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Lagoon Environments Around the World

A Scientific Perspective

Edited by Andrew J. Manning

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Meet the editor

Professor Andrew J. Manning is a Principal Scientist (Rank Grade 9) in the Coasts & Oceans Group at HR Wallingford (UK), and has over 23 years of scientific research experience (in both industry and academia) examining natural turbulent flow dynamics, fine-grained sediment transport processes, and assessing how these interact (including both field studies and controlled laboratory flume simulations). Andrew also lectures in Coastal & Shelf Physical Oceanography at the University of Plymouth (UK). Internationally, Andrew has been appointed Visiting/Adjunct/Guest Professor at five universities (Hull, UK; Stanford, USA; Delaware, USA; Florida, USA; TU Delft, Netherlands), and is a highly published and world-renowned scientist in the field of depositional sedimentary flocculation processes. He is a Fellow of the Royal Geographical Society, was awarded a UoP Vice Chancellor's Research Fellowship (2007), and was presented the 'Exemplary Act Award' by the United States Department of the Interior & U.S. Geological Survey (2015). Andrew has contributed to more than 100 peer-reviewed publications in marine science, of which more than 50 have been published in international scientific journals, plus over 140 articles in refereed international conference proceedings, and currently has an *H-index* of 24. He supervises graduates, postgraduates, and doctoral students focusing on a range of research topics in marine science. Andrew has led numerous research projects investigating sediment dynamics in aquatic environments around the world with locations including: estuaries, tidal lagoons, river deltas, salt marshes, intertidal, coastal waters, and shelf seas.

Contents

Preface

Lagoon Environments Around the World - A Scientific Perspective covers a wide range of topics. Typically bordering between land and sea, lagoons are among the most diversely utilized waterways on the planet. Lagoons are extremely important environments socio-economically, and their usage places ever increasing stress on these very sensitive aquatic regions.

The effective management of shallow aquatic environments requires a detailed scientific understanding of the various contributary natural processes. This has both environmental and economic implications, especially where there is any anthropogenic involvement. Numerical models are often used for predicting the trends and patterns as they can estimate the various spatial and temporal changes. However, the processes (e.g. physical, biological, and chemical) can vary quite considerably depending on local conditions. Thus, for more than half a century, scientists, engineers, hydrologists, and mathematicians have been continuing to conduct research into the many aspects that influence lagoon environments. These issues range from processes such as water quality, pollution, and phytobenthic communities, to how morphodynamics, water column structure, and habitats can be applied within lagoon environmental frameworks.

This book draws on international scientific research to examine the following lagoon related issues: classification, circulation hydrodynamics, ecosystems, sedimentation, anthropogenic stresses, and response to extreme events. These key topics are each supported by case study examples of lagoons from around the world. The research was carried out by researchers who specialize in shallow water processes and related issues.

It has been a great pleasure to write the preface to this book published by IntechOpen. The book comprises 9 chapters written by a truly international group of research scientists, who specialise in areas such as sediment dynamics, morphology, hydrology, and numerical sediment transport modelling. The majority of the chapters cover issues related to natural process in lagoon environments. For example: autonomous systems for lagoon characterization, GIS-based approaches to assess lagoon run-off, assessments of lagoon coral reefs, and statistical models and field observations to assess the dynamic salinity structure. Other contributions in this book include: lagoon morphology, pollution issues, and biological community structure. Authors are responsible for their views and subsequent concluding statements.

In summary, this book provides an excellent source of information on recent research on lagoon environments, particularly from an interdisciplinary perspective. I would like to thank all of the authors for their contributions and I highly recommend this textbook to both scientists and engineers who deal with the related issues.

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Section 1

Water Quality and Pollution

Chapter 1

Pollution Issues in Coastal Lagoons in the Gulf of Mexico

Alfonso Vazquez Botello, Guadalupe de la Lanza Espino, Susana Villanueva Fragoso and Guadalupe Ponce Velez

Abstract

The coastline of the Mexican Gulf of Mexico is an area of paramount importance. It poses valuable biological and ecological resources such as coastal lagoons, rivers, estuaries, wetlands and swamps. It poses 206 coastal systems including 73 coastal lagoons with high biological richness. Their study shows the physicochemical characteristics and pollution levels into the four more productive lagoons of Tampamachoco, Mandinga, Alvarado in the Veracruz state and Terminos Lagoon in Campeche state, México, have the present characteristics. The lagoons show a wide interval in physiochemical parameters (temperature: 18–32°C, salinity: 11–38 ups, and nutrients: oxygen 1.8–9.0 mg/L, total phosphorus 2.6–123 μM total nitrogen 5–70 μM, and chlorophyll 10–50 mg/m^3). All of them oscillated between normal to eutrophication condition. The presence of PAHs and some of the high toxicity as anthracene, and chrysene, as well as naphthalene and its methyl derivatives has been reported. Also, chlorinated hydrocarbons used for agriculture purposes and malaria control (DDT, lindane, endosulfan) have been identified in these lagoons. Metals as Cr, Pb, Ni, Cd, and V among others were recently reported in the lagoons considered in this study. Concentrations of pollutants also show significant variations depending on the time and the type of lagoon, or estuary.

Keywords: Gulf of Mexico, coastal lagoons, physicochemical features, pollution, metals, petroleum hydrocarbons, pesticides, sediments, ecotoxicology, nutrients

1. Introduction

1.1 Main coastal lagoons in the Gulf of Mexico

One of the great problems of the coastal zone of the Gulf of Mexico is the diverse and significant water load of the different anthropogenic activities which have not taken into account the volume that must be conserved for the ecological services for which have been lost atmospheres of diverse biological wealth. The coastal flood plains in the Gulf, associated with coastal zones on the border with the terrestrial zone and the sea, are subject to flooding by rainfall, excess fluvial contribution that makeup dikes and channels but that play important roles in the coastal landscape and they contribute to the high production of the coastal zone, however; they run the risk of various deteriorations with or without recovery [1–6].

The coastal zone associated with rivers, is interconnected by an extensive network of wetlands and floodplains temporary and perennial that allow the retention of water,

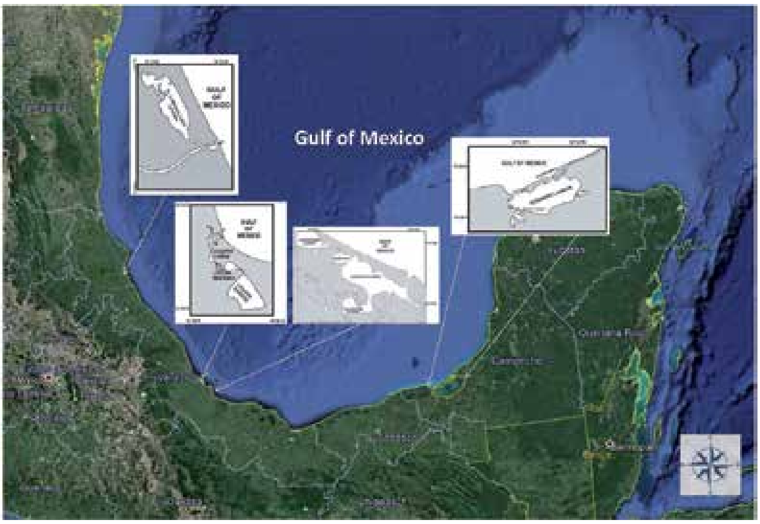

Figure 1.
Location of main coastal lagoons in the Gulf of Mexico.

act as filters, deposits and source for various substances and re the habitat of plant species adapted to these conditions and fauna associated with this vegetation both emerging and submerged. The main problems that lagoons located within or near urban areas have are eutrophication, siltation caused almost always by inadequate management of the urban basin and lack of control of wastewater inlets, but in particular agriculture refuses [7–9]. The Gulf of Mexico is the ninth largest body of water in the world, with five Mexican states to the west. Due to its physical and chemical characteristics, it is a very diverse internal sea as a result of its latitudinal location; from tropical, subtropical to temperate, with climates classified as "dry" (spring), rainy (summer, autumn) and northern (winter) [10]. The coastal lagoons and estuaries of the Gulf of Mexico have been characterized environmentally taking into account: their location, shape, size, runoff and tributary streams, number and size of the mouths of connection with the sea, their behavior throughout the year, their bathymetry, internal currents, the type of sediment they receive from the watershed to which they are associated, gases, dissolved solids or salinity and primary productivity, among others [11]. Based on the foregoing, each coastal lagoon and estuary differs in their mentioned characteristics. Given the high number of coastal systems of the Gulf, the present work has the objective of choosing four coastal lagoons (**Figure 1**) to exemplify their physicochemical natural variations in space and time considering their geographic location two; as well as the level metals, hydrocarbons, and pesticides. This chapter is comprised: a brief description of a four coastal lagoon of the Gulf of Mexico chosen in this study, as well as of the incorporation of previously published information with the methods used to obtain data; the presentation of the results and the consequent discussion; and brief comparison with other lagoons of the coastal region; and the most outstanding conclusion.

2. Methods

2.1 Metals

The technique used for metals was that described [12] consisting of a digestion in a microwave oven (CEM Mars5x) with 3 mL of HF, 10 mL of reagent water and 5 mL of super-pure HNO_3. The samples were read in an ICP-MS (ICP 7500c). Analytical quality was controlled using approved standards, reference material certified for marine sediments (IAE-433). The methodologies used for the analysis of metals are based mainly on the use of acid digestion in a microwave, obtaining afterward the concentrations in an Atomic Absorption Spectrophotometer or in ICP-MS.

2.2 Petroleum (PAHs)

The samples were analyzed for the 16 priority PAHs [13] following the method recommended [14] and used worldwide in marine pollution studies [15–17]. This method involves an organic extraction with n-hexane: methylene chloride 50:50 v/v, concentration of the extract, clean-up using a silica pack, aluminium oxide and anhydrous sodium sulfate, eluted with n-hexane mixtures: methylene chloride 80:20 and 50:50 to obtain the aromatic fraction; the samples were concentrated under a soft N_2 current to dryness.

2.3 Organochlorine pesticides (OCs)

The OCs included the HCH (alpha, beta, gamma and delta isomers), DDT and its metabolites (*p,p'*-DDT, *p,p'*-DDD and *p,p'*-DDE) and the cyclodiene group (heptachlor, heptachlor epoxide, aldrin, dieldrin, endrin, endrin aldehyde, endosulfan I, endosulfan II and endosulfan sulfate); the $\sum$OCPs was calculated from the sum of 16 organochlorine pesticides mentioned. The sediment samples were processed following the technique proposed [18] reported in several studies [19–22]. It consists of extraction with HPLC grade n-hexane, concentration of the organic extract, and cleanup by adsorption chromatography using Florisil and anhydrous sodium sulfate. The cleanup column was eluted with the mixtures n-hexane:ethylic ether 9:1 and 8:2; the final solution was concentrated with N_2 to 2–3 mL for GC analysis. All organic pollutants (PAHs and OCs) were quantified using a Hewlett–Packard 5890 series II gas chromatograph (GC) equipped with an HP-5 silica fused capillary column (30 m × 0.25 mm i.d. with 0.25 μm film thickness).

A flame ionization detector (FID) and an electron capture detector (ECD) were used for PAHs and the organochlorine compounds, respectively. Quantification was carried out using the internal calibration method based on a five-point calibration curve for individual components. The percentage of recovery of PAHs and OCs ranged from 85 to 105%. For each batch of 10 samples, a procedural blank, a spiked blank and reference standard material were processed (IAEA-417). Detection limits (DLs) were 0.01 $\mu g\ g^{-1}$ for PAHs and 0.01 $ng\ g^{-1}$ for OCs.

3. Results

3.1 Physicochemical composition

3.1.1 Tampamachoco lagoon system (TLS)

Tampamachoco lagoon system (TLS) is located in the Coastal Plain of the Gulf of Mexico, in the state of Veracruz, between the parallels 20°58′ 15″–21°05″ N and the meridians 97°20′ 30″–97 24″ W [23]. It is formed by the Tampamachoco lagoon (1500 ha), occupying a total area of 6870 ha. The climate is of the "Aw type 2" (e) that is to say warm subhumid with rain in the summer [24], with an annual rainfall of 1900 mm, being January the driest month and September the rainiest. Is a shallow system with an average depth of one-meter, high turbidity [25] and only discharges to the south the river called Tuxpan near the marine mouth, through which it communicates with the Gulf of Mexico [26, 27]. Total nitrogen and total phosphorus are high, which represent the anthropogenic influence (**Table 1**).

3.1.2 Mandinga lagoon system (MLS)

Mandinga lagoon system (MLS) is located between 19°00′ and 19°06′ N and 6°02′ and 96°06′ W. It has a complex morphological conformation constituted by three lagoon bodies; it has an extension of 3250 ha [9]; these. Receives several affluent of other less important rivers [28]. The type of climate in the MLS is Aw2 (w) (i) W "with average rainfall of 1676 mm/year and average evaporation of 1500 mm/year [28]. The temperature has an interval between 25 and 31°C approximately similar to that of the bottom, according to the geomorphology and the annual climate (rains and drought) (**Figure 1**). This lagoon has a high chlorophyll that represented high primary production (**Table 1**).

3.1.3 Alvarado lagoon system (ALS)

Alvarado lagoon system (ALS) is located in the South Coastal Plain of the Gulf of Mexico, between the coordinates 18°44′00″ and 18°52′15″ of latitude N and 95°44′00″ and 95°57′00″ of longitude W (**Figure 1**). This lagoon system leads to several rivers within the most important is Papaloapan, and it is made up of several internal (7162 ha), the type of climate is subhumid warm (Aw2), with little thermal oscillation. According to INEGI (National Institute of Statistic and Geography) [29], the climate is warm-sub-humid-the wettest of the sub-humid-with rain in summer. The dry season occurs between the months of January to May, the rainy season begins in June and the north winds season which are cold wind masses. In addition, this water body is affected by depressions, tropical storms, and hurricanes. The main river basin is the Papaloapan River, which has a complex system of wetlands and borders on its active agricultural activity. The ALS, is considered the third largest wetland in Mexico (National Commission of Biodiversity) [30, 31], it is also one of the most productive systems of the Gulf of Mexico [32] and a shelter area for the feeding and reproduction of numerous populations of fish and crustaceans [33]. The region where this lagoon is located presents several environmental problems: change in land use such as road construction, landfills, agriculture; also the mangrove felling and modification of the vegetation; the use of biocides (organochlorine, organophosphorus), discharge of urban and industrial waters such as sugar, paper and even urban wastewater from cities upstream, overfishing, among others [34]. Total nitrogen, total phosphorus and ammonium are so high (**Table 1**).

3.1.4 Terminos lagoon system (TELS)

Terminos lagoon system (TELS) is considered the largest coastal estuary in Mexico, it is located at the eastern end of the extensive and complex delta of the Usumacinta River that extends approximately 125 km along the southern coast of the Gulf of Mexico, with an average depth of 3.5 m. The TELS lies between 91°10′ and 92°00′ W longitude and parallels 18°20′and 19°00′ N latitude, in the state of Campeche. Had two marine mouths that communicate it permanently with the Gulf of Mexico [25]. The lagoon receives large volumes of fresh water that vary according to the climatic epochs in a 49,700 km^2 basin. It also receives water from

Area	Physicochemical parameters							
	Salinity	**Temperature**	**Dissolved oxygen**	**Total nitrogen**	**Total phosphorus**	**Ammonium**	**Orthophosphates**	**Chlorophyll "a"**
	ups	**°C**	**mg/L**	**μM**	**μM**	**μM**	**μM**	**mg/m^3**
Tampamachoco lagoon system (TLS)	11–38	18–32	0.3–9	5–71	2.6–123	1–35	0–89	2–14
Mandinga lagoon system (TLS)	8–32	28–33	4–6	5–17	5–10	2–10	0.2–2	10–52
Alvarado lagoon system	0.3–34	25–31	10–18	36–429	17–41	15–25	0.4–6	22–49
Terminos lagoon system (TELS)	28–34	26–32	3–10	2–30 inorg.		4–26	0.1–7	3–20
Yucateco lagoon, Tabasco state	0.5–33	21–35	0.5–8	7–228	3–138	0.5–31	0.5–18	jul-28
Mecoacan lagoon, Tabasco state	1–14	24–30	3–5	29.41		5–14	0.4–4	7–21

Table 1.
Physicochemical composition.

the Yucatan Peninsula, the lowlands of Tabasco and the highlands of Chiapas and Guatemala [35]. Three main rivers discharge their waters to the lagoon. The type of climate is warm sub-humid Amw [36] isothermal, with a rainy season from June to October, Northwinds from November to March and a dry season from April to June. It is influenced by extraordinary natural processes such as northerly and tropical storms and hurricanes [37]. The margins of the lagoon are covered by mangroves with a predominance of *Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa* [38, 39] and the seagrass *Thalassia testudinum* (**Figure 1**). Total nitrogen and ammonium are high (**Table 1**).

3.2 Pollutants

3.2.1 Petroleum (PAHs)

Oil pollution and its derivatives are considered to be one of the biggest environmental problems in the Gulf of Mexico [40] and in its waters have been occurred the two largest oil spills at the sea, such as: the Ixtoc-1 well in the Campeche Sound and that of the Deepwater Horizon, off the coast of Louisiana, USA. Both affected significantly the diverse ecosystems of the coastal areas. Thus and in spite of the fact that the Mexican coastal lagoons settled on the margins of Veracruz, Tabasco, and Campeche, are highly productive and of high economic value. Analysis of petroleum hydrocarbons conducted in these lagoons showed important concentrations of aromatic hydrocarbons originating from the intense oil activities that develop along their coasts. In the present contribution, the updated available information on the levels of concentration of PAHs in sediments of the lagoons of Tampamachoco, Mandinga, Alvarado in the state of Veracruz and one of Terminos in Campeche is gathered. In the cases of the lagoons of Tampamachoco and Alvarado also sedimentary nuclei analysis were carried out, which give us a historical view of these pollutants for approximately 80 years old and in the same way the tendency in time that have these compounds.

3.2.1.1 TLS

The sediments of the TLS and the Tuxpan River, Veracruz, were evaluated during the end of July 2012. From the results of the 16 priority PAHs determined, the greater (1.30 $\mu g\ g^{-1}$ ΣHAPs) was registered in the station located in front of the Thermoelectric Power Plant (CTPALM) and the minimum (0.02 $\mu g\ g^{-1}$) in site located in the north of the lagoon body. The analysis of a sedimentary core [7] in the TLS showed an average concentration of PAHs of the nucleus of 0.98 ± 0.38 $\mu g\ g^{-1}$. When analyzing the vertical distribution of the PAHs content, it was found that the historical pattern showed an increase from the basal level of the ΣPAHs of 0.29 $\mu g\ g^{-1}$ at the beginning of the last century (1908), until reaching the maximum of 1.79 $\mu g\ g^{-1}$ in 1999, and decrease towards the beginning of the twenty-first century in 0.58 $\mu g\ g^{-1}$ (2003) to show a new increase in 2010 with 0.84 $\mu g\ g^{-1}$. The compounds with the highest concentrations were, dibenzo[ah]anthracene (0.28 $\mu g\ g^{-1}$), in order of decreasing followed fluorene (0.13 $\mu g\ g^{-1}$) and benzo[a]anthracene (0.12 $\mu g\ g^{-1}$). The molecular profile in the eight analyzed strata, changed, of petrogenic origin in 1908, to be dominated by pyrolytic compounds and to a lesser extent by petrogenic from 1999 to the present time. It should be noted that the individual concentrations of PAHs in sediments were lower than the international sedimentary quality criterion (**Figure 3**), with less probability of causing adverse effects to the benthic community. Thus, it can be said that there is no risk derived from the intrinsic toxicity of the coastal sediments analyzed from this group of hydrocarbons.

From the analysis of individual PAHs, it can be seen that the predominance of compounds with 3–4 rings indicates inputs of pyrolytic and petrogenic hydrocarbons from human activities around the lagoon.

3.2.1.2 MLS

In **MLS** was in which the highest values of PAHs were determined with a range of 2.2–18.2 $\mu g\ g^{-1}$ (average 5.68 $\mu g\ g^{-1}$). The compounds that stood out were chrysene, benzo[b]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene and benzo[a]anthracene, all of them considered of environmental concern. This lagoon receive directly the urban discharges of settlements south of the Port of Veracruz and refuses from steel and iron plant placed in its nearby.

3.2.1.3 ALS

The analysis conducted in a sediment core into ALS did not show a tendency to increase over time, possibly due to the source types of those compounds. The average sum of the 16 PAHs analyzed in the four strata was 1.84 ± 0.54 $\mu g\ g^{-1}$, which indicates a downtrend from the year 1929 to 1971 (with values from 1.5 to 1.3 $\mu g\ g^{-1}$), and a slight increase near the superficial stratum corresponding to the year 1998 (about 2.0 $\mu g\ g^{-1}$). These values are far below the ERL index of 4.02 $\mu g\ g^{-1}$. The compound with the highest value in all core strata was chrysene, except for the stratum from 26 to 36 cm, where it was below the detection limit; the highest concentration in this stratum corresponded to benzo[α]anthracene with 0.591 $\mu g\ g^{-1}$, benzo[κ]fluoranthene and indeno[1,2,3,c,d]pyrene compounds were not detected by the analytical method employed for their determination [41]; only the latter showed a concentration of 0.0427 $\mu g\ g^{-1}$ in the deepest stratum corresponding to the year 1929. This study showed that compounds with four aromatic rings were predominant in all core strata (**Figure 2**), which suggests that they were byproducts of pyrolytic processes near the study zone, such as high-temperature combustion of organic matter and fossil fuels. The sum of the four-ring PAHs presented practically the same collective tendency as the sum of the 16 quantified PAHs. This indicates that the contribution to the entire historical profile of both

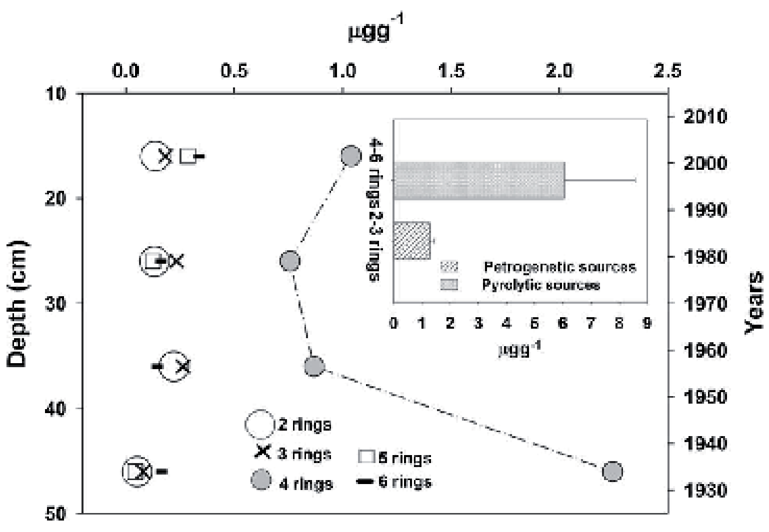

Figure 2.
ALS core concentrations of PAHs ($\mu g\ g^{-1}$) based on number of aromatic rings.

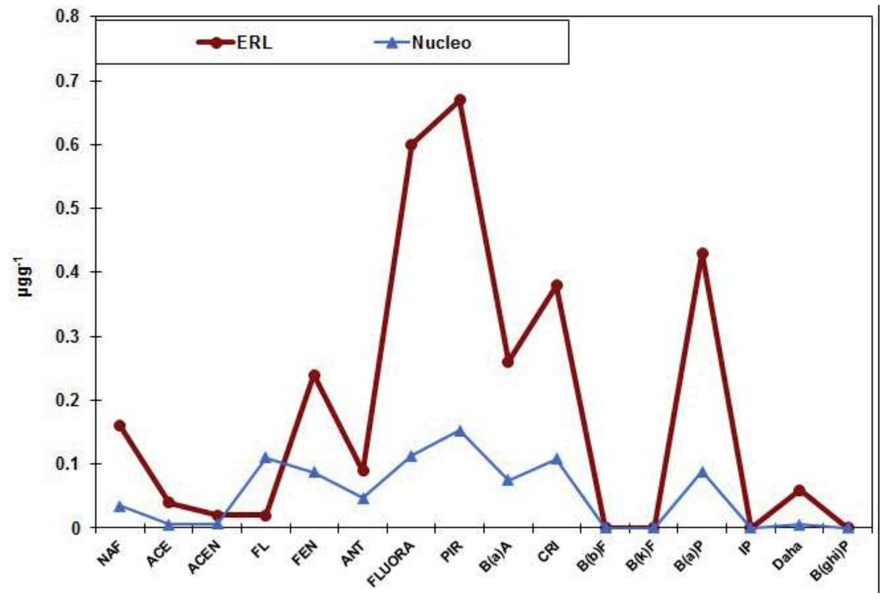

Figure 3.
Individual PAHs and ERL sedimentary quality criteria in the sedimentary core of TLS.

five and six-ring PAHs, as well as two and three-ring ones (which originate from petrogenic sources associated to drilling activities, such as oil extraction and oil spills), was minor (**Figure 2**).

Most of the PAHs in the sediments proceed from pyrolytic sources, while the sources of compounds consisting of two and three rings are of petrogenic origin. The total PAHs sum was mostly contributed to by compounds consisting of four benzene rings, namely chrysene. Despite slightly higher than ERL index concentrations for anthracene, acenaphthylene, fluorene and dibenzo[α,h]anthracene, the total PAH sum did not exceed that limit. It has to be pointed that human activities are very intense in the lagoon as fisheries, shipping port, storage of petroleum and agriculture.

3.2.1.4 TELS

On the other hand, TELS has been intensively studied for organic and inorganic pollutants due to its importance as a fisheries center. Thus, Ref. [42] indicates the presence of PAHs in sediments and oysters of this lagoon, reported PAHs in oyster tissue and the predominance of alkylated compounds of medium and low molecular weight indicating a petrogenic origin attributed basically to off-shore oil activities. This lagoon it is located in front of the main oil wells in the Bank of Campeche were the most intense exploration and exploitation of crude oil takes place.

Another study of PAHs performed on fish tissue from the western zone of TELS, showed that its concentrations exceeded the values maximum recommended by international regulation (greater than 40.0 $\mu g\ g^{-1}$) for the *Petenia splendida* cichlid fish [1]. In recent years [2] evaluated dissolved PAHs and mention that in Boca del Carmen, were determined high concentrations of PAHs; as well as a bacterial community that degrades very abundant PAHs. This is a clear indication that the lagoon arrive at all times dissolved/dispersed PAHs from oil activities carried out in the Sonda de Campeche.

3.2.2 Metals

The investigations on metals in sediments that have been carried out in three of the main coastal lagoons of the Veracruz state, show significant results: the Cd registered similar concentrations for the TLS and MLS with values of 0.46 and 0.66 μg g^{-1} respectively, and these values were below the ERL that is 1.2 μg g^{-1}, levels that produce adverse biological effects in sediments [43]. On the other hand, the highest concentration of Cr was for the TLS with 20.52 μg g^{-1}, the concentrations for ALS and MLS registered similar values with 13 μg g^{-1}. The concentrations for the three lagoons were below the limit of the ERL which is 81 μg g^{-1}. The Cu values for MLS and ALS were 15.77 and 17.49 μg g^{-1} respectively. These also stayed below the ERL which is 34 μg g^{-1}. The Pb showed values for MLS and ALS of 23.37 and 27.49 μg g^{-1}, while for TLS they recorded lower values (11.42 μg g^{-1}). The concentrations of this metal in the three lagoons remained below the ERL which is 46.7 μg g^{-1}. They report that Zn showed similar values for ALS and MLS with 55.81 and 56.14 μg g^{-1} respectively, and their concentrations were below the ERL which is 150 μg g^{-1}. The Ni was presented with values of 71.80 and 72.26 μg g^{-1} in the lagoons of ALS and MLS respectively, and which are above the ERL which is 20.9 μg g^{-1}. The enrichment of Ni in the surface sedimentary substrate is due to the contribution of urban discharges from urban discharges and industries that are close to the coastal areas where the present study was conducted (**Figure 4**) [1, 44].

Villanueva and Ramirez [6] carried out the determination of Cd, Cr, Ni, Pb and V in sediments of the TLS, collected in seven stations. The concentrations decreased in the following order Cr > Ni > Pb > V > Cd, where the latter has not increased since 2010. Although Cd and Pb did increase in 2012, the determined values did not exceed the ecological criteria of the minimum and maximum adverse conditions for the biota (ERL and ERM), while the levels of Ni decreased compared to 2010, since they have a direct influence of the terrestrial and riparian drainages, which present higher hydrodynamics and a greater mixture due to the salt wedge coming from the sea. Likewise, there were no specific changes in metal concentrations between the years 1985 and 1988, the period in which the Thermoelectric Power Plant was built and started to operate. In the period from 1996 to 2012, the concentrations of Cd, Cr and Pb showed slight increases, while the Ni showed variation. Similarly, Vazquez-Botello et al. [23] performed the analysis of a sedimentary core in this lagoon, which concludes that there is a tendency to increase from the oldest

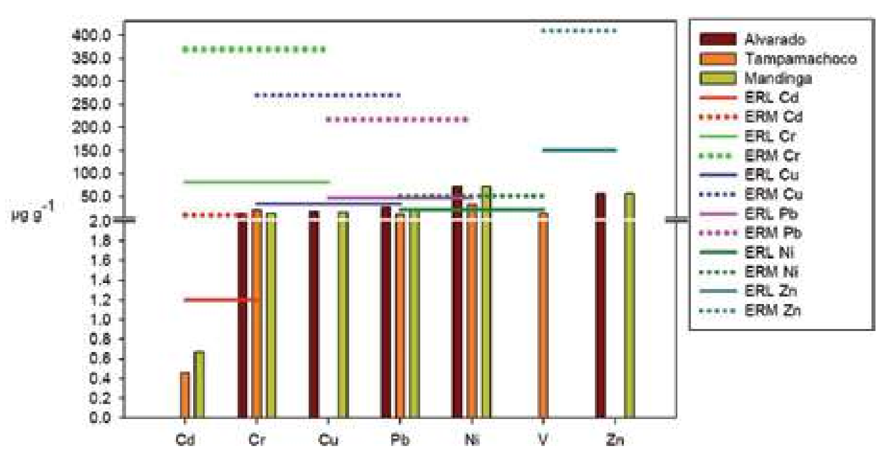

Figure 4.
Average concentrations of metals in superficial sediments of coastal lagoons of the Veracruz state.

stratum (1908) with surface maximums, the values of Ni and Pb are below the concentrations reported in Literature for other coastal and lacustrine systems. The basal values of Cd (0.22 μg g^{-1}), Cr (31 μg g^{-1}), Ni (26 μg g^{-1}) and Pb (12 μg g^{-1}) were also determined. From previous reports, becomes clear that the atmospheric transport is one of the main sources of Pb towards the lagoons, rivers, and oceans; and this is reflected in its levels in the sediments of the lagoons studied. For which it is recommended to analyze sedimentary nuclei and determine the origin of it. Also, the Ni detected in the studied lagoons, has a mixed origin: one part is of lithological origin and another part from the urban discharges through the particulate solids, as well as through the use of fertilizers and the mining industry and steel, and whose concentration surpasses the ELR and ERM values proposed by Long et al. [43] to the up to 100%, causing enrichment of the sedimentary substrate analyzed.

3.2.3 Organochlorine pesticides (OC)

The data for organochlorine pesticides (OC) are presented in sediments of the lagoon systems considered in this study. The TLS has records of these agrotoxics of three practically continuous annual cycles (2009, 2010 and 2012), while the remaining ecosystem data correspond to a particular year; the values are given in ng g^{-1} dry weight. **Figure 5** shows the total data of the OC (ΣOC) reported in sediments of these coastal lagoons. For ALS the sediments evaluated in 2009 occupy the first place with a value of 36.2 ng g^{-1} [3] while in lower concentrations were TLS in the same year with 13.3 ng g^{-1} decreasing to 4 ng g^{-1} in 2012 and the lowest total concentration of organochlorines was for the TELS with 0.18 ng g^{-1} [4]. This marked difference between lagoon systems in the same coastal region of Mexico may be due to the local uses of these agrochemicals, as well as to the particular conditions of temporary runoff and large permanent flows and to the human activities carried out in the nearby of these ecosystems. The area of continental influence of the ALS has a great agricultural activity mainly due to the sugarcane plantations and its main tributaries, the Blanco and Papaloapan rivers, that cross several hundred kilometers of cultivation areas ending in this lagoon. Thus, the suspended material with large amounts of organic matter and a high probability of carrying adsorbed pesticides are finally stored in the lagoon sediments. On the other hand, the hydrodynamics of the TLS is contrasted since human activity in this area is more urban and industrial, and applying pesticides as vector control and to a lesser extent to the agricultural use. The TELS in the south of the GoM, has greater dimensions and a great interaction with the GoM in the replacement of its body of water, as well as a more estuarine environment due to the mixture with tributaries of the flow fluvial Grijalva-Usumacinta

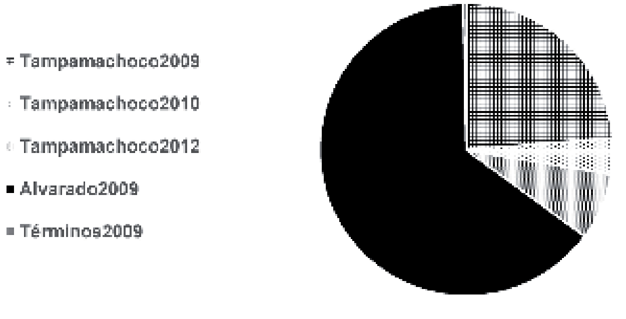

Figure 5.
Total concentration of organochlorine pesticides (ΣOC) in coastal lagoon sediments of three Mexican systems, Tampamachoco, Alvarado and Terminos in the Gulf of Mexico. Values in ng g^{-1} dry weight.

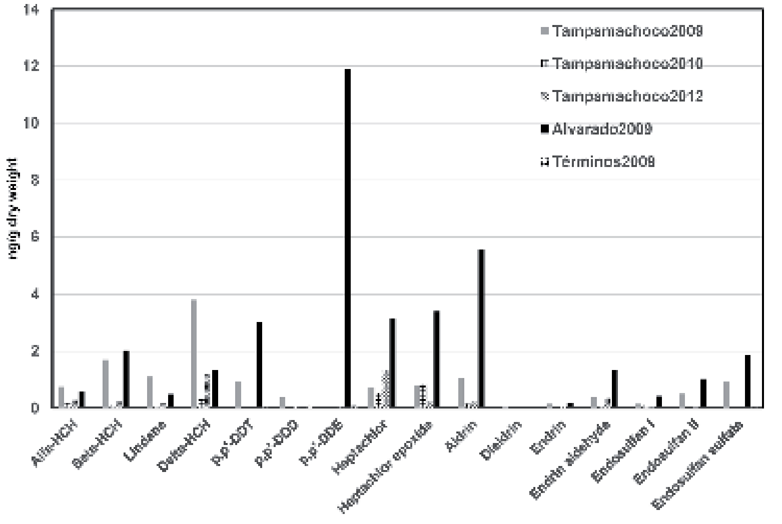

Figure 6.
Individual pattern of organochlorine pesticides in coastal lagoon sediments of three Mexican systems, Tampamachoco, Alvarado and Terminos in the Gulf of Mexico. Values in ng g^{-1} dry weight.

which can contribute with materials and energy to the lagoon system and likewise export to the GoM what can explain the low concentration of reported OC.

The diversity of OC reported for these three Mexican lagoon systems is presented in **Figure 6**, where 16 representative compounds of the three major chemical families were registered: alicyclic or Lindane group, aromatics or conglomerate of DDT and cyclodienes the most diverse group that includes the "Drines," Heptachlor and Endosulfan. The highest data corresponded to the ALS, the *p,p'*-DDE was the pesticide with the highest concentration with 11.9 ng g^{-1} and from this same group there was record of *p,p'*-DDT in these sediments of ALS with 3 ng g^{-1} what shows until that date of an old use of the insecticide. From the Lindane family, the delta-HCH isomer was found at a higher level in the TLS sediments of 2009 with a value of 3.8 ng g^{-1} and beta-HCH in ALS of 2 ng g^{-1}, which highlights the fact that application of this commercial tick due to the persistence of these isomers as a geochemical trace of its use on all livestock. Of the cyclodienes, there were records of a wide variety, in ALS were present Heptachlor and its epoxide and it was worrying the concentration found of Aldrin with 5 ng g^{-1} since it is a pesticide banned in Mexico since 1991 [45]; this same pesticide although to a lesser degree was also registered in TLS and in TELS, which shows the persistence of this organochlorine and probably recent illegal uses since in the ALS it was higher than that found in Dieldrin and Endrin. Endosulfan and its sulfate form were also recorded in the sediments analyzed in this study, without showing a clear trend; however, an incipient pattern in the degradation of the commercial mixture of Endosulfan can be seen due to a higher level of sulfate in the three lagoon ecosystems.

Because there are no maximum permissible limits for OC in coastal sediments in Mexico, it is important to consider the international sedimentary quality criteria that environmental agencies such as the NOAA of the United States of America have as the reference [46]. In this sense, the concentrations reported for lindane or the gamma-HCH isomer were higher than the threshold concentration or TEL by its acronym in English, of 0.32 ng g^{-1} to cause adverse effects to estuarine benthos for the coastal system TLS of 2009 and ALS of the same year and also in the first case was also greater than the criterion of probable alteration known as PEL of 0.99 ng g^{-1}, so it can be considered a scenario of real anthropogenic environmental alteration and of potential risk to human health since various benthic organisms of these coastal sites are for food consumption [47]. Another similar case is that which occurs for *p,p'*-DDT since in the sediments of the ALS, it exceeded the biological damage threshold established in 1.19 ng/gas well as a second ecotoxicological criterion, the ERL was known as the level of effect low by its acronym in English that has a value of 1 ng g^{-1}; of this aromatic family, the *p,p'*-DDE reported in this analysis was much higher than the environmental references TEL and ERL, that is, 2.07 and 2.2 ng g^{-1} respectively for what was reported in ALS, as has already been described, means that, in spite of the biogeochemical transformation of *p,p'*-DDT in *p,p'*-DDE, the benthic toxicity continues for this ecosystem that harbors several species of edible mollusks such as oysters and clams. It is worth mentioning the case of Dieldrin in the context of biotic damage since, despite not having presented large concentrations in the analyzed systems, its environmental reference concentrations are very low, evidencing the danger it has for organisms since from 0.02 ng g^{-1} can cause harmful effects (ERL) so, this risk already exists initially in the TLS since 2009.

4. Discussion

4.1 Physicochemical composition

The study and protection of coastal systems, such as coastal lagoons, wetlands, and estuaries, should be a priority for countries that have benefited from an extensive coastal zone such as Mexico. However, the accelerated development and industrialization of these areas have led to processes of degradation and alteration in these important systems.

Although Mexican coastal lagoons are important sites for fishing, aquaculture, the development of communities and that provide economic resources of great value, reports on increasing levels not only in nutrients, hydrocarbons, metals and pesticides two, that appear in the literature every day and lately plastics and microplastics that impact them and put at risk environmental and human health.

The coastal system of Gulf of Mexico has different climate, morphology and complex river flow which discharges to the lagoons, resulting in wide natural physicochemical water composition, but it must be considered the high urban settlement with their economic activities as different industry that incremented the concentration of certain chemical compounds. This is the case of inorganic nutrients that in the present work included four coastal aquatic system (Tampamachoco, Mandinga, Alvarado and Terminos lagoons), all of them with a eutrophication conditions by high total nitrogen, total phosphorus and ammonium result of urban, agriculture and others economic activities, settlement in the margin of the river and lagoons and the residual water that are dispose to this system. This situation is in a great number of many lagoon system in the Gulf of Mexico; for example: la Mancha, Farallon, El Llano and El Verde located at the north of the Gulf of Mexico, in which were register high concentration of nitrogen, phosphorus and ammonia that result in eutrophication two [40, 48].

4.2 Pollutants

4.2.1 Petroleum (PAHs)

The results on PAHs indicate that these compounds are widely distributed in coastal areas and are stored in lagoons, estuaries, and wetlands. There is abundant literature on this [49] and thanks to the use of sedimentary cores we know that these pollutants have been introduced to the lagoons more than 50 years ago and that their presence can originate as waste from oil activities or by the pyrolysis such as volcanism, burning of coal, burning of pastures and forest fires. Regarding its presence, the dominant PAHs are formed by four rings (pyrolytic) such as chrysene, benzo[a]anthracene, benzo[k]fluoranthene and benzo[b]fluoranthene. In general, their concentrations do not exceed the criterion of maximum concentration to cause adverse biological effects [46].

4.2.2 Metals

Comparing the concentrations of metals in the sediments listed in **Table 2**, the Yucateco and Mecoacan lagoons report high levels with respect to the three lagoons considered in this study. The Cd presented up to an order of magnitude higher (1.84 and 1.46 $\mu g\ g^{-1}$), this shows that Cd has a lithological as well as anthropogenic origin. The Cr and Pb are up to 100% above the areas of this study (36.32 and 48.30 $\mu g\ g^{-1}$), while Pb has a natural origin, by atmospheric transport, as well as anthropogenic. However, the V was the one that reported the highest concentrations in the Mecoacan lagoon with 18.78 $\mu g\ g^{-1}$. What is clear is that part of the Ni and V has their origin in the composition of the dominant oil in the area. These levels can be considered normal and expected, since there are oil wells in the vicinity of the Yucateco lagoon and Mecoacan lagoon. In **Table 2**, it is clearly observed how the variations in the concentrations of the metals analyzed are influenced by the

	Pollutants								
Area	**PAHs ($\mu g\ g^{-1}$)**	**Cd ($\mu g\ g^{-1}$)**	**Cr ($\mu g\ g^{-1}$)**	**Cu ($\mu g\ g^{-1}$)**	**Pb ($\mu g\ g^{-1}$)**	**Ni ($\mu g\ g^{-1}$)**	**V ($\mu g\ g^{-1}$)**	**Zn ($\mu g\ g^{-1}$)**	**OC ($ng\ g^{-1}$)**
Tampa-machoco lagoon system (TLS)	0.98	0.46	20.52	N.D	11.42	31.11	13.91	N.D	19.65
Mandinga lagoon system (TLS)	5.68	0.66	13.00	15.77	23.37	72.26	N.D	56.14	NR
Alvarado lagoon system	2.00	N.D	13.75	17.49	27.49	71.80	N.D	55.81	36.21
Terminos lagoon system (TELS)	6.12								0.18
Yucateco lagoon, Tabasco state	3.85	1.84	36.32		48.30	53.90	1.61		57.71
Mecoacan, Tabasco state	0.15	1.47	28.93		21.22	58.94	18.78		5.1

Table 2.
Average levels of pollutants in sediments of the four lagoons analyzed.

activities carried out in each of the surrounding areas, as well as the special and temporary hydrodynamic predominant according to the different seasons of the year [50, 51].

4.2.3 Organochlorine pesticides (OC)

The analysis carried out to determine the presence of OC in sediments of various coastal lagoon ecosystems of the Gulf of Mexico, provides information on the anthropogenic alteration that has been occurring for several years on these sites, given the lack of vigilance on the part of the Mexican environmental authorities in order to avoid the use of banned pesticides and internationally designated as highly dangerous, so it is urgent to modify agricultural practices, and to promote the integrated management of pests that include biological control and agroecology [52]. For comparison purposes, in **Table 2**, OC data from two tropical coastal lagoons of the Gulf of Mexico were integrated, the first being El Yucateco, whose history of anthropogenic impact has been remote since 1950 at the beginning of oil exploration and exploitation. The second is Mecoacán, considered the area of greatest fishing production in this Mexican coastal region, both located in the tropical state of Tabasco. The data of the ΣOC recorded in the recent sediments of El Yucateco were the highest in the comparison, with a value of 57.71 ng g^{-1} and the high presence of beta-HCH one of the highly persistent isomers of Lindane as an unequivocal trace of the use commercial of this acaricide, as well as high levels of Heptachlor epoxide, records of other cyclodienes, mainly Aldrin, Endosulfan sulfate as a product of biogeochemical transformation of the commercial product Endosulfan and the whole group of DDT with higher prevalence of *p,p'*-DDT [53, 54]. In decreasing order, Alvarado and Tampamachoco followed with a total concentration of OC of 36.21 and 19.65 ng g^{-1}, respectively, as already described in this chapter; Subsequently, the global data on sediments from Mecoacan lagoon was presented with 5.1 ng g^{-1} contrasting with El Yucateco and the neighboring coastal systems of southern Veracruz already mentioned; The dominant pesticides in the sediments of this Tabasco lagoon were similar to those of El Yucateco, Heptachlor epoxide and, to a lesser degree, Aldrin, Dieldrin and beta-HCH as a Lindane residue. The DDT family was not detected [55]. Finally, the Terminos lagoon presented the lowest total concentration of OC of the comparison presented in **Table 2** with 0.18 ng g^{-1}, so it can be clearly observed the coastal sites that require greater environmental monitoring as well as the adequate application of the regulation on these xenobiotics to reduce the sedimentary load of OC to concentrations of lower or no biological risk and to avoid the ecological impact and human health given the persistence and biomagnification capacity of these agrotoxics.

5. Conclusions

The difference physicochemical characteristic and pollutants concentrations of analyzed in the coastal lagoons of the Gulf of Mexico are due to the biochemical behavior, climatic factors and, of course, the industrial and urban discharges that reach these lagoons over time. Other factors are the morphology of the coastal lagoons, presence of mangrove isles that can serve as traps of inorganic or organic matter and pollutants retention. In general, it is considered that urban wastewater constituted the most important source of nutrients which tendency to eutrophication in those lagoons.

This urban wastewater constitutes the most important source of metals in rivers and lagoons two. These effluents consist of (1) untreated or mechanically treated waters only; (2) substances which have passed through filters and biological treatment plants, either solubilized or as finely divided particles; and (3) substances that are served by an emitter and that discharge to the coastal zone. The solid particles of wastewater from coastal cities cause the enrichment of metals, such as Cr, which can have high concentrations, as well as the use of chromates in petrochemical processes during oil extraction. It is worth mentioning that there are numerous studies on the role of atmospheric transport as a source of pollutants (metals, pesticides and aromatic hydrocarbons) and the one that stands out is the contribution of Pb which has been demonstrated in the ice of the North Pole and Greenland, where concentrations of 0.200 μg Pb/kg of ice [56]. The foregoing reveals the fact that the atmospheric contribution, far from being assumed insignificant, even becomes the main source of supply of some pollutants for coastal systems. However, the accelerated development of certain economic activities such as the oil industry, energy generation, tourism, agricultural development and maritime transport have led to disorderly growth in the national coastal areas, with consequent environmental conflicts arising from competition for space, the use of resources and the generation of toxic and polluting waste. Indeed, the conflicts that affect the quality of life and decrease the competitiveness of the same sectors and their economic activities.

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Chapter 2

Environmental Monitoring of Water Quality as a Planning and Management Tool: A Case Study of the Rodrigo de Freitas Lagoon, Rio de Janeiro, Brazil

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Abstract

The Rodrigo de Freitas Lagoon is an urban water body, representing one of the most popular spots for the local community. It underwent serious environmental degradation, at first through its water mirror reduction and more recently through sewer inflows. Concurrently, the difficulty in renewing the water combined with adverse climatic conditions has repeatedly led to an alarming fish mortality rate. The monitoring of its water quality has been carried out as a management and planning tool that lead to the improvement of the environmental conditions. This study seeks to assess monitoring results by correlating the factors that might be the cause of a failure to comply with environmental regulations. Although it is evident that particular places in the Lagoon might be more often affected by illegal sewer discharges, no evidence could be found of any variations between the six sampling points. However, the rise in the levels of Escherichia coli, nitrogen and phosphorus, and the general temperature conditions, pH, and salinity of the water shows that the most significant alterations occurred in spring 2018.The complexity of the period of phytoplankton growth followed by the fish mortality from anoxia underlines the need for monitoring as a tool for a better understanding of the alterations, providing guidance with regard to the planning and management of the ecosystem.

Keywords: coastal environment, water resource management, environmental impact, water quality monitoring, fish mortality

1. Introduction

The Rodrigo de Freitas Lagoon (LRF) is a permanent area of leisure for the inhabitants of Rio de Janeiro and the site of important rowing and canoeing competitions such as those of the 2016 Olympic Games—it is one of the picture postcard panoramic scenes of the "Wonderful City." As well as its topographical features, this region includes parks, areas for sport, a skating rink, a heliport, a path for walking, and a cycle track; in effect, it is one of the main tourist centers in the city and famous for its landscapes.

The LRF has been suffering from the environmental effects of anthropic activities which have been practiced for decades, including the inputs of organic matter responsible for phenomena such as the constant eutrophication of the water bodies [1]. Rosso [2] suggests that the main culprits of the problems that have been detected are the intense urban occupation of the hydrographic basin, together with the growth of anthropic activities and a lack of compliance with elementary standards of urbanism or the basic regulations for environmental sanitary conditions such as sewage systems and urban drainage.

In view of its importance, the LRF has become a frequent target of controversy with regard to the quality of its water. More recently, the Lagoon has given way to speculation about whether it could be safely used for the rowing and canoeing events in the Olympic Games, in a way that would not put the competitors at risk. However, after a period of delay and heated debate with specialists being consulted and other interventionary measures, the events went ahead as planned without causing any subsequent problems.

The LRF has attracted a good deal of concern because of its valuable socioeconomic and environmental attributes and its great exposure in the national and international media with regard to the quality of its waters. The Lagoon is widely used by the public, and this includes recreational activities of a secondary kind or, in other words, activities in which contact with the water is sporadic or accidental and there is little likelihood of ingesting it. It is also used by traditional fishermen whose subsistence has depended on it for many generations.

As in the case of Fonseca and Santoro [3], as well as other lagoons along the coast of the State of Rio de Janeiro, the LRF has aroused interest among academics owing to the extent to which it has undergone adverse natural phenomena such as stagnation and the deterioration of the quality of its water, the release of gases, silting, and the huge fish mortality rate.

The poor circulation and renewal of the waters of the Lagoon mean that the seawater which enters in small quantities and at a slow speed in its depths—where it is more dense—becomes anaerobic in a short time and full of gases, and this is further aggravated by the oxidation of the already present organic matter [4, 5]. The existence of natural barriers like Piraque Island, on the east shore, and Caicaras Island, on the south shore, underlines the difficulty faced by the Lagoon in being regularly replenished by the affluent rivers and the entry of water from the sea.

Several interventions have been made, in particular over the past few years, with a view to improving the environmental conditions of the Lagoon. These include the following: (a) a greater degree of surveillance with regard to the construction and irregular waste disposal in the sewers and drainage system, (b) the improvement of the alteration and renewal of the waters by adhering to stricter standards, and (c) forging a better link with the sea through the Jardim de Alah (Garden of Allah) Canal and its respective floodgate. A comprehensive environmental monitoring system was also installed which was based on frequent analyses of various physicochemical and bacteriological parameters at strategic points placed along the Lagoon; this formed a solid database for the support of decision-making, as well as the management and planning of preventive and control measures.

The objective of this research study is to analyze the data from the environmental monitoring which was carried out in the LRF. The purpose of this is to determine the conditions of the quality of the water that is not in compliance with the regulatory standards, as well as the failure to adhere to these parameters, especially with regard to the limits of CONAMA 357/05. On the basis of this analysis, the aim is to relate these failures to the occurrence of environmental degradation and anthropic activities, as well as the managerial and operational shortcomings with regard to the Lagoon. Some measures are recommended to mitigate these adverse effects and improve the environmental conditions of this vital and emblematic hydric body in the city of Rio de Janeiro.

The chapter is divided in a way that can make it easier to discuss and reach a conclusion about the results obtained from monitoring the quality of the water in the LRF. It sets out by characterizing the features in the area under study and reflecting on the environmental monitoring that is carried out. Following this, there is a methodological description and examination of the implications of the analyses conducted of the water in the Lagoon through physicochemical and biological data.

2. General characterization of the scope of the study

2.1 Relief, hydrography, and vegetable coverage

The Rodrigo de Freitas Lagoon is situated in the southern zone of the city of Rio de Janeiro, between two mountains (Sumare and Corcovado) and the seafront of Ipanema, and is also bordered by the districts of Humaita and Gavea. With an area of 32 km^2, its drainage basin covers a large part of the districts of Gavea, Jardim Botânico (the Botanical Gardens), Ipanema, and Leblon, including the Lagoon, which necessarily serves as a storage basin in the periods of heaviest rainfall. The LRF has a water feature of about 2.2 km^2, a perimeter of 7.8 km, and an average depth of the order of 2.80 m, with a maximum of 4.0 m and a volume of approximately 6,200,000 m^3 [6]. It was noted that after the sand removal works that were carried out on the bed of the Lagoon during the period preceding the Olympic Games in 2016, some parts showed a greater depth than 4.0 m.

The LRF is replenished by the rivers that flow down from the surrounding slopes and currently this water is salubrious. The main rivers concerned are the Rios dos Macacos e Cabeca (Rivers of the Monkeys and Head) which flow into the Lagoon through the Rua (Street) General Garzon Canal and River Rainha (Queen), which is currently being diverted by the Avenida Visconde de Albuquerque Canal (**Table 1**) [7].

The interconnection of the Lagoon with the sea is being effected by the Jardim de Alah, a man-made canal which is 800 m long and has a width which ranges between 10 and 18 m, although one section of its depth is 0.70 m (**Figure 1**). The RIOAGUAS Foundation is responsible for controlling the level of the water feature of the Lagoon by operating the sluices in the canals of the Jardim de Alah, from Visconde de Albuquerque and General Garzon, with a view to improving the environmental conditions of the LRF and the bathing in the Ipanema and Leblon beaches.

TECMA (Environmental Technology) [8] states that it is essential to take note of the rivers and canals linked to the Rodrigo de Freitas Lagoon to obtain a full understanding of its complexity, insofar as any alteration in the quality or volume of the inflow system can affect the dynamics of these waters.

Serious flooding has been recorded in the region, especially in the less steep areas of the basin that are closest to the water feature of the Lagoon—such as in J. Botanico. This occurs during periods of heavy rainfall, together with a rise in the water level of the LRF. At these times, the floodgates of the Jardim de Alah Canal are opened, to allow the outflow of water to the sea, as well as the floodgates of the General Garzon Canal, with the aim of preventing the overflow of the water of this canal and hence extensive flooding in the surrounding area. However, this management of the sluices of CGG is only undertaken as a secondary strategy when the outflow of the water to the sea through the floodgates of the Visconde de Albuquerque Canal is not a sufficient response to the crisis [11].

Water course	Drainage area (km^2)	Hydrographic conditions	Districts that have been drained
Rio Cabeça	1.9	Flows from the foothills of Morro do Corcovado, in sections of 520 m, and is drained in the Av. Lineu de Paula Machado Canal which in turn issues from Rio dos Macacos, on the stretch along the Rua Gal. Garzon	Jardim Botânico
Rio Macacos	7.2	Flows from the foothills of the Queimado Sumaré mountains, in sections of 520 m, and is diverted in its final stretch, from Rua Gal. Garzon to the Canal of the Jockey Club	Alto da B. Vista, Horto e Botânico
Rio Rainha	4.3	Flows from the southern slopes of Serra da Carioca, with paths of 680 m, and is drained into the da V. de Albuquerque Canal	Gávea

Table 1.
Features of the hydrographic basin of the Rodrigo de Freitas Lagoon [9].

Figure 1.
Connection of the Lagoon with the sea through the Jardim de Alah Canal [10].

2.2 Population and socioeconomic factors

The LRF lies within the borough of the Lagoon and is situated in a region with a community that has a high purchasing power, with the exception of some local people who have informal occupations and whose houses lack a separate drainage system. Three of these areas are well known and stand out: (i) the irregular occupation in the area located at the end of the Rua Pacheco Leao, alongside the Jardim Botânico; (ii) the housing complex called Cruzada Sao Sebastiao, situated close to the Jardim de Alah; and (iii) the community in the area situated at the end of Rua Viuva Lacerda, near to Rua Humaita, in the district with the same name.

Soares et al. [1] provide the census for 2000 which showed that the population consisted of 18,221 inhabitants with 6652 households, while in 2010 this had risen to 21,198 inhabitants and 9361 households (when restricted to the area surrounding the Lagoon). The data provided by IPPUR and IBGE [12] suggest that the region (Macrozona VI-Lagoon) has a demographic density of 119.18 inhab/ha, which corresponds to 2.97% of the total population of the municipality.

Feature	Data	Source
Drainage basin área (km^2)	32	INEA [6]
Water feature (km^2)	2.2	INEA [6]
Perimeter (km)	7.8	INEA [6]
Average depth (m)	2.80	INEA [6]
Volume (m^3)	6,200,000	INEA [6]
Districts	Ipanema, Leblon, Gávea, J. Botânico, Humaitá e Lagoa	RIO DE JANEIRO [10]
Population (inhab/number of households in 2000)	18,221/6,652	Soares et al. [1]
Population (inhab/number of households in 2010)	21,198/9,361	Soares et al. [1]
Demographic density (inhab/ha)	111.18	IPPUR and IBGE [11]
% of total population of the municipality of RJ	2.97%	IPPUR and IBGE [11]
IDHM	0.959–0.970	SEBRAE [12]

Table 2.
General data concerning the LRF and its surroundings.

According to the data provided by SEBRAE [13], based on figures published by IBGE, the IDHM of the region ranges from 0.959 (Lagoon) to 0.970 (Ipanema), which are situated at the two highest points in the municipality. This represents a highly valued region of the city with high-rise buildings of a good standard, diversified trading practices, services, and leisure activities, including the shoreline of the Lagoon which is provided with clubs, beaches, bars, beach huts, and various tourist activities.

According to the portal of RioTur [14], some of the most expensive buildings in Rio can be found in this region: in its ranking in the real estate market, the district is second only to Leblon. RioTur also states that at weekends, the three parks that encircle the picture postcard panorama—Patins, Taboas, and Cantagalo–are visited by 120,000 people in search of leisure and relaxation, where they are served by 15 food bars. **Table 2** shows some general features of the LRF and its surroundings.

2.3 Use and occupation of the soil

The layout for the occupation of the region can basically be divided into three separate typologies. The first are areas with little or no occupation and linked to regions that are densely forested with steep slopes and form a part of (or are close to) the Forest of Tijuca. These places are difficult to reach, and the construction of allotments and new buildings is impeded by the environmental conditions of the area. There are some large areas with good vegetable coverage such as Parque Lage and Jardim Botânico that are nearby.

The second typology for land use is linked to a large area of low occupation and includes areas of social interaction and recreation such as the numerous squares (Santos Dumont Square and others), the waterfront of the Lagoon (Patins and Catacumba Parks), as well as the extensive area of Gavea and Hipica Racecourse.

The third typology encompasses the buildings (including various commercial and residential properties), shopping centers, schools, public roads, and sidewalks where the degree of urbanization and waterproofing protection is much greater than in the first two typologies.

Urban growth, particularly informal settlements, have aggravated the problem of organic matter being dragged to the Lagoon, which, owing to a lack of investment in sanitary sewage systems in the last 30 years, has led to a very serious situation with regard to the effects of drainage on the water body [7].

2.4 Traditional environmental problems in the LRF

Traditionally, both the LRF and its surroundings have been densely populated in recent decades, and this urbanization has been accompanied by several harmful environmental effects, such as those arising from numerous landfills and silting that have sharply reduced its water features. According to Soares et al. [1], at the beginning of the 1970s, there occurred a spate of particularly aggressive property speculation in the district surrounding the Lagoon, which had experienced landfills since 1808 and lost almost a half of its original area. Despite the fact that Municipal Decree 130/1975 had stipulated the boundaries of the surface area of the water features, it was only finally protected definitively by Decree 9.396/1990.

Another serious impact, which is still prevalent, is closely bound up with the continuous discharges of sanitary effluent into its waters. This is generally caused by illegal sewerage networks for the rainwater drainage system that pours into the Lagoon and the affluent rivers and canals [15]. For this reason, the quality of the water of LRF greatly deteriorated in the period 1970–2000, as a result of the installation of drainage pipes, through the water supply system, as well as through contact with the tributaries of the rivers that contained a considerable polluting load when they reached the entry of the floodgates of the General Garzon Canal [6, 16].

For several years, the situation was aggravated by the presence of two craters at the bottom of the Lagoon: one between the Caicaras and Flamengo Clubs and the other in front of Cantagalo. These depressions arose from the withdrawal of material for landfills and led to the accumulation of a good deal of organic matter in anaerobic decomposition, where it produced toxic gases such as sulfidic ores and methane. It was found that the pit that was less deep (Caicaras) was completely filled with silt sediment at one part of the bed of the Lagoon. This discovery was made in the period preceding the Olympic Games of 2016, when an attempt was made to attain a minimum depth of 3 m in the whole region used for the competition. With regard to the deepest pit (Cantagalo), there is no information about its current depth, because no bathymetry was employed after these proceedings. Mello [17] states that the filling of the pits could be regarded as a positive effect of the silting mentioned above, since it could operate as an anaerobic biodigester and lead to an increase of the area of water circulation (albeit on a small scale).

2.4.1 Evolution of fish mortality in the LRF

The first studies on the stagnation of the water and the mortality of fish in the LRF were reported in 1877 by the Baron of Lavradio and in 1880 by the Baron of Teffe. According to a survey carried out by Andreata [18], there are about 60 species of fish in the LRF and, hence, different degrees of sensitivity and tolerance to a wide range of factors such as temperature, dissolved oxygen, pH, and salinity.

The mortality rate of the fish recorded in the Lagoon can mainly be attributed to the following causes: a lack of renewal of the waters, algae toxicity, the disposal of wastewater, the stirring up of soil, and the anoxic sediment layer at the bottom [1]. It has been argued that the serious problem of the mortality rate of the fish in the Rodrigo de Freitas Lagoon was not caused by the installation of a sewage system but rather by the current stock of nutrients that can be found today which result from a combination of the older sewage systems *in natura* and the rainfall drainage and the fact that there is an ineffective outlet to the sea [19]. However, what has been observed by the monitoring is that the influence of the sewage system is essential for the nutritional intake in the Lagoon [17].

The entry of this organic load as well as the stirring up of the sediment at the bottom has made available a large number of nutrients for the water column. This can allow algae to flourish and lead to phenomena of natural or anthropic origin which can be defined as an explosive growth that is self-limiting and confined to just one or a few species of microorganisms [20].

Lima [5] notes that even gentle breezes can prevent the stratification of the water column and lead to the horizontal uniformity of the water mass. He stresses the fact that, when in a condition of instability, the ecosystem in question is more vulnerable at nighttime since at this time there is no primary production (i.e., photosynthesis), but only the absorption of oxygen that is dissolved through respiration.

There is no doubt that the situation in the LRF has improved, as can be confirmed by the reduction in the mortality rate of the fish. This improvement has also been demonstrated by the results of the analyses conducted to monitor the quality of the waters of the LRF and also by the decreasing rates of the parameters such as mortality and DBO shown by CEDAE itself. The Sustainability Management Plan for the Olympic Games in Rio (2016), published in 2013, recorded an improvement in the quality of the water. However, the situation is still far from being effectively remedied, and these mass deaths continue to occur, although they are less frequent than was found in the past, as explained above.

2.5 Urban infrastructure

The region is served by infrastructural facilities of a good standard which include telephones, electricity, a transport system and a road network (with streets and a cycle path), a water supply system, a public drainage system, and sanitary sewage system, as well as a completely separate system operated by CEDAE. Nonetheless, it is still possible to find polluted water being discharged into the Lagoon through a network of drains and through the rivers that flow into the LRF, even in periods of serious drought. Thus, it can be proven that there is still a link between the public sewerage system and the installation of drains in the streams themselves. These installations end up by reaching and polluting the water in the rivers and the Rodrigo de Freitas Lagoon itself. This is the case, for example, of the pollution witnessed in the Macacos Canal, which is connected to the river with the same name, as well as the Rainha and Cabeca rivers, before flowing into the Lagoon.

On the basis of the analysis conducted by INEA [6], the Macacos River was found to be in an excellent condition above the Forest of Tijuca but began to be extremely polluted after it had passed the Jardim Botânico. The analysis of its water revealed that at certain times the Macacos River records a high level of pollutants. Researchers and officials at the Jardim Botânico found that some animals had symptoms of diseases that could be linked to this pollution and contaminated water.

According to Bess D'Alcântara et al. [15], the occurrence of problems in the sanitary sewage system in the LRF basin resulted in large amounts of waste in the water feature of the Lagoon, which further impaired the indicative parameters of the quality of its waters.

2.5.1 System of culverts for the LRF protection

In recent years, the region has been the object of several projects and public measures aimed at reducing, or even eradicating, this problem of wastewater and hence improving the environmental conditions of the Lagoon. These include an increase in inspection, carrying out awareness programs among the public and detecting and removing the illegal systems. The last measure taken of any great significance was the building of culverts around the Lagoon, which began in 2001.

Further expansionary work was undertaken by CEDAE em 2009 and included reforming and broadening the sanitary sewage system of the region and adapting it to several lift stations, as well as capturing the effluent discharged irregularly in the drainage system during the dry season. Together with the sewage from the separate system, the effluent captured is currently being canaled to the submarine pipeline of Ipanema.

The expansion of the culverts took place in the stretch of water from the shore of Leblon along the Jardim de Alah Canal and envisaged only three of the 12 points of the rainwater drains that were identified in the canal—the system came into operation in the second semester of 2016. The incorporation of these points took account of their recurrent signs of pollution from sanitary effluent. As a result of this intervention in the CJA, the final destination of the sewage which could perhaps be found in the culverts of rainwater began to be the submarine pipelines of Ipanema. However, there are still reports of the overflow of effluent in this stretch of water, which suggests that the operation of the CJA culvert is not suitable, even in periods of drought. The daily inspections carried out by the RIOAGUAS Foundation to detect signs of effluent through the chemical reagents of *Nessler* often recorded positive results for the presence of recent sewage in the samples at the key points of the drainage system.

Bess D'Alcântara et al. [15] state that the system of culverts is based on measures taken in periods of drought—these structures were of a provisional character and designed to collect sewage discharged irregularly in the rainfall drainage system as an emergency measure. The absence of any long-term planning and lack of financial investment to curb the use of illegal pipelines changed the "catchment hydrology in periods of drought" into definitive units. As a result, the initial benefits of their installation have been wiped out by the worsening of the operational situation and become one of the factors that add to the vulnerability of the system. Bess D'Alcântara et al. [15] also argue that the contribution made by rainfall to the system is a key factor and indicator of this vulnerability since it is not foreseen in the Brazilian standards for a sanitary sewage system of a completely separate type, as this is regarded as unsuitable and unauthorized. The contributions made by rainfall (mixed with the sewage system that involves illegal pipelines) are responsible for the main overflows from the culverts which have the Rodrigo de Freitas Lagoon as their final destination and further worsen the quality of its water feature.

2.6 Institutional aspects and management

The Rodrigo de Freitas Lagoon covers a Permanent Protected Area that is regulated by the Organic Law of the municipality of Rio de Janeiro, as stipulated in Article 463 of 2008, and has had its water feature protected since the 1990s.

The management of LRF involves a wide array of skills and public bodies in particular INEA, CEDAE, RIOAGUAS, and SMAC, the last two of which form a part of the structure of municipal governance. **Table 3** shows the main public bodies involved. The activities of the policymakers cover a number of areas such as projects, public works, inspection, maintenance, and the monitoring of the Lagoon and its surroundings.

Although the responsibility for managing the water bodies lies with the States, the National Policy of Hydraulic Resources, instituted in 1997, explicitly recommends the effective participation of the municipalities in the local environmental management, while the significant need for the planning and management of the

Public agencies/ companies	Level of governance	Main attributions
RIOAGUAS Foundation	Municipality of RJ	Construction, operation, and monitoring of the public rainwater systems; daily inspections and monitoring of the rainfall/runoff discharge points on the LRF; water level control and operation of the sluices of the Jardim de Allah (CJA) channel and of the Visconde de Albuquerque channel; fish productivity; survey and registration of fisheries production; dredging operations in the CJA; activation of the organs and agencies involved in the LRF management; monitoring and support in specific actions for the environmental protection of the LRF
Municipal Secretary for the Environment (SMAC)	Municipality of RJ	Monitoring and assessment of water quality of the LRF, and related rivers, channels, and canals of its watershed; assessment of protection monitoring parameters of the biota and aquatic communities; issuing of daily and weekly bulletins with information about the conditions of LRF; activation of the organs and agencies involved in the LRF management; monitoring and support in specific actions for the environmental protection of the LRF
State Institute of the Environment (INEA)	State of RJ	Monitoring of balneability of the local beaches such as Ipanema and Leblon; environmental permitting of activities and enterprises
State Water and Sewage Company (CEDAE)	State of RJ	Construction, operation, and monitoring of the public potable water and sewer systems, including the system of culverts
COMLURB (Municipal Urban Solid Waste Company)	Municipality of RJ	Removal of garbage, solid waste, and dead fish of the water mirror of the LRF

Table 3.
Main attributions of the public agencies which are involved in the environmental governance and management of the LRF.

waters is underlined by IBAMA [21, 22]. For this reason, the Cooperative Agreement between the State of Rio de Janeiro and the Town Council of the municipality of the city was celebrated in 2007. The purpose of this was to delegate to the Town Council the relative skills needed by the water bodies located within the municipality, as in the case of the Rodrigo de Freitas Lagoon and the rivers linked to it [23].

The current management of the system of the Rodrigo de Freitas Lagoon is the responsibility of the RIOAGUAS Foundation, in collaboration and partnership with other bodies. The monitoring of the quality of the water of the Lagoon and the affluent rivers and canals is undertaken by the Municipal Secretary for the Environment (SMAC), by means of the Coordinated Body of Environmental Monitoring (CMA) which, in 2011, revived and improved the program previously run by the State Institute of the Environment of Rio de Janeiro (INEA). The RIOAGUAS Foundation carries out daily inspections to detect signs of the *Nessler* effluent reagents, to manage the floodgates, and collect information about fishing and the water level, as well as the silting of the Jardim de Alah Canal through dredging operations.

On the basis of the results of this monitoring, it can be claimed that, in general terms, there has been a noticeable improvement in the environmental standards of the LRF, insofar as its water level has risen. However, the maintenance of the water level of the Lagoon has a direct influence on the flow of rainwater from the districts in the southern zone which are within its surroundings. Hence, there is always a concern to maintain its level at around 0.40 m, as a preventive measure to reduce the risk of flooding (since events of this kind have been growing in intensity and frequency) which can cause serious damage and immense suffering to the public.

According to Ricci and Medeiros [24], the implementation of policies involving water resources in the basin of the Rodrigo de Freitas Lagoon is still in its early stages. This is because it requires an active attempt to design tools linked to planning, as well as to encourage the strengthening of bodies attached to the Management System of Water Resources. This particularly applies to the planning of activities and the gradual integration of the bodies that already play a role in this area. Ricci and Medeiros [24] argue that the structure created through the cooperative agreement between the State and municipality for the management of the hydrographic basin of the Rodrigo de Freitas Lagoon has become a proof of the considerable importance attached to the management of water resources, since it includes, as an essential prerequisite, the presence of the municipal authorities in the area of management and requires the structuring of municipal power from a techno-administrative, financial, and political standpoint.

These authors recommend that municipal power should be exercised in three fronts to ensure the underlying assumptions about the necessary policies for water resources are made effective: (1) a strengthening of the Management System of Water Resources, in particular, the Committee for the Integration of the Hydric Basin and the Advisory Board; (2) an effective and integrated application of the management tools for water resources; (3) the integration of policies for water resources and other strategic sectors of municipal planning such as sanitation and housing.

It is worth underlining that as a result of the recognized importance of the Lagoon among the people of Rio and the fact that it was a site for Olympic Games competitions in 2016, the LRF has ended up becoming one of the most closely inspected and monitored water bodies in the country.

3. Environmental monitoring and the quality of the water of LRF

3.1 General considerations

It is not only owing to its environmental importance but also because of its economic, social, and touristic value that the quality of the waters of the Rodrigo de Freitas Lagoon is the object of constant research projects that seek its improvement.

The basic aim of the program called the "Assessment of the Quality of Water in the Rodrigo de Freitas Lagoon and the Rivers and Canals" attached to it is to examine the environmental management of the system formed by its water bodies. Its scope covers the obtaining of environmental information in real time, combined with services for the collection of samples and physicochemical and biological analyses to form a database that can allow an investigation to be carried out of the quality of the water of the Lagoon in the face of natural and anthropic interferences.

Bulletins are issued on the "Quality of the Water in the Lagoon" on a daily basis, and these provide information about the condition of the water with regard to protecting the aquatic communities and making a secondary contact classification (i.e., "appropriate" or "inappropriate"); these are then published in the bulletins from the Center of Operations of the City Council (COR) and also in the Portal of the Council. In the case of the classification of secondary contacts, a limit for the density of 2000 NMP/100 ml of *Escherichia coli* was established for at least 80% of the six samples collected for each of the three areas established in the Municipal Decree 18.415/2000, in accordance with the methodology employed by CONAMA 357/2005.

As well as the bulletins, flags are hoisted on masts that are located in the Parques dos Patins e Pedalinhos (parks for roller skates and paddle boats). Information is provided on the conditions related to the protection of aquatic communities: green flag (balanced state), conditions suitable for an aquatic life; yellow flag (state of alert), conditions of imbalance, which if aggravated, can adversely affect the survival of the aquatic community; and red flag (critical state), unsuitable conditions for aquatic life which can lead to the mass death of the fish.

The control of the quality of the water in the LRF has been carried out by TECMA since 2011, through a contract for undertaking services that include data collection, analyses, making results available, and drawing up periodical reports for the clients (SMAC).

3.2 Monitoring carried out by TECMA

The main purpose of the current monitoring which depends on specific and continuous collections is to follow the physical, chemical, and biological alterations resulting from anthropic activities. It also examines the natural phenomena which can impair the quality of the water both for the protection of aquatic communities and for sporting activities in secondary contact and thus recommends what necessary measures should be taken to maintain the quality of the water of the hydric body [11].

The Lagoon requires constant monitoring since it is a naturally vulnerable system that is subject to natural phenomena like stagnation and the deterioration of the quality of the water, the emission of gases, silting, and the high mortality rate of fish [9]. These kinds of problems can be aggravated further by intense urbanization and the discharging of effluents into its waters.

3.2.1 Sampling stations and the monitoring parameters

The specific monitoring of the Lagoon is carried out in six sampling stations, codified from LRF1 to LRF6, with collections being made twice a week by means of portable field equipment and then sent to the laboratory for analysis. This monitoring allows the assessment of the hydric body to be made in sectors that take account of the local dynamics, while the continuous monitoring is carried out by a multiparametric probe located in the center of the Lagoon (LRF3). This allows variations in the quality of the water to be followed in real time and thus rapid action to be taken in the event of situations of imbalance (**Figures 2** and **3**). Every 30 seconds, the probe transmits the measurements to a database made available for the SMAC.

The distribution of the collection stations of the Rodrigo de Freitas Lagoon are designed to gather samples of the three sectors established by the Municipal Decree 18.415/2000, in a representative way. Area 1 depends on four sampling points: LRF1, LRF2, LRF3, and LRF5, according to **Figure 4**. Area 2 has point LRF4, and area 3 has point LRF6. All the points were georeferenced by using the UTM coordinates and are shown in **Table 4**.

In addition to the water of the Lagoon, the water from the rivers of Macacos and Cabeca was also assessed, together with the canals of General Garzon, the Jockey Club (the stretch of the Visconde de Albuquerque Canal which passes by the Jockey Club of the Lagoon), and the Jardim de Alah. One meteorological station, installed at the Rowing Stadium of the Lagoon is responsible for continuously monitoring the climatic conditions of the local region and sending the information to a database every 15 minutes.

Some parameters are monitored in the LRF in both a precise and continuous way, such as is the case with dissolved oxygen, turbidity, salinity, and pH.

Figure 2.
Portable equipment involved in the precise monitoring.

Figure 3.
Buoy containing the multiparametric probe multiparamétrica. (Source: Photos supplied by the TECMA, 2016).

The specific monitoring still depends on measurements of ammonia nitrogen, total phosphorus, orthophosphate, nitrate, silica, total coliforms, *Escherichia coli*, and the phytoplankton community. There is still continuous monitoring of the chlorophyll parameter a.

In times of drought, technicians from the RIOAGUAS Foundation carried out daily inspections at the points of the rainwater drains where wastewater was directly discharged into the Lagoon or the Jardim de Alah Canal, for the detection of *Nessler* effluent reagents (through a qualitative test for the presence of ammonia which is indicative of recent drainage). However, it was found that, owing to the

Figure 4.
Location of the collection stations of the Rodrigo de Freitas Lagoon [8].

Collection stations	Location (UTM coordinates)	
	X	Y
LRF1	683289	7459128
LRF2	683910	7459151
LRF3	683250	7458571
LRF4	684117	7458011
LRF5	683023	7457937
LRF6	683898	7457684

Table 4.
Coordinates for the collection stations of the Rodrigo de Freitas Lagoon [8].

delay in the renewal of the contract between the RIOAGUAS and the company that rendered the operational service for operating the floodgates of the canals linked to the LRF, there was a suspension of the activities required for managing these devices. Added to this, there was an interruption of the desludging, as well as the inspections and conveying of information about the water features and fishing, in the period from November 26 to December 3, 2018.

3.2.2 Monitoring data assessment

On the basis of an assessment of the history of the monitoring and through a comparison of the points that were analyzed, it was found that even after the interventions carried out by the policymakers, with the aim of eradicating the effects of effluents, some areas of the Lagoon still had unsuitable environmental conditions with parameters of a quality below what was recommended, as is shown in **Table 5** which refers to data obtained from six monitoring points.

	pH	Temperature (°C)	Salinity of	OD (mg/L)	Turbidity (NTU)	Secchi Disc (cm)	*E. coli* (NMP/100 mL)	Nitrogen ammonia (mg/L)	Total phosphorus (mg/L)	Total phosphate (mg/L)
Averages of the results for the parameters at the monitoring points—Spring 2014 (Period 22/09 to 20/12)										
LRF1	8.0	27.7	15.3	6.7	2.8	108.3	63	0.234	0.050	0.016
LRF2	8.0	27.7	15.4	6.9	2.6	107.6	70	0.183	0.046	0.016
LRF3	7.8	27.6	15.4	6.2	2.3	119.8	235	0.192	0.047	0.016
LRF4	7.9	27.4	15.4	6.2	2.0	124.3	71	0.185	0.042	0.016
LRF5	7.9	27.6	15.4	6.0	1.7	163.9	396	0.217	0.044	0.016
LRF6	7.9	27.4	15.5	6.1	1.8	134.8	144	0.211	0.040	0.016
Averages	7.9	27.6	15.4	6.4	2.2	126.5	163	0.203	0.045	0.016
Standard Deviation	0.1	0.1	0.1	0.4	0.4	21.0	132	0.020	0.004	0.000
Averages of the results for the parameters at the monitoring points—Spring 2015 (Period 22/09 to 21/12)										
LRF1	8.1	27.6	14.2	6.9	7.7	93.9	642	0.192	0.016	0.016
LRF2	8.2	27.8	14.3	7.1	7.8	93.1	1136	0.147	0.016	0.016
LRF3	8.1	27.6	14.4	6.8	6.9	99.3	835	0.157	0.016	0.016
LRF4	8.2	27.7	14.5	6.8	6.5	102.2	670	0.150	0.016	0.016
LRF5	8.2	27.8	14.5	7.2	7.0	95.0	2916	0.144	0.016	0.016
LRF6	8.1	27.6	14.5	6.7	6.2	102.3	874	0.139	0.016	0.016
Averages	8.1	27.7	14.4	6.9	7.0	97.6	1179	0.155	0.016	0.016
Standard Deviation	0.1	0.1	0.1	0.2	0.6	4.2	869	0.019	0.000	0.000

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	pH	Temperature (°C)	Salinity of	OD (mg/L)	Turbidity (NTU)	Secchi Disc (cm)	*E. coli* (NMP/100 mL)	Nitrogen ammonia (mg/L)	Total phosphorus (mg/L)	Total phosphate (mg/L)
Averages of the results for the parameters at the monitoring points—Spring 2016 (Period 22/09 to 21/12)										
LRF1	8.3	26.6	16.5	7.4	5.7	125.8	61	0.170	0.033	0.016
LRF2	8.4	26.6	16.6	7.1	5.5	130.3	398	0.161	0.037	0.016
LRF3	8.4	26.6	16.6	7.1	4.9	127.5	38	0.160	0.040	0.016
LRF4	8.3	26.6	16.6	7.0	5.2	122.2	78	0.151	0.036	0.016
LRF5	8.3	26.7	16.6	6.9	5.3	115.0	180	0.181	0.034	0.016
LRF6	8.3	26.6	16.6	6.9	5.2	113.6	255	0.172	0.037	0.016
Averages	8.3	26.6	16.6	7.0	5.3	122.4	168	0.166	0.036	0.016
Standard Deviation	0.0	0.1	0.0	0.2	0.3	6.8	139	0.010	0.002	0.000

Table 5.
Comparison of the parameters analyzed in the spring season of 2014, 2015, and 2016 [25] (Note: change all the fractions, e.g., 0.1 > 0.1).

On the basis of the results for monitoring, an attempt was made to identify the cause(s) and origin of the failure to comply with standards detected in the quality of the water and grounded on the occurrence of parameters that were outside the fixed standards and above the limits recommended. In light of this, analyses of the contributing basins adjoining the nearest discharge points were also taken into account and assessed.

On the basis of its history and previous experiences, as well as the analysis of the points that were being monitored by TECMA, it can be inferred that the values found above the limits can be, without question, related to the illegal links to the sewage and drainage system that discharged waste into the LRF. These links can in turn be attributed to the existence of some remaining vestiges of the informal occupation with regard to the respective drainage basins (and sanitary sewage overflow) in question. In areas of this nonformal typology, the local community lacked suitable sanitation (i.e., an appropriate coordinated system for collecting and/or disposal of the sanitary drainage of the buildings). As infiltration in the soil is not a feasible alternative, what tends to occur is that the effluent waste is discharged in any drainage system that is available.

4. Methodology

The first stage of the methodology employed was to conduct a survey of the bibliographical references, including those regarding the selection of the parameters adopted for this analysis. Several more specific data were investigated that are related to the local drainage basin and the sanitary sewage system, together with an analysis of the locality. The plants and records available of the drainage and sewage systems were investigated together with the respective basins concerned.

These were investigated together with the responsible bodies, including the municipal government of Rio de Janeiro and CEDAE (The State Water and Sewage Company) and the historical data obtained through the monitoring of the quality of the water carried out by the TECMA in the last few years.

There was also an analysis of the field measurement data and the specific collections of the samples taken from the surface water of the Lagoon. This took place twice a week during the period from January 1 to December 31, 2018, in the six sampling points that were strategically placed around the water body (LRF1 to LRF6). These data were made available by the TECMA, and a third party was responsible for analyzing the samples of water from the Lagoon.

Despite the wide array of parameters that were analyzed in the course of the monitoring plan, in the particular case of this study, the physicochemical parameters that were examined were as follows: temperature, salinity, pH, turbidity, dissolved oxygen, ammonia nitrogen, total phosphorus, and orthophosphate. The biological parameters included *Escherichia coli*. The selection of these parameters was based on their degree of importance in representing the hydric quality for required use and grounded on the bibliographical support provided by this study. It should be noted that the parameters for monitoring were the same as those employed by Mello [17].

The temperature, salinity, pH, turbidity, and concentration of dissolved oxygen were determined in situ by means of the portable field recording equipment with electrodes. The samples of water for the analysis of the other parameters were obtained with the aid of collecting bottles and packaged in polyethylene flasks of appropriate volumes. These were duly labeled and preserved and then packed in thermal boxes with ice and sent to the TECMA laboratory for analysis in a timescale that ensured the tests were carried out within the deadline for preserving validity.

It was found that the different groups of phytoplankton displayed variations in their levels of chlorophyll a; since not all the blooming of the algae affected the values of the parameter, they were not regarded as important for the purposes of this study. The benchmark determination methodology in situ, for the collection and preservation of the samples, as well as the analysis, was that recognized by the Standard *Methods for the Examination of Water and Wastewater*, APHA-AWWA-WEF, 22th Edition, 2012.

The results for each parameter were analyzed per season and formulated into line graphs that contain the maximum, minimum, and average values at each stage of the sampling. Calculations were also made of the average values for the surface of each parameter in the years 2014, 2015, and 2016, with a view to supplying comparative values for the seasonal averages of 2018 and thus assisting our understanding of the alterations that were observed. The spatial and temporal variations that were noted were discussed together with the other results. The data were also assessed by comparing them with meteorological data on rainfall, radiation, and air temperature, which was collected from the meteorological station installed in the Rowing Stadium of the Lagoon and also supplied by TECMA, with the aim of determining their influence on the results of the physicochemical and biological parameters.

5. Results and discussion

5.1 Temperature

Temperature is a factor of paramount importance for the aquatic ecosystem because it plays an essential role in the control of the environment by influencing physical, chemical, and biological processes including vital factors such as primary productivity and the decomposition of organic matter [25, 26]. The Central Institution of the Environmental System of São Paulo (CETESB) [27] stresses the importance of analyzing the temperature of the water, since aquatic organisms have differentiated limits of thermal tolerance and the best temperatures for growth. Thus as high solar radiation naturally results in an increase in the temperature of the water, the supply of water used in refrigeration systems results in a rise in the receptor body which can lead to a reduction in the concentration of dissolved oxygen and/or an acceleration of the metabolism of the phytoplankton which is favorable for the occurrence of blooming. Alterations in temperature can also sharpen the sensation of taste and smell in the water [28].

In the period being analyzed, it was noted that there was a horizontal uniformity in terms of water temperature on the surface layer of the Rodrigo de Freitas Lagoon. The averages, with regard to the six sampling points, ranged from 24.1 to 30.0°C, with lower temperatures in winter and higher in summer (**Figure 5**).

5.1.1 Temperature and phytoplanktonic blooming

It was noted that together with other factors, the high temperatures of the water in the Lagoon in the spring of 2018 could have favored the phytoplanktonic blooming of the cyanobacteria *Synechocystis* spp., which occurred in the period December 10–17. It should be underlined that the fact that cyanobacteria have a preference for high temperatures has been demonstrated in a number of studies [29–31].

When compared with the springs of 2014, 2015, and 2016, the parameter in 2018 was 1–1.5°C above the others as can be observed in **Table 6**.

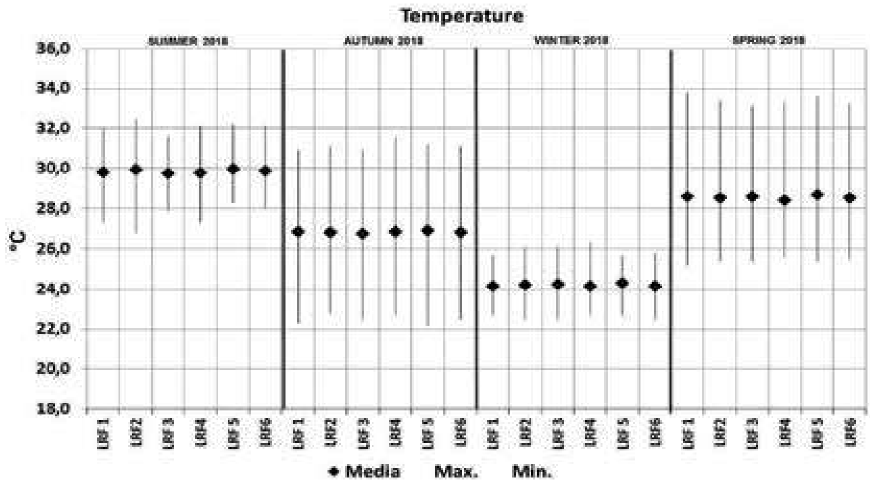

Figure 5.
Temperature of the surface of the LRF in 2018.

5.2 Salinity

Water temperature (°C)				
Averages at sampling points	2014	2015	2016	2018
	27.6	27.7	26.6	28.2

Table 6.
Average water temperature at the LRF during the monitored spring seasons.

Salinity is another factor that influences the biodiversity of hydric bodies, since different species have different ways of adapting to concentrations of mineral salts [28]. They are reduced to colonies of brackish environments by aquatic animals and superior vegetation, owing to the difficulties of osmoregulation which, according to Reid and Esteves [32], constitute one of the main factors responsible for the low phytoplanktonic diversity of the coastal lagoons of the State of Rio de Janeiro.

In the same way as temperature, salinity can have a great influence on the stratification of the water bodies, since the density of the water increases when there is a rise in the concentration of salts [28]. Esteves [33] underlines the fact that when there is a rise in temperature, an increase in salinity reduces the capacity of the water for the dissolution of oxygen.

The values for salinity that were observed for spring 2018 were relatively low, and this can probably be attributed to the pluvial and fluvial effects of the waters and to a less extent, to the sea and evaporation (**Figure 6**). It was found that the three greatest falls in salinity occurred in the periods November 8, 19, and 26 and coincided with the heavy rainfall recorded on those days. Attention should also be drawn to the fact that there was a lack of an entry for water from the sea owing to the low tide, a failure in the operation of the floodgates, and the constant silting of the Jardim de Alah Canal.

This silting was also recorded by Kaippert [16] and Lima [5] as a factor that involved a marine influence on the LRF. It is also worth noting that the values

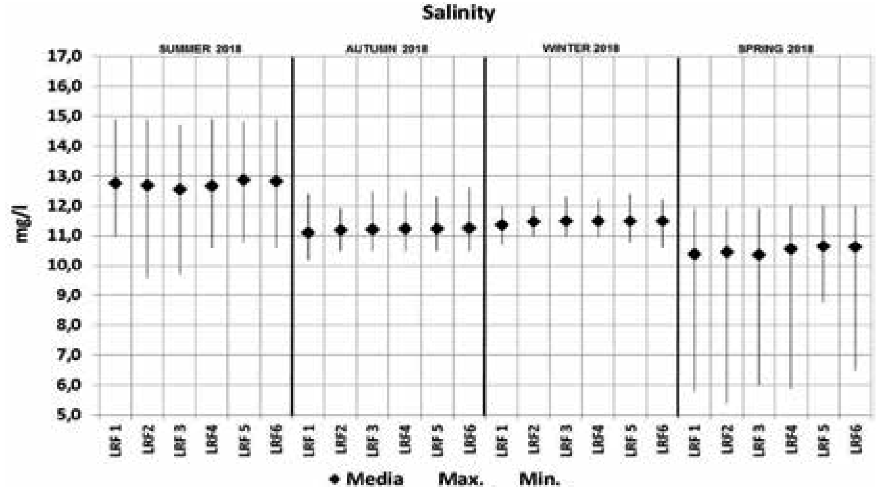

Figure 6.
Salinity of the surface of LRF in 2018.

Salinity				
Averages at sampling points	2014	2015	2016	2018
	15.4	14.4	16.6	10.4

Table 7.
Average water salinity at the LRF during the monitored spring seasons.

recorded on the days in question in November 2018 were the lowest since the monitoring by TECMA first started in 2011 and that the parameter that can influence the establishment of organisms includes the phytoplankton community.

5.2.1 Salinity and phytoplanktonic blooming

In the spring of 2018, there were records of phytoplanktic blooming of the cyanobacteria *Synechocystis* spp., in the period December 10–17. Domingos et al. [1] argue that a rise in salinity is a limiting factor for the presence of cyanobacteria of the *Synechocystis* genus. This means that the reduction of the values of the parameter may have provided conditions that were favorable to their growth in the Lagoon.

When compared with the springs of 2014, 2015, and 2016, the parameter was between 4 and 6 units below the others in 2018 as induced in **Table 7**.

5.3 pH

Another key parameter for the monitoring of hydric bodies is the pH, because not only it influences the solubilization and sedimentation of metals and other substances, but also it acts in different ways on the metabolism of aquatic communities by making a direct intervention in the distribution of the organisms [33, 34]. The pH must be situated in values of 6.0–9.0 for the maintenance of aquatic life, since values outside this range are usually harmful to most aquatic creatures [35, 36].

The values of pH are caused by natural phenomena such as the dissolution of rocks, the absorption of atmospheric gases, oxidation of organic matter and photosynthesis, as well as anthropic factors like the discharge of domestic effluent

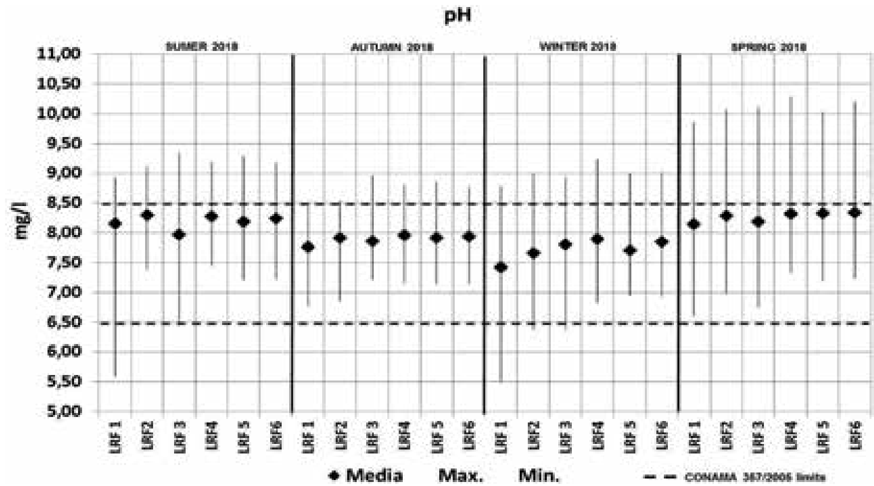

Figure 7.
pH of the surface of LRF in 2018.

(oxidation of organic matter) and industrial waste, which underlines the importance of this parameter in the assessment of human interference in the quality of water [35]. In the case of the lagoons which undergo influence from the sea, the salt water can bring about large quantities of carbonate and bicarbonate ion by causing a rise in pH, in the same way that an increase in rainfall can lead to a reduction of the values. In environments where there is a high phytoplanktonic density, the pH can naturally reach values above 9.0 during the period of maximum sunlight, owing to the photosynthetic activity of the algae which consume the CO_2 [37].

The average surface values of the pH range from 7.42 to 8.35, with maximum values being recorded in the spring (**Figure 7**). It was noted that during the year of 2018, all the maximum surface values of pH surpassed the maximum limit of the 6.5–8.5 bands that was established by law for brackish waters of class 2.

5.3.1 pH and the phytoplanktonic blooming

When compared with the springs of 2014, 2015, and 2016, the parameter in 2018 was slightly above the others, which as pointed out by CETESB [27] might be linked to greater photosynthetic activity caused by a higher intake of CO_2 as induced in **Table 8**.

It is noteworthy that in the spring of 2018, there was a blooming of the cyanobacteria *Synechocystis* spp.

5.4 Turbidity

Alterations in the penetration of light are described as turbidity, and this can be caused by particles in suspension such as bacteria, phytoplankton clays, silting, organic and inorganic detritus, and dissolved compounds [25, 33]. Apart from a rise in the turbidity of the waters caused by a discharge of effluent, a natural phenomenon that also causes this rise is the erosion of the shores of the water bodies in periods of heavy rainfall. Since a high level of turbidity hinders the penetration of the solar rays in the water, this is able to reduce the photosynthesis of the plants and submerged algae and, as a result, influence the dynamics of the local biological community. In addition, it has an adverse effect on the domestic, industrial, and recreational use of the water in question [26].

pH				
Averages at sampling points	2014	2015	2016	2018
	7.9	8.1	8.3	8.4

Table 8.
Average water pH at the LRF during the monitored spring seasons.

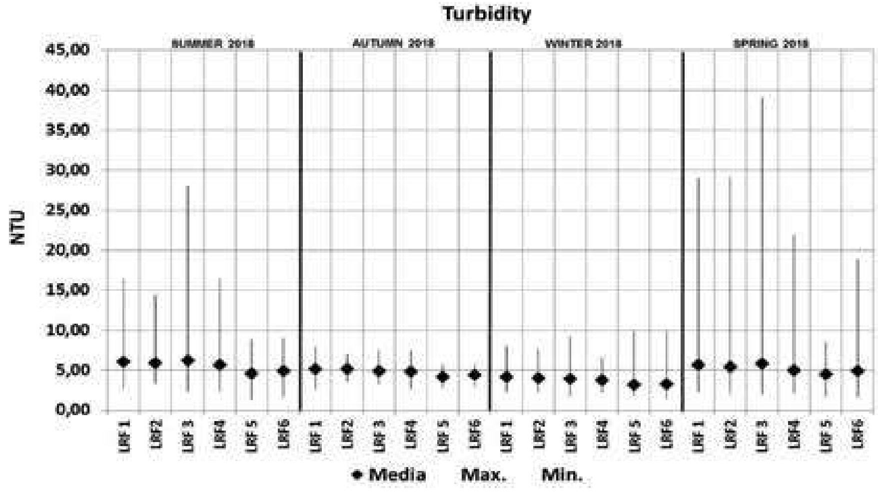

Figure 8.
Turbidity of the surface of the LRF in 2018.

The Lagoon showed low levels of turbidity for most of the year although some peaks were observed, particularly in the summer and spring which are the months with most rainfall. The averages in the seasons when the sampling was carried out range from 3.2 to 6.2 NTU (**Figure 8**).

It was found that in the collection of November 26, there was a sharp rise in all the points of the parameter that is represented by the maximum values observed in spring. These results reflected the heavy rains recorded on that day, when the second highest accumulation of rainfall in the year was recorded in a period of 24 h (102.60 mm). Rosman [4] points out that since it is the lowest point of the hydrographic basin, the LRF has enormous inflows of dissolved substances carried along by the force of the downpours of rain. It should be noted that although the legislation (CONAMA 357/2005) does not determine the maximum value for the parameter, in the case of brackish waters, it recognizes that there are virtually no signs of substances that produce turbidity.

However, when compared with the springs of 2014, 2015, and 2016 in **Table 9**, the spring of 2018 did not stand out with regard to the turbidity parameter. It is noteworthy that the spring of 2014 was the driest among all the monitored spring seasons.

5.5 *Escherichia coli*

The role of the microorganisms in the aquatic environment is essentially confined to transforming matter within the cycle of various elements with a view to obtaining energy for survival. The decomposition of organic matter into simpler substances, which is largely carried out by putrefactive bacteria, is one example of these changes. This is because it is vital for the aquatic environment, given the

Turbidity (NTU)				
Averages at sampling points	2014	2015	2016	2018
	2.2	7.0	5.3	5.9

Table 9.
Average water turbidity at the LRF during the monitored spring seasons.

fact that the resulting nitrates, phosphates, and sulfates are reassimilated by other organisms in the environment [36]. Nonetheless, there are also microorganisms that are potentially an obstacle to the maintenance of the quality of the water body.

For this reason, a biological parameter of crucial importance in monitoring the quality of the water is the number of coliforms, in particular those that are thermotolerant and are present in the sample obtained. Since in most circumstances, the populations of thermotolerant coliforms predominantly consist of *Escherichia coli*, this group is regarded as a suitable indicator of the quality of the water since its presence is a sign of recent fecal contamination [36, 38]. The limit of ***E. coli*** used by SMAC for the Lagoon is based on the CONAMA Resolution 357/2005, which is 2000 NMP/100 mL.

In 2018, the densities of *Escherichia coli* showed a wide variation, although without any seasonal fluctuation being characterized (**Figure 9**). However, it should be noted that in winter, the average density was, in general terms, reduced, whereas in summer and spring, (the period with more rainfall), the maximum and average values were higher. It was found that that the results were a great deal higher at the points LRF1 and LRF2.

When compared with the springs of 2014, 2015, and 2016 in **Table 10**, the parameter for 2018 was between 5 and 30 times higher than the others.

Some of the factors that can influence the colimetrics results in the LRF are as follows: entries of organic matter through surface drainage, the opening of the floodgates, and the entry of the sewer system originating from an excessive number of leaks in the culverts during periods of rainfall [7, 8, 15]. In addition, there are often reports of the discharges of effluent in periods of drought at the rainwater

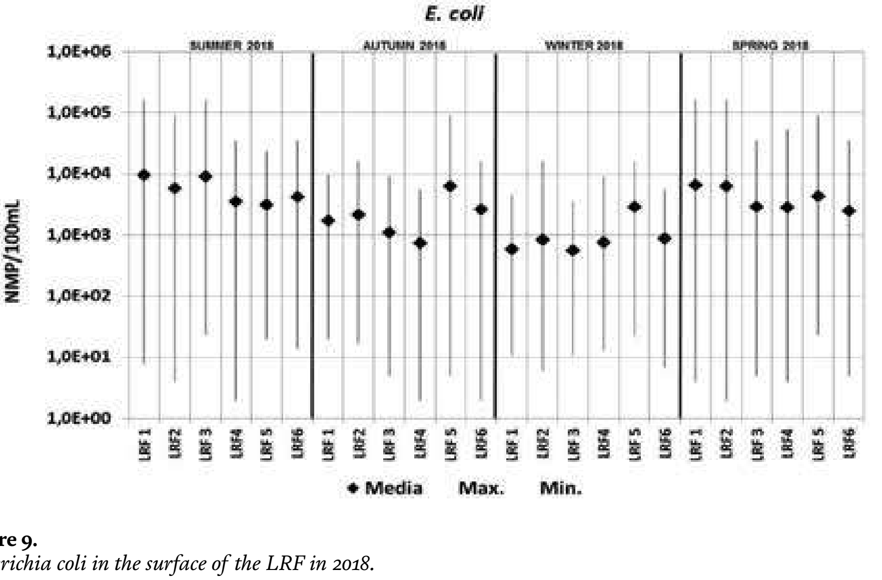

Figure 9.
Escherichia coli in the surface of the LRF in 2018.

***Escherichia coli* (NMP/100ml)**				
Averages at sampling points	2014	2015	2016	2018
	163	1.179	168	4,745

Table 10.
Average Escherichia coli at the LRF during the monitored spring seasons.

outlets arranged around the Lagoon, as already mentioned [16, 17]. The presence of ammonia in the water can be detected through the reaction of the *Nessler* reagent to a qualitative test for the presence of ammonia, which is an indicator of recent drainage.

5.6 Ammonia nitrogen

Ammonia nitrogen is formed by ammonia species (NH_3) and ion ammonia (NH^{4+}), which is the most toxic species in the aquatic organisms [39]. The CONAMA Resolution 357/2005 stipulates 0.70 mg/L N as the limit of total ammonia nitrogen for the brackish waters of class 2, regardless of the pH [40]. Nitrogen is regarded as one of the most important elements in the metabolism of aquatic ecosystems for directly protecting aquatic life. This is also due to its role in the formation of proteins and chlorophyll [33].

The values of ammonia nitrogen showed a wide variation in 2018, although the seasonal fluctuations were not defined (**Figure 10**). However, it should be pointed out that, generally speaking, in summer the averages were reduced, while spring showed the highest maximum values, with the detection of a considerable increase in the parameter after heavy rainfall, mainly on October 15 and November 26. This rise in ammonia nitrogen can be attributed to the entry of organic matter and other substances into the Lagoon.

The inorganic forms of nitrogen, mainly ammonia nitrogen and nitrate, are ideally assimilated by phytoplankton [41–43]. During the period of phytoplanktonic blooming which took place between December 10 and 17, 2018, there was a reduction in the values of ammonia nitrogen, with a subsequent rise of the parameter at the end of the blooming period.

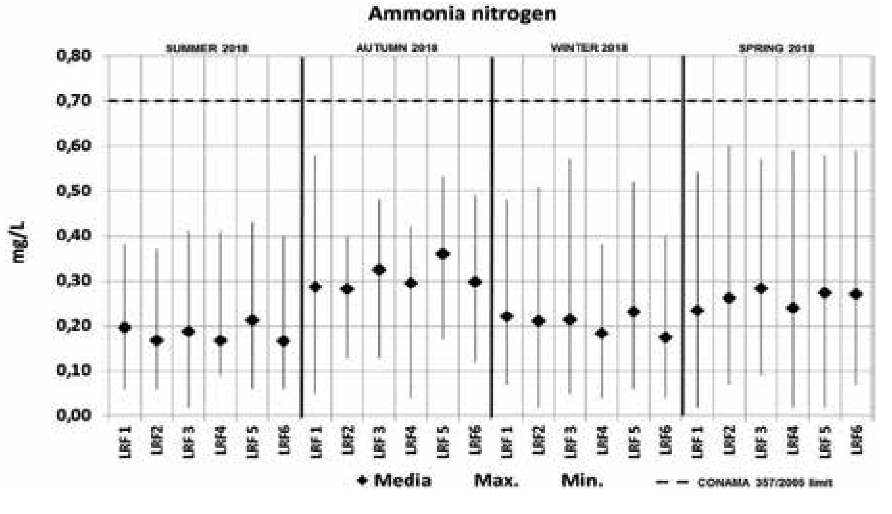

Figure 10.
Ammonia nitrogen on the surface of the LRF in 2018.

Ammonia nitrogen (mg/L)				
Averages at sampling points	2014	2015	2016	2018
	0.203	0.155	0.166	0.274

Table 11.
Average Ammonia nitrogen at the LRF during the monitored spring seasons.

When compared with the springs of 2014, 2015, and 2016 in **Table 11**, the parameter in 2018 was between 0.071 mg/L and 0.119 mg/L above the others.

CETESB [26] establishes that the control of eutrophication by reducing the intake of nitrogen was adversely affected by the numerous sources, some of which are hard to control like the fixation of atmospheric nitrogen on the part of the algae. In this way, an investment was made in controlling the sources of phosphorus.

5.7 Dissolved oxygen

Dissolved oxygen (DO) is the main element in the metabolism of aerobic aquatic organisms such as fish and planktonic microorganisms. It is because of its importance in the maintenance of aquatic life that the DO is used as the main parameter for the quality of the water. CONAMA 357/2005 stipulates a minimum value of 4.00 mg/L of DO for class 2 brackish water.

The principal sources of oxygen for the aquatic ecosystem are the atmosphere and the photosynthesis of the algae, while its consumption is related to the decomposition of organic matter, the respiration of aquatic organisms the oxidation of ions, and losses to the atmosphere [39]. Low concentrations of dissolved oxygen in the water can cause delayed growth, a reduction in efficient feeding practices, and an increase in the incidence of diseases and the mortality of fish [44].

Polluted water tends to have low concentrations of dissolved oxygen owing to its consumption in the oxidation of the organic compounds, whereas clean water displays higher concentrations of DO [34]. However, systems with eutrophication can have supersaturated conditions, with concentrations of oxygen higher than 10 mg/L, even in temperatures above 20°C. According to CETESB [26], this mainly occurs in lakes with low speeds where algae soil crusts are formed on the surface.

5.7.1 Dissolved oxygen during blooming and fish mortality

During the year that was analyzed (2018), there was a wide variation in the concentrations of DO on the surface of the Lagoon (**Figure 11**). Esteves [33] points out that the rise in temperature and salinity reduces the capacity of the oxygen to dissolve in water. For this reason, summer (the season which showed the highest values in these parameters) recorded the lowest average concentrations of DO. However, it should be noted that the lowest minimum concentrations of DO occurred in spring, after the senescence. Then there was a sharp reduction and consequent aerobic decomposition of the phytoplanktonic population of *Synechocystis* spp., which was in bloom, leading to records of the mortality of fish by anoxia in the LRF, from December 20 to 23, 2018.

Esteves [33] states that owing to high temperatures, the decomposition of organic matter in tropical waters occurs 4–10 times more rapidly than in temperate climates, which involve a proportionally greater intake of oxygen. In the case of shallow water bodies, like the case of LRF, the concentration of organic matter combined with high temperatures is a decisive factor in determining the degree of deoxygenation.

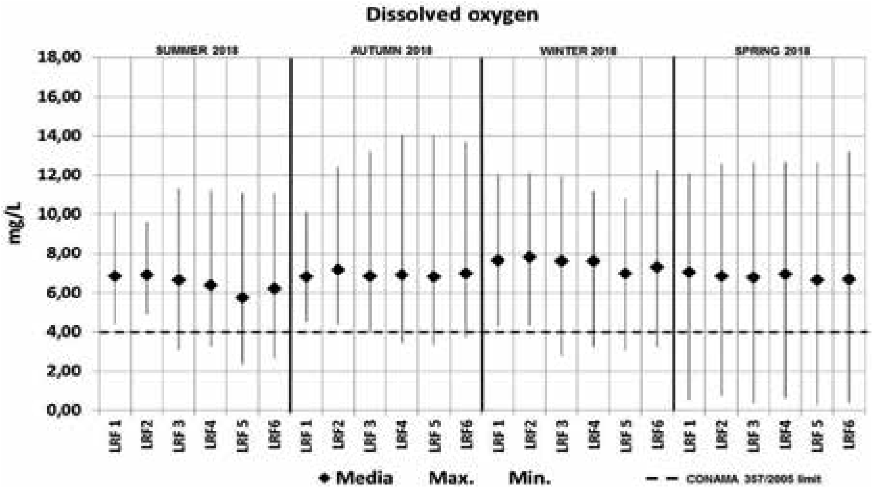

Figure 11.
Dissolved oxygen in the surface of the LRF in 2018.

When compared with the springs of 2014, 2015, and 2016 in **Table 12**, the parameter in 2018 was between 0.6 and 1.2 mg/L above the others.

The amount of oxygen can either increase through the intensification of photosynthetic production or decline if there is greater respiration among the local communities and/or a greater oxidation of organic matter. Temperature has a direct influence on both the respiration of the organisms and the other oxidative processes like the decomposition of organic matter by aerobic microorganisms and hence has an effect on the levels of dissolved oxygen.

5.8 Total phosphorus and orthophosphate

Organic matter is rich in nutrients like nitrogen and phosphorus which, in excess, can cause an imbalance with regard to the production and consumption of biomass, a condition known as eutrophication [45]. According to Esteves [33], phosphate is cited as being responsible for the artificial eutrophication of continental waters, the most important artificial sources being the sewage systems and the particle material of industrial origin.

Although the legislative regulations of CONAMA (357/2005) define the maximum limit of 0.186 mg/L for total phosphorus and separate phosphate fractions, it is the monitoring of the orthophosphate in water bodies that is most important since it is the main means of assimilating primary end consumers [33].

No significant differences were observed in the average levels of total phosphorus between the different points (**Figure 12**). Although the highest values were found in spring, it was only in point LRF6 that the limit of 0.186 mg/L (that was established by CONAMA Resolution 357/2005) was surpassed for brackish water of class 2. It was

Dissolved oxygen (mg/L)				
Averages at sampling points	2014	2015	2016	2018
	6.4	6.9	7.0	7.6

Table 12.
Average water DO at the LRF during the monitored spring seasons.

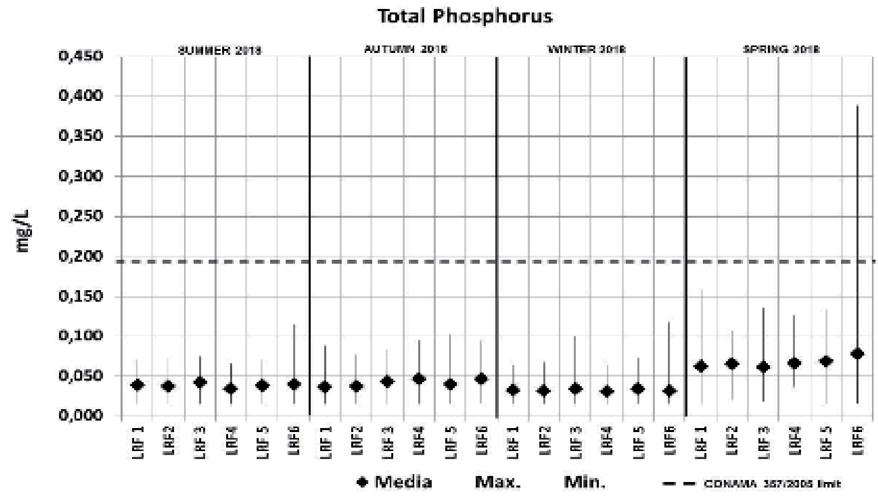

Figure 12.
Total phosphorus in the surface of the LRF in 2018.

noted that this failure in compliance occurred on December 19, or in other words, at the end of the phytoplanktonic bloom that took place in the Lagoon in the spring of 2018.

When compared with the springs of 2014, 2015, and 2016 in **Table 13**, the parameter in 2018 was 0.026–0.055 mg/L above the others.

Similarly, no significant differences in the average levels of the orthophosphate were found between the points (**Figure 13**). A similar behavior for the total phosphorus was noted with higher values in spring.

When the springs of 2014, 2015, 2016, and 2018 are compared in **Table 14**, it was only in the last that average values of orthophosphate were recorded above 0.016 mg/L, suggesting there was a rise in the input of nutrients in this particular spring.

The rise in total phosphorus and the more significant orthophosphate was recorded on December 3 and could have resulted in the entry of a large amount of organic matter and other substances into the Lagoon after the rainfall that occurred between November 26 and December 8. The significant rise of the parameters on December 19 might be owing to the decomposition of the phytoplankton, which was in bloom, which means these nutrients were replaced and made available in the environment. In the same way, the higher values recorded in December 26 may have resulted from the decomposition and the return to the environment of the components after the mortality of about 89 tons of fish which took place in the LRF between December 20 and 23, 2018.

It should be noted that Lopes and Magalhães [34] point out that the growth, death, and decomposition of aquatic organisms have a harmful interference on the quality of the water owing to alterations in the levels of nitrogen, phosphorus, pH, and dissolved oxygen.

Total phosphorus (mg/L)				
Averages at sampling points	2014	2015	2016	2018
	0.045	0.016	0.036	0.071

Table 13.
Average total phosphorus at the LRF during the monitored spring seasons.

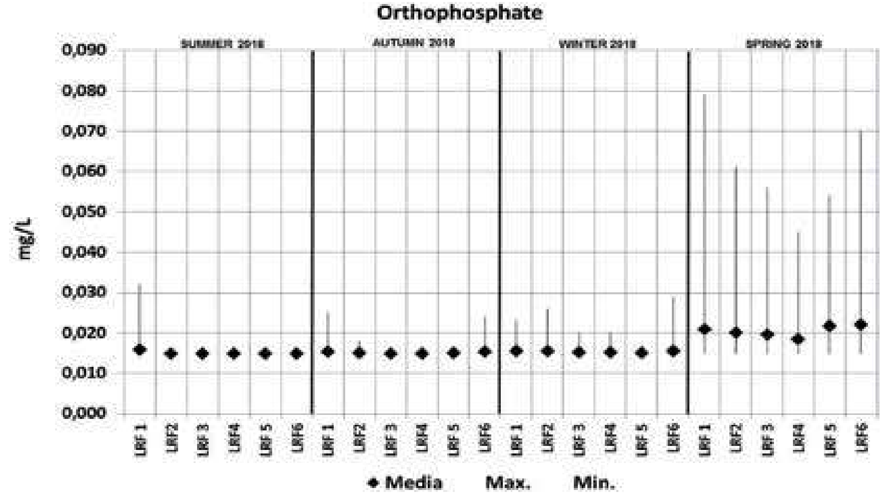

Figure 13.
Orthophosphate in the surface of the LRF in 2018.

Orthophosphate (mg/L)				
Averages at sampling points	2014	2015	2016	2018
	0.016	0.016	0.016	0.022

Table 14.
Average orthophosphate at the LRF during the monitored spring seasons.

6. Conclusion and recommendations for further study

In the analysis that has been conducted which adopted an approach from a seasonal standpoint, it was not evident from the results of the parameters used for monitoring that there was a considerable variation in the results between the different collection points (LRF1 to LRF6). On the other hand, it can be argued that in general (with regard to all the points monitored), the spring of 2018 was the season of the year that had the most significant alterations. When compared with the previous springs (those of 2014, 2015, and 2016), it was also shown to have undergone most alterations in the parameters that were analyzed.

It is worth stressing that the blooming of the algae occurred in December 2018, as the result of the combination of two factors: the availability of nutrients and the suitable conditions with regard to temperature and salinity. High temperatures were found in this period, which favored lower levels of oxygen in the water column, as well as heavy rainfall which led to a large input of nutrients going to the Lagoon.

In addition, there was a period of failure in the floodgate management which affected the entry of water from the sea and hence heightened the problem of the reduction of the values of salinity, which is an important (if limited) parameter for the establishment of *Synechocystis* spp. At the end of the blooming period of these algae, there was a large fish mortality caused by anoxia. In view of this, attention should be paid to the influence of the Rua General Garzon Canal (notorious for its contamination) in the LRF when its floodgates are opened. For this reason, there is a serious need for a suitable management of floodgates that comply with the guidelines of the protocol of the Municipal Contingency Planning of the Rodrigo de

Freitas Lagoon. By analogy, the desludging operations of the Jardim de Alah Canal are of extreme importance. As reported earlier, even gentle breezes can mix with the column of water and favor the horizontal uniformity of the water mass, while specific alterations can influence the Lagoon as a whole.

On the basis of the detailed results, it can be argued that particular places in the Lagoon are more prone to the harmful effects of the illegal dumping of sewage, such as those close to the General Garzon Canal and also the Jardim de Alah Canal. However, in light of seasonal factors, it cannot be stated which points undergo a significantly more serious impact from the release of sewage, and further continuous monitoring is needed together with more detailed analyses to make this determination.

At all events, it is of crucial importance to carry out the monitoring and surveillance activities of the illegal dumping of waste material. This should be undertaken in a systematic and continuous way at the customary outlet points with a view to detecting and eradicating these illegal systems. Tests should be carried out to detect the origin of these clandestine practices in the drainage system and include dyes and tracers in the piping, upstream and downstream, beginning with the places where these practices are occurring. This can be assisted by drawing on the records available of the sewage systems (CEDAE) and drainage networks (RIOAGUAS), as well as information about the respective operational districts that are responsible for the maintenance of these systems. Setting out from a clear idea of the origins of the clandestine and illegal practices, a specific study should be undertaken to adjust these situations of non-compliance. This can entail introducing a project about sanitary sewage disposal which can make the economic infrastructure of the area viable without the need to be interconnected with a completely separate waste disposal system.

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Section 2

Water Column and Seabed

Chapter 3

Hypersaline Lagoons from Chile, the Southern Edge of the World

Gonzalo Gajardo and Stella Redón

Abstract

Hypersaline lagoons distributed in arid and semiarid regions are unique ecosystems with unique value stemming from their extremophile biodiversity, limnological properties and services, like mining and waterbird habitat. They are natural laboratories to understand how life evolved in extreme environments and how simple ecosystems function to provide waterbird habitat, an essential noneconomic service. Policymakers need this knowledge to protect these ecosystems increasingly affected by climatic change and human-driven perturbations. Hypersaline lagoons from contrasting latitudinal conditions in Chile provide a study case to evaluate how such conditions affect their microscopic and macroscopic diversities. Those in the hyperarid Atacama Desert in northern Chile are an integral part of mineral-rich salars, whereas Patagonian lagoons are unique among freshwater lakes of glacier origin. Despite latitudinal differences, prokaryotic diversity tends to be similar in both extremes. However, genetically distant brine shrimp (*Artemia*) species, *A. franciscana* (north) and *A. persimilis* (Patagonia), inhabit them. This crustacean is a keystone taxon in the food web, and its abundance indicates ecosystem quality and attracts waterbirds. This chapter stresses the need to systematically monitoring *Artemia* abundance and all factors affecting its fitness (gut microbiota, parasites, environmental conditions). Finally, the need to conserve these unique and extreme ecosystems is highlighted.

Keywords: hypersaline ecosystems, extremophile biodiversity, waterbird habitat, natural laboratories, Atacama Desert, Patagonia, Chile

1. Introduction

Hypersaline lakes or brines (over 40 g/L) [1] are unique ecosystems with unique extremophile biodiversity and scientific value, which also have economic, esthetic, cultural, and recreational value [2, 3]. They represent a significant volume (~45%) of inland waters [4] and hence are essential components of the biosphere, mostly located in arid and semiarid regions around the world where high evaporation rates exceed rainfall. However, they also occur in unusually cold places such as Tibet in China and Patagonia in southern Chile and Argentina [5, 6]. Due to their wide ecological diversity related to their coastal (thalassohaline) or inland origin (athalassohaline) [7, 8], altitude, salinity, and island-like distribution, these lagoons display unique extreme biodiversity and limnological features. Besides, hypersaline lagoons are also affected by the combined effect of multiple stressors such as UV exposure, temperature, pH, low nutrient, and oxygen availability [8], which means these lagoons are polyextremophile environments. As a consequence, the microscopic and macroscopic biodiversity reflects their evolution to cope with multiple stresses that are unbearable for most organisms.

Since biodiversity declines as salinity increases, hypersaline lagoons are relatively low-diversity ecosystems with simple food webs [9] and hence are considered suitable natural laboratories [10] to address fundamental questions of biology. Due to the multiple stressors shaping such unique biodiversity and the potent mutagenic role variation in ionic strength has on DNA-protein interactions, and protein structure, the biodiversity of these lagoons exhibits an accelerated rate of evolution, at least as demonstrated for brine shrimps (*Artemia*) [11]. Among the relevant biological questions salty ecosystems allow to investigate are those related to the origin of life from simple forms, and what are the limits and prominent features of life in extreme environments, topics addressed by the new discipline of astrobiology [12]. Likewise, what is the microbiological and macroscopic (zooplanktonic) diversity salty lagoons harbor, and how latitudinal, climatic, lagoon-specific conditions, or anthropic perturbations modulate such diversity? Their microbiological diversity has received significant attention due to the potential economic benefits attached to the metabolic responses evolved to cope with extreme conditions (antioxidant pigments, hydrolytic enzymes) [13–15]. While the stress response in the prokaryotic world tends to be unidimensional, multicellular systems experience critical life conditions at all levels of functionality; in other words, adaptation takes place at different domains, from the individual (molecular-cellular-physiological) to the population level. As discussed later on in this chapter, the brine shrimp *Artemia* is a relevant extremophile model to understand what means to survive and reproduce under harsh conditions [6].

From a more practical perspective, hypersaline lagoons are considered low-diversity natural laboratories to understand how simple ecosystems function to provide economic services like mining salt and brine shrimp (*Artemia*) biomass, like in the Great Salt Lake in Utah, an example of a well-managed lake to allow the coexistence of economic and noneconomic services like waterbird habitat. The lake is the main source of *Artemia* cysts for world aquaculture [16], but the *Artemia* biomass required to harvest tonnes of cysts also attracts local and migratory waterbirds that need to be protected, some of which are endangered [17, 18]. Hypersaline lakes and lagoons around the world are, however, shrinking at an alarming rate due to climate oscillations and water or brine diversion for mining [19]; hence, there is a need to conserve their unique biodiversity, properties, and services to comply with international treaties on biodiversity, ecosystem, and wetland conservation. The lack of systematic and long-term spatial and temporal studies on most hypersaline ecosystems that are often in remote places and tend to exhibit high seasonal variation in their biodiversity [9] makes difficult to understand or predict how they will respond to climate oscillations and increased anthropic pressures.

The importance of saline lakes and lagoons in the twenty-first century was highlighted by Williams [3], who in 2003 predicted they would be shrinking by 2025. Other reviews have also highlighted the fragility of these unique ecosystems [2, 4], while recent literature pinpoints the biotechnological importance of the microbiological diversity they harbor [12–15] as an argument to protect them [14]. This chapter focusses on Chilean hypersaline lagoons (or Lagunas) located at contrasting latitudinal and altitudinal settings at the southern edge of the world, i.e., southwest of South America (below 18° latitude south). In the north, inland (athalassohaline) lagoons are an integral part of mineral-rich evaporitic basins or salars (salt crusts) scattered at different altitudes in the hyperarid Atacama Desert. The aridity of the desert has raised the question if life can persist in water-less environments, and because of this and other soil characteristics, the desert is considered a terrestrial model of Mars and hence a target of astrobiological research as already mentioned.

Instead, in Patagonia, there are subantarctic low-altitude lagoons, some of which are relatively close to the Pacific coast but cannot strictly be considered thalassohaline. The unique feature of these hypersaline lagoons is their location in an area where freshwater lakes of glacier origin abound. Both contrasting latitudinal settings represent useful case studies to address how their prokaryotic and eukaryotic diversity evolved. The brine shrimp *Artemia*, a key taxon in the food web of these salty lagoons, becomes relevant in the discussion on how these lagoons function to provide suitable habitat for waterbirds, as the abundance of this crustacean seems to be a good predictor of their presence [17] and the animal is also considered an indicator of environmental quality. In this context, some of the remarkable animal's adaptations are discussed, including the sort of symbiotic *Artemia*-bacteria relationship and other factors affecting *Artemia* fitness and hence the abundance of this crustacean. The aims of this chapter are as follows: (1) To provide a glimpse to the ecological characteristics of hypersaline lagoons of Chile, which are unique ecosystems located at contrasting latitudinal edges. They are a natural heritage harboring unique extremophile biodiversity that provides conditions to host a significant waterbird diversity. (2) To review studies on their microbiological communities that coexist with *Artemia*. (3) To get insights on *Artemia* species inhabiting such contrasting environments, and their ability to tolerate high salt concentration (salt-lover), and to perceive ecosystem quality. The *Artemia*-bacteria interaction is also discussed as it contributes to *Artemia* fitness and abundance. (4) To highlight the need to monitoring hypersaline lagoon dynamics on a long-term basis to predict waterbird presence. (5) To alert on the fragility of these ecosystems increasingly affected by climatic oscillations and human-driven perturbations like mining.

2. Hypersaline lagoons from Chile: natural heritage at the southern edge of the world

Chile is a sort of biogeographical island at the southern edge of the world, isolated by the hyperarid Atacama Desert on the north, the Antarctic ice on the south, the Andes Mountains on the east, and the Pacific Ocean on the west. This long and narrow land (**Figure 1**) exhibits a wide latitudinal (18°–56°S latitude, excluding the Antarctic) and altitudinal range, from sea level to the high Andes. Natural hypersaline lagoons or brines exist at both latitudinal and climatological extremes. The Atacama Desert (17°–27°S latitude) is the driest, oldest, and most extreme world environment [20, 21], well-known as a terrestrial Mars analog, as already mentioned, with microbial life similar to what could be expected to exist in the red planet [21, 22]. This desert contains numerous inland athalassohaline lagoons (**Figure 1A** and **B**), i.e., with salt proportions different from seawater [7, 8], which are an integral part of different evaporitic basins, salars, or salt crusts, located at different altitudes, just to name a few: Salar de Llamará (21°18′S, 69°37′W) at 850 m; Salar de Atacama (23°30′S, 68°15′W) over 2300 m, the largest in the Altiplano-Puna region of the Central Andes (~3000 km^2); Salar de Huasco (20°18′S, 68°50′W), a protected National Park and Ramsar site at 4000 m; and Salar de Surire (18°48′S, 69°04′W) at 4245 m. Only Andean countries like Perú, Bolivia, Argentina, and Chile share the geomorphological, climatic and hydrological conditions that originated these salars and hypersaline lagoons [7, 20–23].

The Chilean Patagonia belongs to the administrative region of Magallanes and Chilean Antarctica. This steppe-like landscape with cold, semi-humid climate and very windy condition are characteristic of this region where few lagoons exist. Although some are close to the coast such as Laguna Cisnes (**Figure 1D**), it is difficult to classify it as thalassohaline (marine origin) [8] due to mineral runoff from agriculture and other sources.

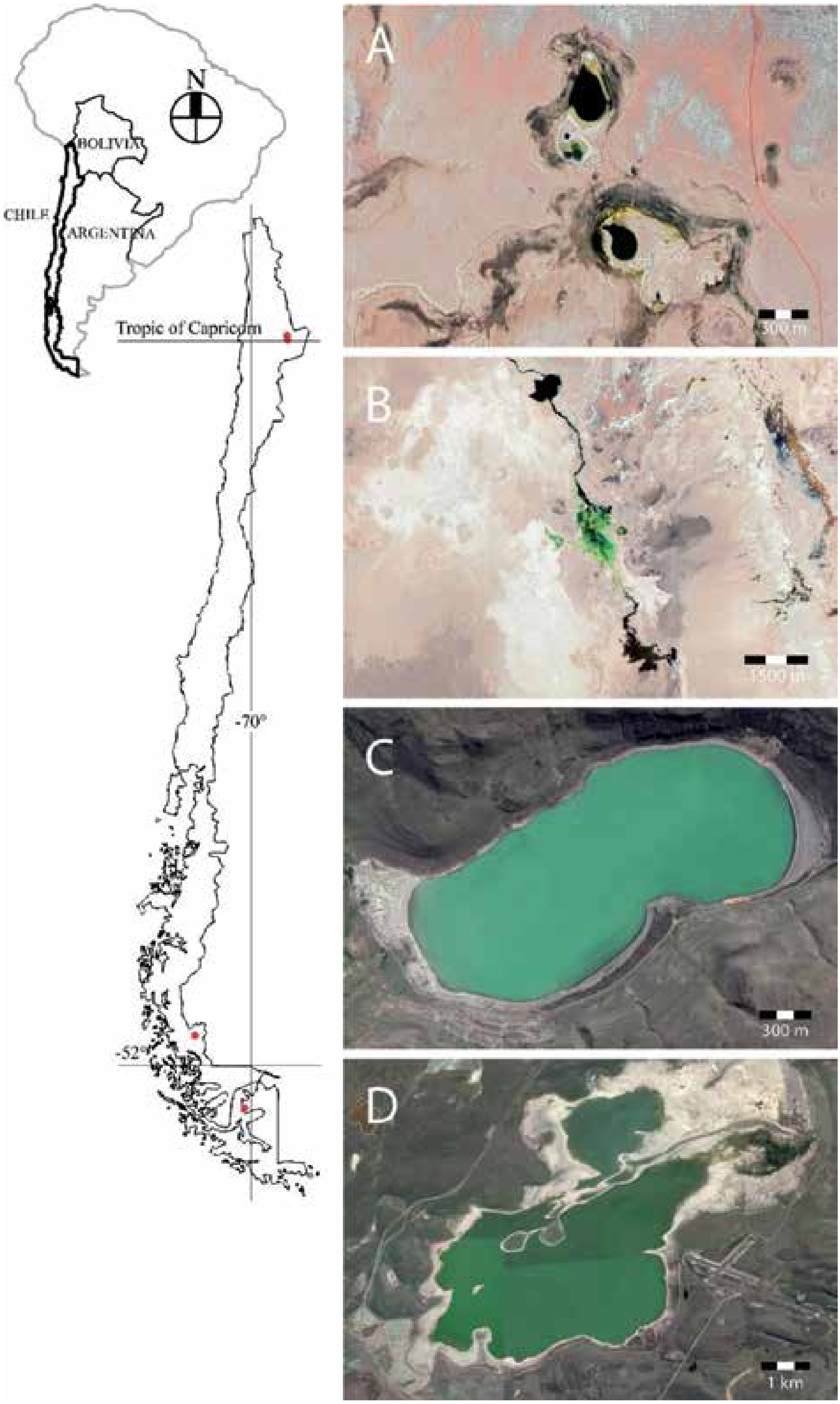

Figure 1.
Hypersaline lagoons from contrasting latitudinal environments in Chile, the southern edge of the world. Atacama Desert: (A) Piedra and Céjar lagoons. (B) Los Flamencos National Reserve, from north to south: Chaxa lagoon (0.37 km²), Canal Burro Muerto (0.1 km²), Barros Negros lagoon (1.03 km²), and Puilar (0.84 km²). Patagonia: (C) Amarga and (D) Cisnes lagoons.

Figure 2.
Cisnes (left) and Amarga lagoons in the Chilean Patagonia, the former was declared a national monument to protect waterbird diversity. Both are unique hypersaline ecosystems in an area where freshwater lakes of glacier origin abound. Bacterial diversity and the brine shrimp Artemia persimilis coexist, a subsample of wild bacteria diversity represented in the Artemia-gut microbiota.

These are (1) Laguna Amarga (Bitter lagoon, 50°29′S, 73°45′W) (**Figures 1C** and **2**), located in the province of Última Esperanza at 80 m above sea level, close to the eastern border of the Torres del Paine National Park; (2) Cisnes lagoon (53°15′S, 70°22′W) (**Figures 1D** and **2**), close to the city of Porvenir in the northeast of Tierra del Fuego (fireland) and the Magellan Strait; and (3) Laguna de la Sal (salt lagoon, 53°17′S, 70°23′W), a small and shallow lagoon located southern to Los Cisnes lagoon. The lagoon's salinity varies highly year-round and so its biological composition. Minor quantities of salt are extracted during the dry season (December) time at which salinity peaks to the maximum. At that time, the population of the most conspicuous planktonic inhabitant disappears (the brine shrimp *Artemia persimilis* in Patagonia). However, *Artemia* cysts abound, the mechanism that permits population continuity once suitable conditions recover [6, 24]. Although no systematic and long-term studies exist on these subantarctic lagoons, some literature allows getting a glimpse to their basic characteristics. Amarga lagoon is mesohaline [25], shallow (maximum depth: 4.1 m), and alkaline (pH 9.1), whereas the average annual temperature was 11.7°C when authors sampled the lagoon. About the same period, Saijo et al. [26] confirmed that water was strongly alkaline (pH 9.4), salinity was 77 g/L, and the significant ions were sodium and sulfate. Fuentes-González and Gajardo [27] sampled Cisnes lagoon in December, the dry period, when the UV index is the highest (6.84 ± 0.63) and temperatures range from 15.18 ± 1.31 to 6.25 ± 0.85°C according to the 14-year search they report. The salinity was 51 g/L, the water cold (9°C), and the lagoon was considered eutrophic, according to the high concentrations of phosphorous (0.30 ± 0.73 mg L^{-1}), nitrate (0.66 ± 0.14 mg L^{-1}), and chlorophyll-a (44.25 ± 2.52 μg L^{-1}). The microalga *Spirogyra* sp. and the crustacean *Artemia* were the predominating plankton. The salinity of both lagoons was recently reported in 2 consecutive years with values of 55 and 51 g/L in Cisnes lagoon and 86 and 81 g/L in Amarga lagoon, for spring 2017 (November) and autumn 2018 (April), respectively [28].

3. Microscopic and macroscopic biodiversity

Hypersaline lagoons contain the three domains of life, Archaea, Bacteria, and Eukarya [29], and this section provides a glimpse to the prokaryotic and eukaryotic diversity of lagoons located at the latitudinal extremes already described. As a representative eukaryotic, the brine shrimp *Artemia* is the obvious choice taking into account its key role in the food web of hypersaline lagoons [17] and because it is a model extremophile for studies of evolution and adaptation [10, 6]. Some adaptations explain *Artemia* abundance and the ability of females to perceive forthcoming environmental conditions. Although both domains have coexisted and evolved under similar environmental pressures, the historical trend has been to consider them independently. However, later in this chapter, the *Artemia*-bacteria (microbiota) interaction is considered as an example of a symbiotic relationship.

3.1 Microbial communities

Studies on the microbiology of hypersaline lagoons in Chile are biased to lagoons in the Atacama Desert for various reasons. One the one hand, these lagoons provide a unique diversity of habitats to study microbial ecology and diversity as they spread in salt flats (Salars) at different altitudes, with varying salinities and ionic compositions [7, 23, 30]. On the other hand, and as previously said, the desert is a terrestrial Mars analog, and so a study case for researchers exploring the origin and limits of life on earth as a potential analog to life on Mars [21, 22]. Such diversity of microbial ecosystems (soil and brines) provides an opportunity to understand the physiological adaptations of microorganisms to extreme environmental conditions. A more practical argument has to do with the lithium richness of Salar de Atacama, the largest salt flat in the Atacama Desert, and so interest exists in evaluating the microbial diversity associated with this economically important mining process. The bacteria found in pools where brines are evaporated to concentrate lithium are expected to exhibit a range of unique molecular and metabolic capabilities to cope with high lithium concentration [31]. In a more general context, extremely salty lagoons both in Chile [32] and around the world are the source of metabolites and enzymes of biotechnological interest [12, 13]. Microbial mats are another bacterial ecosystem reported in Salar de Atacama, consisting of flat laminated communities with unicellular cyanobacteria (*Synechococcus* and *Cyanothece*), and filament forms (*Microccoleus*, *Oscillatoria*, *Gloeocapsa,* and *Gloeobacter*) [33].

The advent of culture-independent techniques such as the 16S rRNA gene sequencing has improved biodiversity studies in hypersaline lagoons, revealing hidden diversity not previously discovered by culturable-dependent techniques. This technique combined with the metagenomics [34] and other "omics" (transcriptomics, proteomics, metabolomics) has facilitated to get an integrated picture of the adaptive microbial response to extreme conditions and other aspects of microbial evolution such as antimicrobial resistance, pathogenesis, and the underlying genetic determinants of these capabilities [12].

Demergasso et al. [23] compared lagoons in Salars with strong altitude gradient (Llamará, Ascotán, and Atacama), qualitative differences in ionic compositions, and subject to different UV influence, finding predominance of phylum *Cytophaga-Flavobacterium-Bacteroides* (CFB) (now Bacteroidetes) and few Proteobacteria at high salinity and altitude (Salar de Ascotán), whereas diversity decreased in Salar de Atacama (in the pre-Andean Depression) and Llamará. Archaeal assemblages corresponded to uncultured haloarchaea distantly related to cultured strains obtained from thalassohaline environments. The study considered samples from 19 different environments of Céjas (or Céjar) (**Figure 1A**), Burro Muerto (**Figure 1B**), and Tebenquiche lagoons to conclude that athalassohaline environments are excellent sources of new microorganisms that are different from their counterparts in thalassohaline environments. A spatiotemporal study (three sites; summer and winter season) in Tebenquiche lagoon (**Figure 3**), the largest water body in Salar de Atacama [7], found abundance of genera belonging to phylum Bacteroidetes and Gammaproteobacteria, such as *Vibrio*, *Halomonas*, *Acinetobacter*, *Alteromonas*, *Psychrobacter*, and *Marinococcus*. The authors highlighted the remarkable novelty found as 16S rRNA gene sequences of Bacteroidetes. Another study on Bacteroidetes [35] evaluated brine and sediment samples from lagoons in Salar de Huasco, Salar

Figure 3.
Laguna Tebenquiche, the largest water body in Salar de Atacama harbors rich prokaryotic diversity varying spatiotemporally and coexisting with the brine shrimp Artemia franciscana.

de Ascotán, and also in Tebenquiche lagoon, finding high microbial diversity in Tebenquiche and Salar de Ascotán, whereas diversity decreased in Salar de Huasco. Most of the 16S rRNA gene sequences corresponded to the following genera (Flavobacteriaceae): *Psychroflexus*, *Gillisia*, *Maribacter*, *Muricauda*, *Flavobacterium*, and *Salegentibacter*. The most abundant phylotype was related to *Psychroflexus* spp. A study of hypersaline wetlands in salars of the Altiplano at a higher altitude than those previously mentioned [36, 37], including Salar de Huasco and Salar de Ascotán, also showed significant differences in their microbial community attributed to habitat type and physicochemical properties of the lagoons. Bacteroidetes and Proteobacteria predominated with a smaller contribution of Firmicutes, Actinobacteria, Planctomycetes, Verrucomicrobia, Chloroflexi, Cyanobacteria, Acidobacteria, *Deinococcus-Thermus*.

The study of Azua-Bustos et al. [21] took advantage of unusual rain events in the hyperarid core of the Atacama Desert, which created temporal lagoons for some time. The authors observed that surface bacteria died due to osmotic stress but were able to isolate a newly identified species of *Halomonas* metabolically active and reproducing in the lagoon. Another study took soil samples at 2 m of depth in the core of the Atacama Desert [22], where life was not expected to exist, analyzed the samples with a life detector chip containing 300 antibodies, and found bacteria, Archaea, DNA, and exopolysaccharides. They identified members of the alpha, beta, gamma, and epsilon—Proteobacteria, Actinobacteria, Firmicutes, Acidobacteria, *Deinococcus*, Bacteroidetes, and Euryarchaeota. Back to hypersaline lagoons, the study of Cubillos et al. [31] assessed microbial communities in evaporating pools where lithium-rich brines pumped from beneath the Salar surface are concentrated (55.6% salinity) by lithium-exploiting companies. They found the archaeal family Halobacteriaceae and genera *Halovenus*, *Natronomonas*, *Haloarcula*, and *Halobacterium.* Instead, abundant families in natural brines were Rhodothermaceae and Staphylococcaceae. As these concentrated brines represent one of the most saline environment described, the authors concluded that the microorganisms found should shed further light on the adaptive response to such extreme conditions.

3.2 Microbial communities of Patagonian lagoons

A study in our laboratory (Quiroz and Gajardo unpublished) (**Figure 4**) compared the microbial diversity of two Patagonian lagoons (Cisnes and de la Sal) with the *Artemia*-gut microbiota composition. The phylum Bacteroidetes was the most common in brines of both lagoons in agreement with the study described earlier [30]. Proteobacteria and Cyanobacteria (de la Sal lagoon) were less represented. At the genus level, the diversity is high, *Psychroflexus* predominating, though a significant diversity remains unidentified. The microbiota of individuals collected in Cisnes lagoon contains a reduced amount of Bacteroidetes, whereas the proportion of Proteobacteria and Firmicutes is higher. The most frequent genera in the *Artemia* gut of Cisnes lagoon individuals are *Halolactobacillus*, *Psychroflexus*, *Halomonas*, and *Vibrio*, a pattern similar to that previously described [30]. The observation that some bacteria present in the gut of *Artemia* individuals are in low frequency in the environment, or not found, supports the idea that in some polyextremophile environments like Salar de Atacama, microbial habitats are serving as a refuge, i.e.,

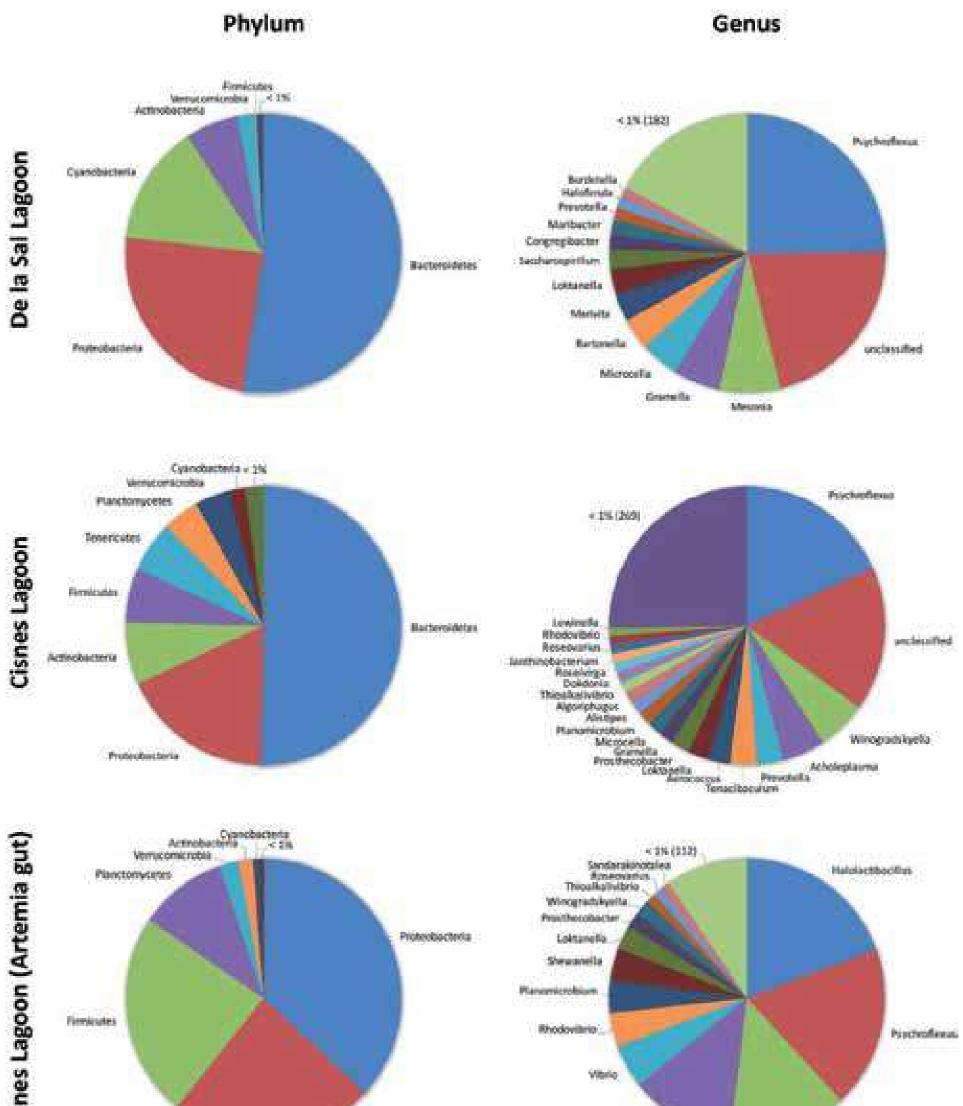

Figure 4.
Bacterial diversity in brines of Patagonian lagoons De la Sal and Cisnes and bacterial communities in the Artemia gut of individuals from Cisnes lagoon (bottom).

the so-called endolithic habitats [38]. From data in **Figure 4**, it is possible to think that the *Artemia*-gut microbiota could also serve as a refuge to bacteria uncommon in natural brines such as *Halomonas* and *Halolactobacillus*.

4. The salt-lover brine shrimp *Artemia*: adapted to critical life conditions

The brine shrimp *Artemia* is a branchiopod crustacean well adapted to the harsh conditions of hypersaline environments impose on survival and reproduction and hence is considered a model extremophile or a salt-lover sensu Wharton [39]. It displays remarkable adaptations at different domains, one of the most striking being a highly efficient osmoregulatory system to withstand high salinities (up to 340 g/L) [6]. Also, *Artemia* females can perceive when the environment becomes suboptimal, an ability that makes *Artemia* an indicator of ecosystem quality. Under suboptimal conditions, i.e., when a shallow lagoon dries up, females switch to produce encysted offspring (oviparity), in other words, cysts or diapause embryos highly resistant to extreme conditions. Instead, offspring in the form of free-swimming nauplii (ovoviviparity) allows rapid population expansion under optimal environmental conditions. The cyst shell protects from UV irradiation, large temperature fluctuations, osmotic pressure, dryness, and other stresses, so cysts remain viable practically dehydrated [40–42]. Such evolutionary solution for populations to escape extinction when conditions become unfavorable suggests that cysts contain a memory of the past [6] that can be retrieved when cyst resurrect (sensu [43]) either naturally or experimentally, i.e., resume metabolic activity and hatch once the environment returns to normal. Since cysts deposited in saline lagoons at different times accumulate at shores and all have the chance to hatch at the same time when the environment allows it, females face a critical mating decision of choosing the right male to maximize their reproductive output. They can mate either contemporary males (hatched from cysts of the same age), males from the past (hatched from older cysts), or males from the future (hatched from more recent cysts). Females tend to select contemporary males, which would be a demonstration of male-female coevolution [44]. The sophisticated mate choice behavior of *A. franciscana* would be a consequence of such coevolution [45]. The question of how females perceive in advance when conditions will become unfavorable remains unclear, but it would be reasonable to advance the hypothesis that bacterial communication (quorum sensing) to maintain their functional diversity in extreme ecosystems could be involved. This is possible as bacteria interact with all kind of life forms in a given ecosystem, and such interaction may affect the adaptation of other species. For example, the microalgae *Dunaliella salina*, commonly found in saline environments, responds to quorum sensing [46].

In Chile, two out of the six regionally endemic and highly divergent sexual species co-occur, *A. franciscana* Kellogg, 1906 and *A. persimilis* Piccinelli and Prosdocimi, 1968 [6, 24]. The latter was previously thought endemic to Argentina, though it is now clear that inhabits Chilean Patagonia lagoons [47, 48]. Both species are segregated by a latitudinal barrier coincidently with their differential ability to colonize and cope with different environments, which is the case of *A. franciscana*, the most widely distributed of all, and considered a younger species in evolutionary expansion [24]. The species inhabits lagoons of the Atacama Desert in northern Chile, which is the southern limit of a broad north-south distribution in the Americas (North, Central, South). Instead, *A. persimilis* is restricted to Patagonia, with a probable hybrid zone between both species in solar saltworks of central Chile [49, 50]. Other sexual species are restricted to the Mediterranean area (*A. salina*), Lake Urmia and some lakes in Ukraine (*A. urmiana*), China (*A. sinica*), and Tibetan Plateau

(*A. tibetiana*). The situation in Asia seems now to be a bit complex as a mix of sexual and asexual *Artemia* species, including the invasive *Artemia franciscana* coexist as shown with mitochondrial (COI) and nuclear DNA markers (ITS) [51]. The species has also invaded and even displaced local species in Europe [52]. Such evolutionary plasticity depends on the species overall high genetic variability, which is heterogeneously distributed over the populations [49, 53]. As Gajardo and Beardmore put it [6], the species gene pool is distributed over different safety baskets.

With the advent of massive sequencing and transcriptomics, new information has been reported on the genetics of sex differentiation [54–56] and stress or adaptation-related genes [41]. A transcriptomic study in *A. franciscana* identified genes responding to salt stress by experimentally comparing *Artemia* individuals reared under hypersaline and marine conditions [57]. Authors found ~100 genes differentially expressed under hypersaline conditions controlling critical biological functions such as signal transduction, gene regulation, lipid metabolism, transport, and stress response (Heat shock 70 kDa), all contributing to maintaining homeostasis-repairing mechanisms in *Artemia.*

4.1 The *Artemia*-bacteria relationship

The brine shrimp *Artemia* and bacteria coexist and interact in hypersaline lagoons, as demonstrated by Quiroz et al. [30]. One evident expression of this interaction is that *Artemia* gets energy grazing on bacteria [58–60], which also provide enzymes to digest the algae and yeasts that are also *Artemia* food items. Additionally, environmental bacteria colonize and establish in the *Artemia* gut conforming the microbiota, which is known to provide multiple functional benefits to the host such as protection against pathogens, energy balance, immunological enhancement, and behavior [61]. Thus, imbalances (i.e., reduced diversity) in the microbiota composition due to environmental or other factors such as pathogens seriously affect the performance of the host in a given environment. The *Artemia*-microbiota is an example of facultative symbiosis in which mutual benefits are provided [62]. The most evident benefit for *Artemia* is fitness, which can be constrained or expanded depending on salinity in such a way that under optimum salinity, fitness should be maximized. Therefore, the *Artemia*-gut microbiota interaction influences *Artemia* abundance, which is a good predictor of waterbird presence in hypersaline wetlands. This would explain why not all hypersaline lagoons attract the same amount of waterbirds. The importance of *Artemia* in this regard was experimentally demonstrated [17] with the introduction of *A. sinica* in a Tibetan hypersaline lake where the species did not exist. Such introduction created the conditions to attract waterbirds not previously present in the lake. Another case was the introduction of *A. franciscana* in Godolphin lakes, an artificial hypersaline wetland created to attract flamingos and charadriiform birds in Dubai [63]. The flamingo species *Phoenicopterus roseus* is a regular visitor in that habitat, as well as other bird groups such as sandpipers, plovers, avocets, grebes, ducks, and gulls, and their presence is correlated with *Artemia* blooms.

The study of Quiroz et al. [30] assessed the microbial diversity of natural brines and those present in the gut microbiota of adult individuals collected in the same environment in lagoons of the Atacama Desert, solar saltworks in Central Chile, and Patagonian lagoons. The microbiota of animals collected in natural brines contains a subsample of environmental diversity, and the authors evaluated some reported functions of the bacterial communities of the gut microbiota to test the hypothesis that they should contribute to *Artemia* fitness. For example, the genus *Sphingomonas* (Alphaproteobacteria), found in the gut of wild *Artemia* individuals, contains a species (*S. wittichii*) reported to degrade polycyclic aromatic hydrocarbons (PAHs) that are persistent pollutants accumulated in the food chain [64]. The genus *Chromohalobacter* (Gammaproteobacteria), also identified in the gut of wild individuals collected both in northern and southern lagoons, contains the species *C. salexigens* that produce ectoine (or hydroxyectoine), a compound protecting proteins from degradation, and other environmental stressors such as salinity changes, oxidative stress, and high UV radiation [65]. Ectoine and other compatible solutes also act as osmoprotectants facilitating bacteria establishment in the saline environment. The authors were surprised to find psychrophilic bacteria known to produce antifreeze proteins in Céjar (north) and Amarga lagoons (south). Moreover, some bacteria found in the Atacama Desert are phylogenetically closer to some types found in the Antarctic, similarity that tells about convergent environmental conditions or a similar adaptive pattern despite the latitude difference. Such similarity includes the Great Salt Lake in Utah, where bacterial sequences most closely related to genera *Halomonas*, *Psychroflexus*, and *Alkalilimnicola* were found in the water [66].

5. The need to monitoring hypersaline lagoons dynamics to predict waterbird presence

The food web of these lagoons is simple and sensitive to environmental conditions such as salinity changes caused by water or brine diversion. The main ecosystem components are bacteria, microalgae, and different zooplankters (Ostracoda, Copepoda, Branchiopoda); among the latter the brine shrimp *Artemia* plays a key ecological role in the ecosystem grazing on bacteria and phytoplankton (such as the halotolerant unicellular green algae *Dunaliella*) and hence modulate their biomass. Studies in the Mediterranean [67], Crimean lakes in Ukraine [17], and Dubai [63] have evidenced the *Artemia* role to predicting waterbirds presence. Besides, *Artemia* is an intermediate host for avian helminth parasites, particularly cestodes and nematodes [68–70], also providing useful information on waterbird abundance and diversity in hypersaline ecosystems. In turn, *Artemia* abundance is controlled by copepods and amphipods species that are common at lower salinities but can also tolerate high salinities, particularly copepods [71, 72].

Waterbirds inhabiting hypersaline wetlands, particularly flamingos, disperse *Artemia* by carrying cysts in their feathers or in the digestive tube which are released to the environments with their feces [52, 53]. This service provided by flamingos would favor the colonization of new suitable habitats and would explain *Artemia* distribution to some extent [73]. The knowledge on the halophilic biodiversity of hypersaline lagoons is, therefore, a first step toward understanding why local and long migratory waterbirds use them as a source of energy and as breeding sites. Lagoons in Salar de Atacama are essential habitats for flamingos and shorebirds [74–76], some of them with conservation problems according to the IUCN Red List of Endangered Species. The Chilean flamingo and the Puna flamingo are both near threatened; meanwhile, the Andean flamingo is recognized as a vulnerable species. Lagoons from Salar de Atacama (particularly Puilar) represent the most important breeding site in the world for the Andean flamingo (**Figure 5**). In addition, these lagoons are important for migrating interhemispheric species such as Baird's sandpiper *Calidris bairdii* and Wilson's phalarope *Steganopus tricolor*, among others, despite there is no quantitative data for these species in the area. Charadriiformes and Anseriformes such as the Andean gull *Larus serranus*, and the Andean Goose *Chloephaga melanoptera* (Anatidae) are also present in the Salar.

Patagonian saline lagoons also hold a great diversity of waterbirds, including flamingos, swans, grebes, and shorebirds [77]. Among the most abundant birds in

Figure 5.
Saline lagoons in northern Chile (Salar de Atacama) provide waterbird habitat, a relevant noneconomic service. (A) Flamingos. (B) Nests. (C) Nestlings. (D) Salar de Atacama is the epicenter of the world's largest lithium exploitation from brine pumped from beneath the Salar. The challenge ahead is how will both services coexist in a scenario of soaring lithium demand, and hence brine diversion, to support electromobility.

Amarga lagoon are the Black-necked swan *Cygnus melancoryphus*, Coscoroba swan *Coscoroba coscoroba*, upland goose *Chloephaga picta*, white-tufted grebe *Rollandia rolland*, and silvery grebe *Podiceps occipitalis* and several species of dabbling ducks. Cisnes lagoon is used mainly as feeding places by sandpipers and plovers (Charadriiformes) such as the White-rumped sandpiper *Calidris fuscicollis*, the Baird's sandpiper, Two-banded plover *Charadrius falklandicus*, Rufous-chested plover *Charadrius modestus*, and the Magellanic plover *Pluvianellus socialis*, a species near threatened at a global scale. Both lagoons include representatives of Anseriformes, such as the shelducks (Tadorninae) *Chloephaga rubidiceps* and *C. picta* and dabbling ducks (Anatinae) such as *Speculanas specularis* (near threatened), *Anas georgica*, *Lophonetta specularioides*, *Tachyeres patachonicus*, and *Mareca sibilatrix* [78]. Among Phoenicopteridae, the Chilean flamingo is abundant in Patagonian saline lagoons, being one of the main *Artemia* predators, and such abundance is likely to explain the abundance of flamingo parasites recorded in the *Artemia* population from Los Cisnes lagoon [28].

6. Current threats and future perspective

A serious problem to conserve the biodiversity of hypersaline lagoons in Salar de Atacama or Patagonia is to make it visible to policymakers, miners, ecotourists, birdwatchers, and even to people from the local communities controlling the access to lagoons, as it is the case in the north. However, a practical way of raising awareness on the relevance of these lagoons is aquatic birds' conservation [73]. That is why we have emphasized the relationship between hypersaline lagoons dynamic, *Artemia*, and waterbird abundance. Indeed, particularly charismatic species like flamingos inhabit hypersaline wetlands in the Altiplano (**Figure 5**), some of which are considered endangered [74–76]. Three South American flamingo species occur associated with these wetlands: Puna flamingo (*Phoenicoparrus jamesi*), Andean flamingo (*Phoenicoparrus andinus*), and Chilean flamingo (*Phoenicopterus chilensis*), the latter species is also abundant in hypersaline lagoons from the Chilean Patagonia [77].

As mentioned in the previous sections, hypersaline lakes and lagoons produce commercial services like salt extraction and brine shrimp cysts, as in the Great Salt Lake in Utah, the major cyst producer for aquaculture in the world. The lake is an example of good management to combine economic and noneconomic services like waterbird habitat [18]. However, mining is the cause of water and brine diversion and, together with climate oscillations, is the main driver accounting for the actual shrinking of hypersaline ecosystems around the world [19]. Lagoons of the Atacama Desert are indeed highly sensitive to the water budget in such a way that little changes can result in significant and amplified response in the physicochemical, ionic, and biological properties of the lagoons [8]. These lagoons are an integral part of the world largest lithium exploitation from brine (**Figure 5D**) [18, 37] pumped from beneath the surface of Salar de Atacama, the largest salt flat in Chile. The water and brine diversion associated with lithium exploitation represent a significant volume per day and is expected to increase as lithium demand has soared to support the growing fleet of electric cars. Because of this, we have alerted on the need to protect these highly fragile ecosystems [18]. In this chapter, the role as a bioindicator of the ecosystem health of the brine shrimp *Artemia* has been highlighted, as this crustacean is also a predictor of waterbirds abundance. *Artemia* abundance or fitness depends on the combined effect of the environment (salinity or brine quality) [8], the microbial diversity in the *Artemia* gut and in brines [30], and controllers like copepods [71, 72], depending on the salinity, parasites [68–70], and waterbird grazing pressure. This is a delicate cascade of events that need to be monitored regularly to be understood in order to advance science-based management decisions.

7. Conclusions

1. Hypersaline lagoons from north and south of Chile hold unique prokaryotic and eukaryotic biodiversity adapted to cope with extreme conditions. Microbiological studies are, however, biased to lagoons in the Salar de Atacama for various reasons. They provide a diversity of habitats, ideal for studies of microbial ecology. The fact that the Atacama Desert is considered a terrestrial analog of Mars makes it a target area for astrobiologists.

2. Chilean hypersaline lagoons are a natural heritage as they contain a unique halophile biodiversity and provide waterbird habitat, a relevant noneconomic service, to local aquatic birds and some endangered long-distance, migratory species like flamingos and so are a matter of global concern and a flagship to raise awareness on the need to protect these ecosystems. Several Ramsar sites exist in the north, and Laguna Cisnes in Patagonia has been declared a natural monument to protect waterbirds.

3. Hypersaline lagoons have relatively simple food web and so are kind of natural laboratories to understand how the ecosystem functions to attract waterbirds.

This knowledge is useful for policymakers to take science-based management decisions in relation to these ecosystems.

4. The brine shrimp *Artemia,* a keystone taxon of hypersaline lagoons, is a model extremophile to study adaptation to critical life conditions, and some of these adaptations explain why the animal is an indicator of environmental quality and a predictor of waterbirds abundance. Thus, all the factors affecting *Artemia* fitness (gut microbiota, copepods, parasites, birds grazing pressure, and environmental quality) should be monitored. *Artemia* abundance depends on a delicate cascade of events that require careful long-term spatiotemporal monitoring.

5. Two regionally endemic *Artemia* species occur in Chilean hypersaline lagoons separated by a latitudinal barrier, *A. franciscana* in Atacama Desert and *A. persimilis* in Patagonia. The former is widely distributed in the Americas (North, Central, South) and considered a species in expansion, whereas *A. persimilis* is restricted to southern latitudes in Chile and Argentina. Given the importance of *Artemia* as an indicator of environmental quality and a predictor of waterbirds abundance, these species need further studies.

6. Climatic oscillations in the hyperarid Atacama Desert along with water and brine diversion due to the large lithium exploitation based in Salar de Atacama are severe threats to hypersaline lagoons stability and hence to waterbird presence. Moreover, in a scenario of increased lithium demand to support electromobility how will Chile combine lithium exploitation with agreements on biodiversity and wetlands conservation?

7. The Patagonian lagoons are yet less intervened but very sensitive to climatic conditions. They represent a special case of hypersaline lagoons where freshwater lakes of glacier origin abound.

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Chapter 4

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 downslide 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 timescales 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

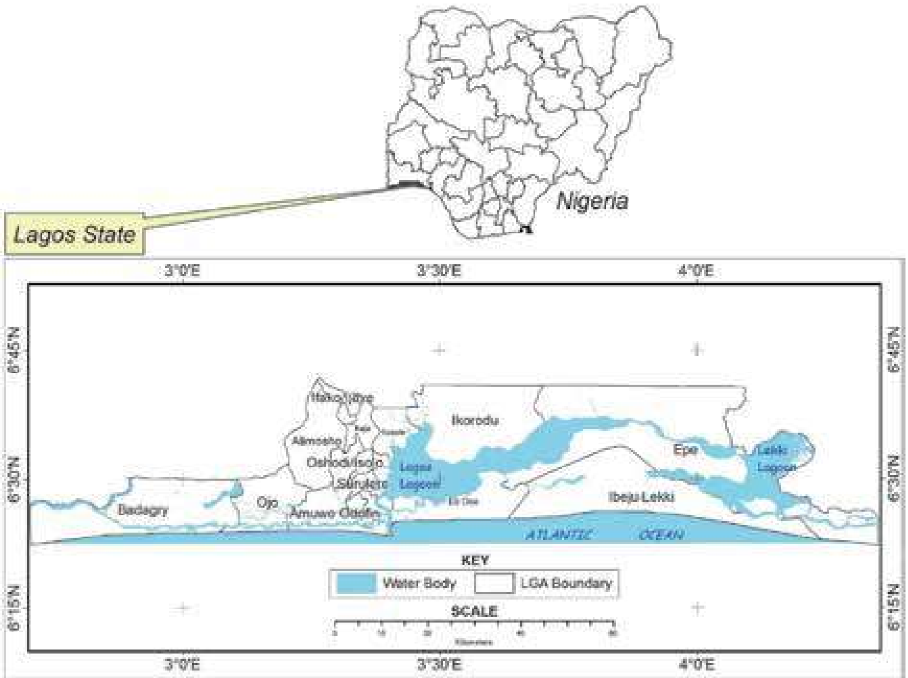

Figure 1.
Map showing Lagos Lagoon as situated in Lagos within Nigeria. The lagoon is surrounded by settlements (local government areas).

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

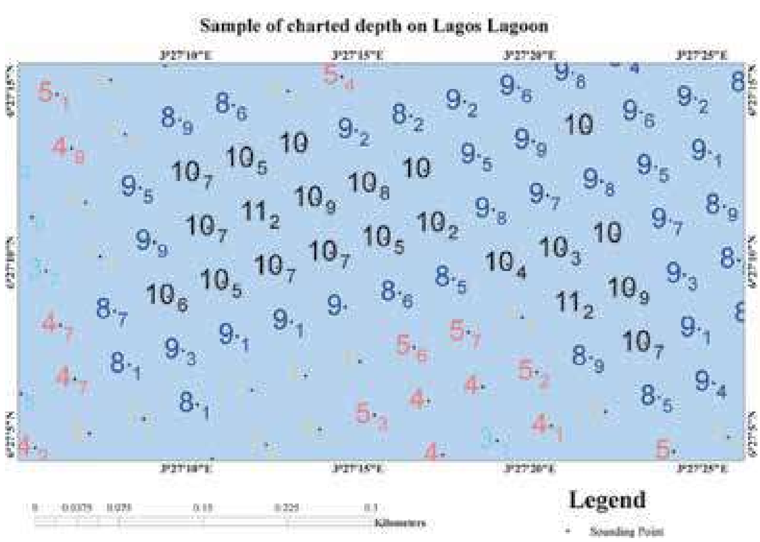

Figure 2.
Sample of charted bathymetric data of 2014 dry season, plotted in decimal number.

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

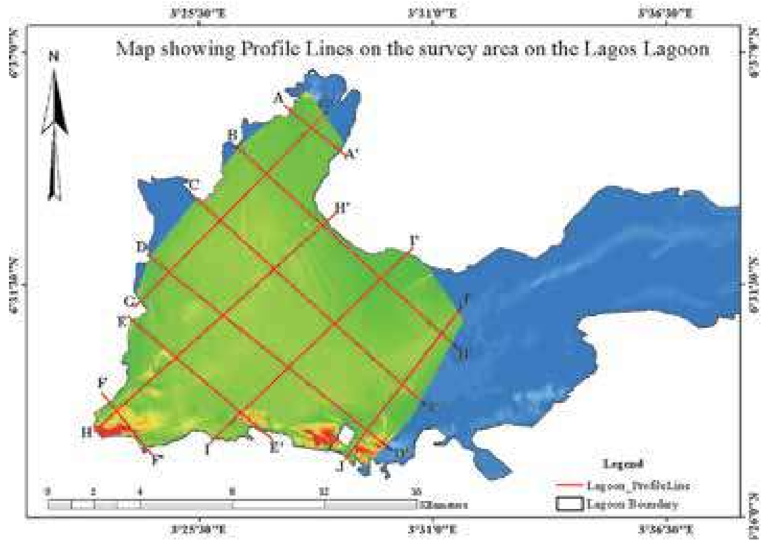

Figure 3.
Lagos Lagoon with profile lines on the study area. The area on the map with colour blue indicates area covered by the bathymetric survey of 2008, while the area with greenish yellow colour shows area surveyed in 2014.

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 mid-way 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

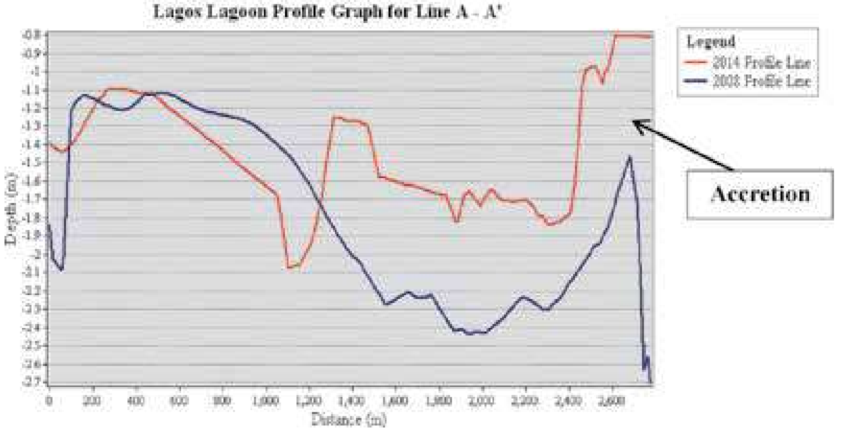

Figure 4.
Profile section A-A′ showing trend of variation in the repeated bathymetric data.

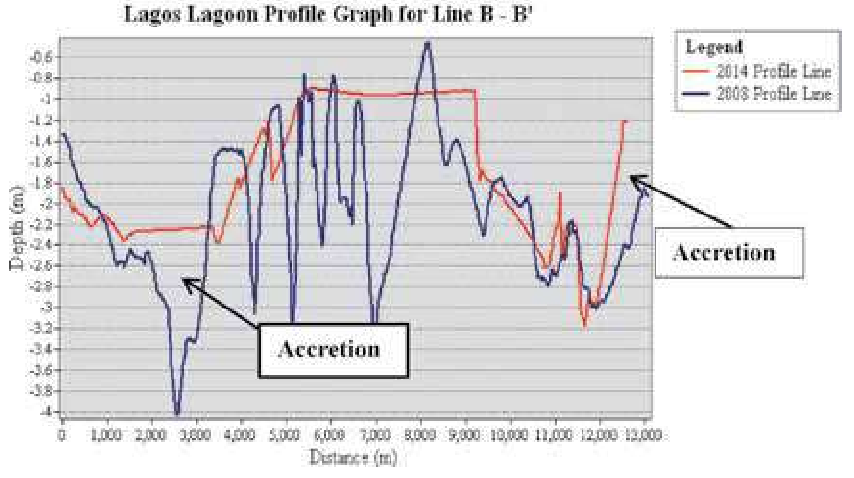

Figure 5.
Profile section B-B′ showing trend of variation in the repeated bathymetric data.

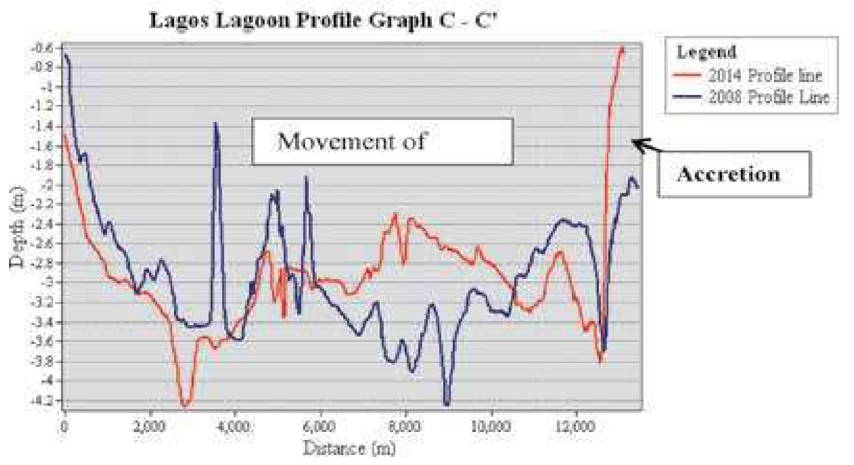

Figure 6.
Profile section C-C′ showing trend of variation in the repeated bathymetric data.

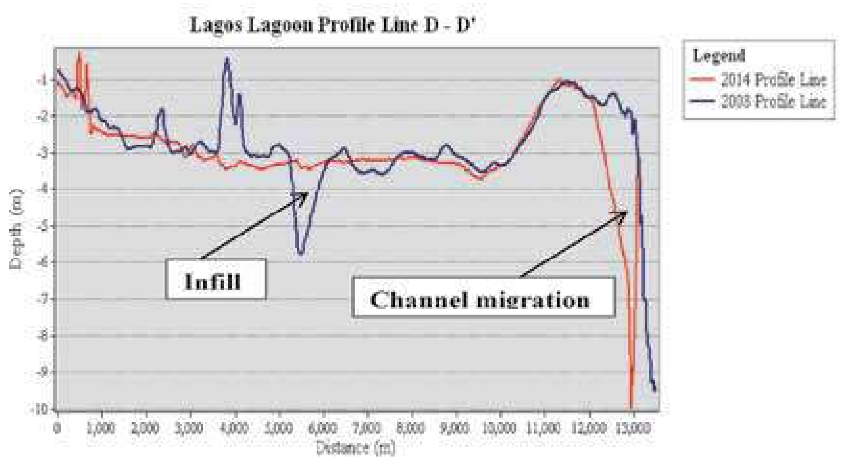

Figure 7.
Profile section D-D′ showing trend of variation in the repeated bathymetric data.

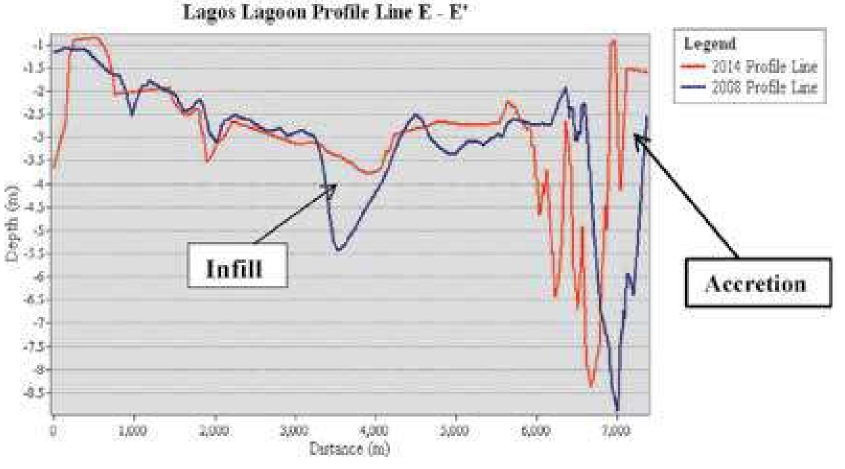

Figure 8.
Profile section E-E′ showing trend of variation in the repeated bathymetric data.

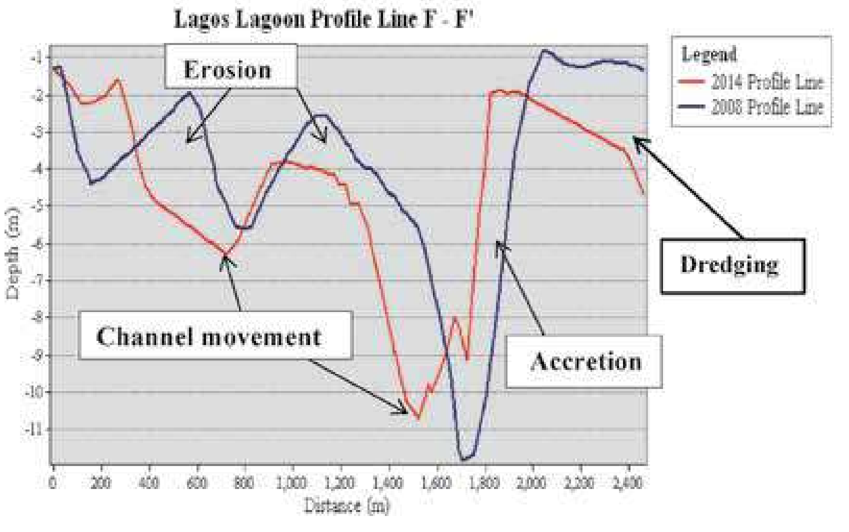

Figure 9.
Profile section F-F′ showing trend of variation in the repeated bathymetric data.

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

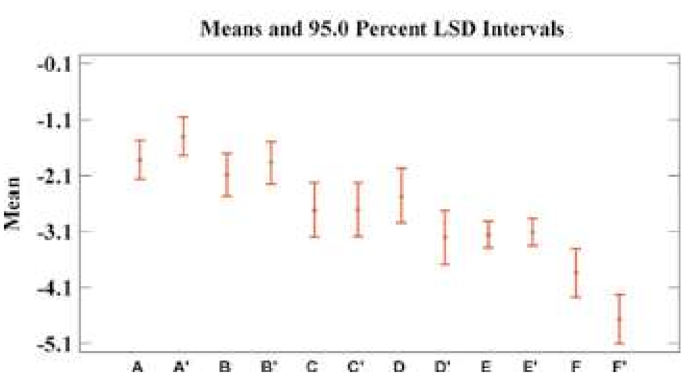

Figure 10.
Multiple comparisons means plot with 95.0% LSD intervals.

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.

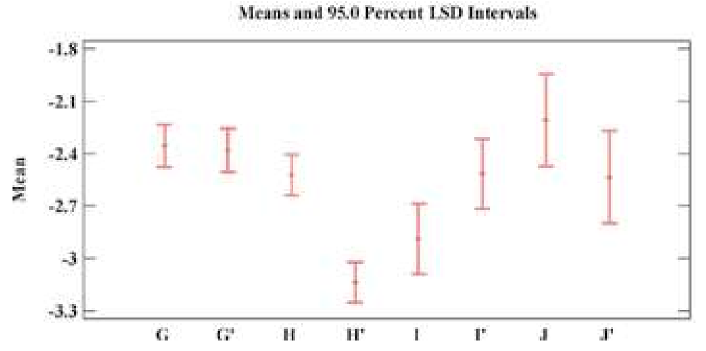

Figure 11.
Multiple comparisons mean plot with 95.0 percent LSD intervals for south-north direction profile.

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.

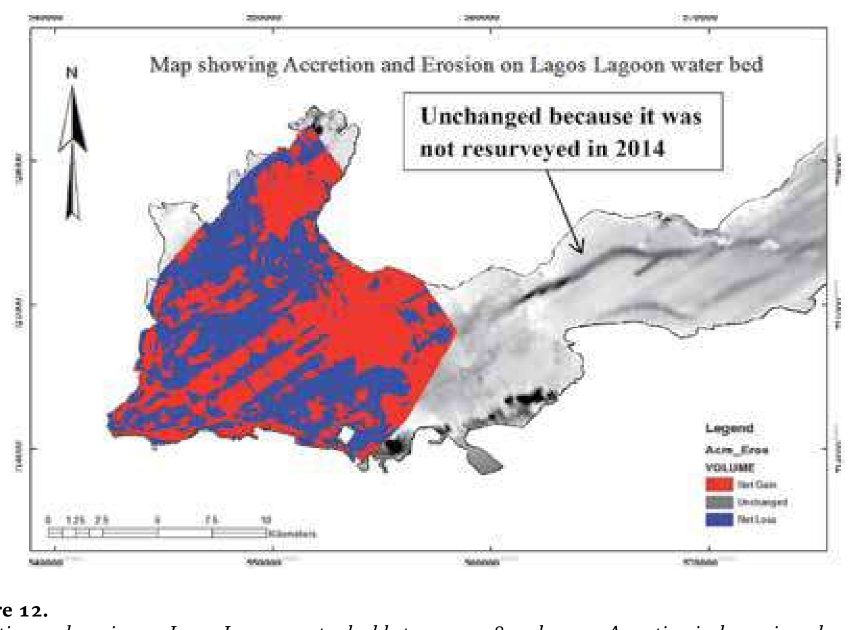

Figure 12.
Accretion and erosion on Lagos Lagoon water bed between 2008 and 2014. Accretion is shown in red as sediment net gain, while erosion is in blue colour as sediment net loss.

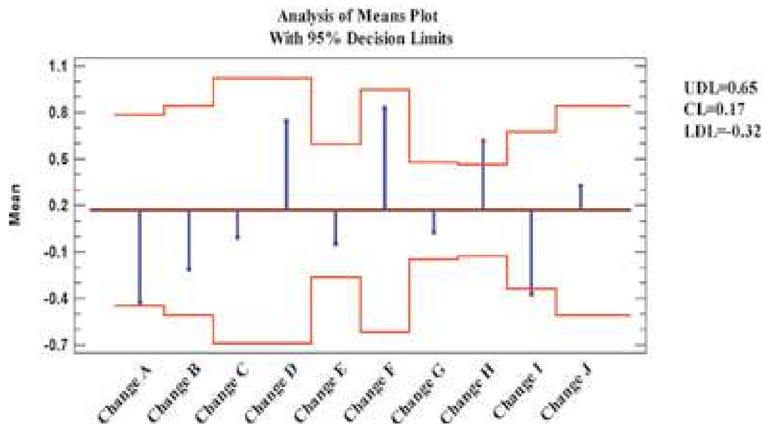

Figure 13.
Analysis of mean for all changes in depths from profile A-A′ to J-J′.

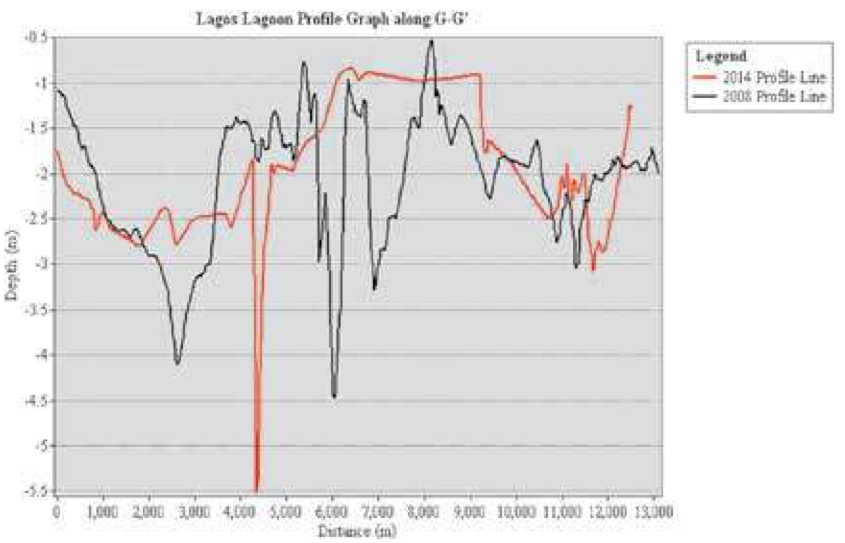

Figure 14.
Profile section G-G′ showing degree of variation in the depths of the lagoon repeated bathymetric data.

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.

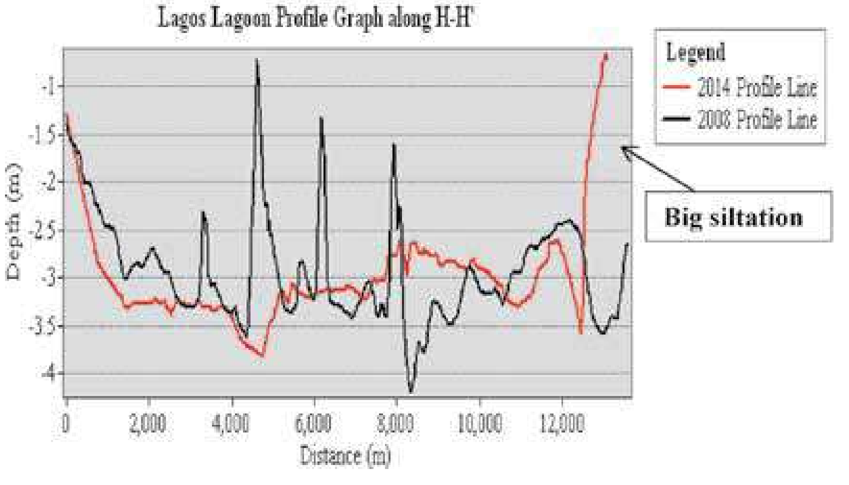

Figure 15.
Profile section H-H′ showing degree of variation in the depths of the lagoon repeated bathymetric data.

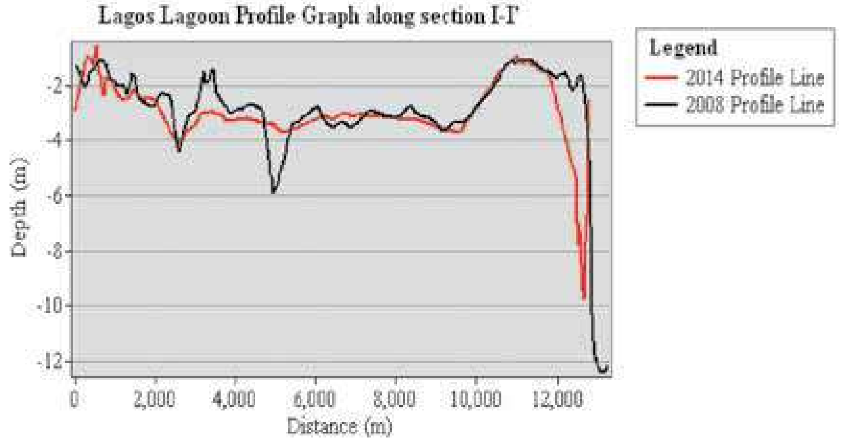

Figure 16.
Profile section I-I′ showing degree of variation in the depths of the lagoon repeated bathymetric data.

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.

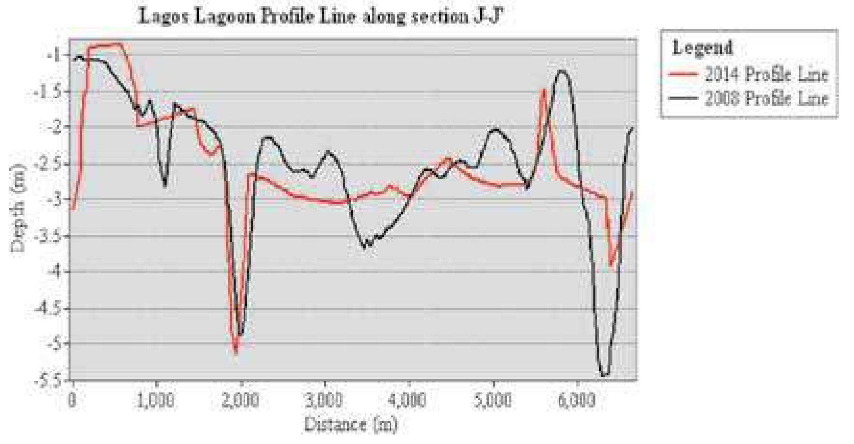

Figure 17.
Profile section J-J' showing degree of variation in the depths of the lagoon repeated bathymetric data.

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 (±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.

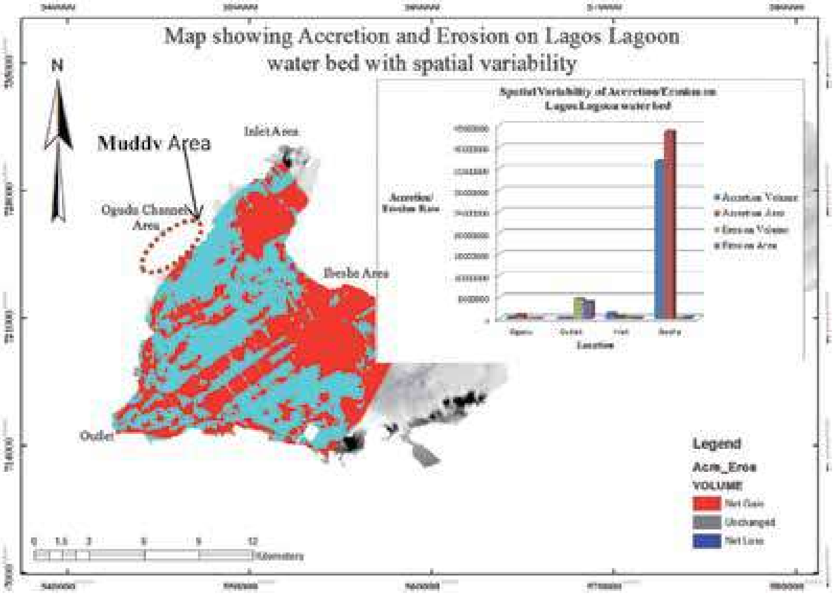

Figure 18.
Spatial variability of sediment accretion and erosion on Lagos Lagoon water based on 2008 and 2014 repeated bathymetric data. Area = metres squared and volume = metres cubed.

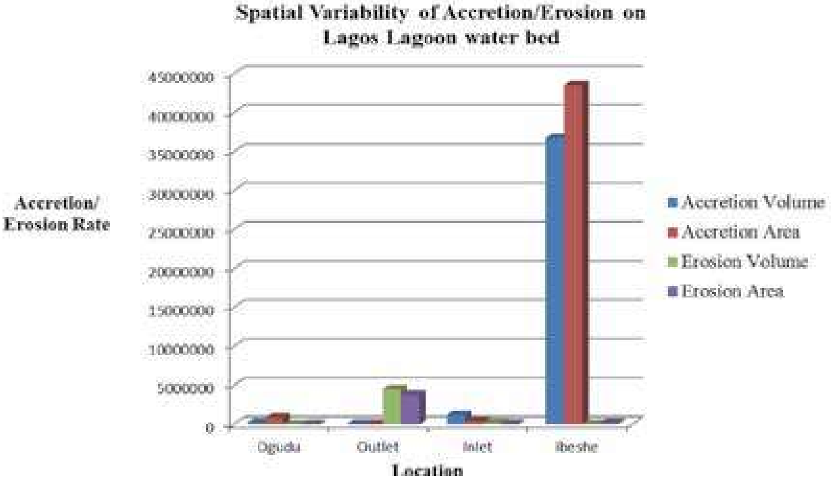

Figure 19.
Chart showing spatial variability of sediment accretion and erosion on Lagos Lagoon bed based on two repeated bathymetric data of 2008 and 2014. Area = metres squared and volume = metres cubed.

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 $\pm$ 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:

$$MLE = \frac{2 \times \Delta z}{\Delta z_{ave}} \tag{1}$$

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:

$$\Delta \mathrm{z} = 0.27\,\mathrm{m} \tag{2}$$

$$\Delta z_{ave} = 1.211\,\mathrm{m} \tag{3}$$

Therefore,

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

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 bathymetric 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 volume 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 uncertainty, 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 calculation 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.

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Section 3

Assessment Techniques