We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

BOOK CITATION INDEX
CLARIVATE ANALYTICS
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter

Morphodynamics in a Tropical Shallow Lagoon: Observation and Inferences of Change

Alfred Sunday Alademomi, Andrew J. Manning,
Victor J. Abbott and Richard J.S. Whitehouse

Abstract

The Lagos Lagoon system and its adjacent tidal basins exhibit dynamics that are significantly different on both spatial and temporal scales. As urbanisation and human activities around the lagoon have intensified, the volume of sediment deposited into the basin is increasing on a daily basis. Changes on the lagoon bed over a 6-year time scale using repeated bathymetric data (2008, 2014) are presented, and the related data acquisition technique is explained. Data reduction is followed by analysis of the lagoon water bed dynamics using abstracted profile lines from the bathymetric data within a GIS environment. The results of the significant accretion and erosion within the lagoon system were analyzed spatially to quantify the volume of sediment gain or loss on the lagoon bed. The findings partly show that over 6 years, an average height of 0.16 m was gained by the lagoon. This amount translates into an annual accretion rate of 0.026 m. These findings enhance the prospect of verifying in the long term whether the Lagos Lagoon is gradually disappearing. To the best of the author's knowledge, this research reveals for the first time the complex evolutionary changes (channel movement, accretion, erosion, infill and movement of shoal) on the Lagos Lagoon bed.

Keywords: dynamics, ecosystem, lagoon, coastal, morphology, sediment, stratification

1. Introduction

The coastal environment has been faced with various enormous challenges throughout the world over time due to increased human pressure and the down-slide still continues [1, 2]. It is a matter of great concern as this induces incessant changes on its morphodynamics, hydrodynamics and geomorphological structure that in turn affect the natural well-being of the environment and its features as well as the health of its inhabitants. Coastal lagoons are common landforms of the world's low-lying coastal plains that are formed on coastal plains, which are gently sloping seaward and where there is an abundance of sand [3]. They are widespread all over the world, being shallow aquatic ecosystems that develop at the interface between coastal terrestrial and marine ecosystems [4]. They play a major role in the

coastal dynamic equilibrium for the exchange of materials between land and sea. Consequent upon this, wetlands that function as a medium of water quality improvement, biological productivity and flood risk reduction, always co-exist parallel with lagoons [5].

Due to the nearness of lagoons to wetlands and the morphological characteristic that allows for their restricted exchange of water with the adjacent ocean, they are generally vulnerable to organic processes that occur as a direct impact of increasing population densities along the coastline [6, 7]. In addition, coastal lagoons that are considered as one of the most fragile marine environments could likely be altered by global environmental climate change [6]. Such effects may include loss of wetlands due to sea level surface temperature rise, sea level rise, change in hydrodynamics of water masses, alteration in water salinity and increased dissolved oxygen. However, the rise in sea level or global environmental change normally produces a morphological response in the coastal area that drowns many river-valley systems. These, if eventually isolated by longshore current barriers, form lagoons of complex outline [8].

Coastal lagoons according to Kjerfve and Magill [9] are landforms along the margins of most continents. They are shallow water systems formed in a marginal depression behind barriers [10] and connected to the sea by one or more entrances and with little freshwater influence. Lagoons generally have restricted connections to the ocean [9] compared to their surface area, and hence the water body is poorly flushed. This makes them exhibit long residence times in contrast to a flowing river. The degree of human activities and increased coastal urbanisation, and the impact of natural phenomena (like biological processes, physical processes and erosion, tide and wave propagation) will affect the level of morphological and hydrodynamic changes that will be experienced in any coastal lagoon.

Lagoons are sensitive areas that play a vital role among the coastal zone ecosystems as they provide suitable breeding areas for many species. In terms of formation, lagoons are formed with their long axes parallel to the coastline [8, 11] where offshore barriers developed more or less parallel to the original shoreline. Nonetheless, the interaction of various coastal processes [12] and increased human action are the major forces controlling the lagoon morphology [13–15] leading to gradual or rapid changes in the landscape of the coastal lagoons. Such morphology can be viewed in two dimensions, lateral or horizontal and vertical or bathymetric.

1.1 Rationale for the research

No coastal lagoon and its immediate catchment area remain static over any timescale (short or long). The natural balance of the coastal lagoon can be seen as the sustainability of the natural ecosystem between the sea and the coastal lagoon. However, no matter how carefully managed the natural balance of the lagoon and its ecosystem, it will be susceptible to change. As a result of the general morphological features, lagoons are naturally very sensitive to dynamic balance in all aspects [16].

The rapidly induced changes in the morphological nature of coastal lagoons due to an incessant increase in population around the coast are prominently brought into display around the Lagos Lagoon, Nigeria (West Africa), the study area in this research. This is the major force that propels this investigation of the morphological and hydrodynamic changes in the Lagos Lagoon. Lagos' population is currently about 17 million, up from 2 to 3 million in the 1970s. Despite this pressure, research to date on the lagoon only identifies ecological studies [17–19], lagoon sensitivity and pollution studies [17, 20, 21], fishery and plankton sustainability [22, 23] and

partial pressures on the lagoon ecosystem habitat. All these, although, are part of the outcome of the impact created by the growing population (about 17 million) of the city of Lagos Nigeria around the Lagos Lagoon. However, despite the high pressure on the lagoon and its ecosystem, no specific studies have been undertaken to address the lagoon's morphological changes.

The physical variability is not considered in geological or other long-term time-scales but in the short-term. This means that changes in the lagoon over a long timescale of about hundred years to thousands of years are not the concern of this study but there is a focus on changes within the range of about 20–50 years due to human activities since post-industrial expansion in Lagos. Consequent upon this, a general research question is generated on which the research aim is focused.

1.2 Research aims and objectives

The coastlines and the adjacent lagoons of the Nigerian coast have suffered several losses mainly as a result of an inability to manage the sensitive natural balance of the lagoon and its catchment area and retain the initial ecosystem structure and forces that control the natural processes within and around the lagoon's morphological regime. Due to increased urbanisation and industrial expansion witnessed in Lagos from the mid-1970s until the present, the Lagos Lagoon must have been seriously affected, with no remedial action in place.

The existing problem of an overcrowded human population in Lagos, the incessant repository of industrial effluence into its lagoon and increased flooding issues from the immediate watershed has generated two primary research questions for this study. They are as follows:

- What is the spatial and temporal variability of coastal urban expansion impact on the lagoon ecosystem?

- Are there significant spatio-temporal hydrodynamic changes that have been impacted on the lagoon as the urban growth increases?

The aim of this study is to investigate the spatial dynamics of the Lagos Lagoon water floor. In terms of objectives, this chapter analyses the changes on the lagoon water bed resulting from the impact of urbanisation and the changes experienced along its coastline through bathymetric data sets and different statistical tests and analyses on the spatial difference in the lagoon depth characterisation. Moreover, a volume analysis was performed; it enhances the study to calculate erosion and accretion, which was also depicted in map format. Lastly, the significance of the accretion variation with factors that account for uncertainty in the lagoon bottom dynamics is discussed and the chapter ends with concluding remarks and recommendations.

2. Literature review

This section provides a brief review of the relevant scientific state-of-the-art relating to morphological and hydrodynamic changes in lagoon systems. A coastal lagoon can be seen as a shallow water body that exists in the low-lying coastal plain, it always has a barrier island that separates it from the ocean and the system always has one or more connecting channel with the ocean, the connection that influences

the hydrological behaviour of the lagoon depending on the dimension of the channel's cross-sectional area [24, 25].

2.1 Origin and size of coastal lagoons

The genesis of coastal lagoons and the barrier island enclosing them depends primarily on the sea-level history of a region [26]. In terms of climatic setting, there is no restriction to the formation of coastal lagoons. Coastal lagoons exist where coastal embayment are separated from the adjacent sea by a barrier [27]. The barriers that separate the lagoons from the sea could at times be sand or gravel deposited by erosion and flood or are created by vegetation, coral growth or tectonics [28]. Lagoons are best formed on transgress coasts going towards the landward area, especially where the continental margin has a low gradient and sea-level rise is low [27].

In terms of spatial distribution, they occur in tropical, temperate and cold coasts extending along 13% of the world's coastline [29]. Even though coastal lagoons are found everywhere all over the world, however, they are more common in low-lying coastal parts of the world where sea level, shore-face dynamics and tidal range are common parameters that influence their formation [30]. Also, coastal lagoons can be recognised either in coasts where sea level has been rising (transgressive) or dropping (regressive). Formation of coastal lagoons was discussed by Anthony et al. [30] as a system formed and nourished through sediment transport. The transported sediment is carried by rivers, waves, currents, winds and tides [31] and gathers either in tidal deltas and rivers or on marshes and flats where immersed aquatic vegetation slows current movement.

2.1.1 Definition of coastal lagoon

Early research surrounding coastal lagoons focused on understanding processes of coastal lagoon formation, identification of defining characteristics and the development of classification schemes within which to group water bodies that are similar in geomorphology. Coastal lagoon was described by Kjerfve [32] as: "an inland body of water, usually oriented parallel to the coast, separated from the ocean by a barrier, always connected to the ocean by one or more restricted inlets, and having depths which seldom exceed a couple of metres", although some recent definitions [33, 34] have considered deposition of sediment as well as littoral drift in an attempt to define coastal lagoon. In addition, much of the sediment present in lagoons can be cohesive in composition and will therefore flocculate (e.g., [35]) when resuspended and subsequently produce a range of floc settling velocities (e.g., [36, 37]) that will affect depositional fluxes [38, 39] throughout a lagoon and, similarly, will have an effect on both bed erodibility (e.g., [40]) and subaqueous bed form sizes (e.g., [41, 42]).

2.1.2 Geological origin and formation of coastal lagoons

Geological evolution of coastal lagoons is typically expressed in terms of the rate of basin fill through sedimentation, and this is thus helpful to consider lagoon fill in terms of maturity [43]. The geological evolution of coastal lagoons from unfilled to deltaic stage is described as a seamless progression [43] that progresses correspondingly to the rate of sediment supply. In addition, Adlam [44] used a model of geologic evolution to explain the formation of the coastal lagoons in geological scale and found that the threshold between the two phases relates to depth and is defined as the depth at which wind waves are able to suspend sediments within the system

central mud basin. If we consider geological time scales, coastal lagoons like estuaries are short-lived coastal features of recent origin. They are formed during the eustatic (uniform worldwide change in sea level) rise of sea level between the times of the Wisconsin glaciation 18,000 years before present (BP) and stand the risk of being completely in-filled by sediments or closed off from the sea by littoral drift [24].

2.1.3 Lagoon's definition in relation to depth and size

Various authors with different studies on coastal lagoons have consensus agreement on the depth of the lagoon all over the world, and they all affirmed that lagoons are generally shallow with a few metres depth [8, 9, 11, 24, 29, 30, 32, 44–46]. In terms of size, coastal lagoons can be features originating within a plain of beach ridges (good example is deltaic plain) or shallow basins existing in environments of over 10,000 square km [47, 48] partially blocked by a barrier island (example is Lagoa dos Patos, Brazil).

2.1.4 Lagoon stratification

However, being a shallow coastal feature, lagoons tend to be well-mixed (mainly by winds rather than by currents), and they vary from brackish to hyper-saline, depending on the geographic location which dictates the level of balance between evaporation, precipitation and river flow. In equatorial regions, lagoons can be hyper-saline during dry seasons as a result of low influx of fresh water and high intrusion of saline water. But the same lagoon may become entirely fresh during rainy seasons [49]. Even though lagoons are shallow water bodies, the Lagos Lagoon that is the lagoon for consideration in this chapter (our research) has some parts around the inlets that are deep (12–17 m) as a result of continuous dredging either for the purpose of sand mining and reclamation or for channel navigation. Likewise, it is considered too brackish during the dry season and a fresh water lagoon during the raining season [50, 51].

2.2 The response of coastal lagoon to sea level rise (SLR)

The fourth Intergovernmental Plan on Climate Change (IPCC) report (AR4) projected the estimate of sea level rise for this century that it could likely range from 18 to 59 cm [52]. However, the estimation of IPCC's AR4 did not include the contributions from Greenland and Antarctica [53]. Basically, the actual rise may be higher or lower than the projection of IPCC. Hence, there is uncertainty in the estimation of sea level rise; this dilemma in the rise projection could be as a result of variation in the greenhouse gas both now and in the future. Climate model of IPCC 2001 report indicates spontaneous rise in the annual global mean temperatures [54, 55].

Sea level is raised by warmer temperature that melts the glacier ice sheets, the melted ice sheet is discharged into the ocean and this in turn increases and expands the volume of the ocean water, which splits into the enclosed water bodies like the lagoons and the estuaries and increases the water level in the systems [53]. The effect of increasing sea level brings negative hazards for coastal areas, including increased erosion, increased flooding/submergence, increased salinisation and threats to coastal cities in terms of storm surges, and all these could create direct negative impact on the urban coastal communities, wetlands, coastal ecosystem and the various infrastructural development around the coast [56–59]. Due to the negative effect of sea level rise, scientists and coastal policy makers face the challenge of
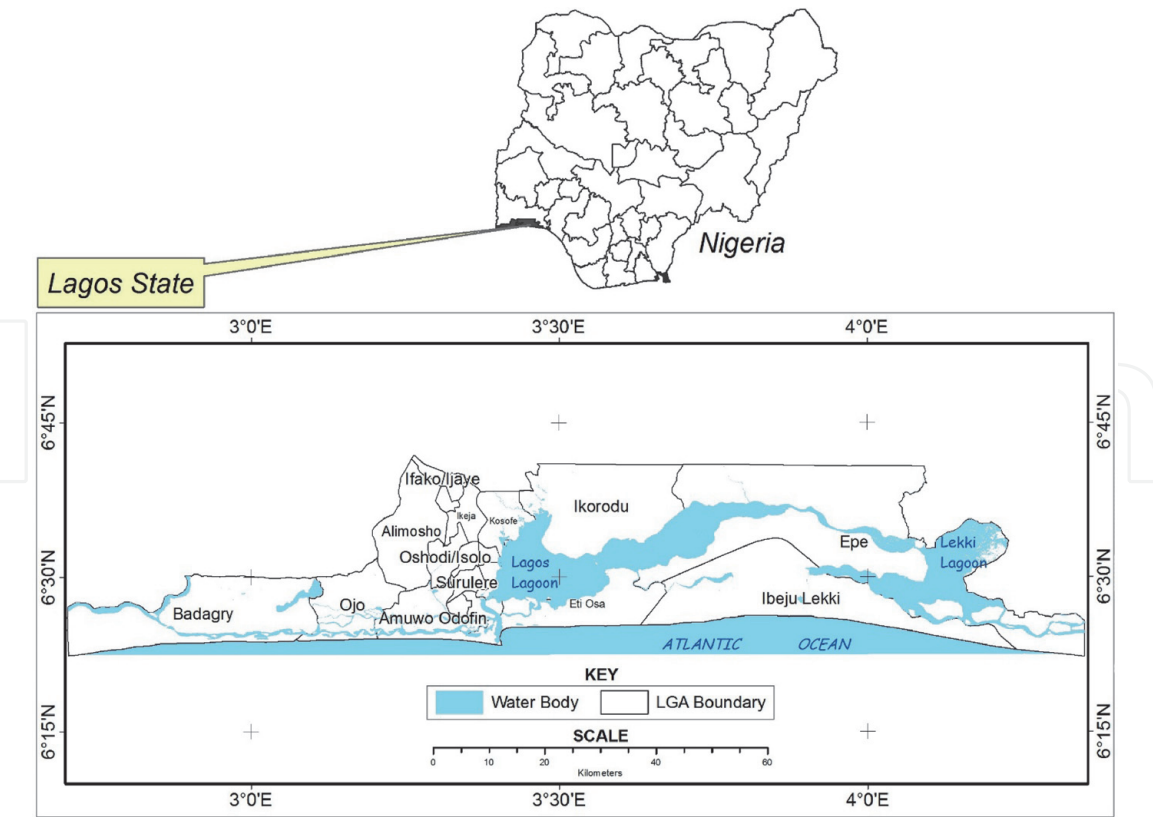
Figure 1.
Map showing Lagos Lagoon as situated in Lagos within Nigeria. The lagoon is surrounded by settlements (local government areas).

understanding how the sea level rise will affect the coastal area and the best management plan that can enhance sustainability [60]. If the sea level rise proceeds at the present rate, it may lead to submergence of most of the coastal lagoons turning it to part of the ocean.

2.3 Overview of Lagos Lagoon (Nigeria)

The Lagos Lagoon (**Figure 1**) is the largest of the four lagoon systems of the Gulf of Guinea [61, 62]. The lagoon complex stretches from Cotonu in the Republic of Benin and extends to the borders of the Niger Delta in Nigeria along its 257 km course [63], longitude 3° 3″ and 3° 53″ E and latitude 6° 26″ and 6° 37″ N. It is a shallow region of water with constrained movement in a micro-tidal environment. Fresh water from upland is fed into the lagoon from the northern part of the system by Ogun River, with a host of other smaller rivers as well as tidal creeks [17]. It discharges in the south into the South Atlantic Ocean through the Lagos Harbour. The vastness of the lagoon may easily hide the many shallow places present within the system [64]. The lagoon system is the final basin of a number of industrial discharges/effluents from the surrounding industries and run-offs at the Lagos Metropolis [65] and there is high urbanisation along the coastline.

3. Methodology

3.1 Overview

In general, the lagoon system and its adjacent tidal basins exhibit dynamics that are significantly different on both spatial and temporal scales. This is expected from

a semi-diurnal tidal regime; as urbanisation and human activities around the lagoon increase, the volume of sediment that is entering into the basin is believed to be increasing on a daily basis. Changes in the Lagos Lagoon water bed over 6 years' time scale using repeated bathymetric data (2008 and 2014) are presented in this section. Bathymetric surveys were carried out on the Lagos Lagoon to cover some section of the lagoon that was easily accessed based on the manpower and logistic available during the research data collection in the wet seasons. The surveys primarily focus on the western part of the lagoon through to the near-central region. The survey vessel (length—5.84 m, width—1.69 m) was equipped with a single beam echo sounder (frequency—200 kHz, model—SDE-285 Single Frequency Digital Echo sounder, type—South) for collection of bathymetric data on Lagos Lagoon. Initially, an overview of the process of acquiring the bathymetric data that was used in the research is outlined. The procedure of the bathymetry and data reduction is followed by analysis of the lagoon water bed dynamics using abstracted profile lines from the bathymetric data. The results of the significant accretion and erosion inside the lagoon were analysed spatially to quantify the volume of sediment gain or loss on the lagoon water floor; this enhanced the possibility of verifying if the lagoon is gradually disappearing. This aspect of the research, to the best of the authors' knowledge, reveals for the first time the various kinds of evolutionary changes (channel movement, accretion, erosion, infill and movement of shoal) on the lagoon water bed.

3.2 Bathymetric survey

This section presents the procedures utilised for gathering bathymetric data used in the analysis of the lagoon bed geomorphology. Hydrographic charting has always been of critical concern for navigation; however, bathymetric survey charts are often out of date due to geomorphic changes in many submarine areas, which most of the time occur rapidly [66], and also lack the detailed resolution required for scientific research level studies. On some navigation charts, it is highly possible that 10 years old bathymetry and the marked depths might have all changed considerably during the period since the chart was first published. This is especially relevant in the areas of strong current activity, of a mass movement, and where there is strong storm activity, as fast changes could be highly likely. Water depths are measured by both direct contact procedures and acoustic methods, and this research made use of a bathymetric chart that was obtained directly with the use of single beam echo sounder. Acoustic depth sounders measure the elapse time an acoustic pulse takes to travel from a generating transducer to the seafloor and back, and with the velocity of sound in water known, the travel time of the reflected wave can be measured and converted into distance. With the use of the single beam echo sounder, the section of the lagoon covered in this study was sounded in October 2014 taking note of the reference datum used in the bathymetric survey of the lagoon in 2008.

3.3 Reduction of soundings to chart datum

The depth data acquired were referenced to the local chart datum used in Nigeria (Lagos 1955 height). However, tidal height readings were not measured during the course of the bathymetry survey relative to chart datum at a tidal station (because of security challenge and lack of personnel). Hence, predicted tidal values were used to reduce the measured depth to chart datum. The tidal heights are a variation in the sea level that is associated with the gravitational forces maintaining the sun, moon and the earth in their orbits [67, 68]. The reduction of soundings

from floating platforms is traditionally based on the observed tidal time and height at one or more tidal stations and some interpolating techniques together with the associated assumptions to obtain tidal height relative to chart datum at other places.

During the hydrographic survey, the single beam echo sounder on the boat simply measures the depth of the water as the boat moves over the water column. However, the boat as a platform moves vertically depending on the water tide. The lagoon being in tidal waters, meaning the elevation of the water surface in the absence of waves (still water), was measured relative to chart datum. Soundings, relative to chart datum, are simply the surveyed depth less than the height of the vessel relative to chart datum. Water depths that were a reference to known datum were obtained by reducing the sounding depth using predicted tidal values by referencing the water surface to a known on-shore reference benchmark (Unilag 01). Depth was estimated to the best efforts at equipment calibration and data processing, the practicably achievable accuracy for coastal surveys when using echo sounders as ±0.15 m [69]. The bathymetric data from the field were processed in the office using HYPACK software; this is a package that contains programs for single beam survey design and data collection. A sample of the final data X, Y and Z (depth) coordinates as plotted on the lagoon is displayed in **Figure 2** and the sample data are displaced in **Table 1**. The number in the chart is the reduced depth value in metres plotted against its corresponding X and Y coordinates.

3.4 Error in bathymetric survey (sounding)

Errors in depth determination using acoustic instruments are caused by physical and mechanical factors, and such factors could include the velocity of sound in water and waves. The velocity of sound (V) in near-surface water ranges from 1400 to 1525 m/s but varies with water density, which is a function of temperature, salinity and suspended sediments [70, 71]. Hence, change in salinity can change the velocity of the water, and due to this, the echo sounder was calibrated onsite frequently using bar check. This check was also necessary for boat specific corrections because as the survey progressed, the vessel's draft changes as loads are exchanged (reduced). Wave error occurs as a result of the survey vessel pitching up and down, in order to obtain true water floor depth, and the transducer was
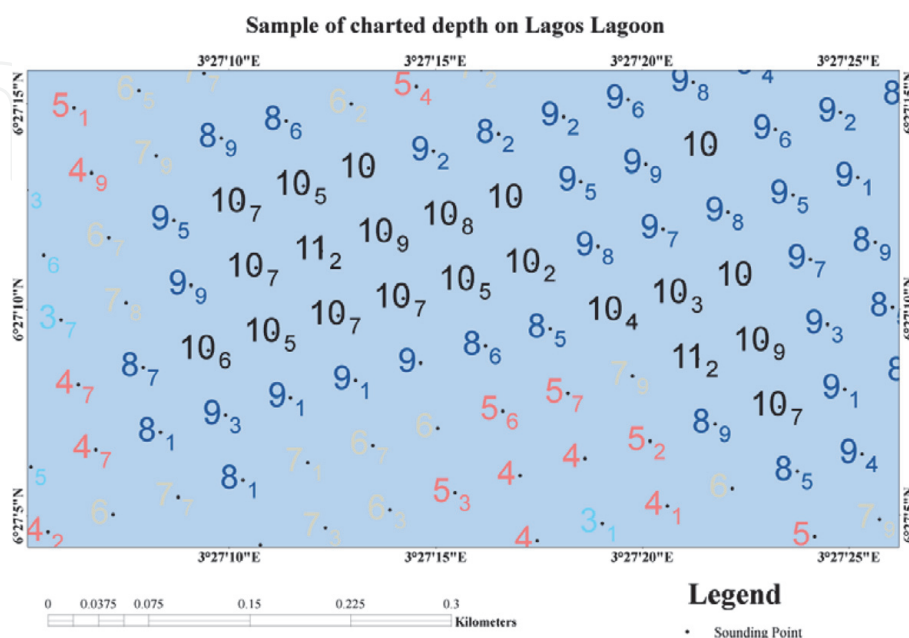

Figure 2.
Sample of charted bathymetric data of 2014 dry season, plotted in decimal number.

X (m)	Y (m)	Z or depth (m)
544,673.4	711,969.8	4.3
544,771.2	711,991	3.93
544,847.7	712,109.9	5.81
544,868.9	712,012.2	4.22
544,890.1	711,914.5	3.42
544,945.4	712,131.1	5.66
544,966.6	712,033.4	4.54
544,987.8	711,935.7	3.85
545,043.2	712,152.3	6.49
545,064.3	712,054.6	4.83
545,085.5	711,956.8	4.25
545,106.7	711,859.1	3.3
545,140.9	712,173.5	7.37

Table 1.
Sample of sounding data after reduction and applied correction.

installed on the heave-compensated mount. This allows the boat to move while the instruments remain fixed.

4. Results

This section presents results from repeated bathymetric surveys to measure and monitor the changes in the lagoon water bed in terms of erosion and accretion. The results were based on the process of achieving bathymetric survey that produced the data, description of the results of vertical profiles in the area that was covered with the acquired data and then the computation of accretion and erosion geomorphologic units in the survey area during the study. Bathymetric survey was carried out on the lagoon to cover a section of the lagoon that was easily accessed based on the manpower and logistic available during the research data collection in wet and dry seasons. The survey covers the western part of the lagoon through to the near-central region.

4.1 Analysis of the lagoon bed dynamics

Profile analysis was carried out on the bathymetric data of 2008 and 2014 from the lagoon, which were plotted in ArcGIS software by creating 10 profile sections (**Figure 3**) at distance interval of 100 m along the coverage area on the lagoon (profile lines A-A′, B-B′, C-C′, D-D′, E-E′, F-F′, G-G′, H-H′, I-I′ and J-J′). This analysis was performed in order to reveal the variability in the lagoon bed elevation patterns and volume dynamic that occur along the profile lines. This method was used by [72] for analysis of beach fill profile, where the result reveals clearly regions of erosion and accretion.

The bathymetric charts (2008 and 2014) were used to depict the changes along each of the profile lines to quantify whether erosion or accretion occurs at a particular location on the lagoon bed. Over the 6-year period, the changes in the lagoon depth were examined and discussed in the subsequent sections. The detailed
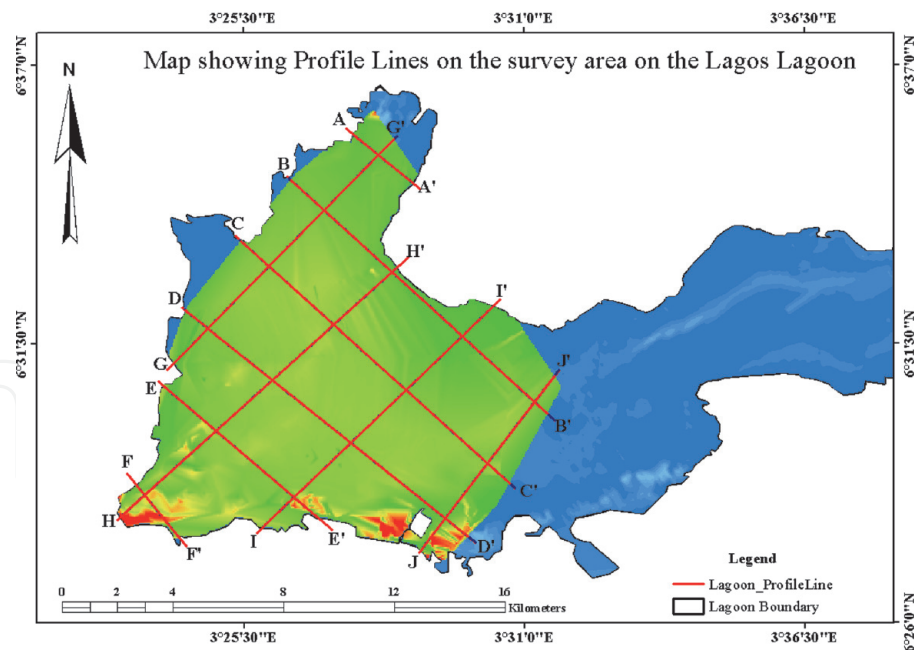
Figure 3.
Lagos Lagoon with profile lines on the study area. The area on the map with colour blue indicates area covered by the bathymetric survey of 2008, while the area with greenish yellow colour shows area surveyed in 2014.

comprehensive results in this section are given in two different segments as comparative results of the profiles running through a west-east direction and a south-north direction on the lagoon. This made use of the depth datasets for the bathymetric data of 2008 and 2014.

4.2 West to east profiles

Detailed analyses were performed on transects that were created by considering west to east direction to indicate changes along the north-south direction on the lagoon bed. The essence of creating the west to east direction profile lines is to ascertain the trend of changes on the lagoon bed moving southward from the freshwater inlets in the north where major sediments from upland intrude into the lagoon. Thus, this analysis determines if there is a significant variation on each of the profile lines on 2008 and 2014 data moving from the north to the south. Therefore, the hypothesis is set as follows to examine if there are significant changes in the lagoon water bed topography:

1. H_0: There is no significant difference between the 2008 bathymetric data sample and the 2014 bathymetric data sample in predicting changes in the lagoon bed.

2. H_1: There is significant difference in the 2008 bathymetric data sample and the 2014 bathymetric data.

In testing the hypothesis, this study carried out t-test to test the significant variation of the depth variables of the two repeated bathymetric data that produced the result of the changes on the lagoon water bed between 2008 and 2014 for the section covered on the lagoon. The t-test compares the actual difference between the means of the two samples: depth of 2008 data and the depth of 2014 data. It constructs confidence intervals or bounds for each mean and for the difference between the means. Of particular interest is the confidence interval for the ratio of the variances that extend between particular ranges of value, and the results show

Profile	t-Statistic	p-Value
Profile A-A′	−3.62781	0.00061912*
Profile B-B′	−1.08967	0.281534
Profile C-C′	−0.0174967	0.986164
Profile D-D′	1.95931	0.060101
Profile E-E′	−0.180016	0.857449
Profile F-F′	1.02115	0.314395

denotes a statistically significant difference.
Data for all the transect lines along west-east direction.

Table 2.
t-test for 2008 bathymetric data against 2014.

in **Table 3** the profile lines with a significant difference between the means of the two samples at the 95% confidence level not containing the value zero (0).

The first step in this analysis is to present (**Table 2**) extent of changes on the lagoon water bed that is represented by the change on the two repeated datasets on each of the profiles depth variables on the lagoon (**Figures 4–9**). Erosion was very prominent at the end of profiles D-D' and F-F′, and this could mainly be because of dredging (**Figures 7–9**). The proving evidence that dredging has taken place at the far end of profile D-D' is the huge sand fill area appearing white on the map in **Figure 3**. However, accretion was the common phenomenon at the end of profiles A-A′, B-B′, C-C′ and E-E′ (**Figures 4–6** and **8**).

Movement of shoals (submerged ridge of sand and unconsolidated materials rising from the bed of the lagoon to near water surface, **Figure 6**) was exhibited around and along the transect C-C′. This implies that navigation could be very dangerous for boats with draft above 1.4 m along the corridor of this transect. However, along transect D-D′ and E-E′, there was infill somewhere along the midway of each transects. The depth of the infill in each transects (approximately 2.3 m) implies fast sediment accretion inside the lagoon and fast erosion of sediment from the lagoon ecosystem basin. Transect D-D' begins from somewhere closer to Ogudu channel and ends near Five Cowrie channel.

It could be observed from **Figure 7** that channel lateral migration (the geomorphological process that involves the lateral migration of sediment across floodplain. This process is mainly driven by the combination of bank erosion and bank
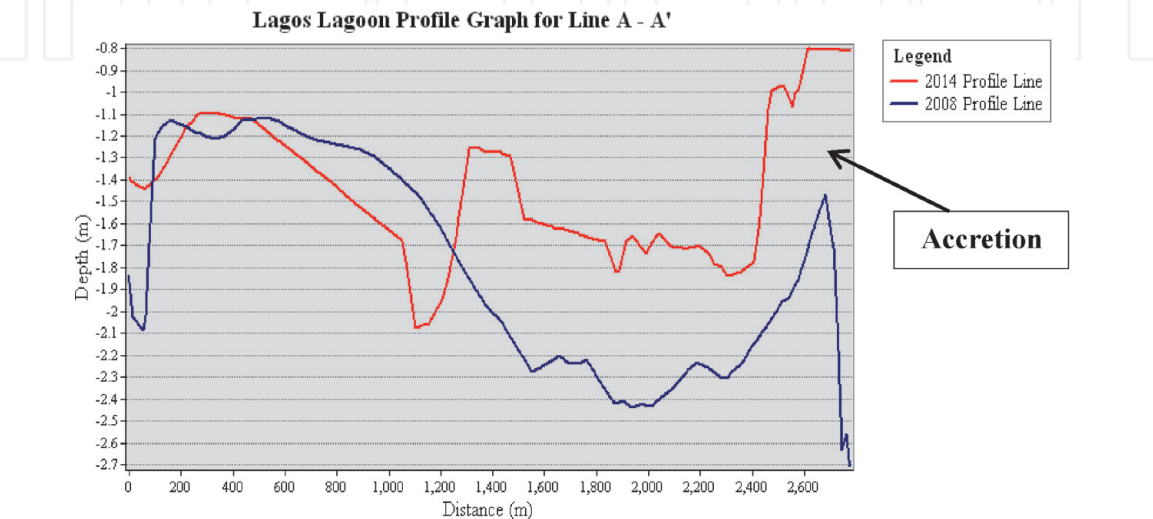

Figure 4.
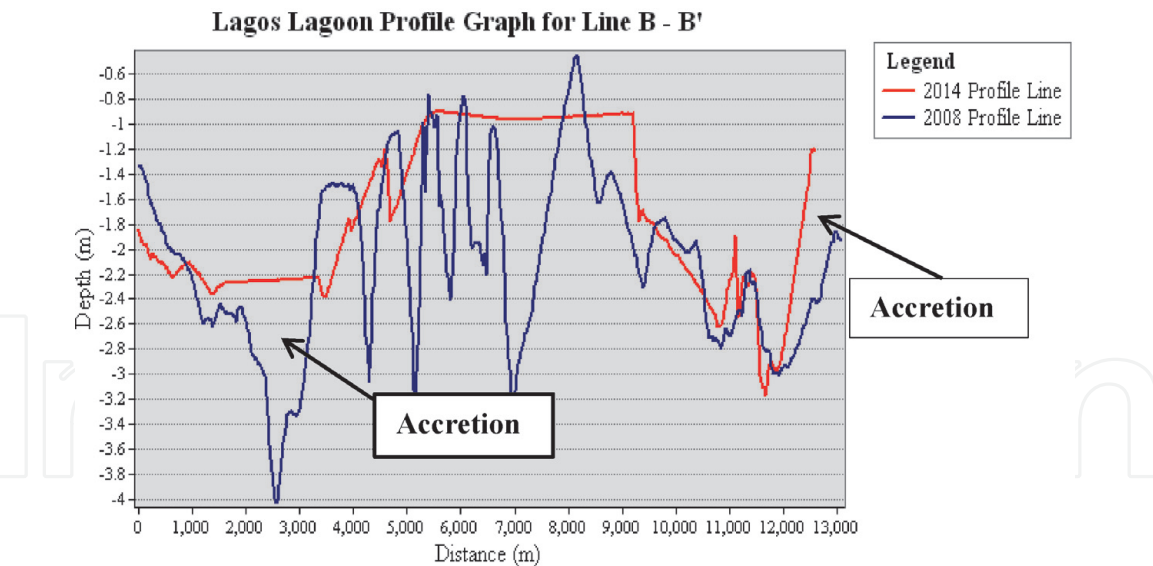*Profile section A-A′ showing trend of variation in the repeated bathymetric data.*

Figure 5.
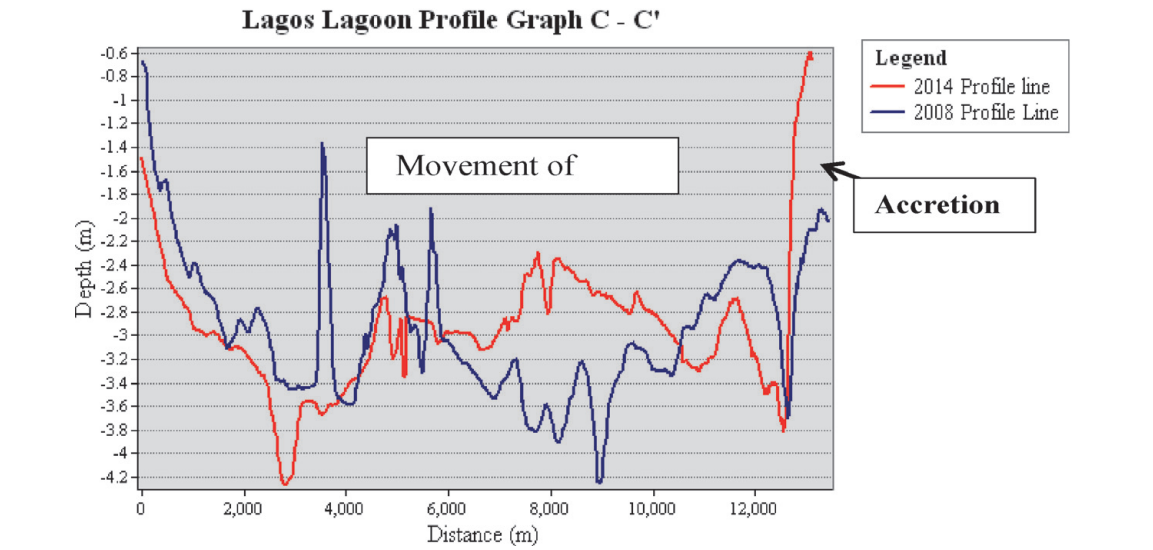*Profile section B-B′ showing trend of variation in the repeated bathymetric data.*

Figure 6.
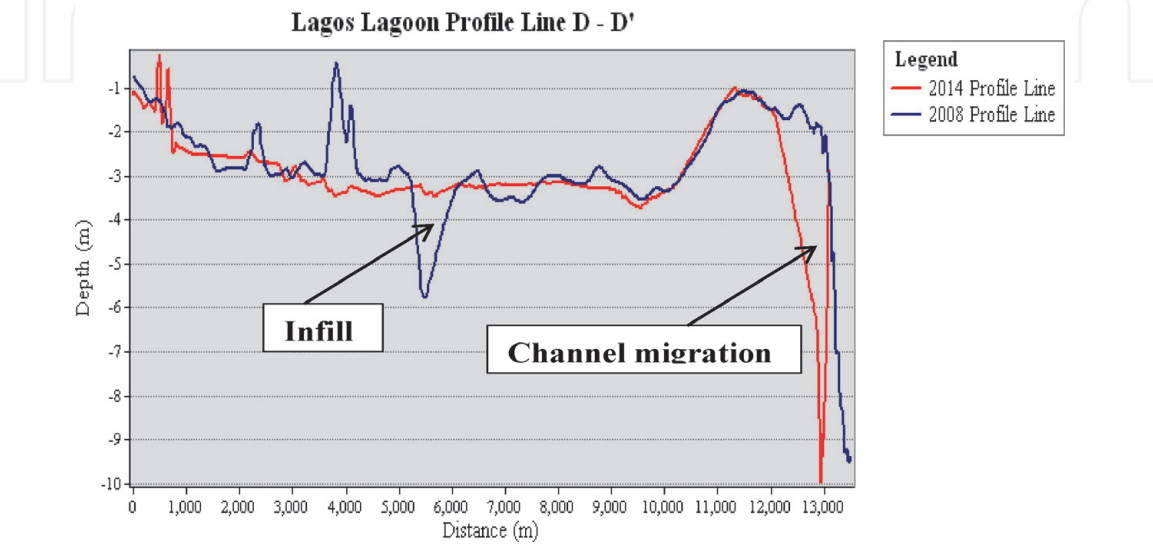*Profile section C-C′ showing trend of variation in the repeated bathymetric data.*

Figure 7.
Profile section D-D′ showing trend of variation in the repeated bathymetric data.

Figure 8.
Profile section E-E′ showing trend of variation in the repeated bathymetric data.

Figure 9.
Profile section F-F′ showing trend of variation in the repeated bathymetric data.
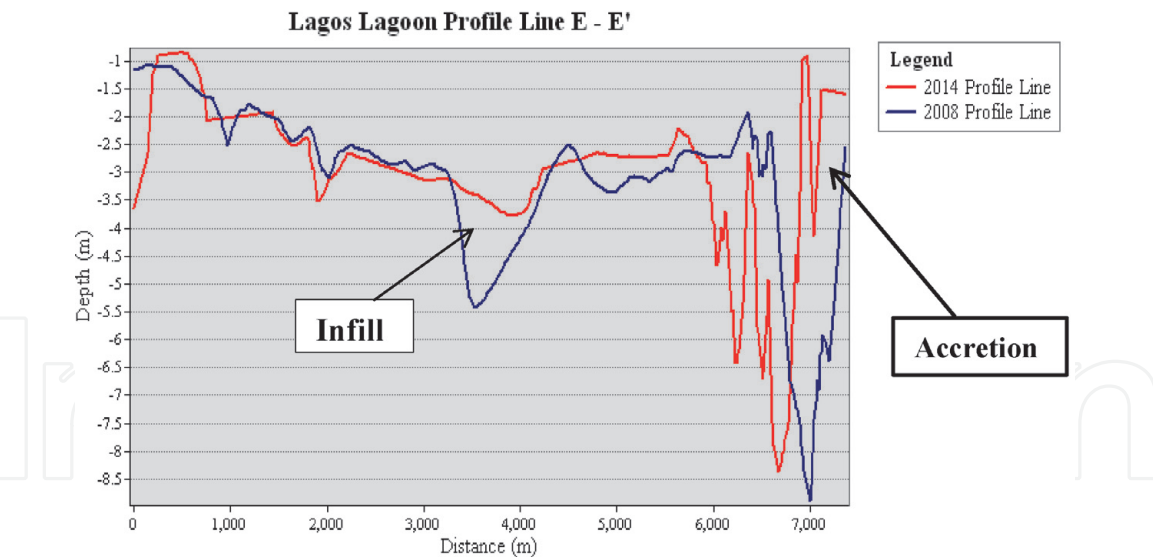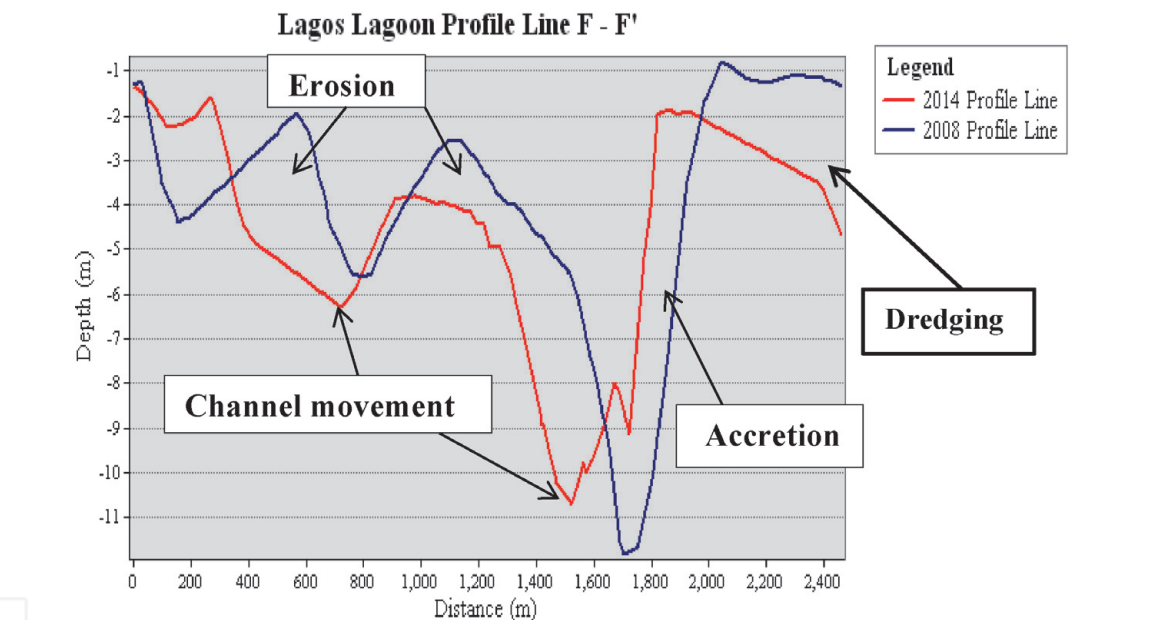
deposition over time. Hence, channel's change is driven by sediment transport) occurred at the end of transect D-D′ toward Five Cowrie channel. Comparing this result with existing literature [73–75], it could be confirmed that lateral migration that occurred at this region that is as a result of the lagoon bank erosion and sedimentation depends upon the ecology of the watershed corridors of the lagoon ecosystem. Hence, the volume of sediment eroded from the watershed corridors is shown to be largely a function of the watershed size and grain size of sediment at the base of the outer bank. Consequently, it appears that bank erosion and channel migration are basically problems of sediment entrainment, which is dependent on total flow from the watershed and sediment size.

Transect F-F′ was characterised by channel movement (which in this case is the up and down meandering of the lagoon bottom morphology), the channel migration by erosion on one side leads to deposition towards the Lagos Island side of the transect; however, toward the end of the transect, there was dredging. This was

confirmed by visual observation during data collection, as serious local dredging was going on in the area by those who are constructing near the lagoon bank.

4.3 Statistical comparison of profiles

In testing the hypothesis, a t-test was conducted to compare the mean values of depths of the two sample data (2008 and 2014 data). The result of the test, that is, the calculated t-test, is in **Table 2**. The tabulated values of t-statistics, p-value and confidence interval were calculated for each of the profiles established on the coverage area of the lagoon at 95% confidence level, which is the probability of making a correct assertion.

4.3.1 Decision on the hypothesis

The six profiles considered along with the direction west to east have different calculated t-values (measure the size of the difference relative to the variation in sample data) and p-values (calculated probability) even though they were all computed with the same confidence interval, and this may be evident that the changes along each profile section are not the same. Only profile line A-A′ has a p-value that is less than 0.05; hence, the null hypothesis is rejected meaning that there is significant variation in the depth range of the 2008 data and that of 2014. The remaining five profiles have p-value greater than 0.05; it implies that there is no significant difference on the changes along each of the profile line, and there could be changes inherent in the profiles that needed a further test to discover it. Hence, the null hypothesis is rejected for profile A-A′ and conversely accepted for the five profile lines from B-B′ to F-F′. The implication is that there was significant change along this profile (A-A′) and it is different from the rest of the profiles B to F.

4.3.2 Multiple sample comparison on the west to east direction profiles

Consequent upon the results of the above t-test in Section 4.3, the six profile sections were further subjected to a robust multiple comparison statistical test. This procedure compares the data in 12 columns of the dataset file. It constructs various statistical tests—F-test, analysis of variance (ANOVA), multiple range tests and variance check (**Tables 3–6**) to compare the significant changes along each of the profile lines. ANOVA test was used in order to examine and analyse the variance between and within the different profile lines.

The F-test in the ANOVA table (**Table 3**) tests whether there are any significant differences among the means. The ANOVA table decomposes the variance of the data into two components: a between-group component and a within-group component. The F-ratio that in this case equals to 11.08 is a ratio of the between-group estimate to the within-group estimate. Since the p-value of the F-test is less than

Source	Sum of squares	Df	Mean square	F-Ratio	P-Value
Between groups	215.41	11	19.5828	**11.08**	0.0000*
Within groups	547.811	310	1.76713		
Total (Corr.)	763.222	321			

denotes a statistically significant difference.

Table 3.
ANOVA table for multiple sample comparison.

Contrast	Sig	Difference	±Limits
A 2008-A 2014		−0.425517	0.686908
A 2008-B 2008		0.262744	0.721798
A 2008-B 2014		0.0548276	0.721798
A 2008-C 2008	*	**0.890828**	0.831887
A 2008-C 2014	*	**0.885494**	0.831887
A 2008-D 2008		0.634828	0.831887
A 2008-D 2014	*	**1.37749**	0.831887
A 2008-E 2008	*	**1.33233**	0.591565
A 2008-E 2014	*	**1.28283**	0.591565
A 2008-F 2008	*	**2.01205**	0.784867
A 2008-F 2014	*	**2.83594**	0.784867
A 2014-B 2008		0.688261	0.721798
A 2014-B 2014		0.480345	0.721798
A 2014-C 2008	*	**1.31634**	0.831887
A 2014-C 2014	*	**1.31101**	0.831887
A 2014-D 2008	*	**1.06034**	0.831887
A 2014-D 2014	*	**1.80301**	0.831887
A 2014-E 2008	*	**1.75784**	0.591565
A 2014-E 2014	*	**1.70834**	0.591565
A 2014-F 2008	*	**2.43757**	0.784867
A 2014-F 2014	*	**3.26146**	0.784867
B 2008-B 2014		−0.207917	0.755078
B 2008-C 2008		0.628083	0.860921
B 2008-C 2014		0.62275	0.860921
B 2008-D 2008		0.372083	0.860921
B 2008-D 2014	*	**1.11475**	0.860921
B 2008-E 2008	*	**1.06958**	0.631744
B 2008-E 2014	*	**1.02008**	0.631744
B 2008-F 2008	*	**1.74931**	0.815577
B 2008-F 2014	*	**2.57319**	0.815577
B 2014-C 2008		0.836	0.860921
B 2014-C 2014		0.830667	0.860921
B 2014-D 2008		0.58	0.860921
B 2014-D 2014	*	**1.32267**	0.860921
B 2014-E 2008	*	**1.2775**	0.631744
B 2014-E 2014	*	**1.228**	0.631744
B 2014-F 2008	*	**1.95722**	0.815577
B 2014-F 2014	*	**2.78111**	0.815577
C 2008-C 2014		−0.005333	0.955106
C 2008-D 2008		−0.256	0.955106

Contrast	Sig	Difference	±Limits
C 2008-D 2014		0.486667	0.955106
C 2008-E 2008		0.4415	0.755078
C 2008-E 2014		0.392	0.755078
C 2008-F 2008	*	**1.12122**	0.914445
C 2008-F 2014	*	**1.94511**	0.914445
C 2014-D 2008		−0.250667	0.955106
C 2014-D 2014		0.492	0.955106
C 2014-E 2008		0.446833	0.755078
C 2014-E 2014		0.397333	0.755078
C 2014-F 2008	*	**1.12656**	0.914445
C 2014-F 2014	*	**1.95044**	0.914445
D 2008-D2014		0.742667	0.955106
D 2008-E 2008		0.6975	0.755078
D 2008-E 2014		0.648	0.755078
D 2008-F 2008	*	**1.37722**	0.914445
D 2008-F 2014	*	**2.20111**	0.914445
D 2014-E 2008		−0.045166	0.755078
D 2014-E 2014		−0.094666	0.755078
D 2014-F 2008		0.634556	0.914445
D 2014-F 2014	*	**1.45844**	0.914445
E 2008-E 2014		−0.0495	0.477553
E 2008-F 2008		0.679722	0.702939
E 2008-F 2014	*	**1.50361**	0.702939
E 2014-F 2008	*	**0.729222**	0.702939
E 2014-F 2014	*	**1.55311**	0.702939
F 2008-F 2014		0.823889	0.871889

denotes a statistically significant difference.

Table 4.
Multiple range test.

	Test	P-Value
Levene's	6.69373	**4.51871E-10**

Table 5.
Variance check.

Number of paired profile	Range of P-value	Significant status
47	Less than 0.05	Statistically significant
19	Greater than 0.05	Statistically not significant

Table 6.
Summary of the statistical test variance check.

0.05 (0.0000), there is a statistically significant difference between the means of the 12 variables of the six profile lines at the 95% confidence level.

To determine which means are significantly different from which others, a multiple range test (multiple comparisons of procedures that use the studentised range statistic to compare sets of means) was performed, and the summary results of which are shown in **Table 3**. Out of the 65 paired groups that were tested, an asterisk has been placed next to 35 pairs, indicating that these pairs show statistically significant differences at the 95% confidence level. It can be inferred from this that significant changes occurred on the lagoon water bed between 2008 and 2014 going from the direction west-east of the lagoon water bed.

To further ascertain the change within and between the 12 pairs of profile lines, a variance check test was carried out using Levene's method [76]. This statistic tests the null hypothesis that the standard deviations within each of the 12 columns are the same. Of particular interest are the generated p-values. A summary of the statistical test results (**Tables 5** and **6**) shows that there is a statistically significant difference among 47 out of 65 paired groups with the standard deviations at the 95% confidence level. **Table 6** shows a comparison of the standard deviations for each pair of samples. P-values less than 0.05, of which there are 47, indicate a statistically significant difference between the two sigmas at 95% significance level.

As part of these analyses, a least significant difference (LSD) assessment was carried out on the 12 pairs using Fisher's LSD; it gives the opportunity to deduce which group is significantly different from another; this is not possible using ANOVA. The LSD calculates the smallest significance between two means as if a test had been run on those two means. It makes direct comparisons between two means from two individual groups and any differences larger than the LSD is considered a significant result. The test takes the square root of the residual mean square from ANOVA and considers that to be the pooled significant difference (SD), taking into account the sample sizes of the groups being compared; it computes a standard error of the difference between the means. It also computes a t ratio by dividing the difference between means by the standard error of that difference. The various results exhibited by each groups is displayed in the graph of **Figure 10**. Comparing the results of **Figure 10** and the summary results (**Table 6**), it can be concluded that significant change exists between 2008 and 2014 on the Lagos Lagoon water bed from the northern region to the southern region of the lagoon.

Finally, of particular interest is the p-value of profile A-A' at the northern-most region very close to the inlets, and this has a p-value of 6.19×10^{-4}, which is less than 0.05. The error bar of the A' transect (2014 transect dataset) does not overlap
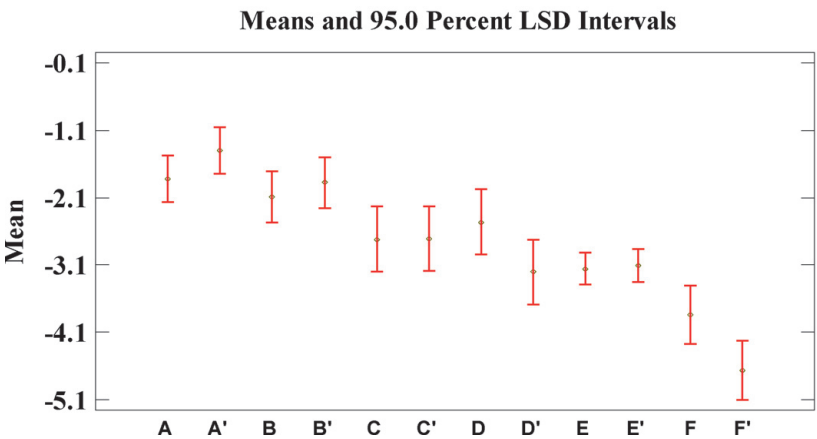

Figure 10.
Multiple comparisons means plot with 95.0% LSD intervals.

with all the transect lines of C to F′, so also does transect A. This indicates that there is a statistically significant difference in the depth values of transect lines AA′ and those of C to F′. However, transect CC′ shows no difference at all but does show significant variation with transects AA′ and FF′. It can be concluded that significant changes have taken place between and within the transect line at varying degrees. Interestingly, it is evident in the results of **Figures 4–9** that erosion, shoaling, channel migration, channel movement and accretion take place along a west-east direction at different spatial location.

4.3.3 South to north profiles

Furthermore, four profile lines (**Table 7**) were created in a longitudinal direction to investigate the changes on the lagoon along the direction west to east. The choice of this transect lines was based on the fact that human activities and urban development are more pronounced in the western part of the lagoon than what goes on in the eastern region, hence the reason for investigating the trend of changes on the lagoon water bed moving from west to east on its water bed. Likewise, some places of significant human activities were identified where a possibility for a high erosion and siltation rate on the lagoon bed could be feasible. A good example of such is the profile HH′ (**Figure 3**) constructed from the southwestern region of the lagoon outlet around Carter Bridge. This region is known for heavy traffic: ferries and other human activities such as local sand mining. The position of profiles I-I′ and J-J′ was strategically chosen because a lot of dredging activities are going on in the area due to increased urban development and a struggle for space around the lagoon coast. It was assumed that accretion due to sediment transport from the uplands would be more pronounced in the western part than in the eastern side of the lagoon; this is assuming there is no dredging activity going on in the lagoon.

Thus, this analysis investigates if there is a significant change on each of the established profile lines of 2008 and 2014 bathymetric datasets along south/north direction. Therefore, the hypothesis is set as follows:

1. H_0 : There is no significant difference between the 2008 bathymetric data sample and the 2014 bathymetric data sample in predicting changes in the lagoon bed along the easting direction.

2. H_1 : There is significant difference in the 2008 bathymetric data sample and the 2014 bathymetric data along the easting direction.

In testing the hypothesis in this section, the research carried out a t-test to test the significant variation of the depth dynamic of the two repeated bathymetric data (2008 and 2014). The test constructs confidence intervals for each mean and for the difference between the means. It also compares the actual difference between the

Profile	t-Statistic	p-Value
Profile G-G′	0.348271	0.727964
Profile H-H′	4.1955	0.000037848[*]
Profile I-I′	−1.71216	0.090557
Profile J-J′	1.30189	0.199436

[*]*denotes a statistically significant difference.*

Table 7.
South to north profiles.

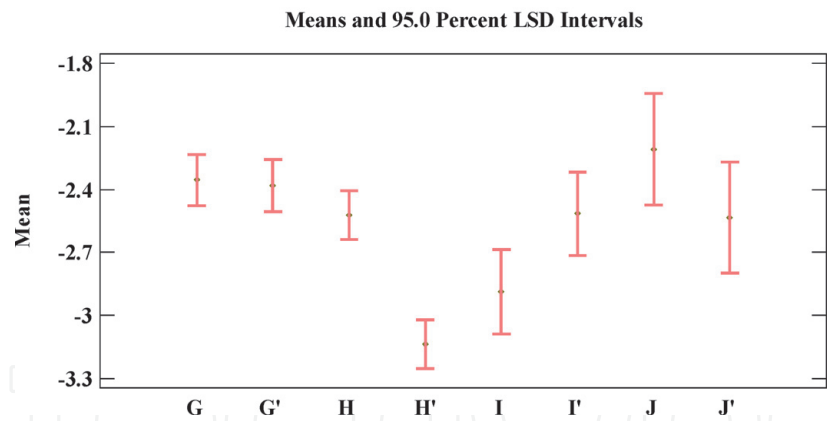**Means and 95.0 Percent LSD Intervals**

Figure 11.
Multiple comparisons mean plot with 95.0 percent LSD intervals for south-north direction profile.

means of the two samples. The analysis presents (**Table 7** and **Figures 11** and **13**) a result of statistically significant differences existing along the profiles and the extent of change along each profile is presented graphically (**Figures 14–17**) and as results from ArcGIS (**Figure 12**).

From the statistical tests of the four south-north directional profiles, the values of t-statistics and p-value are calculated for individual profile section at 95% confidence level. Other statistical tests were performed for further comparison of the individual data files that were involved in constructing each of the profiles. Further tests, F-test, ANOVA, multiple range and variable check (**Tables 7–9**), were constructed to further examine the result of the t-test and confirm the scientific evidence of the statistic tests. The F-test in ANOVA table, the statistically significant difference of the data means and the expression of the multiple range test show a p-value of 0.000037848; hence, there is a significant difference between the 2008 and 2014 bathymetric data around the region of profile H-H′. Consequent upon the result of the F-test, the procedure of the multiple sample comparison compares 8 columns of data to reveal the overall changes between the two data sets in south-north directions.
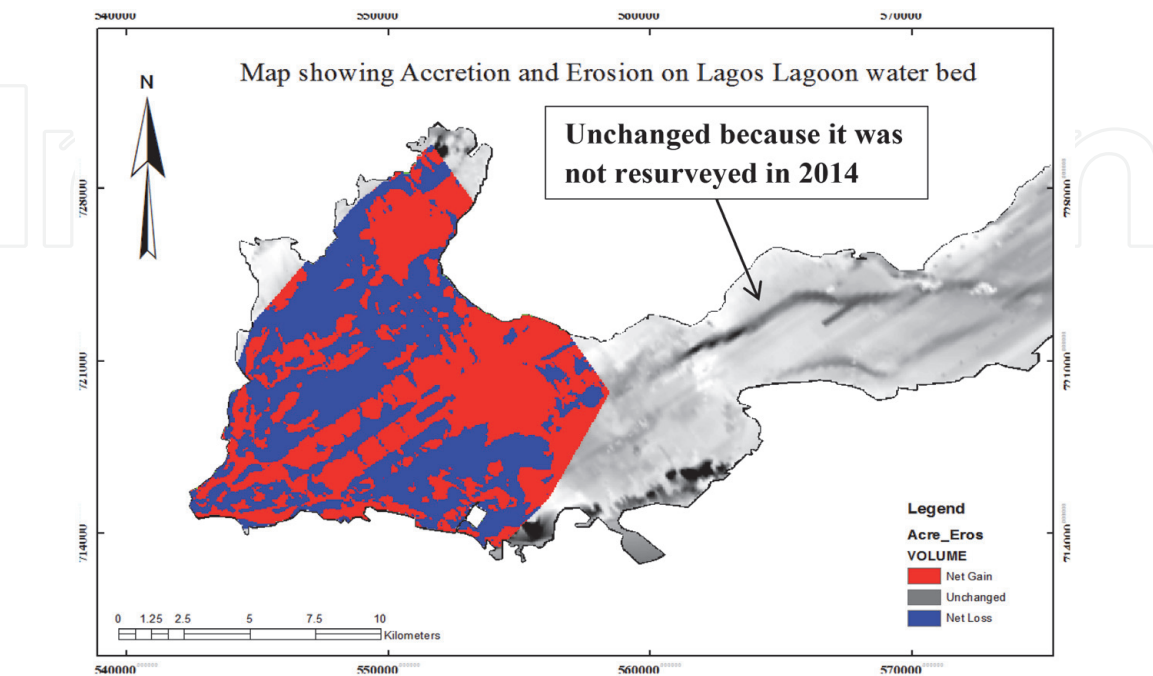

Figure 12.
Accretion and erosion on Lagos Lagoon water bed between 2008 and 2014. Accretion is shown in red as sediment net gain, while erosion is in blue colour as sediment net loss.
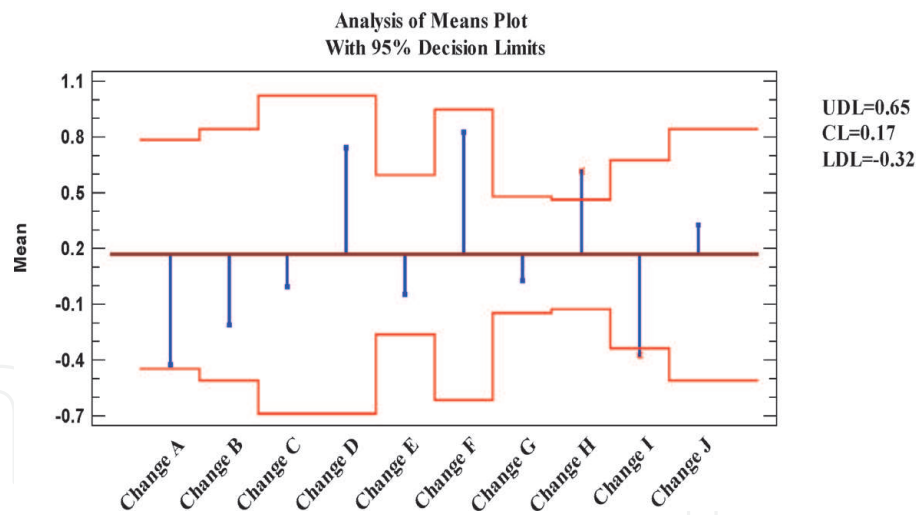
Figure 13.
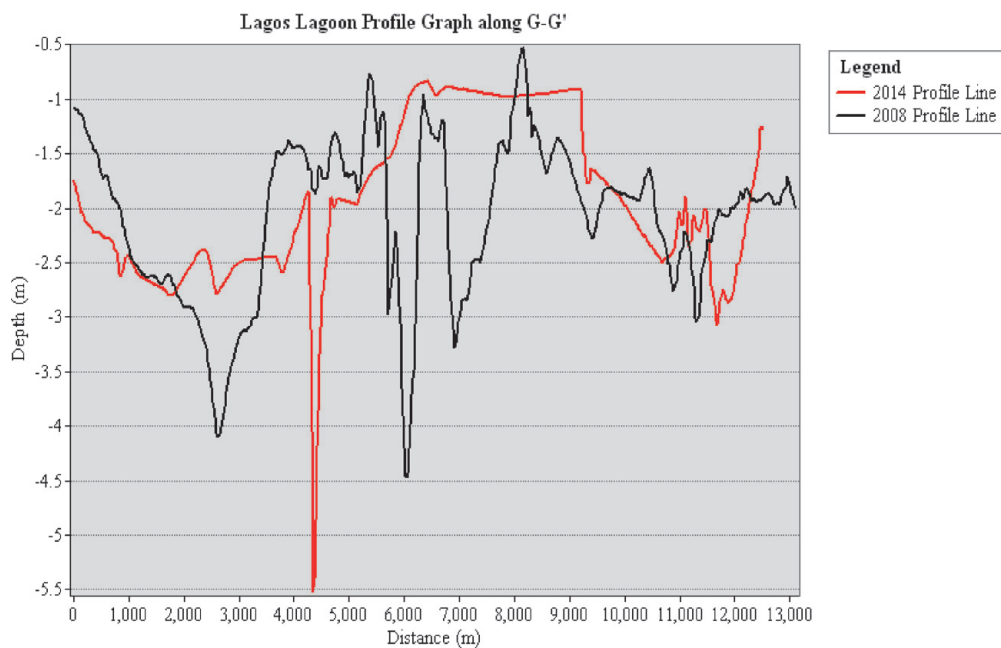*Analysis of mean for all changes in depths from profile A-A′ to J-J′.*

Figure 14.
Profile section G-G′ showing degree of variation in the depths of the lagoon repeated bathymetric data.

4.3.4 Results of the statistical test

The t-test results for each profile line is summarised in **Table 7**. Line H-H′ shows a p-value that is less than 0.05, meaning that statistically, there is a significant difference between the depth values of the 2008 and 2014 data. It implies that some significant changes took place on the lagoon bed either through accretion or erosion around the profile section H-H′.

The fact that the p-values of the other three profile sections (G-G′, I-I′ and J-J′) are greater than 0.05 does not mean there is no change experienced between the gap year of the repeated data. The result of the ANOVA test shows F-ratio as 9.18 (**Table 8**), and this is the ratio of the between-group estimate to the within-group estimate. The p-value of the F-test is less than 0.05; this implies that there is a statistical significance between the means of the 8 variables at 95% confidence level. A multiple range test was carried out on the eight profiles, considering each profile

Source	Sum of squares	Df	Mean square	F-Ratio	P-Value
Between groups	56.9298	7	8.13284	9.18	**0.0000**
Within groups	534.972	604	0.885715		
Total (corr.)	591.902	611			

Table 8.
ANOVA table.

Contrast	Sig.	Difference	±Limits
G 2008-H 2014	*	**0.782877**	0.238985
G 2014-H 2014	*	**0.75562**	0.238985
G 2014-I 2008	*	**0.505063**	0.33051
H 2008-H 2014	*	**0.614762**	0.232394
H 2014-J 2008	*	**−0.928135**	0.410819
H2014-J 2014	*	**−0.603552**	0.410819

denotes a statistically significant difference.

Table 9.
Multiple range test.

as a variable so as to determine which of the profile depth mean (average) is significantly different from the other (**Table 9**).

From the table of results on multiple range tests, six contrasts show a result that is significantly different, which implies significant variations in the depth of the 2008 and 2014 data sets. Further confirmation of the change is graphically displayed in **Figure 15**. The difference in the mean of the dataset on line H-H′ that was overlaid on each other shows a wide variation. The variations in the mean values of the two datasets on the same profiles are very visible on profiles H-H′, I-I′ and J-J′. It could be inferred from **Figure 15** that a mean depth of 3.1 m in 2014 against the mean depth of 2.5 m in 2008 shows erosion (whether by dredging or naturally) around and along the profile section H-H′. On the contrary, accretion (that is sediment gain) was shown from the region of profile H′ to profile J.
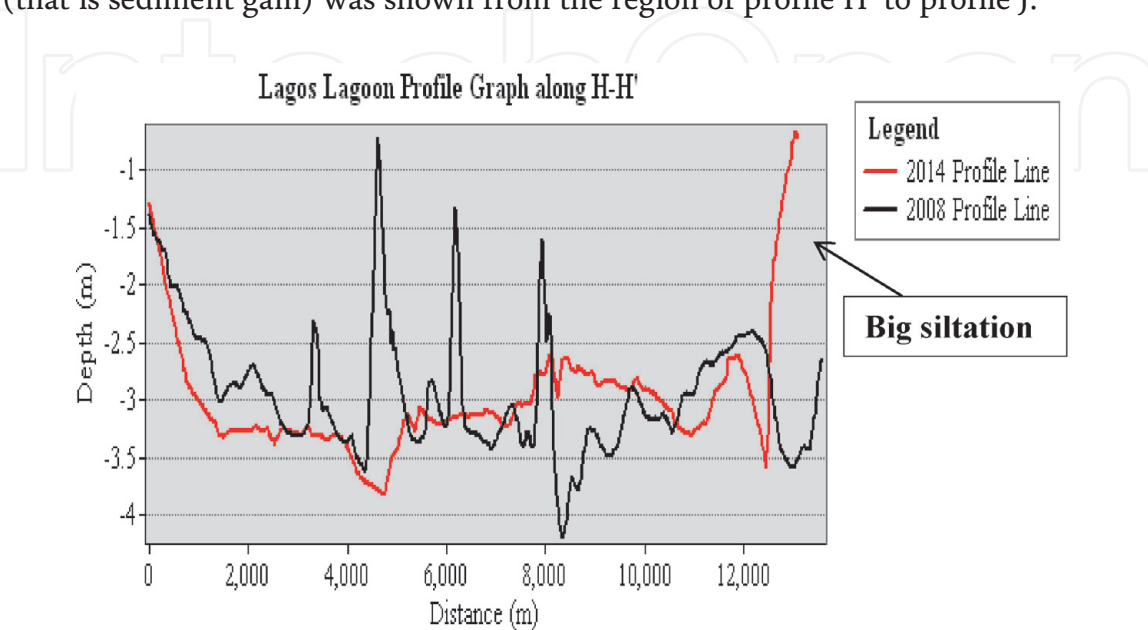

Figure 15.
Profile section H-H′ showing degree of variation in the depths of the lagoon repeated bathymetric data.
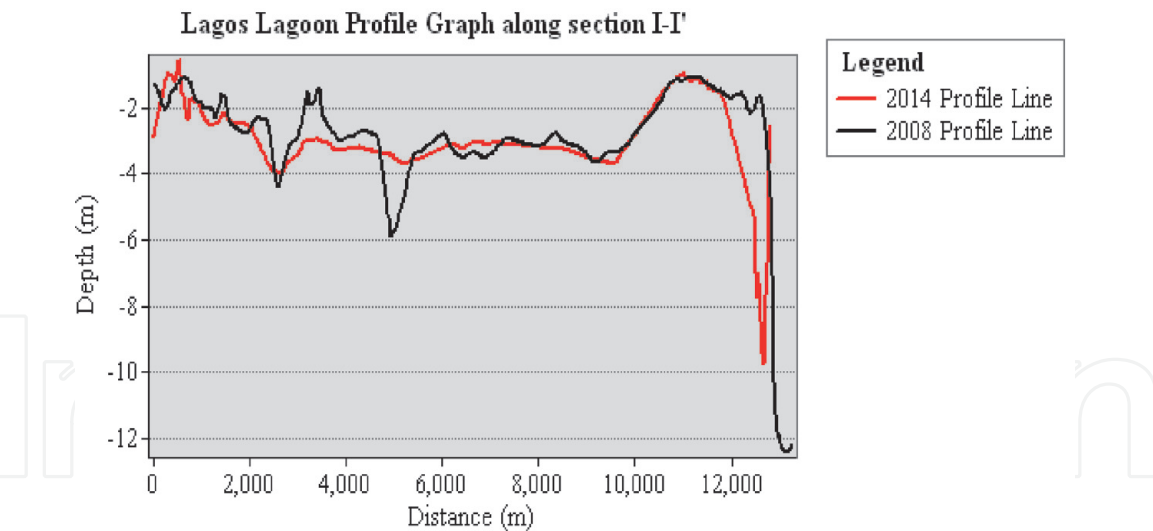
Figure 16.
Profile section I-I′ showing degree of variation in the depths of the lagoon repeated bathymetric data.

However, the ArcGIS model result in **Figure 16** confirms the region of accretion and erosion on the lagoon bed within that interval of 6 years. To put it differently, in a graphical representation, the changes on the lagoon bed moving in the direction west to east are depicted in **Figures 11–14**.

4.4 Overall test on the lagoon spatial depth characterisation

Further to the statistical test carried out on west-east and south-north directional profiles, the differences in the depths of 2008 and 2014 data were extracted and arranged profile by profile. An ANOVA test with a posteriori comparison (**Table 10**) was carried out on the depth differences. The ANOVA decomposes the variances of all the datasets into two components: a between-group and a within-group component. A high value of F-ratio (5.00) with p-value 0.00, therefore, is evidence against the null hypothesis that was originally set as equality of all the profile data set population means. Hence, there is a statistically significant difference in the lagoon bed between 2008 and 2014 derived from the repeated bathymetric surveys. The analysis of means plot with 95% decision limits revealing a high level of significant difference in profiles H-H′ and I-I′. These were the two profiles that exceeded decision limits (**Figure 17**) that were set as 95% decision limits at both upper and lower limit of the mean.

It can be inferred from the results of the test that around the region of profiles H-H′ and I-I′ significant changes took place on the lagoon bed. Correlating the region between profile H-H′ and profile I-I′ with the erosion/accretion result in **Figure 16**, a high level of erosion or loss of sediment has taken place in the area, which is shown as a net loss in **Figure 16**.

Source	Sum of squares	Df	Mean square	F-Ratio	P-Value
Between groups	70.1009	9	7.78898	**5.00**	**0.0000**
Within groups	711.974	457	1.55793		
Total (corr.)	782.075	466			

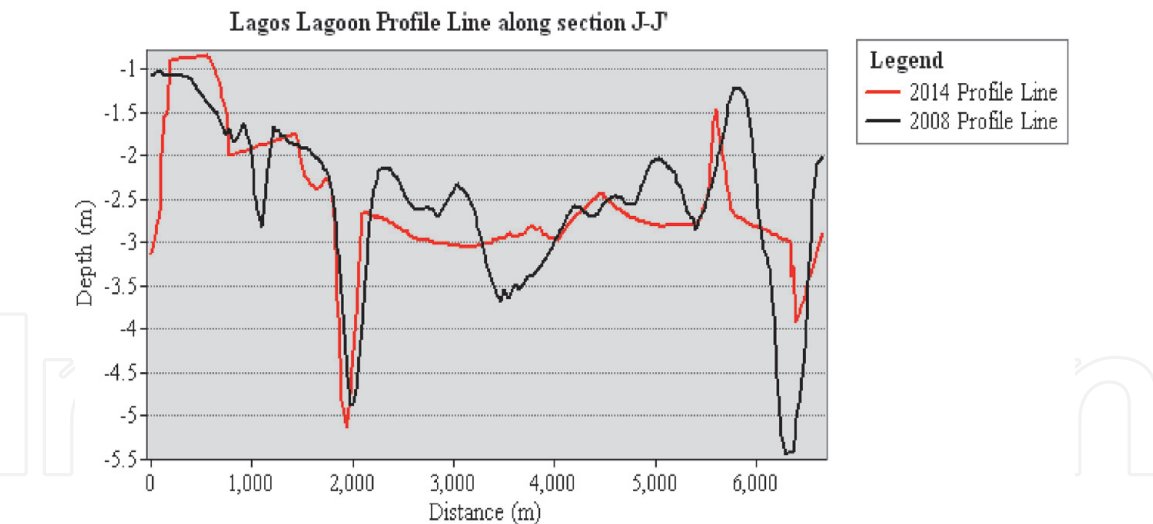**Table 10.**
ANOVA with a posterior test.

Figure 17.
Profile section J-J' showing degree of variation in the depths of the lagoon repeated bathymetric data.

4.5 Volume analysis

Volume estimates were calculated using CUTFILL tool in ArcGIS's 3D Analyst. The uncertainty inherent in the volume estimation using CUTFILL tool is computed in terms of percentage deviation ($\pm$5%). The depth values of the two repeated bathymetric datasets from 2008 and 2014 were used to determine how much sediment has been accumulated or eroded on any part of the lagoon water bed. The two dataset (2008 and 2014 bathymetric data) were plotted on ArcGIS and then converted to shapefiles, and next was the conversion of the shapefile to vector-based digital geographic data using triangular irregular network (TIN) in order to make it a surface morphology. A TIN is a vector data structure that stores and displays surface models; it partitions geographic space using a set of irregularly spaced data points; each of which has x, y and z values. These points are connected by edges that form contiguous, non-overlapping triangles and create a continuous surface that represents the terrain. The CUTFILL tool in the ArcGIS environment was used to identify the areas where dredging/erosion and deposition/accretion have taken place in the study area on the lagoon (**Figure 16**).

4.5.1 Calculation of volume gained

The single beam hydrographic data of 2008 and 2014 were used to determine the degree of changes that took place over a period of 6 years. Hence, the amount of sediment eroded or gained was calculated using the depth range from the datasets created on triangular irregular network (TIN). The TIN morphological surface was converted to raster data and was used in the CUTFILL tool to determine the volume gain or loss. To analyse the change in the sediment volume between 2008 and 2014, a statistical summary from the ArcGIS model was used. A summary of the gain/loss analysis is depicted in **Table 11**. The amount of accretion was found to be higher than that of erosion/dredging on the lagoon water bed despite all the local sand extraction going on consistently in the lagoon.

It can be inferred from **Table 11** that 858,932 m^2 on the lagoon gained 137,429 m^3 volume of sediment between 2008 and 2014. Hence, the depth of accreted sediment over the area was computed as:

Volume = area × height.

137,429.161 = 858,932.254 × height.

Hence sediment gained = 137,429.161/858,932.254.

Average height of sediment gained = 0.16 m.

Between 6 years, the average height of 0.16 m was gained by the lagoon. Going by this rate, it means that in 1 year the height of accretion will be 0.026 m.

4.5.2 Evidence base

If the yearly average accretion (0.026 m/year) persists in the lagoon without any dredging/other removal, the study area of the lagoon will have gained a sediment height of 1.3 m in 50 years. Kjerfve and Magill [9] confirm that lagoons are net material sinks and that they are often subject to rapid sedimentation and will transform into other types of environments through sediment infilling and land-use activities. Hence, its time scale of transition since it is geologically rapid can occur within decades to centuries, and the Lagos Lagoon, as is the case with any other lagoon, is susceptible to disappearing after some decades. Kjerfve and Magill [9] use a systematic review approach and concluded that lagoons will quickly transform into other types of coastal environment without using any data to substantiate their inference. However, this aspect of the research has been able to confirm with scientific evidence that the Lagos Lagoon is a net material sinks, subject to rapid sedimentation, and can easily transform or go into extinction.

The spatial variability of erosion and accretion on the lagoon bed (**Figures 18** and **19**) shows that a large area of about 70,944,744 m^2 was submerged into accretion with approximately 54,148,636 m^3 volume of sediment gained around the area. This large sediment deposition gives an indication that change in the lagoon bed is evident, that sediment is drifting constantly into the lagoon through erosion reducing the depth of the lagoon very fast despite the fact that there local dredging is going on within the system.

4.5.3 The region west of the lagoon: sediment migration around Ogudu Region

The Ogudu inlet area shows a complicated bed pattern, which potentially endangers small boat movement because of its extremely shallow depth possibly due to the influx of industrial effluents and sediments that have been channelled through the place.

It was impossible to take measurements around the Ogudu Region of the lagoon during the research field data collection; possibly, it could be inferred from the result in Section 4.5.1 that a fast accretion of sediment takes place in the western zone of the lagoon where there is a large human population and industrial settlements are located. This region is where the Ogudu channel brings the largest quantity of sediment into the lagoon.

Generally, the mean difference of the depth value of 2008 and 2014 dataset was found to be extremely small. This was shown in the multiple range tests in **Table 4**

Sediment status	Volume (m^3)	Area (m^2)
Accretion	54,148,636	70,944,744
Erosion	54,011,207	70,085,812
Total accretion or erosion	137,429	858,932

Table 11.
Summary of erosion/accretion calculation on the lagoon water bed.
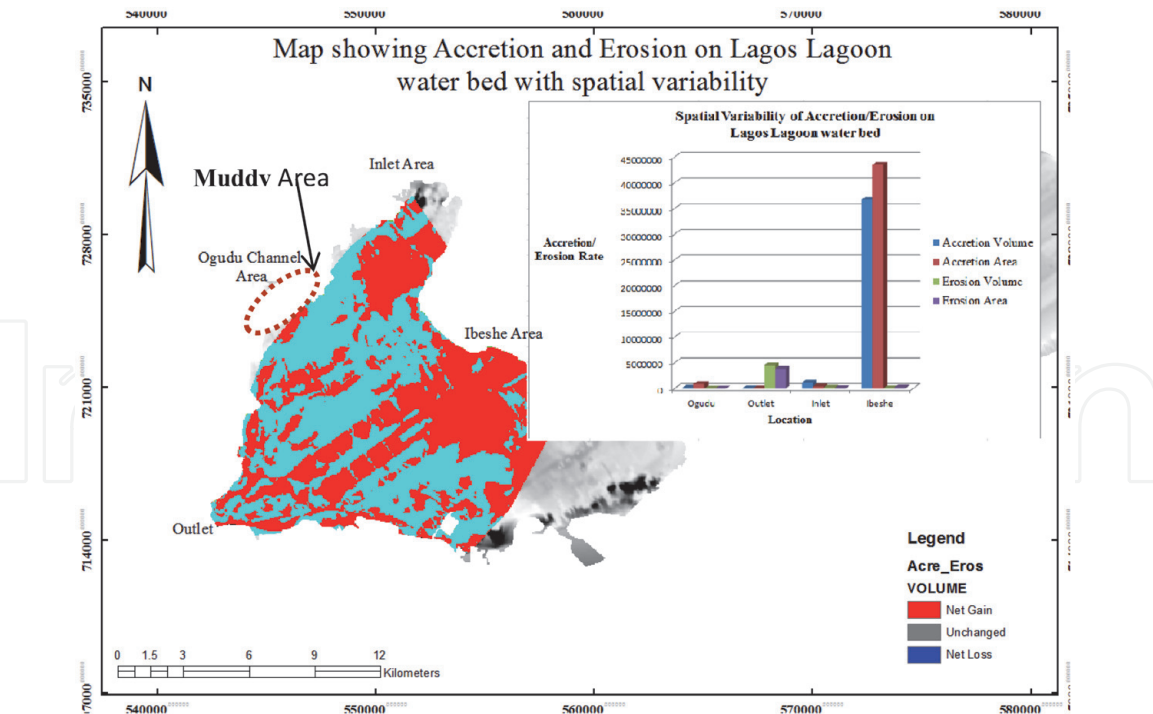
Figure 18.
Spatial variability of sediment accretion and erosion on Lagos Lagoon water based on 2008 and 2014 repeated bathymetric data. Area = metres squared and volume = metres cubed.
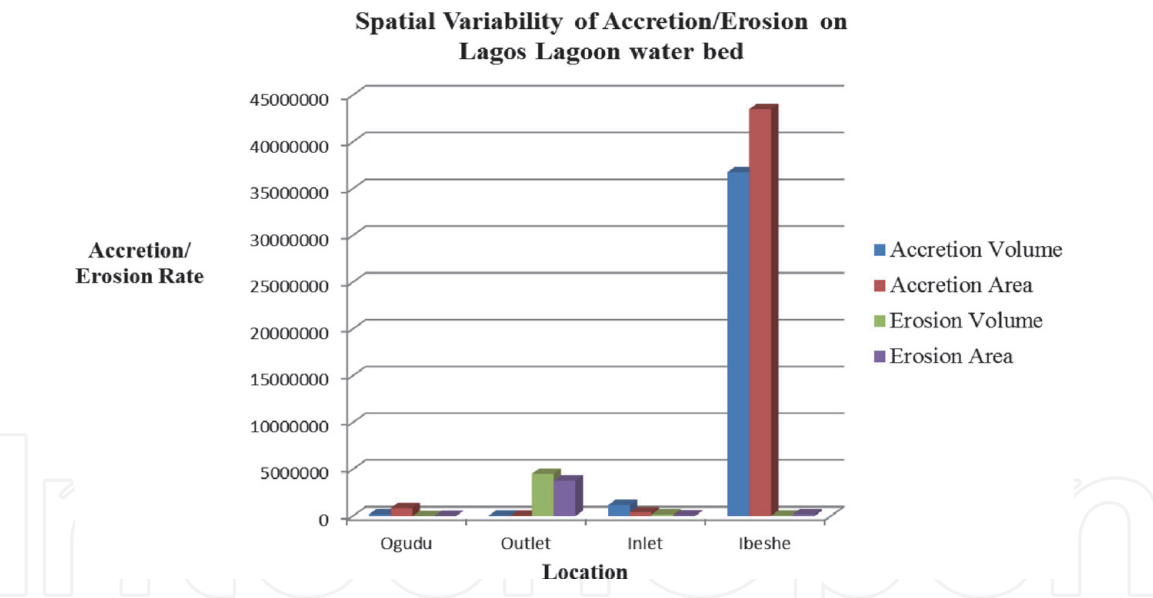

Figure 19.
Chart showing spatial variability of sediment accretion and erosion on Lagos Lagoon bed based on two repeated bathymetric data of 2008 and 2014. Area = metres squared and volume = metres cubed.

as approximately -0.251, the mean difference of profile C of 2014 and profile D of 2008. This implies that whatever the depths range from the area of this region of the lagoon in 2008 it has been reduced excessively in 2014. The decrease in the depth of the lagoon water bed could likely be increasing as a result of urbanisation that has exposed the majority of the lagoon ecosystem, which invariably causes increased erosion of sediment to the lagoon.

4.6 Significance of the accretion spatial variability

Four locations near to urban growth were chosen to take lagoon bed samples. Very significant to the sediments from each of the locations is that their grain sizes

Size of mesh (mm)	Sediment weight (g)	Remark
(i) Five Cowries		
2.36	2.5	100% whitish brown shell
1.18	1.8	Whitish brown
600 μm	3.1	Whitish brown
425 μm	3.6	
300 μm	10.4	
212 μm	29.0	
150 μm	24.0	
75 μm	23.7	
(ii) Ebute-Meta		
2.36	8.22	90% whitish shell
1.18	6.07	White shell and 60% brownish grains
600 μm	12.05	Brownish grains
425 μm	4.97	
300 μm	5.64	Dark and brownish grains
212 μm	10.79	Dark and brownish grains
150 μm	12.95	Dark and brownish grains
75 μm	21.08	
(iii) Ijede		
2.36	1.7	100% whitish shell
1.18	1.63	60% brown pebbles
600 μm	20.46	99% brown pebbles with traces of whitish grains
425 μm	14.27	Grains with black patches
300 μm	16.44	Grains with black patches
212 μm	21.85	Brown with dark grains
150 μm	13.26	Brown with dark grains
75 μm	7.66	Darkish brown grains
(iv) Inlet		
2.36	0	
1.18	0.12	Blackish grains
600 μm	1.28	Blackish grains
425 μm	0.63	Blackish grains
300 μm	0.78	Blackish grains + whitish patches
212 μm	1.00	Blackish grains + whitish patches
150 μm	1.19	Blackish grains with shinning whitish grains
75 μm	26.26	Dark brownish with whitish grains

Table 12.
Sieve analysis of sediment from four spatial locations around the lagoon.

are very similar both in colour and texture, and **Table 12(i-iv)** shows the summary of the sieve analysis performed on the sediments collected from the four locations. The results show the composition of the whitish shell as a major boulder or cobble

Source	Sum of squares	Df	Mean square	F-Ratio	P-Value
Model	1.11515E15	1	1.11515E15	2446.67	**0.0000**
Residual	2.27891E12	5	4.55782E11		
Total (Corr.)	1.11743E15	6			

Table 13.
ANOVA test on change in sediment deposition in six spatial locations on the lagoon.

sediments in three of the locations, this could imply the effect of increased stress (through human activities) on the lagoon ecosystem where the habitats live, and hence, their displacement probably leads to their extinction as their habitation is depleted. The sediments around Ebute-Metta show large grain size than any other locations. This could likely be sediments of industrial refuse that are channelled into the lagoon through Ebute-Metta channel where the sample was collected.

At Ijede, the grain with the largest percentage of sediment during sieve analysis was silt and sand; hence, the prevailing colours were mostly brown (silt sediment) and grey (sand sediment). The texture of the sample at this location was slightly cohesive and frictional. However, the sample at Ebute-Metta was slightly different from that of Ijede in that there is more cobble sediment at Ebute-Metta than the proportion present in Ijede. The sample at the inlet completely displays sediment that is largely cohesive clay, dark brownish in colour, but completely void of cobble-sized sediments from the remains of water snail shells.

Further analysis was carried out on quantitative verification of the sediment gain in some part of the lagoon bed using the initial four spatial locations. The volume of sediment accreted in the area was calculated with the coverage area. To establish the relationship that exists between the volume of sediment and area covered, an analysis of variance (ANOVA) was carried out to test whether there is significant difference between the volume of sediment and the area (with 95% confident interval). The result of the ANOVA test is summarised in **Table 13**, which shows that there is a significant difference in the volume of sediment accretion/erosion in the area subject to the test.

4.6.1 Summary of the analysis of variance

Correlation coefficient = **0.99898**.
R-squared = **99.7961%**.
R-squared (adjusted for d.f.) = **99.7553%**.
Standard error of est. = **675,116**.
Mean absolute error = **477,716**.

4.7 Error analysis

This section outlines the basic procedure that is used for calculating volumetric errors provided the estimates of the vertical (Δd) are known. If Δd values are unavailable for the specific surveys, standard errors of ± 0.15, ± 0.3 or ± 0.45 m can be used based on the class of survey [66]. For every coastal survey (surveys on lagoons, estuaries, lakes and surveys close to the shore), it is assumed that errors in horizontal positioning (Δx and Δy) are random and have an insignificant effect on the volumes compared with possible errors in water depth measurements, tide correction and data reduction.

The volumetric error difference between different repeated bathymetric surveys was estimated by determining how much the average depth in each

chart changes from one survey to another. Maximum likely error (MLE) was computed as:

$$MLE = \frac{2 \times \Delta z}{\Delta z_{ave}} \qquad (1)$$

where Δz is the change in depth between the different surveys at a point and Δz_{ave} is the average of depth changes over the entire survey area.

Three points were sampled at approximately mid-region on the area where bathymetric data were collected on the lagoon, and depth difference between the two repeated bathymetric data was determined, averaged and recorded as Δz. Δz_{ave} was determined by taking difference in the depth between the two bathy data at different parts of the study area and ensure these was distributed almost equally over the data coverage, and the mean was taken and recorded as average of depth changes over the entire survey area. The values of the two variables were computed as:

$$\Delta z = 0.27 \, m \qquad (2)$$

$$\Delta z_{ave} = 1.211 \, m \qquad (3)$$

Therefore,

$$
\begin{aligned}
MLE \quad &= \frac{2 \times \Delta z}{\Delta z_{ave}} \\
&= \frac{2 \times 0.27}{1.211} \\
&= 0.446, \text{approximately } 45\%
\end{aligned}
\qquad (4)
$$

This means that the maximum likely possible error from the two repeated bathymetric data is 45%. The lesser the percentage, the better the surveys and the better the specifications used in the surveys [66]. The computed percentage is allowable for engineers' survey in the coastal area [66]. Hence, for monitoring purpose, the maximum likely error MLE is suitable to detect changes on the lagoon bed.

4.8 Accounting for uncertainty in the lagoon bed dynamics

Depth plays a significant role in the monitoring of the lagoon bed dynamics because depth measurement is a key parameter that influences many processes in lagoon water bed dynamics as is the case in coastal changes [77]. This section of the study has produced maps and statistical summaries of the potential risk of losing the lagoon to sediment accretion and that it could be filled up with sand in a few decades.

Limitations of the monitoring assessment using repeated hydrographic surveys to serve as the uncertainties, which include the disturbances produced by small vessels and the uncontrolled human activities on the water, cannot easily be accounted for. For this study, the uncertainty in the monitoring assessment was not accounted for because of the short time that was allotted for data gathering and unavailability of personnel.

From the four spatial locations selected for comparative analysis of erosion and accretion variability on the lagoon bed floor (**Figure 18**), three of the locations (Ibeshe, Inlet and Ogudu) show that the areas are prone to accretion more than erosion. Ibeshe area (north eastern) of the lagoon recorded the highest rate of sediment accretion. In contrast, the lagoon outlet area exhibits more erosion than accretion.

Considering the degree of accretion on the lagoon water bed and the impact it will have on the lagoon and its ecosystem, it is clear that consistent repeated bathymetric data will be suitable to monitor the dynamics of the lagoon bed. In further investigation, there is need for a multi-beam hydrographic data with a high accuracy of depth values.

5. Discussion and conclusions

5.1 Overview

This study explores comparative analysis between available two repeated bathy-metric data of 2008 and 2014. The findings indicate that overall the Ibeshe region of the lagoon experienced the largest volume of accretion and it has the widest area covered by accretion. Generally speaking, the total accretion was found higher than the erosion that takes place in the lagoon. This gives a signal that the depth of the lagoon is reducing. Joining this finding with the result of Taiwo and Areola [78] that shows loss in the lagoon ecosystem and a gradual reduction in the surface area of the lagoon due to encroachment on its coastline, it can be concluded that as a result of increasing urbanisation, the lagoon is moving toward extinction despite its large area of coverage.

5.2 Dynamics of the lagoon sea bed

A lagoon system and its adjacent basins are dynamic on different spatial and temporal scales. As human activities increase with increased urbanisation, the vol-ume of sediment accreting into the lagoon is assumed to be increasing on daily basis. This, in turn, influences the natural morphology of the lagoon coastline. Van Der Wal and Pye [79] investigated the morphological changes in estuaries with the use of historical bathymetric charts. Again, Hicks and Hume [80] determined sand volume and bathymetric changes on an ebb-tidal delta using repeated bathymetric surveys and they were able to detect net sand gains or losses over the ebb-tidal delta. The repeated bathymetric surveys were treated independently even though they were plotted together on the same ArcGIS interface. They exhibited that the accuracy of the surface-fitting and determinations of mean surface levels varied depending on the local sea bed topography [80]; hence, to avoid error and uncer-tainty, an interpolation method (kriging) that supported the local geographic spread of the data was adopted. A triangular irregular network (TIN) was chosen because it incorporates original height (Z) values not estimates; hence, the calcula-tion of volumes at different spatial locations and differences in mean bed levels between the repeated surveys was performed.

The result shows that over a 6-year period that the repeated bathymetric data covered, the lagoon decreased in depth by an average of 0.16 m (0.026 m/year). Without any dredging or other removal, the study area of the lagoon will have gained 1.3 m of sediment in a 50-year period. Indeed, this result supports Kjerfve [32], Kjerfve [25] and Barnes [8] who said lagoons are short lived in geological time. This fact assisted to understand the choice of data type (temporal scale data) that is fit to detect short-term changes in any lagoon as it was in the research case study area. Hence, a proper monitoring measure must be taken to avert the sudden disappearance of the lagoon some decades from now.

The results in this section are also supported by Van Der Wal and Pye [79] that indicated repeated and sequential bathymetric mapping or bed surveys can be used

to calculate erosion rates and sedimentation. Sources of error and uncertainty are due mainly as a result of the surveying techniques used [81], the density of depth sampling points [82], interpolation and averaging [83] during compilation. The error and uncertainty due to survey methods and density of depth sampling are cared for during the survey exercise, while the careful choice of the interpolation method helps to reduce the uncertainty that could result from interpolation. Documentation on the sea bed morphological development of a lagoon is often needed to support its management, such as navigation, flood defence and habitat preservation, and the effects of changes in natural forcing factors (sea level rise) on the lagoon ecosystem. The present rate of change in the lagoon sea floor must be made a baseline for assessing historic evolution in order to understand and predict its sea bed dynamic trend. However, this demands both reliable data and consistent effective survey methods.

5.3 Sea-level rise and its impact on the coastal lagoon

Numerous possible responses to sea level rise abound among which are inundation and flooding [55, 58, 84–86]. Prospective studies that focus on identifying the complex nature of the changes along the Nigeria coast should precede assessment of sea level; hence, the two combined can be evaluated to see the effect of sea level rise on the lagoon and other lagoons bounded along the Nigerian coastline. This is because the same rate of sea level rise scenario could bring different degrees of impact on different spatial locations on the coastline.

5.4 Concluding remarks

From all the results presented in this study, changes exist on the lagoon bed, which are deemed highly significant. Therefore, it is recommended for any future studies that there is a need for consistent bathymetric data and that it is acquired with a high level of accuracy. This will help in measuring and monitoring the consistent change on the lagoon bed and also facilitate decision-making for better management of the system.

On the basis of the foregoing evidence from the result in this chapter, it can be concluded that the lagoon bed sediment is appreciating gradually over years. If proper caution is not taken to monitor the diversion of effluent, erosion and runoff into the lagoon, in the next few decades, the entire lagoon may have reduced greatly both in plane and depth. With this conclusion, the lagoon can be managed and sustained from immediate future disappearance by employing consistent maintenance dredging on the system. Conversely, the cost of doing such consistent maintenance dredging might be too high for the government and hence a pro-active sustainable management of the lagoon and its ecosystem is the unique solution to the problem.

Although the results of this methodology address a particular lagoon, however, it can be adapted to lagoons and estuaries globally since in the global context, many lagoons and estuaries are faced with increased urbanisation around their ecosystem and the same forcing conditions are responsible for the changes in the systems. This section has been able to provide a synthesis that can be used globally for sustainable monitoring of the lagoon system in any region of the world.

This chapter has been able to use repeated bathymetric measurements to assess the dynamics of the Lagos Lagoon bed. The assessment revealed that a constant change mostly in terms of accretion takes place on the system's bed. However, there are other sections of the lagoon bed that experience erosion. The study achieves a

major part of research objective that aims at assessing the dynamic nature of the lagoon and assesses what effect the changes induce.

6. Summary and recommendations

This chapter has been able to sum up its findings in this research that Lagos Lagoon is highly vulnerable to morphodynamic changes, and these changes include, as investigated in this research, interaction and the adjustment of its floor topography, and sequences of change involving the lagoon spatial sediment. Hence, it has been discovered from the research finding that the lagoon faces the challenge of sustainability and extinction due to poor planning across its ecosystem.

Mitigating the potential effects of morphological and hydrodynamic changes on a lagoon is a controversial issue, with many unanswered questions and a great portion of uncertainty.

The use of a functional mechanism to build a model for detecting the coastline changes of the lagoon was made possible with the application of ArcGIS 10.1. The model derived has been useful to ascertain the degree of transgression and regression of the lagoon coastline. From literature, it was discovered in 2010 that the lagoon surface area was 208 km^2. However, the results of the model revealed the present surface area to be approximately 204 km^2. Hence, the lagoon is gradually disappearing. Likewise, in the lagoon seafloor, specifically in the region used as a case study, the depth has decreased by an average of 0.16 m (0.026 m/year). By implication, without any dredging, the study area will have gained 1.3 m of sediment during a 50-year period.

For better management and sustainability of the lagoon, consistent measurement should go on henceforth especially measurement regarding bathymetry survey, flow and mixing in the lagoon.

Acknowledgements

Author details

Alfred Sunday Alademomi[1,2*], Andrew J. Manning[2,3], Victor J. Abbott[2]
and Richard J.S. Whitehouse[3]

1 Department of Surveying and Geoinformatics, Faculty of Engineering,
University of Lagos, Nigeria

2 Faculty of Science and Engineering, School of Biological and Marine Sciences,
University of Plymouth, Devon, United Kingdom

3 Coasts and Oceans Group, HR Wallingford, Oxfordshire, United Kingdom

*Address all correspondence to: geomfred@yahoo.com

IntechOpen

References

[1] Adger WN, Hughes TP, Folke C, Carpenter SR, Rockström J. Social-ecological resilience to coastal disasters. Science. 2005;**309**(5737):1036-1039

[2] Folke C. Resilience: The emergence of a perspective for social-ecological systems analyses. Global Environmental Change. 2006;**16**(3):253-267

[3] Phleger F. A review of some general features of coastal lagoons. In Coastal lagoon research, present and future: Proceedings of a seminar. UNESCO Technical Papers in Marine Science. Paris, France: United Nations Educational, Scientific, and Cultural Organization; 1981:7-14

[4] Gonenc IE, Wolflin JP. Coastal Lagoons: Ecosystem Processes and Modelling for Sustainable Use and Development. New York, USA: CRC Press; 2004

[5] Mitsch WJ, Gosselink JG. The value of wetlands: The importance of scale and landscape setting. Ecological Economics. 2000;**35**(1):25-33

[6] Lloret J, Marín A, Marín-Guirao L. Is coastal lagoon eutrophication likely to be aggravated by global climate change? Estuarine, Coastal and Shelf Science. 2008;**78**(2):403-412

[7] Newton A, Icely J, Falcao M, Nobre A, Nunes J, Ferreira J, et al. Evaluation of eutrophication in the Ria Formosa coastal lagoon, Portugal. Continental Shelf Research. 2003;**23**(17):1945-1961

[8] Barnes RSK. Coastal Lagoons. Vol. 1. Cambridge, UK: Cambridge University Press; 1980. pp. 106

[9] Kjerfve B, Magill KE. Geographic and hydrodynamic characteristics of shallow coastal lagoons. Marine Geology. 1989; **88**(3):187-199

[10] Oliveira A, Fortunato AB, Rego JR. Effect of morphological changes on the hydrodynamics and flushing properties of the Óbidos lagoon (Portugal). Continental Shelf Research. 2006;**26**(8): 917-942

[11] Barnes R. The coastal lagoons of Britain: An overview and conservation appraisal. Biological Conservation. 1989; **49**(4):295-313

[12] Pari Y, Murthy R, Subramanian B, Ramachandran S. Morphological changes at Vellar estuary, India—Impact of the December 2004 tsunami. Journal of Environmental Management. 2008;**89**(1):45-57

[13] da Silva JF, Duck RW. Historical changes of bottom topography and tidal amplitude in the Ria de Aveiro, Portugal trends for future evolution. Climate Research. 2001;**18**(1–2):17-24

[14] Duck RW, da Silva JF. Coastal lagoons and their evolution: A hydro-morphological perspective. Estuarine, Coastal and Shelf Science. 2012;**110**:2-14

[15] Lopes CL, Plecha S, Silva PA, Dias JM. Influence of morphological changes in a lagoon flooding extension: Case study of Ria de Aveiro (Portugal). Journal of Coastal Research. 2013;**65** (sp2):1158-1163

[16] Mohanty P, Panda B. Circulation and mixing processes in Chilika lagoon. Indian Journal of Marine Sciences. 2009; **38**(2):205

[17] Amaeze NH, Egonmwan RI, Jolaosho A, Otitoloju A. Coastal environmental pollution and fish species diversity in Lagos lagoon, Nigeria. International Journal of Environmental Protection. 2012;**2**(11):8-16

[18] Edokpayi C, Ayorinde A. Physical, chemical and macrobenthic invertebrate

fauna characteristics of swampy water bodies within University of Lagos, Nigeria. West African Journal of Applied Ecology. 2005;**8**(1):129-139

[19] Phillips Olusegun A, Falana Adenike O, Olayiwola Moshood A. Assessment of environmental impact on benthic foraminiferal distribution in Lagos lagoon, Nigeria. Journal of Mining and Geology. 2012;**48**(1):68-78

[20] Amaeze NH, Schnell S, Sozeri O, Otitoloju AA, Egonmwan RI, Arlt VM, et al. Cytotoxic and genotoxic responses of the RTgill-W1 fish cells in combination with the yeast oestrogen screen to determine the sediment quality of Lagos lagoon, Nigeria. Mutagenesis. 2015;**30**(1):117-127

[21] Nkwoji J, Onyema I, Igbo J. Wet season spatial occurrence of phytoplankton and zooplankton in Lagos lagoon, Nigeria. Science World Journal. 2010;**5**(2):7-14

[22] Ajagbe F, Osibona A, Otitoloju A. Diversity of the edible fishes of the Lagos lagoon, Nigeria and the public health concerns based on their lead (Pb) content. International Journal of Fisheries and Aquaculture. 2012;**4**(3): 55-62

[23] Olapoju OA, Edokpayi CA. Ecological study on the impact of mariculture fish cage site on the physico-chemical characteristics of Lagos lagoon, South Western Nigeria. Journal of Ecology and The Natural Environment. 2014;**6**(12):398-405

[24] Kjerfve B. Comparative oceanography of coastal lagoons. In Wolfe DA, editor. Estuarine Variability. Academic Press; 1986:63-81

[25] Kjerfve B. Coastal lagoons. Elsevier Oceanography Series. 1994;**60**:1-8

[26] Kennish MJ, Paerl HW. Coastal Lagoons: Critical Habitats of Environmental Change. CRC Marine Science Series. Boca Raton, Florida USA: CRC Press; 2010

[27] Carter RWG, Woodroffe CD. Coastal evolution: An introduction. In: Coastal Evolution. Late Quaternary Shoreline Morphodynamics. Cambridge, UK: Cambridge University Press; 1994:1-31

[28] Elliott M, McLusky DS. The need for definitions in understanding estuaries. Estuarine, Coastal and Shelf Science. 2002;**55**(6):815-827

[29] Mouillot D, Gaillard S, Aliaume C, Verlaque M, Belsher T, Troussellier M, et al. Ability of taxonomic diversity indices to discriminate coastal lagoon environments based on macrophyte communities. Ecological Indicators. 2005;**5**(1):1-17

[30] Anthony A, Atwood J, August P, Byron C, Cobb S, Foster C, et al. Coastal lagoons and climate change: Ecological and social ramifications in U.S. Atlantic and Gulf coast ecosystems. Ecology and Society. 2009;**14**(1):8. Available at: http://www.ecologyandsociety.org/vol14/iss1/art8/

[31] Nichols MM, Boon JD. Sediment transport processes in coastal lagoons. Elsevier Oceanography Series. 1994;**60**: 157-219

[32] Kjerfve B. Coastal lagoon processes. 1994. Access Online via Elsevier [Accessed: May 2014]

[33] Bhattacharya JP, Giosan L. Wave-influenced deltas: Geomorphological implications for facies reconstruction. Sedimentology. 2003;**50**(1):187-210

[34] Bird ECF. Coastal Geomophology—An Introduction. 2nd ed. West Sussex, England: John Wiley & Sons Ltd; 2008

[35] Manning AJ, Whitehouse RJS, Uncles RJ. Suspended particulate matter: The measurements of flocs. In: Uncles RJ, Mitchell S, editors. ECSA

Practical Handbooks on Survey and Analysis Methods: Estuarine and Coastal Hydrography and Sedimentology. Cambridge, UK: Cambridge University Press; 2017. pp. 211-260. DOI: 10.1017/9781139644426

[36] Manning AJ, Dyer KR. A laboratory examination of floc characteristics with regard to turbulent shearing. Marine Geology. 1999;**160**:147-170

[37] Manning AJ, Dyer KR. Mass settling flux of fine sediments in northern European estuaries: Measurements and predictions. Marine Geology. 2007;**245**: 107-122. DOI: 10.1016/j.margeo.2007.07.005

[38] Mehta AJ, Manning AJ, Khare YP. A note on the Krone deposition equation and significance of floc aggregation. Marine Geology. 2014;**354**:34-39. DOI: 10.1016/j.margeo.2014.04.002

[39] Soulsby RL, Manning AJ, Spearman J, Whitehouse RJS. Settling velocity and mass settling flux of flocculated estuarine sediments. Marine Geology. 2013;**339**:1-12. DOI: 10.1016/j.margeo.2013.04.006

[40] Schoellhamer DH, Manning AJ, Work PA. Erosion characteristics and horizontal variability for small erosion depths in the Sacramento-San Joaquin River Delta, California, USA. Ocean Dynamics. 2017:**67**(6): 799-811. DOI: 10.1007/s10236-017-1047-2.29

[41] Malarkey J, Baas JH, Hope JA, Aspden RJ, Parsons DR, Peakall J, et al. The pervasive role of biological cohesion in bedform development. Nature Communications. 2015;**6**:6257. DOI: 10.1038/ncomms7257

[42] Parsons DR, Schindler RJ, Hope JA, Malarkey J, Baas JH, Peakall J, et al. The role of biophysical cohesion on subaqueous bed form size. Geophysical Research Letters. 2016;**43**(4):1566-1573. DOI: 10.1002/2016GL067667

[43] Roy P, Williams R, Jones A, Yassini I, Gibbs P, Coates B, et al. Structure and function of south-east Australian estuaries. Estuarine, Coastal and Shelf Science. 2001;**53**(3): 351-384

[44] Adlam K. Coastal lagoons: Geologic evolution in two phases. Marine Geology. 2014

[45] Barnes RSK. Estuarine Biology. London: Edward Arnold; 1974. p. 77

[46] Contanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, et al. The value of the world's ecosystem services and natural capitals. Nature. 1997; **387**(6630):253-260

[47] Fernandes EHL, Dyer KR, Moller OO. Spatial gradients in the flow of southern Patos lagoon. Journal of Coastal Research. 2005:759-769

[48] Moller OO, Stech J, Math MM. The Patos lagoon summertime circulation and dynamics. Continental Shelf Research. 1996;**16**(3):335-351

[49] Condie Scott A, Dunn Jeff R. Seasonal characteristics of the surface mixed layer in the Australasian region: Implications for primary production regimes and biogeography. Marine and Freshwater Research. 2006;**57**: 569-590

[50] Ayoola S, Kuton M. Seasonal variation in fish abundance and physico-chemical parameters of Lagos lagoon, Nigeria. African Journal of Environmental Science and Technology. 2009;**3**(5):149-156

[51] Balogun K, Ladigbolu I, Ariyo A. Ecological assessment of a coastal shallow lagoon in Lagos, Nigeria: A bio-indicator approach. Journal of Applied Sciences and Environmental Management. 2011;**15**(1):41-46. DOI: 10.4314/jasem.v15i1.65673

[52] Change IPOC. Climate change 2007: The physical science basis. Agenda. 2007;**6**(07):333

[53] Titus JG, Hudgens D, Trescott D, Craghan M, Nuckols W, Hershner C, et al. State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. Environmental Research Letters. 2009;**4**(4):044008

[54] Houghton JT, Ding Y, Griggs DJ, et al. The scientific basis, intergovernmental panel on climate change. Climate Change. 2001

[55] Nicholls RJ, Marinova N, Lowe JA, Brown S, Vellinga P, De Gusmao D, et al. Sea-level rise and its possible impacts given a 'beyond 4 C world' in the twenty-first century. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences. 2011;**369**(1934): 161-181

[56] McInnes K, Walsh K, Hubbert G, Beer T. Impact of sea-level rise and storm surges on a coastal community. Natural Hazards. 2003;**30**(2):187-207

[57] Morris JT, Sundareshwar P, Nietch CT, Kjerfve B, Cahoon DR. Responses of coastal wetlands to rising sea level. Ecology. 2002;**83**(10): 2869-2877

[58] Nicholls RJ, Cazenave A. Sea-level rise and its impact on coastal zones. Science. 2010;**328**(5985):1517-1520

[59] Titus JG, Park RA, Leatherman SP, Weggel JR, Greene MS, Mausel PW, et al. Greenhouse effect and sea level rise: The cost of holding back the sea. Coastal Management. 1991;**19**(2): 171-204

[60] Nicholls RJ, Hoozemans FM, Marchand M. Increasing flood risk and wetland losses due to global sea-level rise: Regional and global analyses.

Global Environmental Change. 1999;**9**: S69-S87

[61] Ajao E, Fagade S. A study of the sediments and communities in Lagos lagoon, Nigeria. Oil and Chemical Pollution. 1990;**7**(2):85-117

[62] Webb JE. The ecology of Lagos lagoon. V. Some physical properties of lagoon deposits. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences. 1958;**241**(683):335-353

[63] Hill MB, Webb JE. The ecology of Lagos lagoon II. The topography and physical features of Lagos harbour and Lagos lagoon. Philosophical Transactions of the Royal Society A: London. 1958, 1958;**241**(B):317-417

[64] Fagade SO, Olaniyi CIO. Seasonal distribution of the fish fauna of the Lagos lagoon. Bulletin De IFAN Series A. 1974;**36**(1):244-252

[65] Ajao EA. Review of the state of pollution of the Lagos lagoon. In: NIOMR Technical Paper, Nigeria Institution of Oceanography, Lagos Nigeria, No. 106. 1996. 19 pp

[66] Gorman L, Morang A, Larson R. Monitoring the coastal environment; Part IV: Mapping, shoreline changes, and bathymetric analysis. Journal of Coastal Research. 1998:61-92

[67] Helmuth B, Harley CD, Halpin PM, O'Donnell M, Hofmann GE, Blanchette CA. Climate change and latitudinal patterns of intertidal thermal stress. Science. 2002;**298**(5595): 1015-1017

[68] Kelaher B, Underwood A, Chapman M. Experimental transplantations of coralline algal turf to demonstrate causes of differences in macrofauna at different tidal heights. Journal of Experimental Marine Biology and Ecology. 2003;**282**(1):23-41

[69] Hilldale RC, Raff D. Assessing the ability of airborne LiDAR to map river bathymetry. Earth Surface Processes and Landforms. 2008;**33**(5):773

[70] Kuwahara S. The velocity of sound in sea water and calculation of the velocity for use in sonic sounding. Japanese Journal of Astronomy and Geophysics. 1938;**16**:1

[71] USACoE. Hydrographic surveying. In: Engineer Manual EM 1110-2-1003, US Army Corps of Engineers. Washington: DC; 1994

[72] Stauble DK, Garcia AW, Kraus NC, Grosskopf WG, Bass GP. Beach Nourishment Project Response and Design Evaluation: Ocean City, Maryland. DTIC Document. 1993

[73] Brummer CJ, Abbe TB, Sampson JR, Montgomery DR. Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. Geomorphology. 2006;**80**(3):295-309

[74] Nanson GC, Hickin EJ. A statistical analysis of bank erosion and channel migration in western Canada. Geological Society of America Bulletin. 1986;**97**(4): 497-504

[75] Shields FD Jr, Simon A, Steffen LJ. Reservoir effects on downstream river channel migration. Environmental Conservation. 2000;**27**(01):54-66

[76] Gastwirth JL, Gel YR, Miao W. The impact of Levene's test of equality of variances on statistical theory and practice. Statistical Science. 2009: 343-360

[77] Gesch DB. Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise. Journal of Coastal Research. 2009:49-58

[78] Taiwo OJ, Areola O. A spatial-temporal analysis of wetland losses in the Lagos coastal region, southwestern Nigeria, using multi-date satellite imagery. In: 2009 IEEE International Geoscience and Remote Sensing Symposium. IEEE. 2009. pp. III-928-III-930

[79] Van Der Wal D, Pye K. The use of historical bathymetric charts in a GIS to assess morphological change in estuaries. The Geographical Journal. 2003;**169**(1):21-31

[80] Hicks DM, Hume TM. Determining sand volumes and bathymetric change on an ebb-tidal delta. Journal of Coastal Research. 1997:407-416

[81] Cracknell A. Remote sensing techniques in estuaries and coastal zones: An update. International Journal of Remote Sensing. 1999;**20**(3):485-496

[82] Bowyer J. Basin changes in Jervis Bay, New South Wales: 1894–1988. Marine Geology. 1992;**105**(1):211-224

[83] Burrough PA, McDonnell RA, McDonnell R, Lloyd CD. Principles of Geographical Information Systems. Oxford, UK: Oxford University Press; 2015

[84] Church JA, White NJ. A 20th century acceleration in global sea-level rise. Geophysical Research Letters. 2006;**33**(1)

[85] Church JA, White NJ. Sea-level rise from the late 19th to the early 21st century. Surveys in Geophysics. 2011;**32** (4–5):585-602

[86] Nicholls RJ, Wong PP, Burkett V, Codignotto J, Hay J, McLean R, et al. Coastal systems and low-lying areas. In: Parry ML, et al, editors. Climate Change. Impacts, Adaptation, and Vulnerability. Cambridge, UK: Cambridge University Press; 2007: 315-357