., Shenk, G., Keisman, J., & Hupp, C. (2020). Sediment dynamics and implications for management: State of the science from long-term research in the Chesapeake Bay watershed, USA. *WIREs Water*, 7(4). <https://doi.org/10.1002/wat2.1454>

Ntajal, J., Höllermann, B., Falkenberg, T., Kistemann, T., & Evers, M. (2022).

Water and Health Nexus—Land Use Dynamics, Flooding, and Water-Borne Diseases in the Odaw River Basin, Ghana. *Water*, 14(3), 461.

<https://doi.org/10.3390/w14030461>

Nyarko, E., E, K., A, L., & M, B. (2016). Estimating Recent Sedimentation Rates Using Lead-210 in Tropical Estuarine Systems: Case Study of Volta and Pra Estuaries in Ghana, West Africa. *Journal of Oceanography and Marine Research*, 04(01).

<https://doi.org/10.4172/2572-3103.1000141>

Okaka, F. O., & Odhiambo, B. D. O. (2018). Relationship between Flooding and Out Break of Infectious Diseases in Kenya: A Review of the Literature. *Journal of Environmental and Public Health*, 2018, 1–8.

<https://doi.org/10.1155/2018/5452938>

Olbert, A. I., Moradian, S., Nash, S., Comer, J., Kazmierczak, B., Falconer, R. A., & Hartnett, M. (2023). Combined statistical and hydrodynamic modelling of compound flooding in coastal areas—Methodology and application. *Journal of Hydrology*, 620, 129383.

<https://doi.org/10.1016/j.jhydrol.2023.129383>

Osmanoğlu, B., Sunar, F., Wdowinski, S., & Cabral-Cano, E. (2016). Time series analysis of InSAR data: Methods and trends. *ISPRS Journal of Photogrammetry and Remote Sensing*, 115, 90–102.

<https://doi.org/10.1016/j.isprsjprs.2015.10.003>

- Palama, R., Monserrat, O., Crippa, B., Crosetto, M., Bru, G., Ezquerro, P., & Bejar-Pizarro, M. (2023). Radargrammetry DEM Generation Using High-Resolution SAR Imagery Over La Palma During the 2021 Cumbre Vieja Volcanic Eruption. *IEEE Geoscience and Remote Sensing Letters*, 20, 1–5. <https://doi.org/10.1109/LGRS.2023.3238182>
- Palaseanu-Lovejoy, M., Bisson, M., Spinetti, C., Buongiorno, M. F., Alexandrov, O., & Cecere, T. (2019). High-Resolution and Accurate Topography Reconstruction of Mount Etna from Pleiades Satellite Data. *Remote Sensing*, 11(24), 2983. <https://doi.org/10.3390/rs11242983>
- Paprotny, D., & Terefenko, P. (2017). New estimates of potential impacts of sea level rise and coastal floods in Poland. *Natural Hazards*, 85(2), 1249-1277.
- Paprotny, D., Vousedoukas, M. I., Morales-Nápoles, O., Jonkman, S. N., & Feyen, L. (2018). *Compound flood potential in Europe* [Preprint]. Hydrometeorology/Mathematical applications. <https://doi.org/10.5194/hess-2018-132>
- Parwata, I. N. S., Shimizu, N., Grujić, B., Zekan, S., Čeliković, R., Imamović, E., & Vrkljan, I. (2020). Monitoring the Subsidence Induced by Salt Mining in Tuzla, Bosnia and Herzegovina by SBAS-DInSAR Method. *Rock Mechanics and Rock Engineering*, 53(11), 5155-5175.
- Pepe, A., & Calò, F. (2017). A review of interferometric synthetic aperture RADAR (InSAR) multi-track approaches for the retrieval of Earth's Surface displacements. *Applied Sciences (Switzerland)*, 7(12). <https://doi.org/10.3390/app7121264>

- Peter Sheng, Y., Paramygin, V. A., Yang, K., & Rivera-Nieves, A. A. (2022). A sensitivity study of rising compound coastal inundation over large flood plains in a changing climate. *Scientific Reports*, 12(1), 3403. <https://doi.org/10.1038/s41598-022-07010-z>
- Phien-wej, N., Giao, P. H., & Nutalaya, P. (2006). Land subsidence in Bangkok, Thailand. *Engineering Geology*, 82(4), 187–201. <https://doi.org/10.1016/j.enggeo.2005.10.004>
- Polidori, L., & El Hage, M. (2020). Digital Elevation Model Quality Assessment Methods: A Critical Review. *Remote Sensing*, 12(21), 3522. <https://doi.org/10.3390/rs12213522>
- Poppenga, S. K., & Worstell, B. B. (2016). Hydrologic connectivity: Quantitative assessments of hydrologic-enforced drainage structures in an elevation model. *Journal of Coastal Research*, (76 (10076)), 90-106. <http://dx.doi.org/10.2112/SI76-009>
- Posamentier, H. W., & Walker, R. G. (Eds.). (2006). *Facies Models Revisited*. SEPM (Society for Sedimentary Geology). <https://doi.org/10.2110/pec.06.84>
- Poulos, S. E., & Collins, M. B. (2002). Fluvial sediment fluxes to the Mediterranean Sea: A quantitative approach and the influence of dams. *Geological Society, London, Special Publications*, 191(1), 227–245. <https://doi.org/10.1144/GSL.SP.2002.191.01.16>
- Poulos, S., Karditsa, A., Hatzaki, M., Tsapanou, A., Papapostolou, C., & Chouvardas, K. (2022). An Insight into the Factors Controlling Delta Flood Events: The Case of the Evros River Deltaic Plain (NE Aegean Sea). *Water*, 14(3), 497. <https://doi.org/10.3390/w14030497>

Pramita, A. W., Syafrudin, S., & Sugianto, D. N. (2021). Effect of seawater intrusion on groundwater in the Demak coastal area Indonesia: A review. *IOP Conference Series: Earth and Environmental Science*, 896(1), 012070. <https://doi.org/10.1088/1755-1315/896/1/012070>

Proceedings of EUSAR 2016: 11th European Conference on Synthetic Aperture Radar : 6-9 June 2016. (2016). VDE Verlag.

Raff, J. L., Goodbred, S. L., Pickering, J. L., Sincavage, R. S., Ayers, J. C., Hossain, Md. S., Wilson, C. A., Paola, C., Steckler, M. S., Mondal, D. R., Grimaud, J.-L., Grall, C. J., Rogers, K. G., Ahmed, K. M., Akhter, S. H., Carlson, B. N., Chamberlain, E. L., Dejter, M., Gilligan, J. M., Williams, L. A. (2023). Sediment delivery to sustain the Ganges-Brahmaputra delta under climate change and anthropogenic impacts. *Nature Communications*, 14(1), 2429. <https://doi.org/10.1038/s41467-023-38057-9>

Rateb, A., & Abotalib, A. Z. (2020). Inferencing the land subsidence in the Nile Delta using Sentinel-1 satellites and GPS between 2015 and 2019. *Science of The Total Environment*, 729, 138868. <https://doi.org/10.1016/j.scitotenv.2020.138868>

Renaud, F. G., Syvitski, J. P., Sebesvari, Z., Werners, S. E., Kremer, H., Kuenzer, C., Ramesh, R., Jeuken, A., & Friedrich, J. (2013). Tipping from the Holocene to the Anthropocene: How threatened are major world deltas? *Current Opinion in Environmental Sustainability*, 5(6), 644–654. <https://doi.org/10.1016/j.cosust.2013.11.007>

Ribas, F., Portos-Amill, L., Falqués, A., Arriaga, J., Marcos, M., & Ruessink, G. (2023). Impact of mean sea-level rise on the long-term evolution of a mega-nourishment. *Climatic Change*, 176(5), 66.

<https://doi.org/10.1007/s10584-023-03503-6>

Rizzo, A., Vandelli, V., Gauci, C., Buhagiar, G., Micallef, A. S., & Soldati, M. (2022). Potential Sea Level Rise Inundation in the Mediterranean: From Susceptibility Assessment to Risk Scenarios for Policy Action. *Water*, 14(3), 416. <https://doi.org/10.3390/w14030416>

Rocca, F., Prati, C., Guarnieri, M., Ferretti, A., 2000. SAR interferometry and its application. *Surveys Geophys.* 21, 159–176. <https://doi.org/10.1023/A:1006710731155>.

Rodriguez, A. F., Gerber, S., Inglett, P. W., Tran, N. T., Long, J. R., & Daroub, S. H. (2021). Soil carbon characterization in a subtropical drained peatland. *Geoderma*, 382, 114758. <https://doi.org/10.1016/j.geoderma.2020.114758>

Roest, L. W. M. (n.d.-b). *The coastal system of the Volta delta, Ghana Opportunities and strategies for development.*

Rucci, A., Ferretti, A., Monti Guarnieri, A., & Rocca, F. (2012). Sentinel 1 SAR interferometry applications: The outlook for sub millimeter measurements. *Remote Sensing of Environment*, 120, 156–163. <https://doi.org/10.1016/j.rse.2011.09.030>

Rui, R., van Tol, F., Xia, X.-L., van Eekelen, S., Hu, G., & Xia, Y. (2016). Evolution of soil arching; 2D DEM simulations. *Computers and Geotechnics*, 73, 199–209.

<https://doi.org/10.1016/j.compgeo.2015.12.006>

- Rupnik, E., Pierrot-Deseilligny, M., & Delorme, A. (2018). 3D reconstruction from multi-view VHR-satellite images in MicMac. *ISPRS Journal of Photogrammetry and Remote Sensing*, 139, 201–211. <https://doi.org/10.1016/j.isprsjprs.2018.03.016>
- Sadat-Noori, M., Rankin, C., Rayner, D., Heimhuber, V., Gaston, T., Drummond, C., Chalmers, A., Khojasteh, D., & Glamore, W. (2021). Coastal wetlands can be saved from sea level rise by recreating past tidal regimes. *Scientific Reports*, 11(1), 1196. <https://doi.org/10.1038/s41598-021-80977-3>
- Sadat-Noori, M., Rankin, C., Rayner, D., Heimhuber, V., Gaston, T., Drummond, C., & Glamore, W. (2021). Coastal wetlands can be saved from sea level rise by recreating past tidal regimes. *Scientific Reports*, 11(1), 1-10.
- Schipper, L. A., & McLeod, M. (2006). Subsidence rates and carbon loss in peat soils following conversion to pasture in the Waikato Region, New Zealand. *Soil Use and Management*, 18(2), 91–93. <https://doi.org/10.1111/j.1475-2743.2002.tb00225.x>
- Schmidt, C. W. (2015). Delta Subsidence: An Imminent Threat to Coastal Populations. *Environmental Health Perspectives*, 123(8). <https://doi.org/10.1289/ehp.123-A204>
- Seeger, K., Minderhoud, P. S. J., Peffeköver, A., Vogel, A., Brückner, H., Kraas, F., Nay Win Oo, & Brill, D. (2023). *Assessing land elevation in the Ayeyarwady Delta (Myanmar) and its relevance for studying sea level rise and delta flooding* [Preprint]. Coasts and Estuaries/Remote Sensing and GIS. <https://doi.org/10.5194/egusphere-2022-1425>

- Shean, D. E., Alexandrov, O., Moratto, Z. M., Smith, B. E., Joughin, I. R., Porter, C., & Morin, P. (2016). An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*, 116, 101–117. <https://doi.org/10.1016/j.isprsjprs.2016.03.012>
- Shirzaei, M., Freymueller, J., Törnqvist, T. E., Galloway, D. L., Dura, T., & Minderhoud, P. S. J. (2020). Measuring, modelling and projecting coastal land subsidence. *Nature Reviews Earth & Environment*, 2(1), 40–58. <https://doi.org/10.1038/s43017-020-00115-x>
- Silva, T. S. F., Costa, M. P. F., Melack, J. M., & Novo, E. M. L. M. (2008). Remote sensing of aquatic vegetation: Theory and applications. *Environmental Monitoring and Assessment*, 140(1–3), 131–145. <https://doi.org/10.1007/s10661-007-9855-3>
- Simons, M., & Rosen, P. (2007). Treatise on geophysics, interferometric synthetic aperture radar geodesy. Geodesy; Schubert, G., Ed.; Elsevier Press: Amsterdam, The Netherlands, 3, 391–446.
- SNAP (2020). Sentinel Application Platform (Version 8) Help Content. Downloaded from <https://step.esa.int/main/toolboxes/snap/> (accessed on 10 March 2023).
- Snoussi, M., Ouchani, T., & Niazi, S. (2008). Vulnerability assessment of the impact of sea-level rise and flooding on the Moroccan coast: The case of the Mediterranean eastern zone. *Estuarine, Coastal and Shelf Science*, 77(2), 206–213. <https://doi.org/10.1016/j.ecss.2007.09.024>

Soudarin, L., Rosmordu, V., Guinle, T., Nino, F., Birol, F., Mertz, F., Schgounn, C., & Gasc, M. (2018). *Aviso+: Altimetry satellite data and products for ocean-oriented applications (and others)*. 16087.

Soudarin, L., Rosmordu, V., Guinle, T., Nino, F., Birol, F., Mertz, F., ... & Gasc, M. (2018, April). Aviso+: altimetry satellite data and products for ocean-oriented applications (and others). In EGU General Assembly Conference Abstracts (p. 16087).

Sowter, A., Bin Che Amat, M., Cigna, F., Marsh, S., Athab, A., & Alshammari, L. (2016). Mexico City land subsidence in 2014–2015 with Sentinel-1 IW TOPS: Results using the Intermittent SBAS (ISBAS) technique. *International Journal of Applied Earth Observation and Geoinformation*, 52, 230–242.

<https://doi.org/10.1016/j.jag.2016.06.015>

Steckler, M. S., Oryan, B., Wilson, C. A., Grall, C., Nooner, S. L., Mondal, D. R., Akhter, S. H., DeWolf, S., & Goodbred, S. L. (2021). Synthesis of the distribution of subsidence of the lower Ganges-Brahmaputra Delta, Bangladesh. *Earth-Science Reviews*, 224, 103887.

<https://doi.org/10.1016/j.earscirev.2021.103887>

Stockdon H. F., R. A. Holman, P. A. Howd, and A. H. Sallenger, “Empirical parameterization of setup, swash, and 664 run-up,” *coast. Eng.*, vol. 53, no. 7, pp. 573–588, May 2006, doi: 10.1016/j.coastaleng. 2005.12. 005.

Stockdon, H. F., Holman, R. A., Howd, P. A., & Sallenger, A. H. (2006).

Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, 53(7), 573–588. <https://doi.org/10.1016/j.coastaleng.2005.12.005>

2005.12.005

Syvitski, J. P. (2008). Deltas at risk. *Sustainability science*, 3(1), 23–32.

<https://doi.org/10.1007/s11625-008-0043-3>

Syvitski, J. P. M., & Saito, Y. (2007). Morphodynamics of deltas under the influence of humans. *Global and Planetary Change*, 57(3–4), 261–282.

<https://doi.org/10.1016/j.gloplacha.2006.12.001>

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T.,

Brakenridge, G. R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., &

Nicholls, R. J. (2009). Sinking deltas due to human activities. *Nature Geoscience*, 2(10), 681–686. <https://doi.org/10.1038/ngeo629>

Syvitski, J., Ángel, J. R., Saito, Y., Overeem, I., Vörösmarty, C. J., Wang, H., &

Olago, D. (2022). Earth's sediment cycle during the Anthropocene. *Nature Reviews Earth & Environment*, 3(3), 179–196.

<https://doi.org/10.1038/s43017-021-00253-w>

Szabo, S., Brondizio, E., Renaud, F. G., Hetrick, S., Nicholls, R. J., Matthews,

Z., Tessler, Z., Tejedor, A., Sebesvari, Z., Foufoula-Georgiou, E., Da

Costa, S., & Dearing, J. A. (2016). Population dynamics, delta

vulnerability and environmental change: Comparison of the Mekong, Ganges–Brahmaputra and Amazon delta regions. *Sustainability Science*, 11(4), 539–554. <https://doi.org/10.1007/s11625-016-0372-6>

2016.04.001

Taherkhani, M., Vitousek, S., Barnard, P. L., Frazer, N., Anderson, T. R., &

Fletcher, C. H. (2020). Sea-level rise exponentially increases coastal flood frequency. *Scientific Reports*, 10(1), 6466.

<https://doi.org/10.1038/s41598-020-62188-4>

Taveneau, A., Almar, R., Bergsma, E. W. J., Sy, B. A., Ndour, A., Sadio, M., &

Garlan, T. (2021). Observing and Predicting Coastal Erosion at the Langue de Barbarie Sand Spit around Saint Louis (Senegal, West Africa) through Satellite-Derived Digital Elevation Model and Shoreline. *Remote Sensing*, 13(13), 2454.

<https://doi.org/10.3390/rs13132454>

Teatini P., L. Tosi, and T. Strozzi, (2011). Quantitative evidence that compaction

of Holocene sediments drives the present land subsidence of the Po Delta, Italy, *Journal of Geophysical Research - Solid Earth* , 116, B08407, doi:10.1029/2010JB008122.

Teatini, P., Tosi, L., & Strozzi, T. (2011). Quantitative evidence that compaction

of Holocene sediments drives the present land subsidence of the Po Delta, Italy. *Journal of Geophysical Research*, 116(B8), B08407.

<https://doi.org/10.1029/2010JB008122>

Teatini, P., Tosi, L., Strozzi, T., Carbognin, L., Cecconi, G., Rosselli, R., &

Libardo, S. (2012). Resolving land subsidence within the Venice Lagoon by persistent scatterer SAR interferometry. *Physics and Chemistry of the Earth*, 40–41, 72–79.

<https://doi.org/10.1016/j.pce.2010.01.002>

- Teixeira, K. (2023, September 5). *Geological fault spewing mysterious liquid could signal mega earthquake in US*. <https://www.yourweather.co.uk/news/trending/geological-fault-spewing-mysterious-liquid-could-signal-mega-earthquake-united-states-geography.html>
- Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P. M., & Foufoula-Georgiou, E. (2015). Profiling risk and sustainability in coastal deltas of the world. *Science*, 349(6248), 638–643. <https://doi.org/10.1126/science.aab3574>
- Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P., & Foufoula-Georgiou, E. (2015). Profiling risk and sustainability in coastal deltas of the world. *Science*, 349(6248), 638–643.
- Thornton, E. B., & Guza, R. T. (1983). Transformation of wave height distribution. *Journal of Geophysical Research*, 88(C10), 5925. <https://doi.org/10.1029/JC088iC10p05925>
- Tomás, R., Romero, R., Mulas, J., Marturià, J. J., Mallorquí, J. J., Lopez-Sanchez, J. M., Herrera, G., Gutiérrez, F., González, P. J., Fernández, J., Duque, S., Concha-Dimas, A., Cocksley, G., Castañeda, C., Carrasco, D., & Blanco, P. (2014). Radar interferometry techniques for the study of ground subsidence phenomena: A review of practical issues through cases in Spain. *Environmental Earth Sciences*, 71(1), 163–181. <https://doi.org/10.1007/s12665-013-2422-z>

- Törnqvist, T., Wallace, D., Storms, J., Wallinga, J., Van Dam, R., Blaauw, M., Derksen, M., Klerks, C., Meijneken, C. and Snijders, E. (2008). Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nature Geoscience*. 1. 173-176. [10.1038/ngeo129](https://doi.org/10.1038/ngeo129).
- Torres, R., Snoeij, P., Geudtner, D., Bibby, D., Davidson, M., Attema, E., Potin, P., Rommen, B. Ö., Floury, N., Brown, M., Traver, I. N., Deghaye, P., Duesmann, B., Rosich, B., Miranda, N., Bruno, C., L'Abbate, M., Croci, R., Pietropaolo, A., ... Rostan, F. (2012). GMES Sentinel-1 mission. *Remote Sensing of Environment*, 120, 9–24. <https://doi.org/10.1016/j.rse.2011.05.028>
- Tosi, L., Da Lio, C., Donnici, S., Strozzi, T., & Teatini, P. (2020). Vulnerability of Venice's coastland to relative sea-level rise. *Proceedings of the International Association of Hydrological Sciences*, 382, 689-695.
- Tralli, D. M., Blom, R. G., Zlotnicki, V., Donnellan, A., & Evans, D. L. (2005). Satellite remote sensing of earthquake, volcano, flood, landslide and coastal inundation hazards. *ISPRS Journal of Photogrammetry and Remote Sensing*, 59(4), 185–198. <https://doi.org/10.1016/j.isprsjprs.2005.02.002>
- Tung, H., & Hu, J. C. (2012). Assessments of serious anthropogenic land subsidence in Yunlin County of central Taiwan from 1996 to 1999 by Persistent Scatterers InSAR. *Tectonophysics*, 578, 126–135. <https://doi.org/10.1016/j.tecto.2012.08.009>
- Turner, I. L., Harley, M. D., Almar, R., & Bergsma, E. W. J. (2021). Satellite optical imagery in Coastal Engineering. *Coastal Engineering*, 167, 103919. <https://doi.org/10.1016/j.coastaleng.2021.103919>

Tychsen, J; Boamah, D; Ahadjie, J; Sandow Ali, M; Alidu, S; Awuah, P;

Quaicoe, I; Amankwah, R; Fobil, J; Nyame, F; Davis, E (2017), “ASM

Handbook for Ghana” Geological Survey of Denmark and Greenland

(GEUS), Copenhagen, Denmark, 160 pp.

Van de Giesen, N., Liebe, J., & Jung, G. (2010). Adapting to climate change in the Volta Basin, West Africa. *Current science*, 98(8), 1033-1037.

van der Horst, T., Rutten, M. M., van de Giesen, N. C., & Hanssen, R. F. (2018).

Monitoring land subsidence in Yangon, Myanmar using Sentinel-1 persistent scatterer interferometry and assessment of driving mechanisms. *Remote Sensing of Environment*, 217, 101–110.

<https://doi.org/10.1016/j.rse.2018.08.004>

van der Meer, J., Nieuwenhuis, J.-W., Steendam, G. J., Reneerkens, M.,

Steezel, H., & van Vledder, G. (2019). *Wave Overtopping Measurements at a Real Dike* . https://doi.org/10.18451/978-3-939230-64-9_111

Vaze, J., Teng, J., & Spencer, G. (2010). Impact of DEM accuracy and resolution on topographic indices. *Environmental Modelling & Software*, 25(10), 1086–1098. <https://doi.org/10.1016/j.envsoft.2010.03.014>

03.014

- Vitousek, S., Buscombe, D., Vos, K., Barnard, P. L., Ritchie, A. C., & Warrick, J. A. (2023). The future of coastal monitoring through satellite remote sensing. *Cambridge Prisms: Coastal Futures*, 1, e10. doi:10.1017/cft.2022.4
- Vegas-Vilarrúbia, T., Baritto, F., López, P., Meleán, G., Ponce, M. E., Mora, L., & Gómez, O. (2010). Tropical Histosols of the lower Orinoco Delta, features and preliminary quantification of their carbon storage. *Geoderma*, 155(3–4), 280–288. <https://doi.org/10.1016/j.geoderma.2009.12.011>
- Vousdoukas, M. I., Clarke, J., Ranasinghe, R., Reimann, L., Khalaf, N., Duong, T. M., Ouweeneel, B., Sabour, S., Iles, C. E., Trisos, C. H., Feyen, L., Mentaschi, L., & Simpson, N. P. (2022). African heritage sites threatened as sea-level rise accelerates. *Nature Climate Change*, 12(3), 256–262. <https://doi.org/10.1038/s41558-022-01280-1>
- Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P., & Feyen, L. (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nature Communications*, 9(1), 2360. <https://doi.org/10.1038/s41467-018-04692-w>
- Wahl, T., Mudersbach, C., & Jensen, J. (2012). Assessing the hydrodynamic boundary conditions for risk analyses in coastal areas: A multivariate statistical approach based on Copula functions. *Natural Hazards and Earth System Sciences*, 12(2), 495–510. <https://doi.org/10.5194/nhess-12-495-2012>

- Walsh, K. J. E., McInnes, K. L., & McBride, J. L. (2012). Climate change impacts on tropical cyclones and extreme sea levels in the South Pacific—A regional assessment. *Global and Planetary Change*, 80–81, 149–164. <https://doi.org/10.1016/j.gloplacha.2011.10.006>
- Wang, H., Wright, T. J., Yu, Y., Lin, H., Jiang, L., Li, C., & Qiu, G. (2012). InSAR reveals coastal subsidence in the Pearl River Delta, China: *Coastal subsidence in the PRD. Geophysical Journal International*, no. no. <https://doi.org/10.1111/j.1365-246X.2012.05687.x>
- Wang, J., Yu, W., Deng, Y., Wang, R., Wang, Y., Zhang, H., & Zheng, M. (2019). Demonstration of time-series InSAR processing in Beijing using a small stack of Gaofen-3 differential interferograms. *Journal of Sensors*, 2019(January 2017). <https://doi.org/10.1155/2019/4204580>
- Wellens-Mensah, J., Armah, A. K., Amlalo, D. S., & Tetteh, K. (2002). Ghana national report phase 1: integrated problem analysis. *GEF MSP Sub-Saharan Africa Project (GF/6010-0016): development and protection of the coastal and marine environment in Sub-Saharan Africa. Accra, Ghana.*
- Weng, Q. (2010). *Remote sensing and GIS integration: Theories, methods, and applications*. McGraw-Hill.
- Woodworth, P. L., Melet, A., Marcos, M., Ray, R. D., Wöppelmann, G., Sasaki, Y. N., Cirano, M., Hibbert, A., Huthnance, J. M., Monserrat, S., & Merrifield, M. A. (2019). Forcing Factors Affecting Sea Level Changes at the Coast. *Surveys in Geophysics*, 40(6), 1351–1397. <https://doi.org/10.1007/s10712-019-09531-1>

- Wu, Y. (2003). Mechanism analysis of hazards caused by the interaction between groundwater and geo-environment. *Environmental Geology*, 44(7), 811–819. <https://doi.org/10.1007/s00254-003-0819-9>
- Yague-Martinez, N., Prats-Iraola, P., Gonzalez, F. R., Brcic, R., Shau, R., Geudtner, D., Eineder, M., & Bamler, R. (2016). Interferometric Processing of Sentinel-1 TOPS Data. *IEEE Transactions on Geoscience and Remote Sensing*, 54(4), 2220–2234. <https://doi.org/10.1109/TGRS.2015.2497902>
- Yague-Martinez, N., Prats-Iraola, P., Rodriguez Gonzalez, F., Brcic, R., Shau, R., Geudtner, D., Eineder, M., & Bamler, R. (2016). Interferometric Processing of Sentinel-1 TOPS Data. *IEEE Transactions on Geoscience and Remote Sensing*, 54(4), 2220–2234. <https://doi.org/10.1109/TGRS.2015.2497902>
- Yastika, P. E., Shimizu, N., & Abidin, H. Z. (2019). Monitoring of long-term land subsidence from 2003 to 2017 in coastal area of Semarang, Indonesia by SBAS DInSAR analyses using Envisat-ASAR, ALOS-PALSAR, and Sentinel-1A SAR data. *Advances in Space Research*, 63(5), 1719–1736. <https://doi.org/10.1016/j.asr.2018.11.008>
- Yin, J., Jonkman, S., Lin, N., Yu, D., Aerts, J., Wilby, R., Pan, M., Wood, E., Bricker, J., Ke, Q., Zeng, Z., Zhao, Q., Ge, J., & Wang, J. (2020). Flood Risks in Sinking Delta Cities: Time for a Reevaluation, *Earth's Future*, 8(8). <https://doi.org/10.1029/2020EF001614>
- Yuill, B., Lavoie, D., & Reed, D. (2009). Understanding subsidence processes in coastal Louisiana. *Journal of Coastal Research, Sp.Issue*(54), 23–36. <https://doi.org/10.2112/SI54-012.1.intensity>

- Yunus, A. P., Avtar, R., Kraines, S., Yamamuro, M., Lindberg, F., & Grimmond, C. S. B. (2016). Uncertainties in tidally adjusted estimates of sea level rise flooding (bathtub model) for the greater London. *Remote Sensing*, 8(5), 366.
- Yunus, A., Avtar, R., Kraines, S., Yamamuro, M., Lindberg, F., & Grimmond, C. (2016). Uncertainties in Tidally Adjusted Estimates of Sea Level Rise Flooding (Bathtub Model) for the Greater London. *Remote Sensing*, 8(5), 366. <https://doi.org/10.3390/rs8050366>
- Zeitoun, D. G., & Wakshal, E. (2013). *Land subsidence analysis in urban areas: the Bangkok metropolitan area case study*. Springer Science & Business Media.
- Zeybek, M., & Şanlıoğlu, İ. (2020). Investigation of landslide detection using radial basis functions: A case study of the Taşkent landslide, Turkey. *Environmental Monitoring and Assessment*, 192(4), 230. <https://doi.org/10.1007/s10661-020-8101-0>
- Zhang, W., Zhu, W., Tian, X., Zhang, Q., Zhao, C., Niu, Y., & Wang, C. (2022). Improved DEM Reconstruction Method Based on Multibaseline InSAR. *IEEE Geoscience and Remote Sensing Letters*, 19, 1–5. <https://doi.org/10.1109/LGRS.2021.3069239>
- Zoccarato, C., Minderhoud, P. S. J., & Teatini, P. (2018). The role of sedimentation and natural compaction in a prograding delta: Insights from the mega Mekong delta, Vietnam. *Scientific Reports*, 8(1), 11437. <https://doi.org/10.1038/s41598-018-29734-7>

Zuhlke, M., Fomferra, N., Brockmann, C., Peters, M., Veci, L., Malik, J., & Regner, P. (2015, December). SNAP (sentinel application platform) and the ESA sentinel 3 toolbox. In Sentinel-3 for Science Workshop (Vol. 734, p. 21).



LIST OF APPENDICES

APPENDIX A -SAMPLE STAMPS LOG FILE FOR SUBSIDENCE

DATA PROCESSING

```

14-Oct-2021          19:27:16          STAMPS
#####
14-Oct-2021 19:27:16 STAMPS          ##### StaMPS/MTI Version 4.0b6
#####
14-Oct-2021 19:27:16 STAMPS          ##### Beta version, Jun 2018
#####
14-Oct-2021          19:27:16          STAMPS
#####
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT max_topo_err = 20
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT quick_est_gamma_flag = y
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT select_reest_gamma_flag = y
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT filter_grid_size = 50
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT filter_weighting = P-square
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT gamma_change_convergence
= 0.005
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT gamma_max_iterations = 3
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT slc_osf = 1
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT clap_win = 32
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT clap_low_pass_wavelength =
800
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT clap_alpha = 1
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT clap_beta = 0.3
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT select_method = DENSITY
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT density_rand = 20
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT percent_rand = 20
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT gamma_stddev_reject = 0
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT weed_time_win = 730
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT weed_max_noise = Inf
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT weed_standard_dev = 1
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT weed_zero_elevation = n
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT weed_neighbours = n
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_method = 3D
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_patch_phase = n
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT drop_ifg_index = []
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_la_error_flag = y
14-Oct-2021          19:27:16          PS_PARMS_DEFAULT
unwrap_spatial_cost_func_flag = n
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_prefilter_flag = y
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_grid_size = 200
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_gold_n_win = 32
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_alpha = 8

```

```

14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_time_win = 730
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_gold_alpha = 0.8
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT unwrap_hold_good_values = n
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT scla_drop_index = []
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT scn_wavelength = 100
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT scn_time_win = 365
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT scn_deramp_ifg = []
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT scn_kriging_flag = n
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT ref_lon = -Inf Inf
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT ref_lat = -Inf Inf
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT ref_centre_lonlat = 0 0
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT ref_radius = Inf
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT ref_velocity = 0
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT n_cores = 1
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT plot_dem_posting = 90
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT plot_scatterer_size = 120
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT plot_pixels_scatterer = 3
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT plot_color_scheme = inflation
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT shade_rel_angle = 90 45
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT lonlat_offset = 0 0
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT merge_resample_size = 0
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT merge_standard_dev = Inf
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT scla_method = L2
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT scla_deramp = n
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT lambda = NaN
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT heading = NaN
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT insar_processor = snap
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT subtr_tropo = n
14-Oct-2021 19:27:16 PS_PARMS_DEFAULT tropo_method = a_1
14-Oct-2021 19:27:16 STAMPS Will process patch subdirectories
14-Oct-2021 23:24:15 STAMPS
#####
14-Oct-2021 23:24:17 STAMPS ##### StaMPS/MTI Version 4.0b6
#####
14-Oct-2021 23:24:17 STAMPS ##### Beta version, Jun 2018
#####
14-Oct-2021 23:24:17 STAMPS
#####
14-Oct-2021 23:24:18 STAMPS Will process patch subdirectories

```

APPENDIX B -SAMPLE MATLAB CODES FOR EXTREME COASTAL WATER LEVEL DATA ANALYSIS.

```

load('C:\Users\pinac\Desktop\Subsidence
Paper\Objective2\Sea_level_componants_Volta_20220204.mat');
date_year=str2num(datestr(Time,'yyyy')); % Select date by only year
ECWL= R+SLA+Dac+Tide; %Sum for Extreme coastal Water level
ECWL(1:8761)=[];
ECWL=ECWL';
Tide(1:8761)=[];
Dac(1:8761)=[];
R(1:8761)=[];
SLA(1:8761)=[];
date_year(1:8761)=[];

yr=1994:2015;
countn=0;
clear SLAmyr Rmyr Tidemyr Dacmyr Totalmyr
for y=1994:2015;
    countn=countn+1;
    AboveTS= find(ECWL>=1.6501&date_year==y);
    Rmyr(countn)=nanmean(R(AboveTS));
    SLAmyr(countn)=nanmean(SLA(AboveTS));
    Tidemyr(countn)=nanmean(Tide(AboveTS));
    Dacmyr(countn)=nanmean(Dac(AboveTS));
    Totalmyr(countn)=nanmean(ECWL(AboveTS));
end
Factors=[Rmyr' SLAmyr' Tidemyr' Dacmyr'];
FinalF=mean(Factors);

MnT= nanmean(Totalmyr);
MnR= nanmean(Rmyr);
MnSL= nanmean(SLAmyr);
MnDac= nanmean(Dacmyr);
MnTid=nanmean(Tidemyr);
Fact=[MnT MnR MnTid MnSL MnDac];

count=0;
clear SLAyr Ryr Tideyr Dacyr Totalyr
for y=1994:2015;
    count=count+1;
    AboveTS= find(ECWL>=1.6501&date_year==y);
    Ryr(count)=nanmean(R(AboveTS)-nanmean(R));
    SLAyr(count)=nanmean(SLA(AboveTS)-nanmean(SLA));
    Tideyr(count)=nanmean(Tide(AboveTS)-nanmean(Tide));
    Dacyr(count)=nanmean(Dac(AboveTS)-nanmean(Dac));
    Totalyr(count)=nanmean(ECWL(AboveTS)-nanmean(ECWL));
end
factors=[Ryr' SLAyr' Tideyr' Dacyr'];

```

%%Plots%%

figure(11)

```
parameters={'ECWL';'WaveR';'Tide';'SLA';'Dac'};  
parameter=parameters';
```

```
subplot(2,2,[1 3]);  
b=bar(Fact)  
  
grid on;  
xticklabels(parameters);  
xlabel('parameters','FontWeight','bold');  
ylabel('Level(m)','FontWeight','bold');  
legend('Parameters','WaveR','Tide','SLA','Dac');
```

```
hold on  
bar(1,FinalF,'stacked');  
ylim([-0.2 2]);
```

```
hold on
```



APPENDIX C -SAMPLE MATLAB CODES FOR SENINEL 1 AND FABDEM CORRELATION AND RMSE ANALYSIS.

```
% Read DEM and Plot %%%%%%%%%%
addpath 'C:\Users\pinac\Desktop\Works\topo\DEMS\MATLABCODES\rmse'
addpath
'C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\geomread'
addpath
'C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export'
[Z1,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20171024.tif');
[Z2,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20171105.tif');
[Z3,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\201711231.tif');
[Z4,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\201712291.tif');
[Z5,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20180104.tif');
[Z6,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\201803051.tif');
[Z7,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20180323.tif');
[Z8,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20180422.tif');
[Z9,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20181206.tif');
[Z10,lons,lats,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20190204.tif');
[Z11,lons,lats11,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20191101.tif');
[Z12,lons,lats11,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20201119.tif');
[Z13,lons,lats11,~]
=geomread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20210223.tif');
```

```

[Z14,lons,lats11,~]
=geoimread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20220922.tif');
[Z15,lons,lats11,~]
=geoimread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\20221121.tif');
[ZrefS,lonsZ,latsZ,~]=geoimread('C:\Users\pinac\Desktop\Works\topo\DEMS\GHANA\DEMS\New_DEMS\Site1\New_project\Extract\Export\site1_fabdem.tif');

zcomp=(Z1+Z2+Z3+Z4+Z5+Z6+Z7+Z8+Z9+Z10+Z11+Z12+Z13+Z14+Z15)/15;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Smoothingdata %%%%%%%%%
Z1s= smooth2(Z1,5,5);Z2s= smooth2(Z2,5,5);Z3s= smooth2(Z3,5,5);Z4s=
smooth2(Z4,5,5);Z5s= smooth2(Z5,5,5);Z6s= smooth2(Z6,5,5);
Z7s= smooth2(Z7,5,5);Z8s= smooth2(Z8,5,5);Z9s= smooth2(Z9,5,5);Z10s=
smooth2(Z10,5,5);Z11s= smooth2(Z11,5,5);Z12s= smooth2(Z12,5,5);
Z13s= smooth2(Z13,5,5);Z14s=smooth2(Z14,5,5);Z15s= smooth2(Z15,5,5);
compostcor=(Z1s+Z2s+Z3s+Z4s+Z5s+Z6s+Z7s+Z8s+Z9s+Z10s+Z11s+Z12s
+Z13s+Z14s+Z15s)/15;

imagesc(compostcor)
imagesc(zcomp,[2 10])
colorbar

%ZrefSs=smooth2(ZrefS,5,5);

ZrefS1=imresize(ZrefS,[294 211]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Finding areas with nan with selected refrence DEM iimage
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Z1ss=find(isnan(Z1s(:).*(ZrefS1(:)))==0&abs(Z1s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z1s(:))>0.&abs(ZrefS1(:))>0);
Z2ss=find(isnan(Z2s(:).*(ZrefS1(:)))==0&abs(Z2s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z2s(:))>0.&abs(ZrefS1(:))>0);
Z3ss=find(isnan(Z3s(:).*(ZrefS1(:)))==0&abs(Z3s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z3s(:))>0.&abs(ZrefS1(:))>0);
Z4ss=find(isnan(Z4s(:).*(ZrefS1(:)))==0&abs(Z4s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z4s(:))>0.&abs(ZrefS1(:))>0);
Z5ss=find(isnan(Z5s(:).*(ZrefS1(:)))==0&abs(Z5s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z5s(:))>0.&abs(ZrefS1(:))>0);
Z6ss=find(isnan(Z6s(:).*(ZrefS1(:)))==0&abs(Z6s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z6s(:))>0.&abs(ZrefS1(:))>0);
Z7ss=find(isnan(Z7s(:).*(ZrefS1(:)))==0&abs(Z7s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z7s(:))>0.&abs(ZrefS1(:))>0);
Z8ss=find(isnan(Z8s(:).*(ZrefS1(:)))==0&abs(Z8s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z8s(:))>0.&abs(ZrefS1(:))>0);
Z9ss=find(isnan(Z9s(:).*(ZrefS1(:)))==0&abs(Z9s(:))<100000.&abs(ZrefS1(:))<100000&abs(Z9s(:))>0.&abs(ZrefS1(:))>0);

```

```

Z10ss=find(isnan(Z10s(:).*(ZrefS1(:)))==0&abs(Z10s(:))<100000.&abs(Zref
S1(:))<100000&abs(Z10s(:))>0.&abs(ZrefS1(:))>0);
Z11ss=find(isnan(Z11s(:).*(ZrefS1(:)))==0&abs(Z11s(:))<100000.&abs(Zref
S1(:))<100000&abs(Z11s(:))>0.&abs(ZrefS1(:))>0);
Z12ss=find(isnan(Z12s(:).*(ZrefS1(:)))==0&abs(Z12s(:))<100000.&abs(Zref
S1(:))<100000&abs(Z12s(:))>0.&abs(ZrefS1(:))>0);
Z13ss=find(isnan(Z13s(:).*(ZrefS1(:)))==0&abs(Z13s(:))<100000.&abs(Zref
S1(:))<100000&abs(Z13s(:))>0.&abs(ZrefS1(:))>0);
Z14ss=find(isnan(Z14s(:).*(ZrefS1(:)))==0&abs(Z14s(:))<100000.&abs(Zref
S1(:))<100000&abs(Z14s(:))>0.&abs(ZrefS1(:))>0);
Z15ss=find(isnan(Z15s(:).*(ZrefS1(:)))==0&abs(Z15s(:))<100000.&abs(Zref
S1(:))<100000&abs(Z15s(:))>0.&abs(ZrefS1(:))>0);
Z15ss=find(isnan(Z15s(:).*(ZrefS1(:)))==0&abs(Z15s(:))<100000.&abs(Zref
S1(:))<100000&abs(Z15s(:))>0.&abs(ZrefS1(:))>0);
Zcors=find(isnan(compostcor(:).*(ZrefS1(:)))==0&abs(compostcor(:))<10000
0.&abs(ZrefS1(:))<100000&abs(compostcor(:))>0.&abs(ZrefS1(:))>0);

```

```

zcompfx=find(isnan(zcomp(:).*(ZrefS(:)))==0&abs(zcomp(:))<100000.&abs(
ZrefS(:))<100000&abs(zcomp(:))>0.&abs(ZrefS(:))>0);
R1n= corrcoef(zcomp(zcompfx),ZrefS(zcompfx));

```

%%%%%%%%%% Corellations %%%%%%%%%%

```

R1 = corrcoef(ZrefS1(Z1ss),Z1s(Z1ss));
R2 = corrcoef(Z2s(Z2ss),ZrefS1(Z2ss));
R3 = corrcoef(Z3s(Z3ss),ZrefS1(Z3ss));
R4 = corrcoef(Z4s(Z4ss),ZrefS1(Z4ss));
R5 = corrcoef(Z5s(Z5ss),ZrefS1(Z5ss));
R6 = corrcoef(Z6s(Z6ss),ZrefS1(Z6ss));
R7 = corrcoef(Z7s(Z7ss),ZrefS1(Z7ss));
R8 = corrcoef(Z8s(Z8ss),ZrefS1(Z8ss));
R9 = corrcoef(Z9s(Z9ss),ZrefS1(Z9ss));
R10 = corrcoef(Z10s(Z10ss),ZrefS1(Z10ss));
R11 = corrcoef(Z11s(Z11ss),ZrefS1(Z11ss));
R12 = corrcoef(Z12s(Z12ss),ZrefS1(Z12ss));
R13 = corrcoef(Z13s(Z13ss),ZrefS1(Z13ss));
R14 = corrcoef(Z14s(Z14ss),ZrefS1(Z14ss));
R15 = corrcoef(Z15s(Z15ss),ZrefS1(Z15ss));
RS1cR= corrcoef(compostcor(Zcors),ZrefS1(Zcors));

```

%%%%%%%%%% regression values %%%%%%%%%%

```

[a,b,square]=reg(ZrefS1(Z1ss),Z1s(Z1ss),1);
[a2,b2,square2]=reg(ZrefS1(Z2ss),Z2s(Z2ss),1);
[a3,b3,square3]=reg(ZrefS1(Z3ss),Z3s(Z3ss),1);
[a4,b4,square4]=reg(ZrefS1(Z4ss),Z4s(Z4ss),1);
[a5,b5,square5]=reg(ZrefS1(Z5ss),Z5s(Z5ss),1);
[a6,b6,square6]=reg(ZrefS1(Z6ss),Z6s(Z6ss),1);
[a7,b7,square7]=reg(ZrefS1(Z7ss),Z7s(Z7ss),1);
[a8,b8,square8]=reg(ZrefS1(Z8ss),ZrefS1(Z8ss),1);

```

```
[a9,b9,square9]=reg(ZrefS1(Z9ss),Z9s(Z9ss),1);
[a10,b10,square10]=reg(ZrefS1(Z10ss),Z10s(Z10ss),1);
[a11,b11,square11]=reg(ZrefS1(Z11ss),Z11s(Z11ss),1);
[a12,b12,square12]=reg(ZrefS1(Z12ss),Z12s(Z12ss),1);
[a13,b13,square13]=reg(ZrefS1(Z13ss),Z13s(Z13ss),1);
[a14,b14,square14]=reg(ZrefS1(Z14ss),Z14s(Z14ss),1);
[a15,b15,square15]=reg(ZrefS1(Z15ss),Z15s(Z15ss),1);
[aco,bco,square15co]=reg(ZrefS1(Zcors),compostcor(Zcors),1);
imagesc(compostcor);
```

%%%%%%%%%% correction%%%%%%%%%

```
Z1cor=(Z1s-b)/a;Z2cor=(Z2s-b2)/a2;Z3cor=(Z3s-b3)/a3;
Z4cor=(Z4s-b4)/a4;Z5cor=(Z5s-b5)/a5;Z6cor=(Z6s-b6)/a6;
Z7cor=(Z7s-b7)/a7;Z8cor=(Z8s-b8)/a8;Z9cor=(Z9s-b9)/a9;
Z10cor=(Z10s-b10)/a10;Z11cor=(Z11s-b11)/a11;Z12cor=(Z12s-b12)/a12;
Z13cor=(Z13s-b13)/a13;Z14cor=(Z14s-b14)/a14;Z15cor=(Z15s-b15)/a15;
Zcomp=(compostcor-bco)/aco;
```

```
compostcor1=(Z1cor+Z2cor+Z3cor+Z4cor+Z5cor+Z6cor+Z7cor+Z8cor+Z9c
or+Z10cor+Z11cor+Z12cor+Z13cor+Z14cor+Z15cor)/15;
imagesc(Zcomp);
```

%%%%%%%%%% Correlation between Fabdem and corectected
%%%%%%%%%

```
Z1ssc=find(isnan(Z1cor(:).*(ZrefS1(:)))==0&abs(Z1cor(:))<100000.&abs(Zre
fS1(:))<100000&abs(Z1cor(:))>0.&abs(ZrefS1(:))>0);
Z2ss=find(isnan(Z2cor(:).*(ZrefS1(:)))==0&abs(Z2cor(:))<100000.&abs(Zref
S1(:))<100000&abs(Z2cor(:))>0.&abs(ZrefS1(:))>0);
Z3ss=find(isnan(Z3cor(:).*(ZrefS1(:)))==0&abs(Z3cor(:))<100000.&abs(Zref
S1(:))<100000&abs(Z3cor(:))>0.&abs(ZrefS1(:))>0);
Z4ss=find(isnan(Z4cor(:).*(ZrefS1(:)))==0&abs(Z4cor(:))<100000.&abs(Zref
S1(:))<100000&abs(Z4cor(:))>0.&abs(ZrefS1(:))>0);
Z5ss=find(isnan(Z5cor(:).*(ZrefS1(:)))==0&abs(Z5cor(:))<100000.&abs(Zref
S1(:))<100000&abs(Z5cor(:))>0.&abs(ZrefS1(:))>0);
Z6ss=find(isnan(Z6cor(:).*(ZrefS1(:)))==0&abs(Z6cor(:))<100000.&abs(Zref
S1(:))<100000&abs(Z6cor(:))>0.&abs(ZrefS1(:))>0);
Z7ss=find(isnan(Z7cor(:).*(ZrefS1(:)))==0&abs(Z7cor(:))<100000.&abs(Zref
S1(:))<100000&abs(Z7cor(:))>0.&abs(ZrefS1(:))>0);
Z8ss=find(isnan(Z8cor(:).*(ZrefS1(:)))==0&abs(Z8cor(:))<100000.&abs(Zref
S1(:))<100000&abs(Z8cor(:))>0.&abs(ZrefS1(:))>0);
Z9ss=find(isnan(Z9cor(:).*(ZrefS1(:)))==0&abs(Z9cor(:))<100000.&abs(Zref
S1(:))<100000&abs(Z9cor(:))>0.&abs(ZrefS1(:))>0);
Z10ss=find(isnan(Z10cor(:).*(ZrefS1(:)))==0&abs(Z10cor(:))<100000.&abs(
ZrefS1(:))<100000&abs(Z10cor(:))>0.&abs(ZrefS1(:))>0);
Z11ss=find(isnan(Z11cor(:).*(ZrefS1(:)))==0&abs(Z11cor(:))<100000.&abs(
ZrefS1(:))<100000&abs(Z11cor(:))>0.&abs(ZrefS1(:))>0);
Z12ss=find(isnan(Z12cor(:).*(ZrefS1(:)))==0&abs(Z12cor(:))<100000.&abs(
ZrefS1(:))<100000&abs(Z12cor(:))>0.&abs(ZrefS1(:))>0);
```

```

Z13ss=find(isnan(Z13cor(:).*(ZrefS1(:)))==0&abs(Z13cor(:))<100000.&abs(
ZrefS1(:))<100000&abs(Z13cor(:))>0.&abs(ZrefS1(:))>0);
Z14ss=find(isnan(Z14cor(:).*(ZrefS1(:)))==0&abs(Z14cor(:))<100000.&abs(
ZrefS1(:))<100000&abs(Z14cor(:))>0.&abs(ZrefS1(:))>0);
Z15ss=find(isnan(Z15cor(:).*(ZrefS1(:)))==0&abs(Z15cor(:))<100000.&abs(
ZrefS1(:))<100000&abs(Z15cor(:))>0.&abs(ZrefS1(:))>0);
compost1sc=find(isnan(Zcomp(:).*(ZrefS1(:)))==0&abs(Zcomp(:))<100000.
&abs(ZrefS1(:))<100000&abs(Zcomp(:))>0.&abs(ZrefS1(:))>0);

```

```

%%%%%%%%%%%%%% new regression for corected
%%%%%%%%%%%%%%

```

```

R1c = corrcoef(Z1cor(Z1ssc),ZrefS1(Z1ssc));R2c =
corrcoef(Z2cor(Z2ss),ZrefS1(Z2ss));
R3c = corrcoef(Z3cor(Z3ss),ZrefS1(Z3ss));R4c =
corrcoef(Z4cor(Z4ss),ZrefS1(Z4ss));
R5c = corrcoef(Z5cor(Z5ss),ZrefS1(Z5ss));R6c =
corrcoef(Z6cor(Z6ss),ZrefS1(Z6ss));
R7c = corrcoef(Z7cor(Z7ss),ZrefS1(Z7ss));R8c =
corrcoef(Z8cor(Z8ss),ZrefS1(Z8ss));
R9c = corrcoef(Z9cor(Z9ss),ZrefS1(Z9ss));R10c =
corrcoef(Z10cor(Z10ss),ZrefS1(Z10ss));
R11c = corrcoef(Z11cor(Z11ss),ZrefS1(Z11ss));R12c =
corrcoef(Z12cor(Z12ss),ZrefS1(Z12ss));
R13c = corrcoef(ZrefS1(Z13ss));R14c =
corrcoef(Z14cor(Z14ss),ZrefS1(Z14ss));
R15c = corrcoef(Z15cor(Z15ss),ZrefS1(Z15ss));
RS1c= corrcoef(Zcomp(compost1sc),ZrefS1(compost1sc));
% imag=compostcor1(compost1sc);
% imag(imag<=0)=nan
% imagesc(imag)

```

```

%%%%%%%%%%%%%%RMSE PLOT%%%%%%%%%%%%%%

```

```

R1rmse = rmse(ZrefS1(Z1ss),Z1cor(Z1ss));R2rmse=
rmse(ZrefS1(Z2ss),Z2cor(Z2ss));
R3rmse = rmse(ZrefS1(Z3ss),Z3cor(Z3ss));R4rmse=
rmse(ZrefS1(Z4ss),Z4cor(Z4ss));
R5rmse = rmse(ZrefS1(Z5ss),Z3cor(Z5ss));R6rmse=
rmse(ZrefS1(Z6ss),Z6cor(Z6ss));
R7rmse = rmse(ZrefS1(Z7ss),Z7cor(Z7ss));R8rmse=
rmse(ZrefS1(Z8ss),Z8cor(Z8ss));
R9rmse = rmse(ZrefS1(Z9ss),Z3cor(Z9ss));R10rmse=
rmse(ZrefS1(Z10ss),Z10cor(Z10ss));
R11rmse = rmse(ZrefS1(Z11ss),Z11cor(Z11ss));R12rmse=
rmse(ZrefS1(Z12ss),Z12cor(Z12ss));
R13rmse = rmse(ZrefS1(Z13ss),Z13cor(Z13ss));R14rmse=
rmse(ZrefS1(Z14ss),Z14cor(Z14ss));
R15rmse= rmse(ZrefS1(Z15ss),Z15cor(Z15ss));
RS1rmse= rmse(ZrefS1(compost1sc),Zcomp(compost1sc));
imagesc(Z1s)

```

```

imagesc(ZrefS1)
addpath 'C:\Users\pinac\Desktop\Works\topo\DEMS\MATLABCODES\rmse'

%%%%%%%%%% CORRELATIONS %%%%%%%%%%%
CorelaVs1Rde=
([R1rmse,R2rmse,R3rmse,R4rmse,R5rmse,R6rmse,R7rmse,R8rmse,R9rmse,
R10rmse,R11rmse,R12rmse,R13rmse,R14rmse,R15rmse]);
CorelaVs1=
([R1c(3),R2c(3),R3c(3),R4c(3),R5c(3),R6c(3),R7c(3),R8c(3),R9c(3),R10c(3),
R11c(3),R12c(3),R13c(3),R14c(3),R15c(3)]);

scatter(ZrefS1(compost1sc),Zcomp(compost1sc))

```

APPENDIX D -SAMPLE CODES FOR PLIAEDES IMAGE

PROCESSING

```

#!/bin/bash

#####
#####
#####
#####
##### AMES STEREO PIPELINES
#####
#####
#####
#####

#module load nasa_asp
ASP="/data/ecola/travail_en_cours/taveneau/Topo/ASP/StereoPipeline-2.6.2-
2019-06-17-x86_64-Linux/bin"
stereo_def="/data/ecola/travail_en_cours/taveneau/ASP/Doc/stereo.default"
#to define the parameters
tgtGSD=2 # Resolution of the final DEM (Target Ground Sampling Distance)
tgtUTM=31 # Target UTM
searchradiusfactor=5

#####
#### INPUT PARAMETERS ####
#####

IMG1="/data/ecola/travail_en_cours/brempong/Volt_delta/1/6585530101/IMG_
_PHR1A_P_001/IMG_PHR1A_P_202212121026016_SEN_6585530101-
1_R1C1.TIF"

```

IMG2='/data/ecola/travail_en_cours/brempong/Volt_delta/2/6585531101/IMG_PHR1A_P_001/IMG_PHR1A_P_202212121025540_SEN_6585531101-1_R1C1.TIF'

IMG3='/data/ecola/travail_en_cours/brempong/Volt_delta/3/6585529101/IMG_PHR1A_P_001/IMG_PHR1A_P_202212121025465_SEN_6585529101-1_R1C1.TIF'

RPC1='/data/ecola/travail_en_cours/brempong/Volt_delta/1/6585530101/IMG_PHR1A_P_001/RPC_PHR1A_P_202212121026016_SEN_6585530101-1.XML'

RPC2='/data/ecola/travail_en_cours/brempong/Volt_delta/2/6585531101/IMG_PHR1A_P_001/RPC_PHR1A_P_202212121025540_SEN_6585531101-1.XML'

RPC3='/data/ecola/travail_en_cours/brempong/Volt_delta/3/6585529101/IMG_PHR1A_P_001/RPC_PHR1A_P_202212121025465_SEN_6585529101-1.XML'

#----- OUTPUT FILE'S NAME -----##

outputPrefix='Blekusudem's'\$tgtGSD

cd /data/ecola/travail_en_cours/brempong/Volt_delta/Dem

#####

ASP RUNNING ##### # Change the input images and RPCs

#####

\$ASP/stereo -t rpc \$IMG1 \$IMG2 \$IMG3 \$RPC1 \$RPC2 \$RPC3 -s

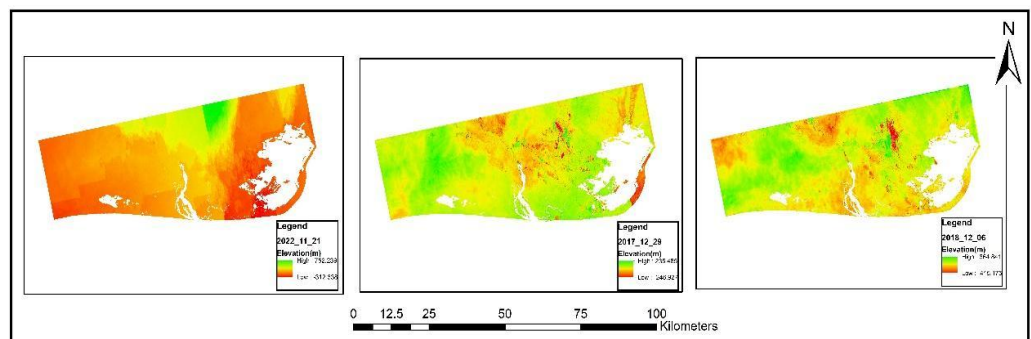
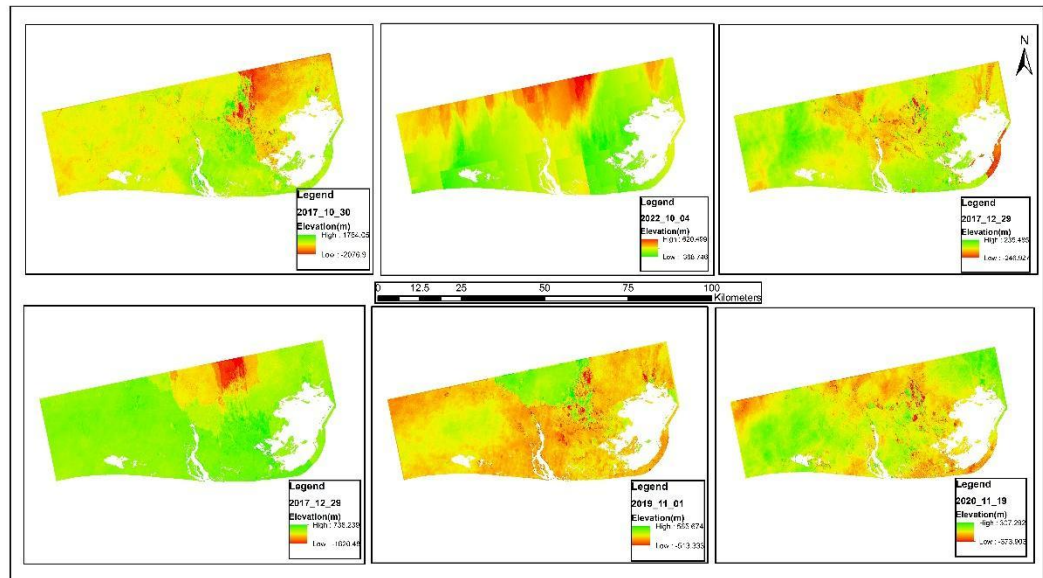
\$stereo_def \$outputPrefix # creates the point

\$ASP/point2dem --search-radius-factor \$searchradiusfactor --tr \$tgtGSD --

utm \$tgtUTM './\$outputPrefix-PC.tif

\$ASP/dem_geoid './\$outputPrefix-DEM.tif

APPENDIX E -SAMPLE SENTINEL 1 GENERATED DEMS



APPENDIX F -IMAGE OF ABSTRACT PAGE OF OBJECTIVE 1



Future flooding of the Volta Delta caused by sea level rise and land subsidence

E. K. Brempong^{1,2,3} · R. Almar³ · D. B. Angnuureng¹ · P. A. D. Mattah¹ · S. Y. Avornyo⁴ · P. N. Jayson-Quashigah⁵ · K. Appeaning Addo⁵ · P. Minderhoud⁶ · P. Teatini⁷

Received: 14 April 2022 / Revised: 28 May 2023 / Accepted: 29 May 2023
© The Author(s), under exclusive licence to Springer Nature B.V. 2023

Abstract

The Volta Delta (Ghana, West Africa) is increasingly impacted by Sea Level Rise (SLR). SLR renders the Volta Delta mostly vulnerable to flooding, salinization of water resources and agricultural fields, and permanent loss of lands. This would potentially threaten its population, infrastructure and economy, and could be worsened by land subsidence (LS). Relative Sea Level Rise (RSLR) in this study is the rate of LS with respect to SLR. It is thus very important to precisely quantify LS rates together with SLR and plan and assess countermeasures. This study presents and discusses recent LS rates in the Volta Delta derived from satellite-based SAR-Interferometry and their impact on relative SLR. Sentinel-1 scenes acquired between 2015 and 2021 were used to quantify recent LS in the study area. The Persistent Scatter Interferometry (PS-InSAR) technique was applied, which allowed for estimating displacement rates of coherent backscatter targets with mm/yr precision. Separate analyses of time series for the Keta lagoon and Songor lagoon areas of the delta give insight into the vertical land movements, with irregularly distributed average rates of up to 4 mm/yr. LS in the Volta Delta is due to various causes, most prominently natural compaction of young deltaic sediments, but also aquifer over-exploitation and salt mining, and probably increasingly less compensated by a drop in sediment supply due to damming. Furthermore, projection of future elevation projections by RSLR was assessed by combining the observed LS rates with three IPCC representative concentration pathways (RCP) scenarios. The RSLR impact assessments computed revealed that by 2100, more than 20% of the Volta Delta districts could potentially be below MSL for all the addressed RCP scenarios, including the fragile but key sand barriers surrounded by water bodies. The study is, however, a preliminary investigation and recommends further local ground-based LS investigations to calibrate PS-InSAR outcome, thus improving our understanding of the areas driving critical present and future changes in the Volta Delta.

Keywords Sea level Rise (SLR) · Subsidence · Relative sea level rise (RSLR) · Flooding · Persistent Scatter Interferometry (PS-InSAR)

APPENDIX G -COVER PAGE OF PUBICATION FOR OBJECTIVE 2

