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Lagoon Environments Around the World

A Scientific Perspective

Edited by Andrew J. Manning

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Published in London, United Kingdom







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http://dx.doi.org/10.5772/intechopen.77559
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Contributors
Susana Villanueva, Alfonso V. Botello, Guadalupe De La Lanza Espino, Guadalupe Ponce-Velez, Hyun Jung Cho, Philip Bellamy, Marcelo Obraczka, Gandhi Giordano, Monique Mello, Carine Marques, Monica Souza, Gonzalo Gajardo, Stella Redón, Monica Rivas Casado, Paul Leinster, Marco Palma, David Eggleston, Amy Nail, Christina Durham, Daniel Torruco, Alicia González, Angel Daniel Torruco, Alfred Sunday Alademomi, Andrew J. Manning, Letícia Donadel, Lezilda Torgan

First published in London, United Kingdom, 2020 by IntechOpen
IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, 7th floor, 10 Lower Thames Street, London,
EC3R 6AF, United Kingdom
Printed in Croatia

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Additional hard and PDF copies can be obtained from orders@intechopen.com

Lagoon Environments Around the World - A Scientific Perspective
Edited by Andrew J. Manning
p. cm.
Print ISBN 978-1-78985-095-6
Online ISBN 978-1-78985-096-3
eBook (PDF) ISBN 978-1-78985-953-9

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.

Andrew J. Manning
Professor,
HR Wallingford Ltd,
Coasts & Oceans Group,
UK

University of Hull,
UK

University of Delaware,
USA

University of Florida,
USA

Stanford University,
USA

Technical University Delft,
Netherlands

University of Plymouth,
UK

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,

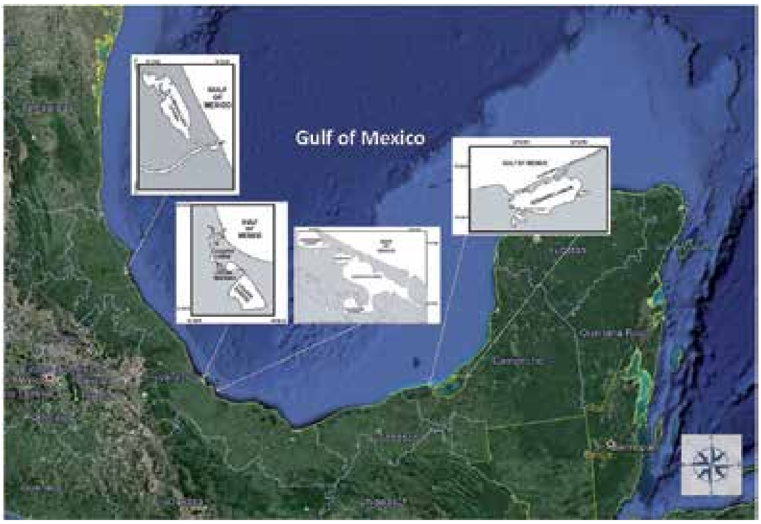

Figure 1.
Location of main coastal lagoons in the Gulf of Mexico.

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

DOI: http://dx.doi.org/10.5772/intechopen.86537

	Physicochemical parameters							
Area	**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 μg g^{-1} (average 5.68 μg 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 μg g^{-1}, which indicates a downtrend from the year 1929 to 1971 (with values from 1.5 to 1.3 μg g^{-1}), and a slight increase near the superficial stratum corresponding to the year 1998 (about 2.0 μg g^{-1}). These values are far below the ERL index of 4.02 μg 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 μg 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 μg 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

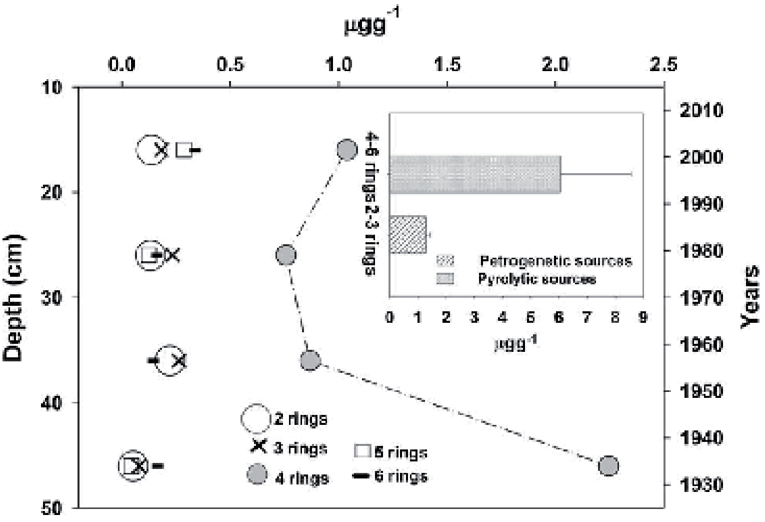

Figure 2.
ALS core concentrations of PAHs (μg g^{-1}) based on number of aromatic rings.

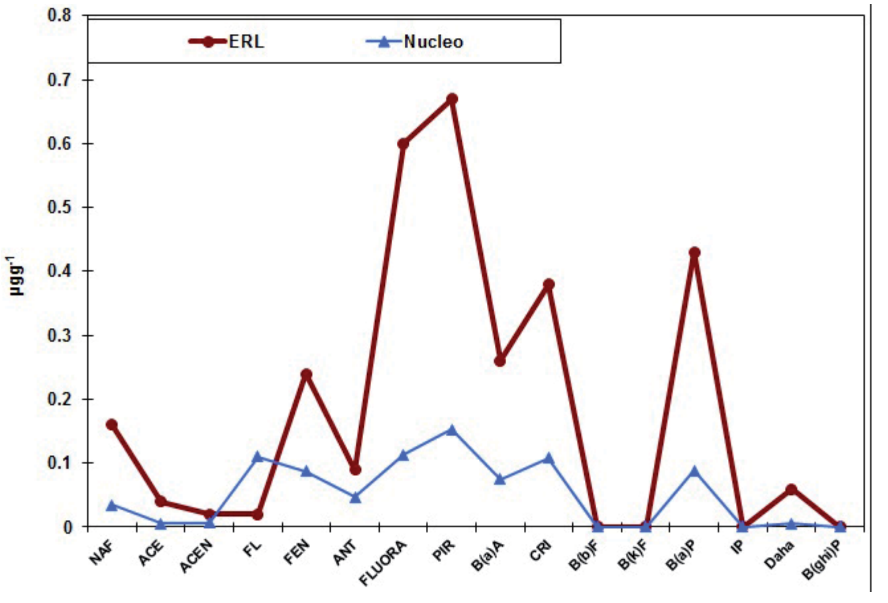

Figure 3.
Individual PAHs and ERL sedimentary quality criteria in the sedimentary core of TLS.

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 µg 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

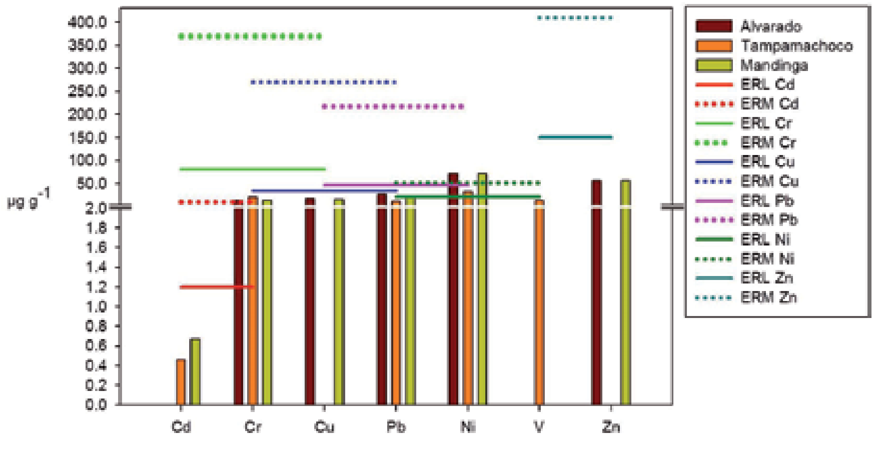

Figure 4.
Average concentrations of metals in superficial sediments of coastal lagoons of the Veracruz state.

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

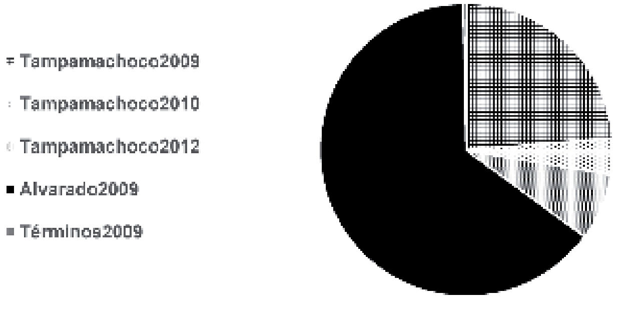

Figure 5.
Total concentration of organochlorine pesticides (ΣOC) in coastal lagoon sediments of three Mexican systems, Tampamachoco, Alvarado and Terminos in the Gulf of Mexico. Values in ng g^{-1} dry weight.

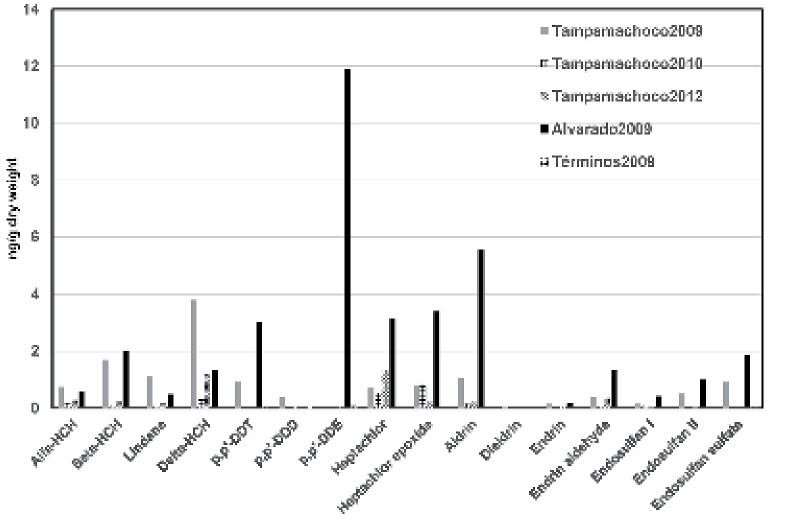

Figure 6.
Individual pattern of organochlorine pesticides in coastal lagoon sediments of three Mexican systems, Tampamachoco, Alvarado and Terminos in the Gulf of Mexico. Values in ng g^{-1} dry weight.

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 μg 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 μg 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 μg 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 (μg g^{-1})**	**Cd (μg g^{-1})**	**Cr (μg g^{-1})**	**Cu (μg g^{-1})**	**Pb (μg g^{-1})**	**Ni (μg g^{-1})**	**V (μg g^{-1})**	**Zn (μg 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.

Acknowledgements

We thank Salvador Hernandez Pulido for his support in the elaboration of the figures and bibliographic search.

Author details

Alfonso Vazquez Botello[1], Guadalupe de la Lanza Espino[2]*, Susana Villanueva Fragoso[1] and Guadalupe Ponce Velez[1]

1 Institute of Marine Sciences and Limnology, National Autonomous University of Mexico, Mexico City, Mexico

2 Institute of Biology, National Autonomous University of Mexico, Mexico City, Mexico

*Address all correspondence to: gdlle@unam.mx

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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

Giordano Gandhi, Obraczka Marcelo, de Souza Monica Medeiros, Mello Monique Alves Leite and e Marques Carine Ferreira

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

DOI: http://dx.doi.org/10.5772/intechopen.88687

	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**.

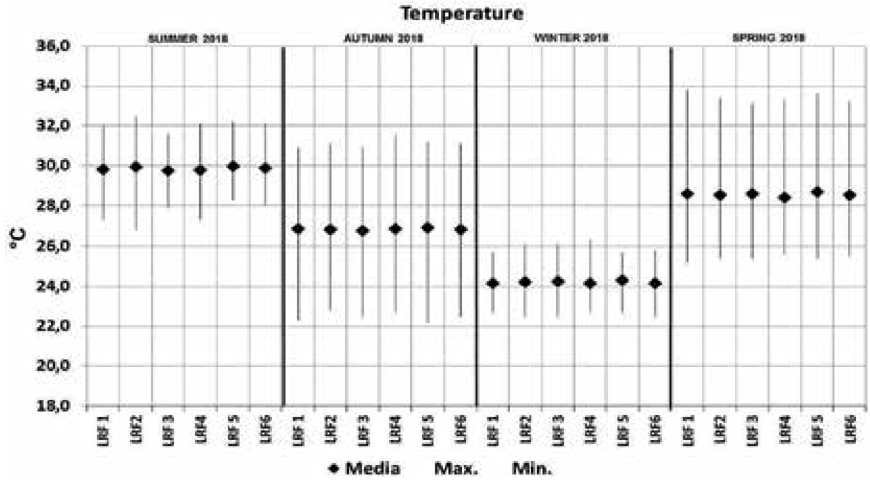

Figure 5.
Temperature of the surface of the LRF in 2018.

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

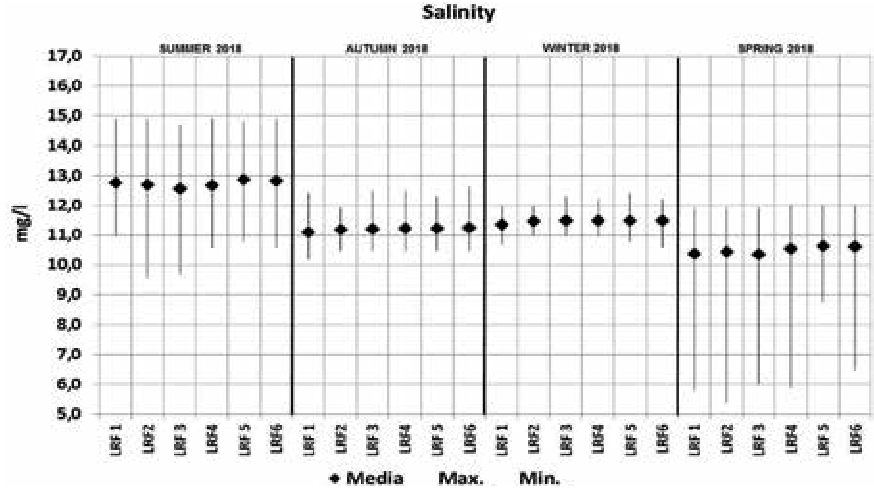

Figure 6.
Salinity of the surface of LRF in 2018.

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

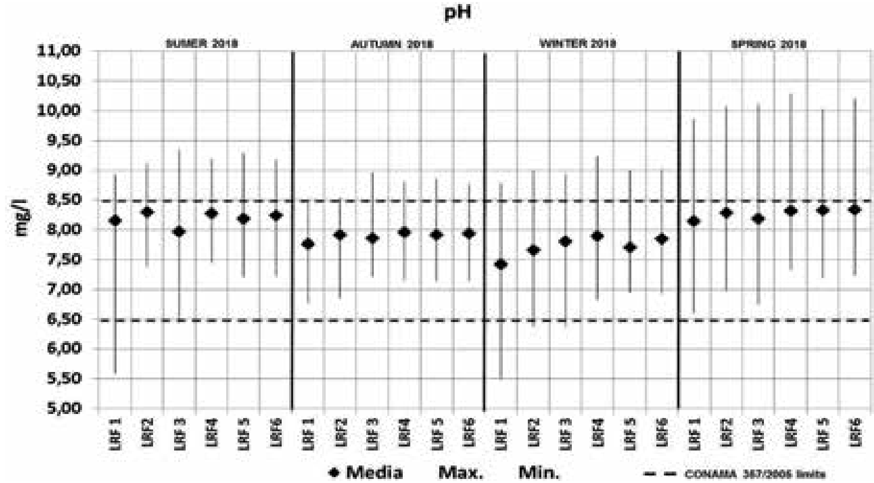

Figure 7.
pH of the surface of LRF in 2018.

(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.

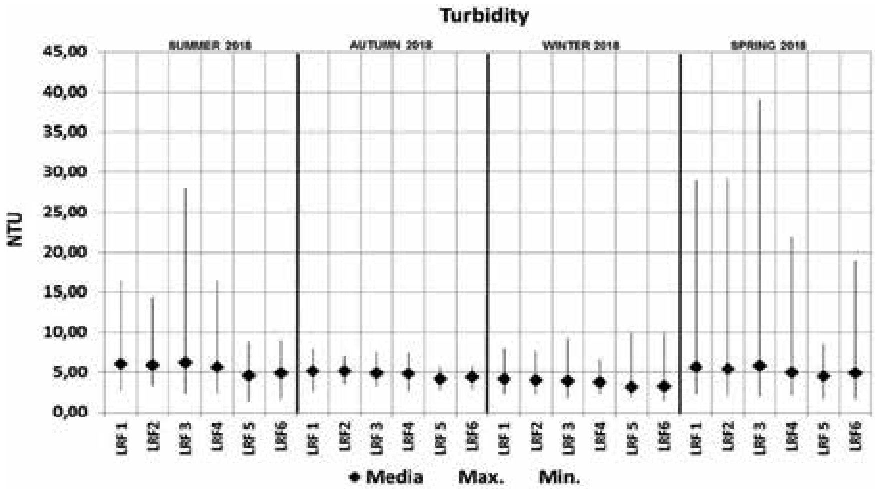

Figure 8.
Turbidity of the surface of the LRF in 2018.

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

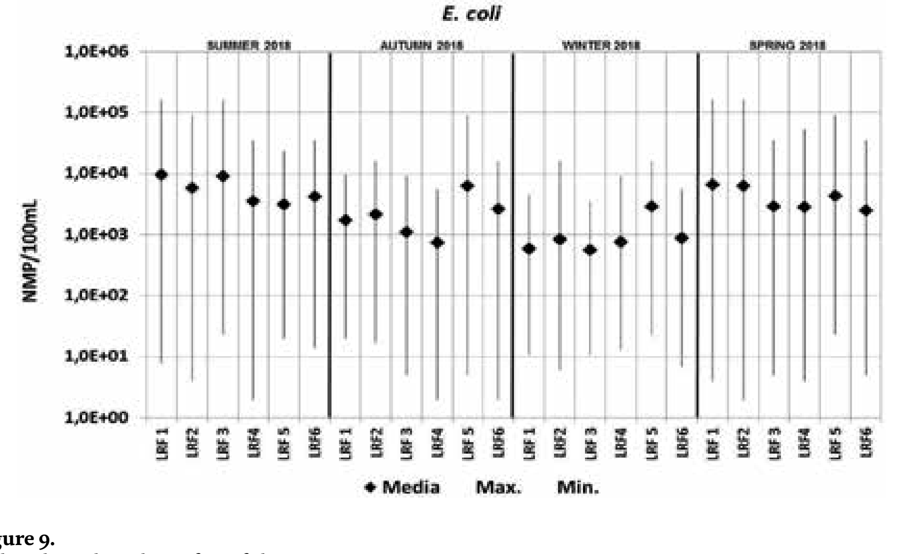

Figure 9.
Escherichia coli in the surface of the LRF in 2018.

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.

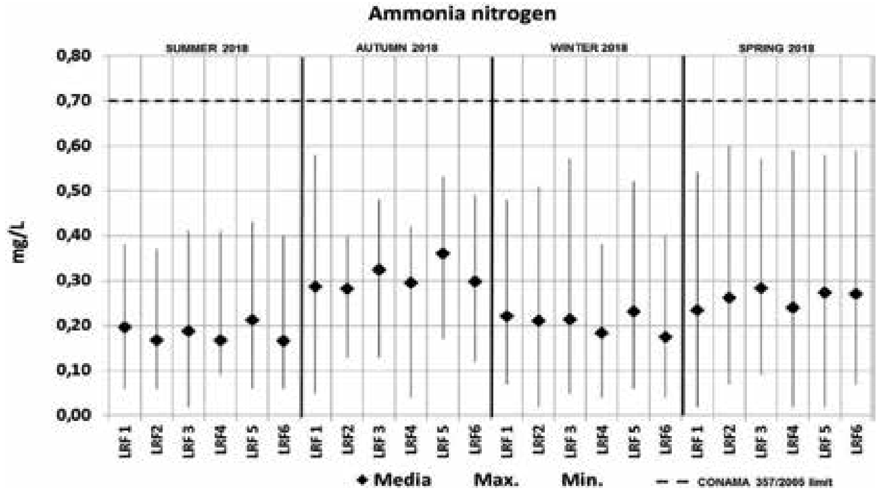

Figure 10.
Ammonia nitrogen on the surface of the LRF in 2018.

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.

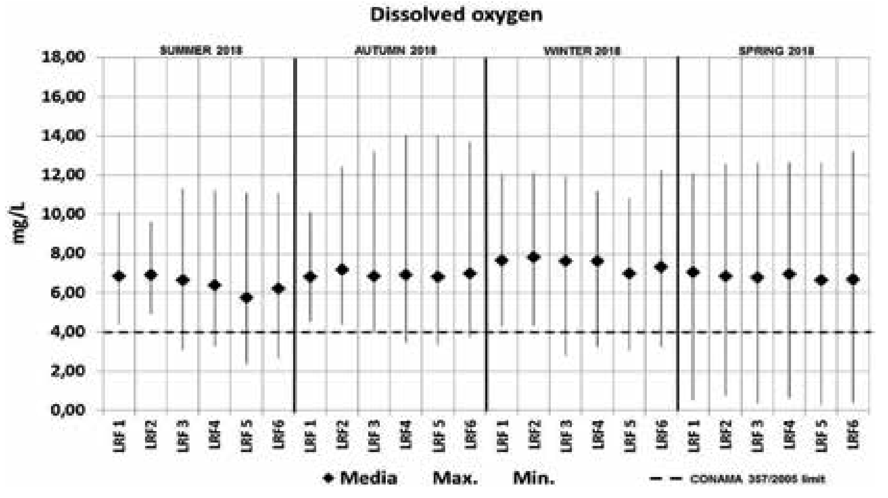

Figure 11.
Dissolved oxygen in the surface of the LRF in 2018.

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.

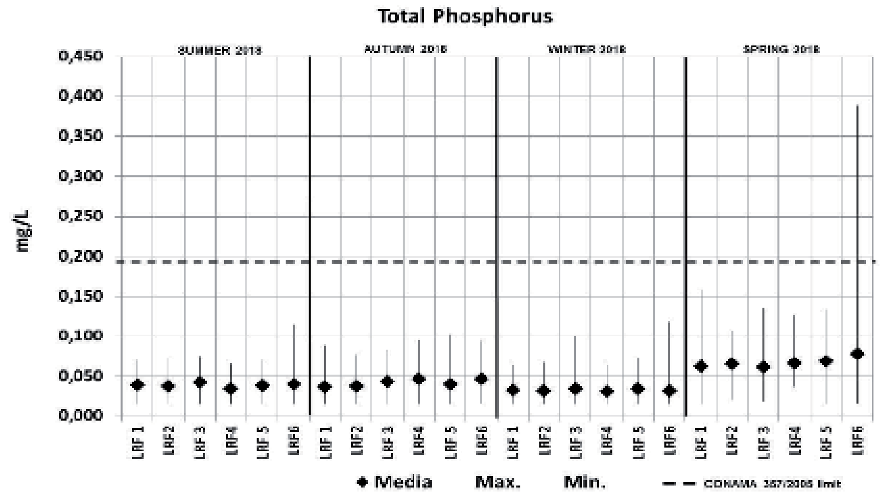

Figure 12.
Total phosphorus in the surface of the LRF in 2018.

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.

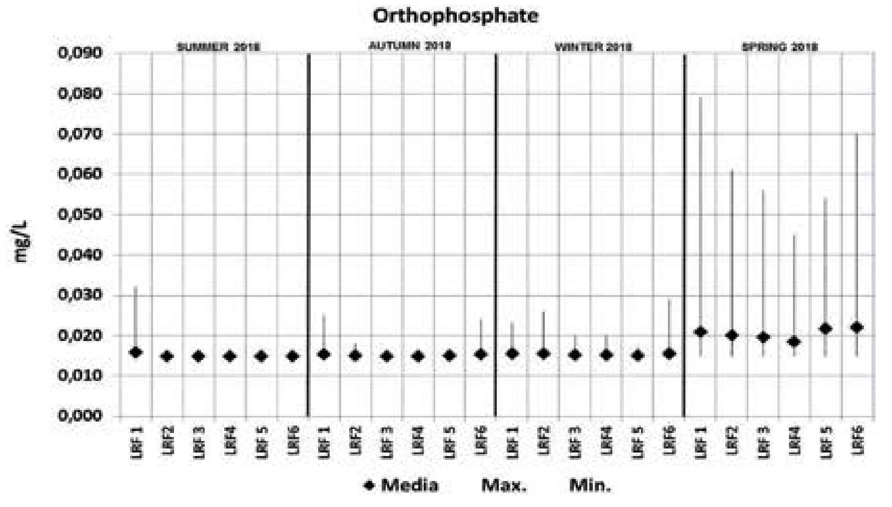

Figure 13.
Orthophosphate in the surface of the LRF in 2018.

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.

Author details

Giordano Gandhi[1], Obraczka Marcelo[1*], de Souza Monica Medeiros[2], Mello Monique Alves Leite[2] and e Marques Carine Ferreira[1]

1 Department of Sanitary and Environmental Engineering of the State University of Rio de Janeiro, Rio de Janeiro, Brazil

2 TECMA Technology and Laboratories LTDA, Rio de Janeiro, Brazil

*Address all correspondence to: obraczka.uerj@gmail.com

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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.

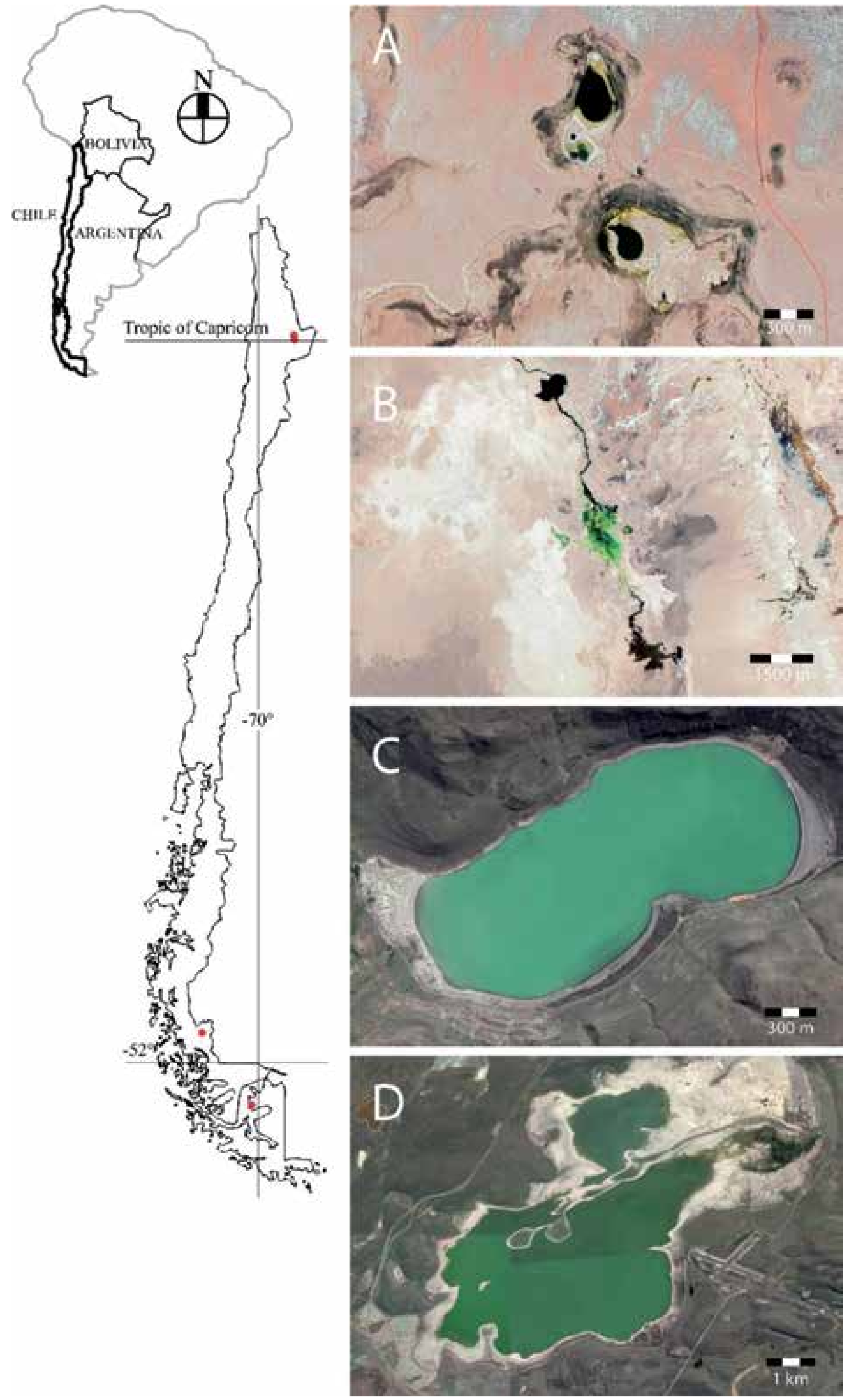

Figure 1.
Hypersaline lagoons from contrasting latitudinal environments in Chile, the southern edge of the world. Atacama Desert: (A) Piedra and Céjar lagoons. (B) Los Flamencos National Reserve, from north to south: Chaxa lagoon (0.37 km^2), Canal Burro Muerto (0.1 km^2), Barros Negros lagoon (1.03 km^2), and Puilar (0.84 km^2). 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.,

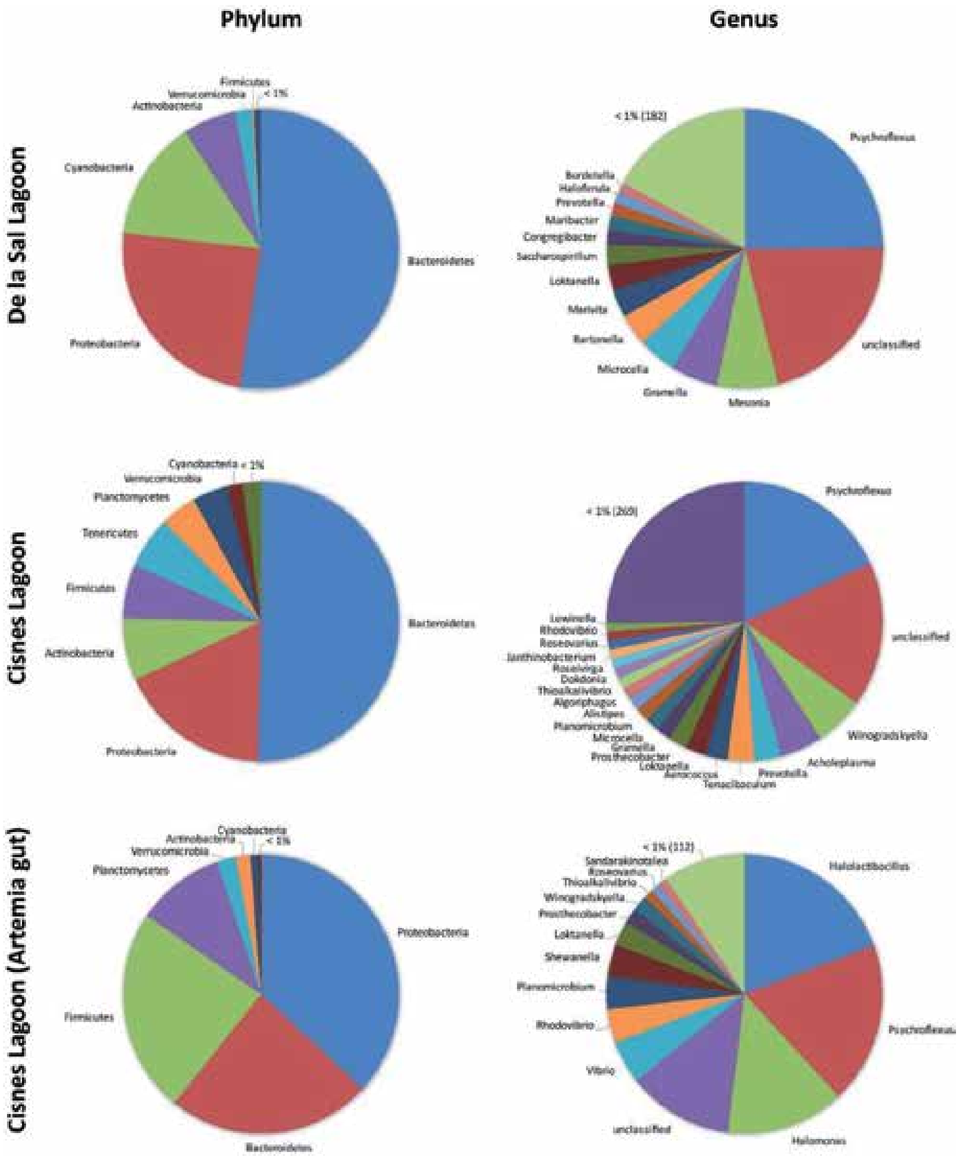

Figure 4.
Bacterial diversity in brines of Patagonian lagoons De la Sal and Cisnes and bacterial communities in the Artemia gut of individuals from Cisnes lagoon (bottom).

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.

Acknowledgements

The authors are most grateful to the people of CONAF for their support during sampling campaigns in the north, in particular to Roberto Cruz, administrator of Los Flamencos Reserve. Kathy Dawson, Felipe González, Alejandro Cruz, and Marcos Cortés, also from CONAF, contributed in different ways. Manuel Silvestre shared his enthusiasm, experience, and knowledge of Chaxa lagoon. In Patagonia, Alejandra Silva, Administrator of the “Natural Monument Laguna de Los Cisnes,” at the time we visited the place, facilitated activities in the lagoon. Dr. Pablo Gallardo, of the University of Magallanes, helped during our activities in the lagoons. Mauricio Quiroz (Universidad de Los Lagos) helped with several figures.

SR acknowledges the support from a Fondecyt (3170939) postdoctoral project of the National Commission for Scientific and Technological Research of Chile (CONICYT).

Author details

Gonzalo Gajardo* and Stella Redón
Laboratory of Genetics, Aquaculture and Biodiversity, Department of Biological Sciences and Biodiversity, Universidad de Los Lagos, Osorno, Chile

*Address all correspondence to: ggajardo@ulagos.cl

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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

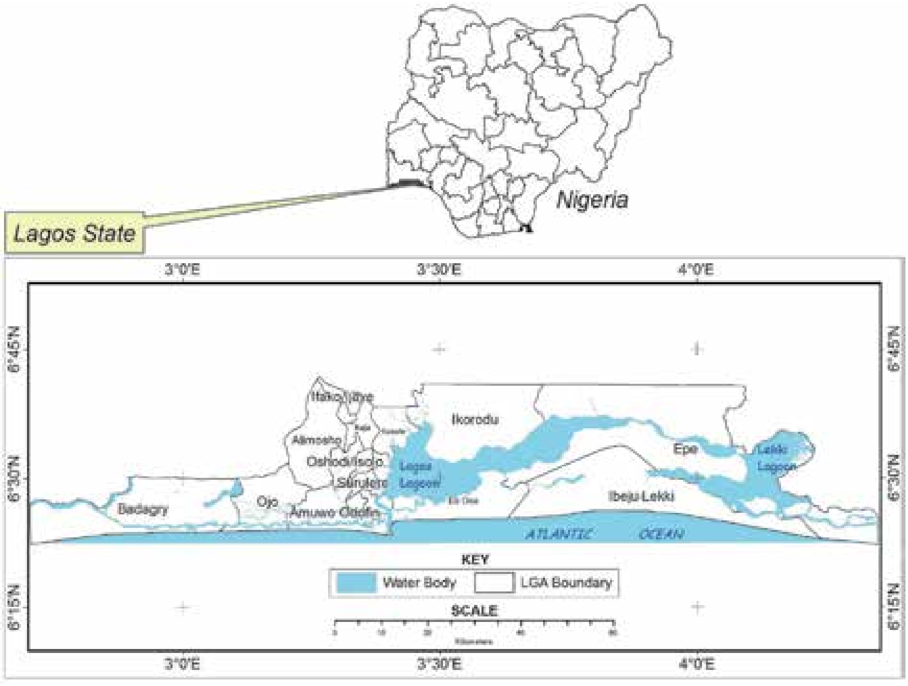

Figure 1.
Map showing Lagos Lagoon as situated in Lagos within Nigeria. The lagoon is surrounded by settlements (local government areas).

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

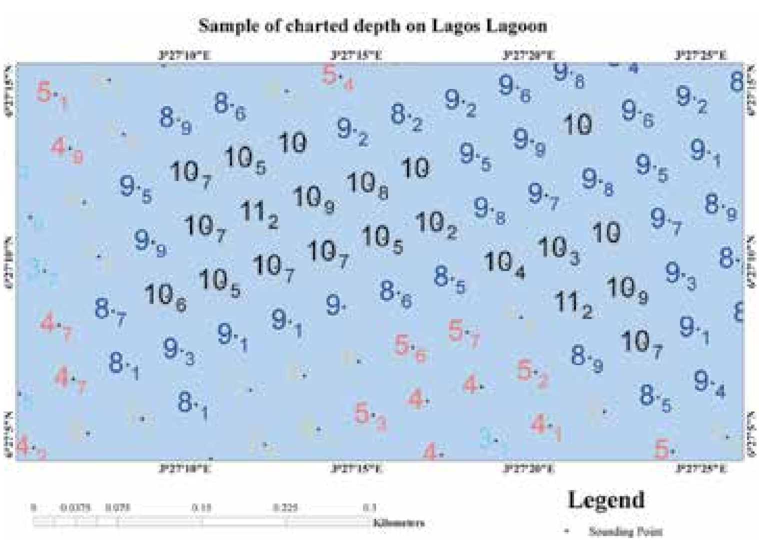

Figure 2.
Sample of charted bathymetric data of 2014 dry season, plotted in decimal number.

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

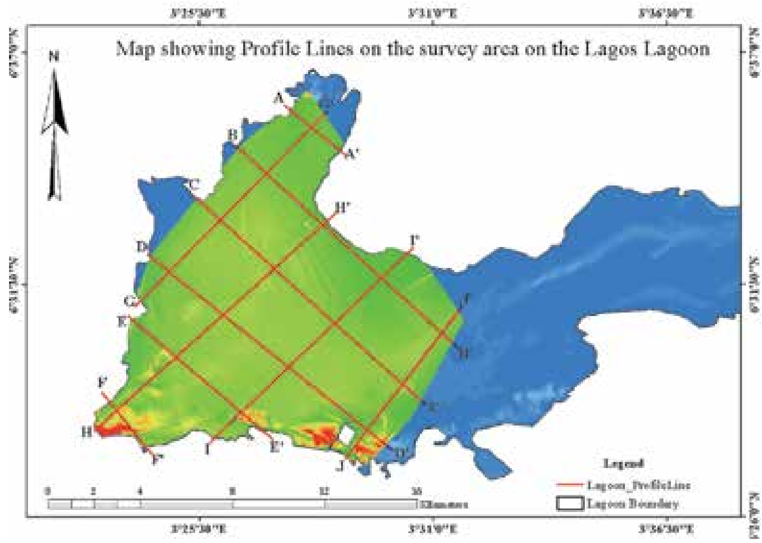

Figure 3.
Lagos Lagoon with profile lines on the study area. The area on the map with colour blue indicates area covered by the bathymetric survey of 2008, while the area with greenish yellow colour shows area surveyed in 2014.

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

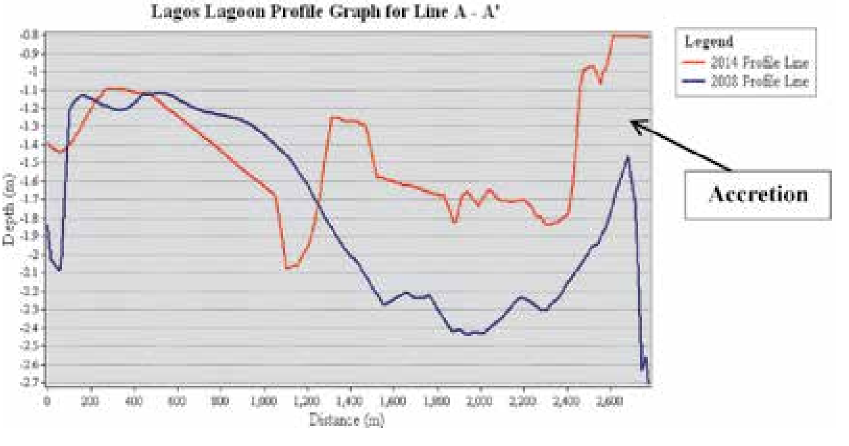

Figure 4.
Profile section A-A′ showing trend of variation in the repeated bathymetric data.

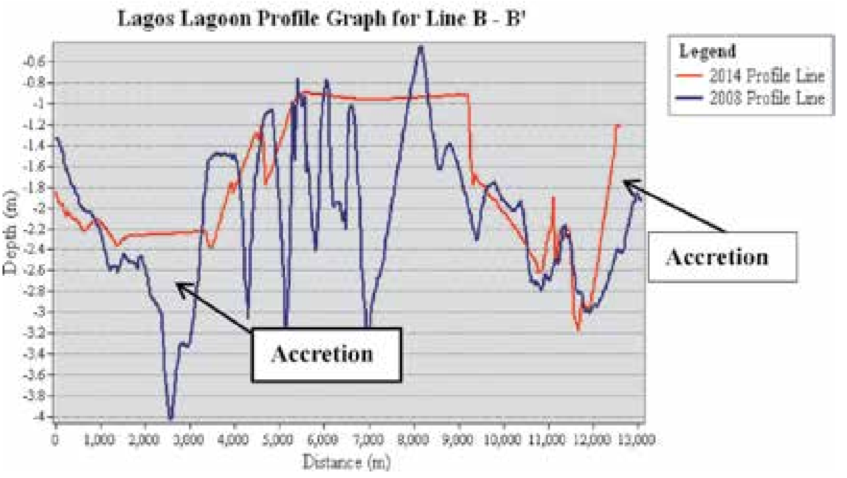

Figure 5.
Profile section B-B′ showing trend of variation in the repeated bathymetric data.

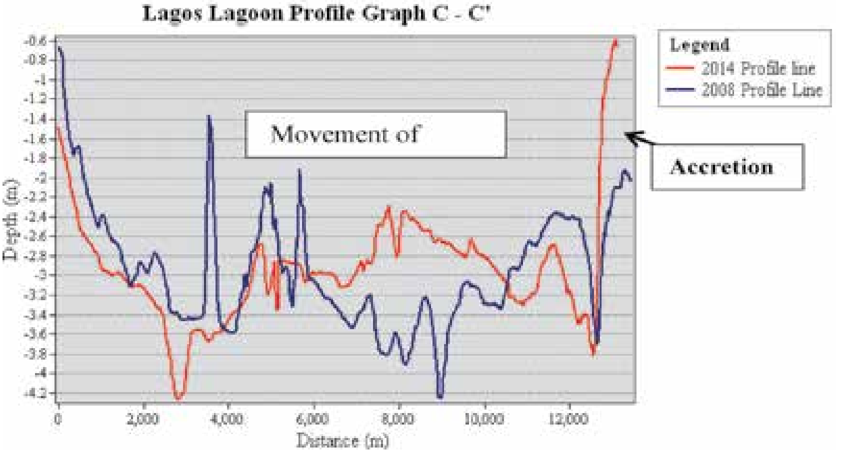

Figure 6.
Profile section C-C′ showing trend of variation in the repeated bathymetric data.

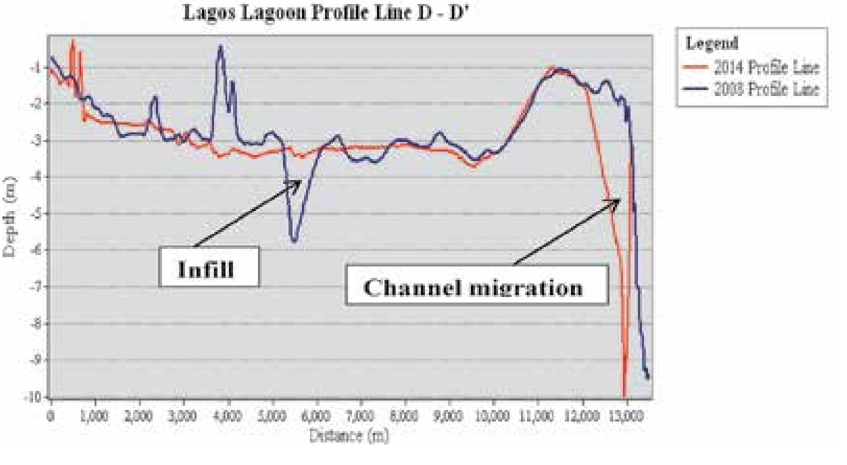

Figure 7.
Profile section D-D′ showing trend of variation in the repeated bathymetric data.

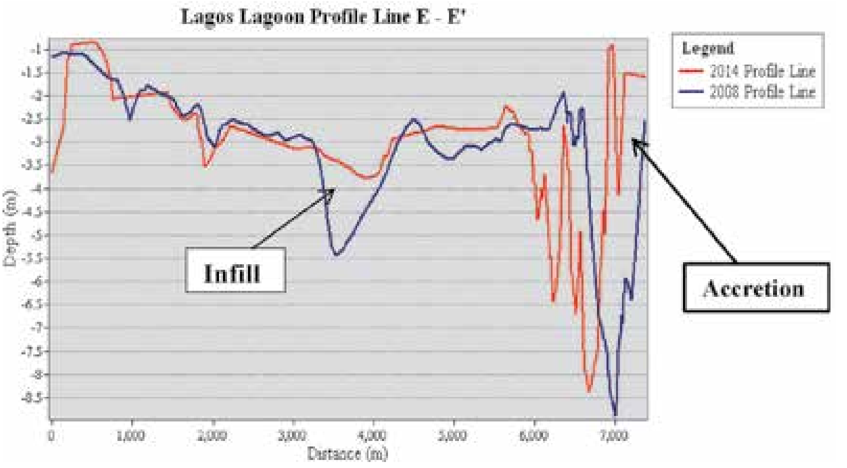

Figure 8.
Profile section E-E′ showing trend of variation in the repeated bathymetric data.

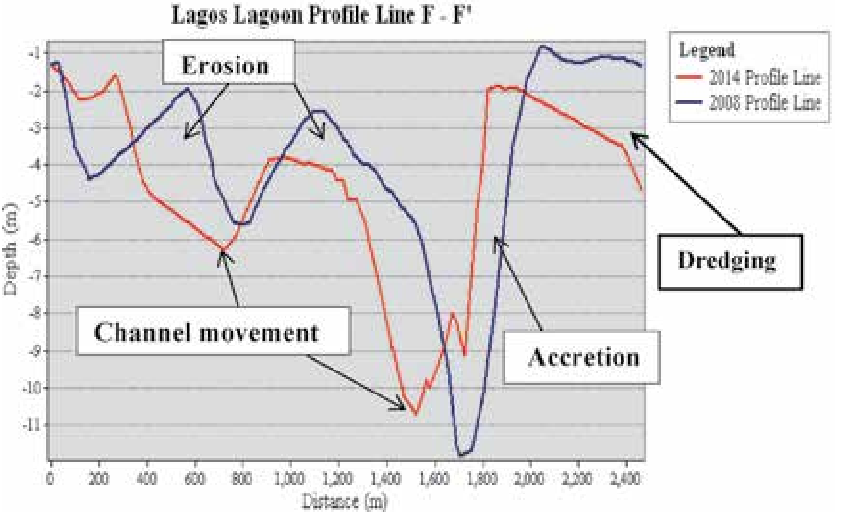

Figure 9.
Profile section F-F′ showing trend of variation in the repeated bathymetric data.

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

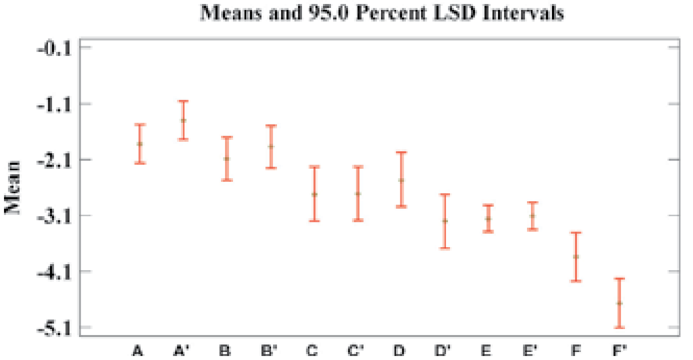

Figure 10.
Multiple comparisons means plot with 95.0% LSD intervals.

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.

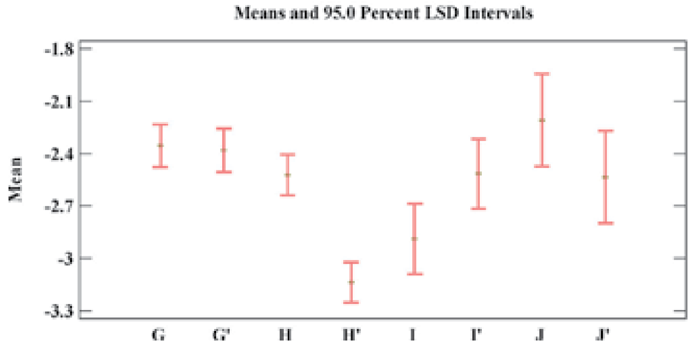

Figure 11.
Multiple comparisons mean plot with 95.0 percent LSD intervals for south-north direction profile.

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.

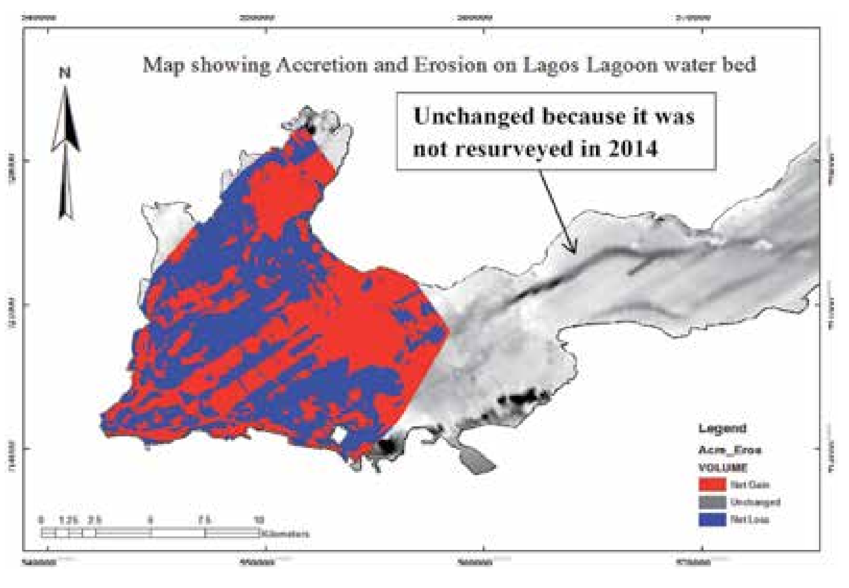

Figure 12.
Accretion and erosion on Lagos Lagoon water bed between 2008 and 2014. Accretion is shown in red as sediment net gain, while erosion is in blue colour as sediment net loss.

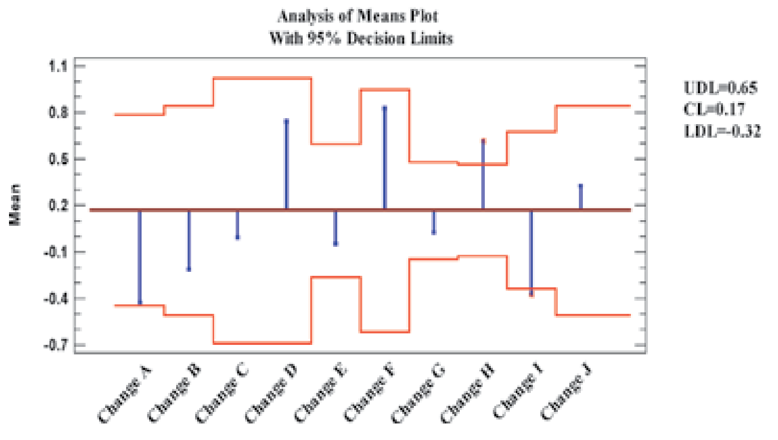

Figure 13.
Analysis of mean for all changes in depths from profile A-A′ to J-J′.

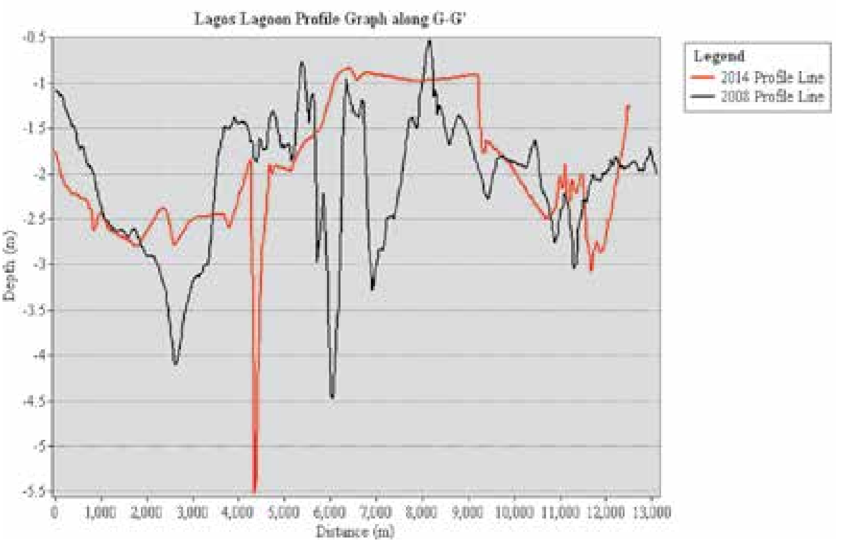

Figure 14.
Profile section G-G′ showing degree of variation in the depths of the lagoon repeated bathymetric data.

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.

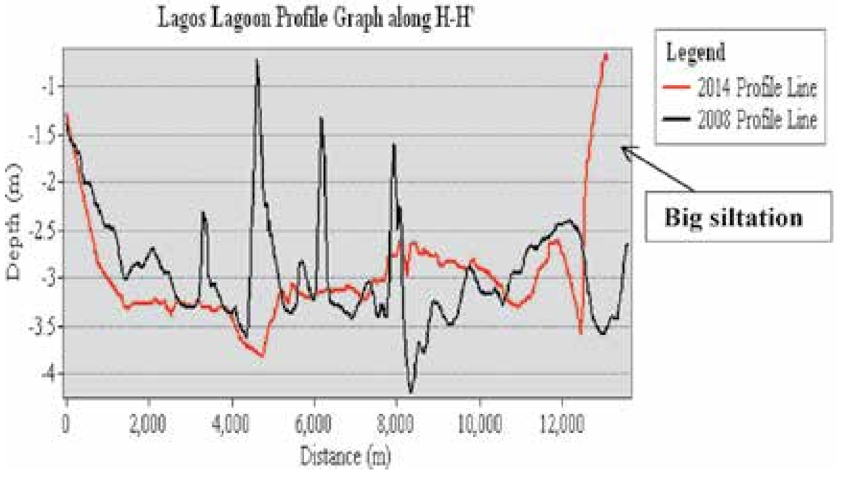

Figure 15.
Profile section H-H′ showing degree of variation in the depths of the lagoon repeated bathymetric data.

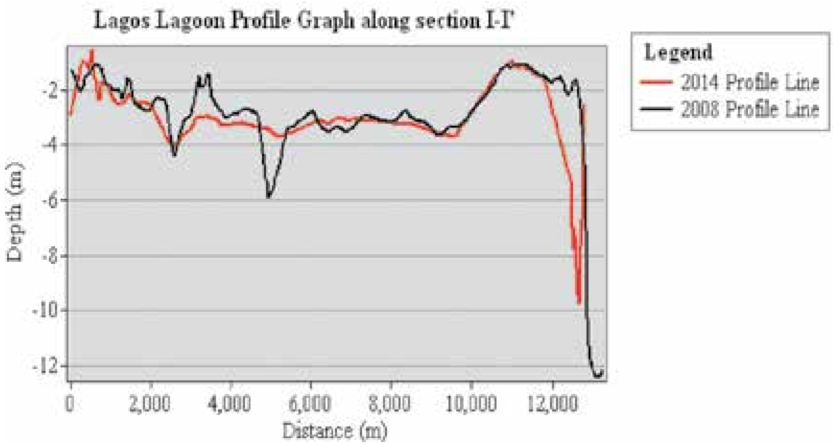

Figure 16.
Profile section I-I′ showing degree of variation in the depths of the lagoon repeated bathymetric data.

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.

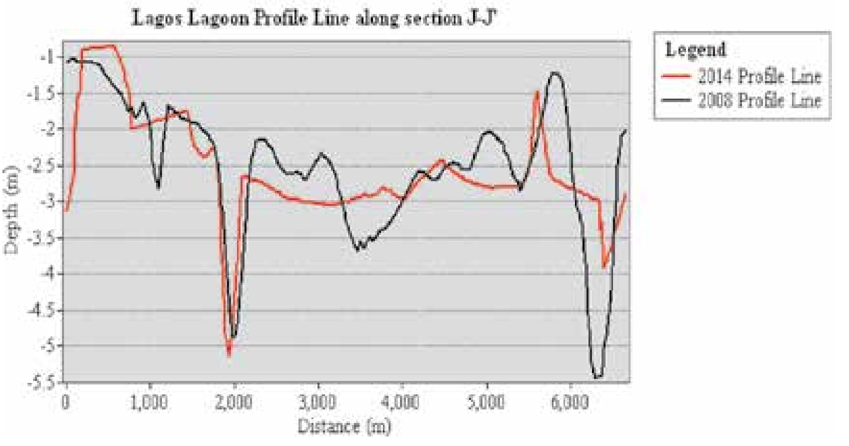

Figure 17.
Profile section J-J' showing degree of variation in the depths of the lagoon repeated bathymetric data.

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.

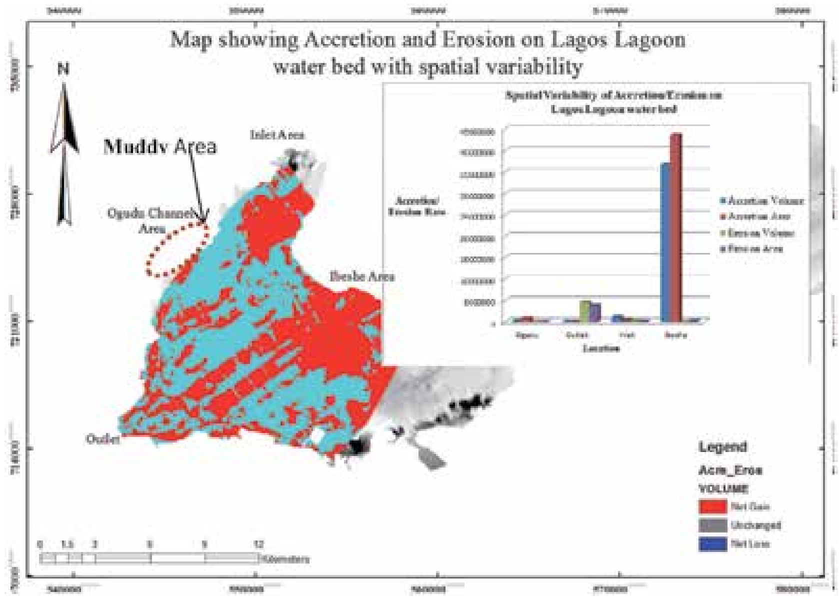

Figure 18.
Spatial variability of sediment accretion and erosion on Lagos Lagoon water based on 2008 and 2014 repeated bathymetric data. Area = metres squared and volume = metres cubed.

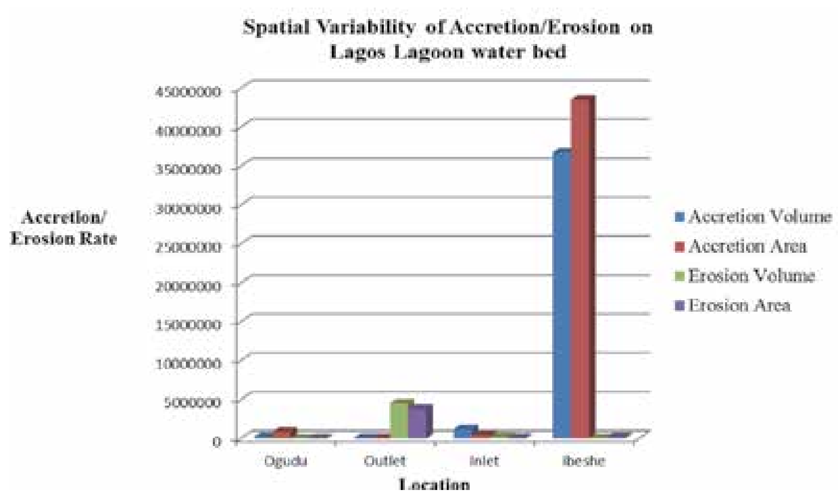

Figure 19.
Chart showing spatial variability of sediment accretion and erosion on Lagos Lagoon bed based on two repeated bathymetric data of 2008 and 2014. Area = metres squared and volume = metres cubed.

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 $\pm$0.15, $\pm$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,

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

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.

Acknowledgements

The authors are grateful to the Tertiary Education Fund (TETFUND) under the Federal Government of Nigeria and Surveyor Registration Council of Nigeria (SURCON) that provided the funding for this research. Thanks to Professor Andrew Manning for his consistent encouragement and effort to ensure that this research is published. Dr Victor Abbott and Prof. Richard Whitehouse are commended for their kind assistance while the research was on-going.

Prof. Manning's contribution towards this research (book chapter) was made possible in part by a grant from The Gulf of Mexico Research Initiative (CSOMIO: Consortium for Simulation of Oil-Microbial Interactions in the Ocean) and in part by the US National Science Foundation under grant OCE-1736668 and HR Wallingford company research FineScale project (ACK3002_62). Data are publicly available through the Gulf of Mexico Research Initiative Information & Data Cooperative (GRIIDC) at https://data.gulfresearchinitiative.org (DOI: 10.7266/n7-0sht-6s68).

The authors wish to thank Dr Leiping Ye for his kind assistance with the data archive uploading.

Author details

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

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

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

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

*Address all correspondence to: geomfred@yahoo.com

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Section 3

Assessment Techniques

Chapter 5

A GIS-Based Approach for Determining Potential Runoff Coefficient and Runoff Depth for the Indian River Lagoon, Florida, USA

Philip W. Bellamy and Hyun Jung Cho

Abstract

The Indian River Lagoon system (IRL), spanning ~40% of Florida's east coast, is one of the nation's biggest and most biodiverse estuaries. In 2011, a super algal bloom event occurred in the IRL with total nitrogen and phosphorus levels that exceeded historical levels. Scientists suspect that nonpoint source pollution through surface runoff may have had a significant impact on the recent recurring algal blooms. Digital Elevation Model, land cover/land use, and soil data were used to calculate a runoff coefficient for the IRL drainage basin. Rainfall data were used to calculate runoff depth for the study area between the years of 2006–2016. When the monthly runoff depth data for 2011 were compared to a previous study on the 2011 super algal bloom in the lagoon, areas with high runoff visually matched the areas with higher chlorophyll *a* concentrations. Land development was a significant variable for determining runoff depth ($p < 0.0001$), and although used to derive runoff depths, the influence of precipitation was marginally significant ($p = 0.06$). Significant spatial autocorrelation indicated local trends between land development and runoff depth ($p < 0.0001$). Outputs will aid with decisions on stormwater management to more sustainable land development planning.

Keywords: surface runoff, runoff coefficient, stormwater, Indian River Lagoon, Halifax River, coastal watershed

1. Introduction

Algae blooms within coastal estuarine systems have been a threat to vital key ecosystem components causing the degradation of ecological integrity. With non-point source pollution being a primary concern, using geographic information system (GIS) approaches to assess the impacts is effective for stormwater management. Therefore, with the use of land use/land cover (LC/LU), soil, and elevation data, the Potential Runoff Coefficient (PRC) and runoff depth were calculated for the IRL and Halifax River watershed. The analysis consisted of manipulating the geospatial data to derive the potential runoff coefficients and runoff depths.

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Considering the contributing factors of surface runoff, the overall goal of the study is to estimate the quantities of runoff within the Indian River Lagoon (IRL) watershed based on a method that encompasses those parameters. The findings can also address whether such method and similar approaches can indicate locations of algae blooms, and aid in stormwater/watershed management. The objectives of this study are listed respectively; **Objective 1:** to calculate the potential runoff coefficients within the IRL watershed. The values will be based on the satellite image classification and validation for land cover/land use, elevation data, and soil data of the study area. **Objective 2:** to calculate the runoff depth of the IRL watershed over an eleven-year duration (2006–2011) using the derived value of the runoff coefficients and rainfall data provided by National Oceanic and Atmospheric Administration National Weather Service (NOAA NWS) River Forecast Centers (RFCs) collected from the Hydrologic Rainfall Analysis Project (HRAP). The outcome will represent the actual quantity of rainfall that was converted to runoff for the year. **Objective 3:** to visually assess if there is a geographic correlation of surface runoff and algae concentrations during months of the 2011 super algal bloom. The finished products can aid in gaining coastal resilience to help adapt to storms, flooding events, and parameters can be used to determine suitability for stormwater parks and infrastructure. The data acquired from the public GIS databases include ground-truthed information and remotely sensed data which were carefully interpreted and validated by professionals.

1.1 The Indian River Lagoon system

The Indian River Lagoon (IRL), spanning ~40% of Florida's east coast, is one of the nation's biggest and most biodiverse estuaries. The IRL consists of barrier islands separating its water from Atlantic Ocean [1]. The exchange of the IRL water with the ocean occurs naturally at Ponce De Leon Inlet in New Smyrna Beach, and Jupiter Inlet near West Palm Beach. The other man-made inlets include Sebastian Inlet, Fort Pierce Inlet, Port Canaveral, and St. Lucie inlet. The estuary stretches 251 km along the east coast of Florida with numerous tributaries [2]. The IRL system is made up of three sub lagoons that include the Mosquito Lagoon, which is in the northern section, the Banana River, and the IRL (**Figure 1**). The natural sources of freshwater for the IRL include Crane Creek (Melbourne, FL), Eau Gallie River, St. Lucie River, St. Sebastian River, and Turkey Creek. A secondary natural source of freshwater in the IRL is the Tomoka River which is located west of the lagoon running north connecting to the Halifax River then eventually the Mosquito Lagoon. Although the Tomoka River is not directly connected to the IRL or in its watershed, the Halifax River (**Figure 1**) is partially connected to the northern lagoon at Ponce Inlet and therefore its watershed is included in this study. The IRL and Halifax River watershed contains ~40 cities. The developed urban land comprises impervious surfaces and residential communities that primarily contain turf grass.

In the summer of 2011, a super algal bloom event occurred in the IRL which reached a high biovolume of dinoflagellate *Pyrodinium bahamense var. bahamense* ($33.9 \times 106\ \mu m^3\ mL^{-1}$) with mean chlorophyll *a* concentrations (6.2–16.4 μg/L) that positively correlated with total nitrogen and total phosphorus levels that exceeded historical levels in various locations [3]. Following the massive algae bloom, there have been recurrent blooms consisting of green macroalgae such as *Chaetomorpha* sp. since 2013 [4, 5]. As a result of the 2011 super algal bloom, the coverage of seagrass within the IRL drastically declined from the loss of photosynthetic light by the surface algae [6]. Although fluctuations in seagrass bed percent cover in the lagoon have been understood as a part of a natural cycle of decline and recovery as seagrass abundance,

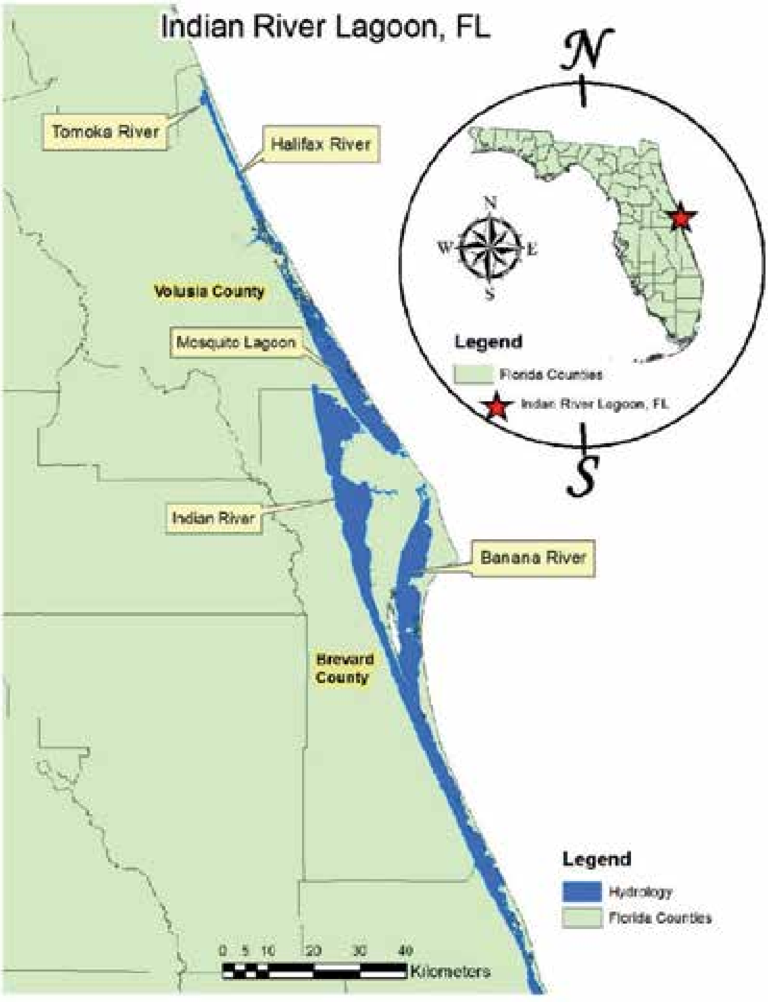

Figure 1.
A map of Indian River Lagoon and Halifax River, Florida. The Indian River Lagoon is composed of three waterbodies: the Mosquito Lagoon, Indian River, and the Banana Lagoon. The inset map provides a reference for the location of the lagoon in Florida.

scientists suspect that nonpoint source pollution via surface runoff may have had a significant impact on the recent recurring algal blooms in the lagoon [7, 8].

1.2 Surface runoff and runoff models

Surface runoff is water from rain or snowmelt that travels over the land before entering nearby waterbodies. Stormwater flowing across surrounding land transports various pollutants, and ultimately contributes to non-point source pollution. Surface runoff negatively affects many aquatic ecosystems as the runoff transports pollutants and other substances into waterbodies, which can alter turbidity, phosphorus and nitrogen concentrations, and organic matter content in receiving waterbodies [9]. The effects of surface runoff can also be intensified by climate change in specific regions that may have highly developed land and altered hydrology from the addition of artificial stormwater structures that modify the flow of water [10]. Human activities have been shown to have a stronger impact on runoff than climate change, but both stressors significantly impacts runoff quantities [10].

Hypothetical land cover change scenarios in a simulated hydrological study within the Lavrinha watershed in Minas Gerais State, Brazil showed that deforestation in the Atlantic Forest biome would lead to increases in soil moisture (5%), runoff (22%), and decreases in runoff interception (71%) from the loss of roots and extensive rhizomes [11]. Impervious surfaces in urban watersheds can influence the biogeochemical processes, organism's abundance, stress, and vulnerability from heated surface runoff during hot summers [12]. Incorporation of the contributing factors such as vegetative cover that may enhance or influence the effects is effective in hydrological modeling for determining the amount of runoff.

The characteristics of the land surrounding waterbodies affect the amount of surface runoff. During the process of rainfall becoming runoff, various characteristics of the land's surface, such as land use, soil type, and topography, will heavily impact the quantity of runoff [13]. Vegetative cover of the surrounding land can potentially act as a buffer for aquatic systems receiving runoff [14]. During rainfall events, impervious surfaces such as roads, parking lots, and other pavements increase runoff due to extremely limited infiltration into the ground. Areas with 75–100% imperviousness can yield runoff that represents up to 55% of any rainfall [15].

The potential runoff coefficient (PRC) represents the portion of rain that becomes surface runoff during a rain event, and it is determined by the land use, soil texture, and slope [16]. The potential runoff coefficient was derived from methods of developing a unit hydrograph (UH) for specific depths of rainfall. The hydrograph provided the assumption that discharge at any time is proportional to the volume runoff, and the temporal factors for a given duration are constant [17]. Runoff coefficients have been widely utilized in the hydrological modeling along with other computational factors for research in flood frequency, flood prediction, and storm management [18–20]. Hydrologic simulation model software's have been developed using spatial data and GIS [5]. Another method that includes runoff coefficients to hydrological modeling is the runoff curve number (CN) method created by the United States Department of Agriculture Natural Resources Conservation Service. Unlike the potential runoff coefficient, the CN can be calculated for each watershed and encompass the potential maximum retention of the soil over a given period of time.

PRC can be determined for land surfaces with different characteristics along with the quantity of runoff known as the "runoff depth." Given the quantity of runoff being influenced by the determining conditions, spatial variation in PRC can be estimated for a specific time duration within a given estuarine drainage area. In order to demonstrate this, runoff coefficients and runoff depths were calculated using geographic information systems (GIS) for the drainage basin of the Indian River Lagoon (IRL), Florida, which recently had recurring severe algal blooms. Nonpoint source pollution from surface runoff may have had been a cause for the recurring algal blooms in the lagoon [7, 8]. Use of the spatially contiguous PRC across an area of interest provides additional resources and information for stormwater research within a coastal watershed. Runoff coefficients of a watershed along with other information can be utilized for analytical processes to gain further insight of stormwater dynamics on local and regional scales.

Since 2011, IRL experienced severe algal bloom events; and non-point source pollution through surface runoff is suspected to be one of the causes for the algal blooms. The goal of this study is to calculate the spatially contiguous PRC and runoff depth for the drainage basin of IRL and the connected estuary, the Halifax River, Florida for an eleven-year period (2006–2016) in order to determine which areas and factors contribute to the runoff. The 2011 monthly runoff depth of the draining areas was compared with the 2011 monthly algal bloom maps of a previous study in order to see any visible correspondence between the locations of algal bloom initiation and the locations with high runoff depth values.

2. Data for model components

The procedure to derive the PRCs and runoff depths for the IRL consisted of processing satellite imagery to derive the land cover and land use (LC/LU), collecting the soil textures throughout study area, and calculating slope using terrain elevation data within the watershed.

2.1 Land cover/land use

Land cover and land use (LC/LU) is one of the factors for calculating PRC. The LC/LU was derived by classifying the European Space Agency (ESA) Sentinel 2 Level 1C 10 m satellite imagery from November of 2016. Four images were downloaded from the ESA Sentinel Scientific Data Hub website to encompass the elongated watershed of the IRL (https://scihub.copernicus.eu/dhus/#/home). The images were preprocessed with the ESA Sentinel Application Platform (SNAP) remote sensing software along with the Sentinel 2 toolbox. Before classifying LC/LU of the study area, an atmospheric correction was applied to the images using the Sen2cor 2.3.2 plugin within ESA SNAP to eliminate the effects of water vapor, aerosols, and cirrus clouds when utilizing spectral reflectance data. The preprocessing output of the Sentinel 2 data produces Sentinel Level-2A data which includes values that represent the radiation at the bottom of the atmosphere (BOA). Once the BOA output was produced, the four images were mosaicked to produce a continuous raster image of the IRL. By applying a supervised maximum likelihood classification in ENVI 5.4, the images were classified into five categories; forest, grass, bare soil, crop, and impervious.

2.2 Slope

A digital elevation model (DEM) from the United States Geological Survey National Elevation Dataset (USGS NED) was used to generate terrain slope at a spatial resolution of 10 m (http://viewer.nationalmap.gov/basic/?howTo=true) within ESRI ArcMap 10.5 (380 New York Street, Redlands, CA 92373-8100). The elevation values were collected with Interferometric Synthetic Aperture Radar, and referenced to the North American Vertical Datum of 1988 (NAVD 88). A preliminary analysis of the DEM was performed to fill in the low areas or “sinks” that are considered to be errors so that modeled runoff would flow smoothly across the land’s surface. The filled output map was used to create the slope for the areas surrounding IRL. The percent slope was classified into three classes due to the low elevation throughout Florida.

2.3 Soil

The soil data used in the analysis were obtained from the Web Soil Survey (WSS) (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). The WSS is operated by the United States Department of Agriculture Natural Resources Conservation Service (NRCS) and contains geospatial data and information produced by the National Cooperative Soil Survey. The NRCS soil data are produced from soil samples collected from NRCS State Soil Scientist for counties throughout the United States and are available in tabular and geospatial data. The spatial data are provided in the Geographic Coordinate System and World Geodetic System of 1984 datum (GCS_WGS_84). The data for soil classification were acquired for six Florida coastal counties: Volusia, Brevard, Indian River, St. Lucie, Martin, and Palm Beach. Tabular information for the soil texture was extracted from the Web Soil Survey Microsoft Access Database file and imported into the ArcMap 10.5 software. The data contained a variety of different soil names for classification: muck, Myakka fine sand, and Turnbull muck, that are all used for determining the slope constant along with LC/LU.

2.4 Precipitation for runoff depth

The runoff depth represents the amount of rainfall that is converted into runoff [16]. Therefore, rainfall data for the Halifax River and IRL watershed were collected to calculate the runoff depth using the runoff coefficients. The data were acquired from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) River Forecast Center (RFC) website. The data were downloaded in the ArcGIS shapefile format as point data with a projection of the Hydrologic Rainfall Analysis Projection (HRAP) grid coordinate system that has a North Pole Stereographic projection, and a grid resolution of 4762.5 m (https://water.weather.gov/precip/download.php). The rainfall data are acquired in a multi-sensor process that uses radar and rain gauge to estimate the precipitation. After extracting the point data, the shapefiles were converted into raster data. Due to estimation of multi-sensor collected data, the data are first stored in a binary file format called XMRG. This file is then read into the HRAP grid coordinate system through the NWSRFS Operational Forecast System using the NEXRAD Mean Areal Precipitation Preprocessor (MAPX) to associate grid points from XMRG data to represent the hourly average precipitation for each area [21].

3. Data analysis

3.1 LC/LU accuracy assessment

Before assessing the PRCs for the study area, the LC/LU image was tested for its accuracy. The accuracy assessment test consisted of collecting 600 referenced points using a stratified random method that randomly assigns points in each class. A 2016 Digital Globe basemap in ArcMap 10.5 of a higher spatial resolution (0.62 m) was utilized to visually interpret the land cover for each reference point. The output table consisted of a confusion matrix that displays the error of omission, the error of commission per class, and overall accuracy ranging from 0 to 1. Another test for accuracy of the LC/LU classification image included calculating the Cohen's kappa (K) coefficient [22].

3.2 PRC

Potential runoff coefficient (PRC) values were derived to represent ratio of the rainfall that would convert to surface runoff per pixel. The PRC for the IRL area was determined by combining the soil texture, LC/LU, and the slope data. The PRC is calculated from a linear relationship between the runoff coefficients and slope, which is shown in Eq. (1) [23].

$$C = C_0 + (1 - C_0)\frac{S}{S + S_o} \tag{1}$$

C is the PRC, S (%) is the slope of the land surface, C_0 is the PRC for the near zero slope in reference to the first row of every land use class in PRC values for different land use, slope, and soil texture published in [23] which is sourced from published material [24–28]. $s_o$represents the slope constant for different land use and soil textures that were empirically derived over a collection of studies. Following reclassification, classes for both parameters were assigned arbitrary weighted values and the soil and LC/LU values for the data were multiplied in the ArcMap 10.5 "Raster Calculator" tool. The arbitrary values were assigned to the classes to conveniently identify each combination of LC/LU and soil texture per pixel from the products. The products of the combinations helped derive the $C_0$and s_0 per pixel in the image. The products for the variables were also used to calculate the PRC (Eq. (1)) using the Raster Calculator Tool.

3.3 Runoff depth

The total precipitation values were collected for eleven years (2006–2016), and imported into ArcMap 10.5 to be interpolated. The precipitation values (in.) for each of the years were interpolated using the Kriging method with a spherical semivariogram model. The method assumes that the values are more related when in close proximity, and the spatial autocorrelation decreases with distance. After the precipitation was interpolated for each year, the data were multiplied (cell-by-cell) by the PRC raster of the corresponding year using the raster calculator tool provided in ArcMap 10.5 toolboxes. The output of the images provided the runoff depth (centimeters) for each year, and the average runoff depth for the eleven-year period (2006–2016) was calculated per pixel (10 m). The outputs of this image can delineate potential sources of runoff for inland waterbodies that may be connected to the lagoon through a network of drainage systems.

Concentrations of chlorophyll *a* in the IRL during the 2011 super algal bloom were compared to runoff depth of surrounding areas. Kamerosky et al. [29] estimated and mapped the Chi *a* concentrations using the Medium Resolution Imaging Spectrometer (MERIS) platform aboard the European Space Agency (ESA) Environmental Satellite (ENVISAT) and calculated Normalized Difference Chlorophyll Index (NDCI) [29, 30].

3.4 Linear regression between LDI and runoff depth

In order to meet proper data conditions for linear regression analysis in ArcMap 10.5, the raster images were sampled into vector data as a point feature class. Land development intensity (LDI) data was collected from the Florida Department of Environmental Protection (FDEP) Geospatial Open Data Site (http://geodata.dep.state.fl.us/). The LDI serves as a human disturbance gradient that incorporates land use and energy used per unit area [31]. It is used in watershed modeling to delineate human-dominated areas, and to scale the human induced impacts on physiological, biological, and chemical processes. A total of 600 points were randomly placed within the Halifax River and IRL watershed via "Create Random Points" tool. Points that were placed over large waterbodies were deleted, leaving 528 sample points left for the analysis. Values from the LDI and runoff depth were extracted to the points.

To adequately assess the relationship between urbanized areas of intense impervious coverage and surface runoff, an ordinary least squares (OLS) regression analysis and geographically weighted regression (GWR) was performed in ArcGIS 10.5. These regression analyses use bandwidth methods to find the optimal sampling distances between data points, adding a geospatial component to regression analysis. The OLS regression is designed as a "Global Model" with an assumption that the explanatory and dependent variables have global trends over a particular study area. In simplified context, it is assumed that the data are continuous throughout the area therefore being "stationary" data.

For the OLS analysis, the Jarque-Bera statistic tests for model bias that can arise from nonstationary data, misspecification of independent variables, and skewed residuals [32]. Due to the positively skewed data for LDI and runoff depth values, a logarithmic transformation was applied to data to ensure a normal distribution of the datasets while making the variance independent of the mean. The Koenker's Studentized Breusch-Pagan (Koenker BP) statistic tests for nonstationary with a null hypothesis that the dependent and independent variables have a consistent relationship in geographic space, thus being stationary [33]. A rejected null hypothesis of this test indicates that there are local trends between the variables within the study area.

Presence of significant spatial autocorrelation using the Global Moran's Index (Moran's I) is based on the assumption of stationary data. In this case there will be clustering of standard residuals from heteroscedasticity, thus indicating a local model such as GWR is more appropriate. Therefore, the standard residuals produced from both regression analyses were tested for significant clustering using the Moran's I test. On the other hand, a GWR is a "nonstationary" model that accounts for the local trends in relationships between the variables. In OLS analysis, LDI data from the FDEP and 11-year mean precipitation were used as the independent variable, and the 11-year mean runoff depth as dependent variable. The GWR only included the LDI as independent, and runoff depth as dependent variable due to collinear relationships with rainfall within clustered locations within the study area.

4. Results

4.1 LC/LU classification

There are six LC/LU classes delineated from the supervised classification. The land that mostly consists of agriculture occurs in the southern section of the watershed. The overall accuracy of the LC/LU classification image was 0.82, and the lowest accuracies were in the impervious (User accuracy of 0.65) and bare soil (0.53) classes. This may have been due to the spectral similarity between bare sand along the coast and impervious surfaces such as roof tops. The reference points that appeared to exist in unhealthy brown vegetation were misclassified as bare soil. The kappa coefficient for the LC/LU image was 0.77, with an overall average of 0.82.

4.2 Slope

The slope for the study area was assigned a quantile classification to exclude the effects from outliers in the digital elevation map. The elevation in the state of Florida is relatively flat with an average slope of ~0.47 m per pixel. The areas of high percent slope are manmade structure such as buildings, walls, or homes in developed areas. Some manmade structures with unusually high slopes were identified as the outliers. The other cities have slopes ranging from 0.50 to 1.79 average percent.

4.3 Soil

The soil texture classification for central east Florida consists of mostly fine with Myakka Fine Sand as a native soil, covering more than 1.5 million acres of land, and labeled as the Florida Official State Soil [34]. The soil data were reclassified into the 12 different textures within the USDA Soil Texture Triangle to accurately implement the values: sand, loamy sand, sandy loam, silt loam, sandy clay loam, silty clay loam, sandy clay, silty clay, and clay. The total study area was composed of 67.7% sand, 4.5% loamy sand, and 8.7% silty clay.

4.4 PRC

The PRC values range from 3 to 100% (**Figure 2**). The PRCs are higher in runoff values in developed areas that are in close proximity to the coastal waterbodies of the IRL and Halifax River. The spatial resolution (10 m) of the image shows a detailed delineation of the manmade infrastructure within urban coastal communities such as roads, buildings, homes, and airports.

4.5 Precipitation

The precipitation data in the IRL watershed from 2006 to 2016 were divided into four quarters with each quarter representing the average of three-month intervals: January–March, April–June, July–September, and October–December. Although the quarterly intervals do not accurately align with seasons, the data are segmented to show the temporal shifts of the rainfall pattern in this area. The IRL watershed precipitation is usually the lowest within the first quarter averaging ~5.48 cm. As the seasonal rainfall increases in spring and summer moving from 10.03 cm in second quarter to 15.55 cm in the third quarter. The rainfall decreases towards the end of the year with an average of 5.58 cm.

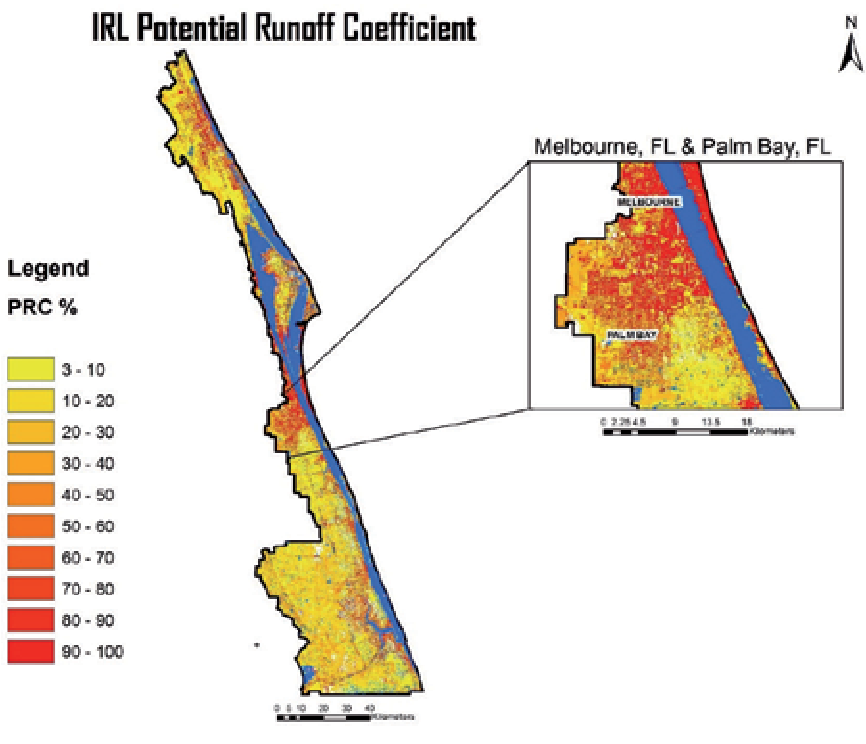

Figure 2.
Map displaying the potential runoff coefficients (PRC; %) for the Indian River Lagoon and Halifax River watersheds, FL.

4.6 Runoff depth

The runoff depth values for the IRL ranges from 2.51 to 141.48 cm. The monthly runoff depth was calculated for 2011, the year of the super algal bloom in the IRL, to serve as potential explanation for the contribution of high surface runoff to locations of the algal blooms (**Figures 3** and **4**). The average runoff per sub-basin (**Figures 3** and **4**) was compared to the chlorophyll *a* concentrations quantified from European Space Agency's Medium Resolution Imaging Spectrometer (MERIS) for 2011 [29] (**Figures 5** and **6**). The maps were all assigned the same symbology to aid easier depictions of changes in quantities, and for comparison between months.

4.7 Ordinary least squares regression

For the OLS model, LDI is statistically significant ($p < 0.0001$) for and robust probability. Precipitation determines the runoff depth, however, appears to be also significant at the 5%, but not as significant according to the robust p value ($p = 0.05$, robust $p = 0.06$). The variance inflation factor (VIF) tests for the redundancy amongst the explanatory variables that are added to the model. If two or more explanatory variables tell the same story because they are linearly related, the error variances are inflated, and the resulting multicollinearity produces a higher VIF. Studies suggest that accepting VIFs fewer than 7.5 or 10 is the rule of thumb for determining if there is multicollinearity within a dataset [35].

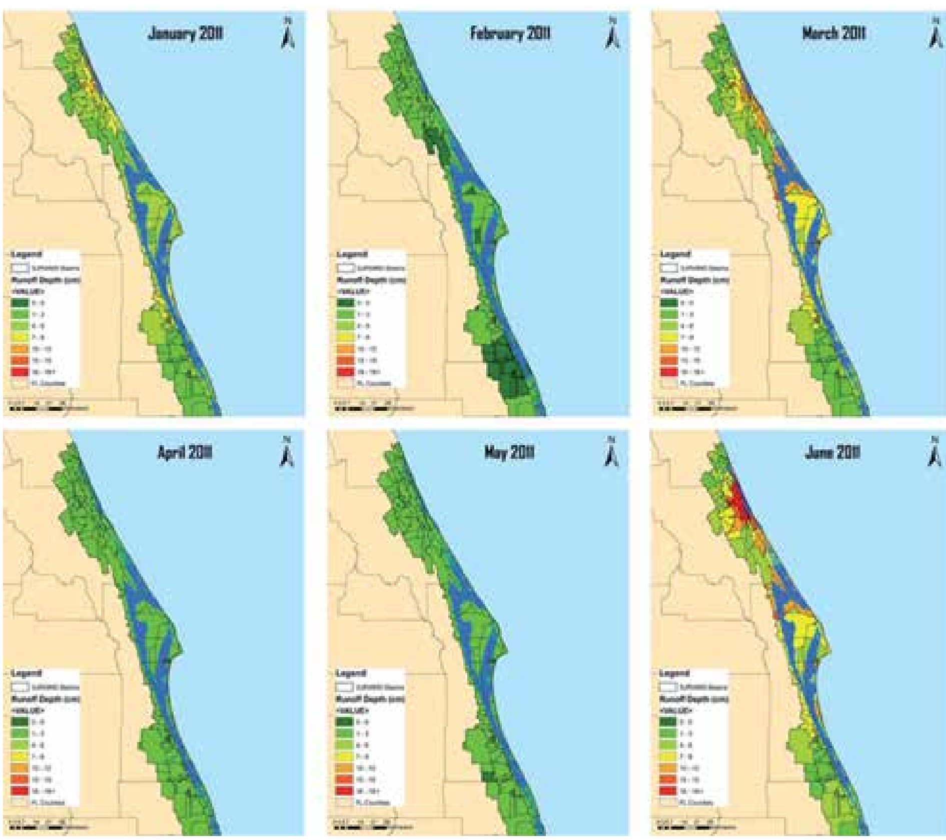

Figure 3.
The monthly mean runoff depth per sub-basin in the Indian River Lagoon from January 2011 to June 2011. The values increase form dark green, to warmer colors.

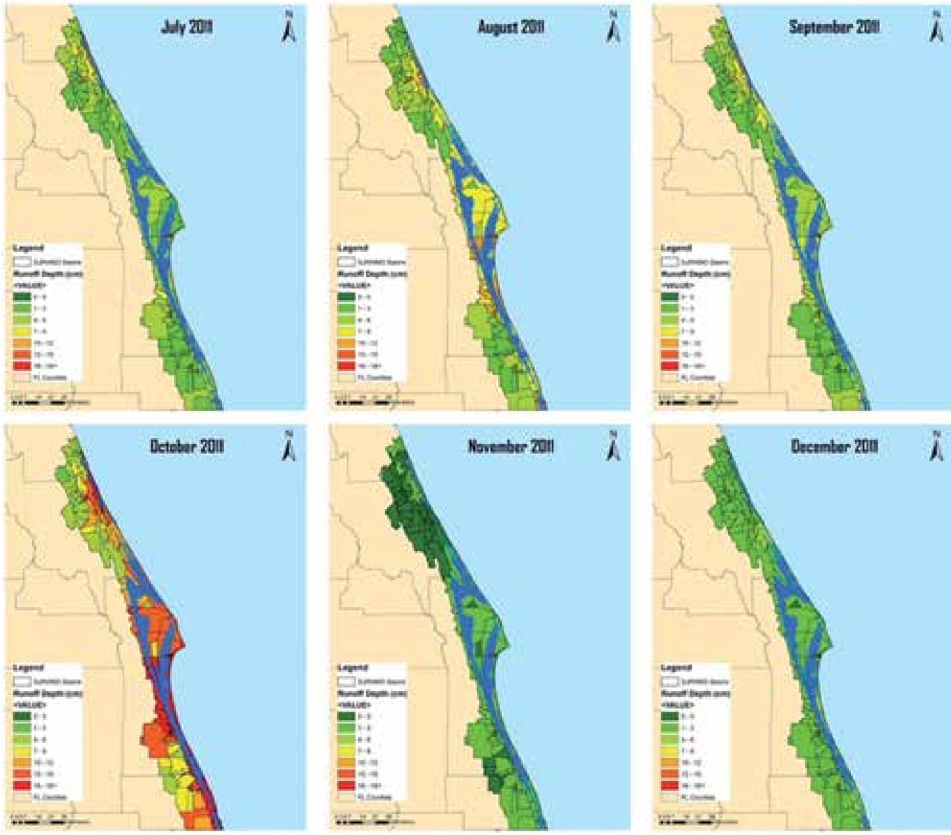

Figure 4.
The monthly mean runoff depth per sub-basins in the Indian River Lagoon from July 2011 to December 2011. The values increase form dark green, to warmer colors.

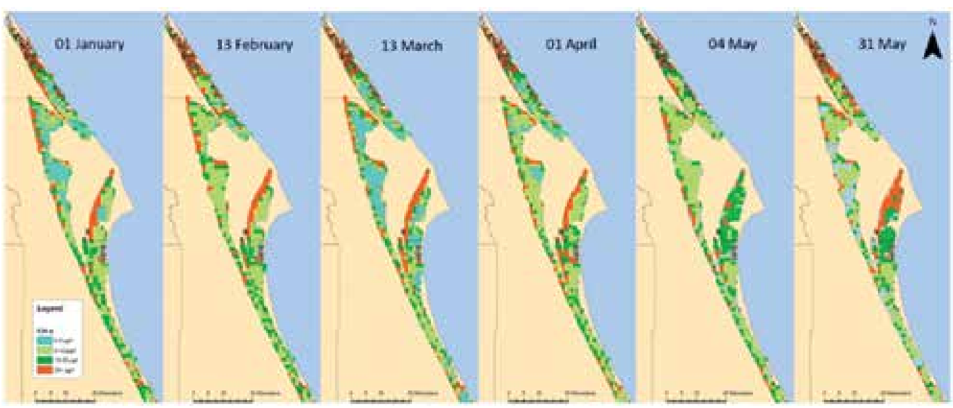

Figure 5.
Indian River Lagoon chlorophyll a *concentrations for spring 2011. The concentrations are estimated using medium resolution imaging spectrometer normalized difference chlorophyll index (image source: [29]).*

Within the OLS diagnostic results, statistical values provide information describing the performance of the model along with indicators for choosing an alternative model to adequately address the overall question (**Table 1**). The Akaike's information criterion (AIC) measures the overall model performance, which can be used in comparison to other regression analyses [36]. The multiple R^2 explains how

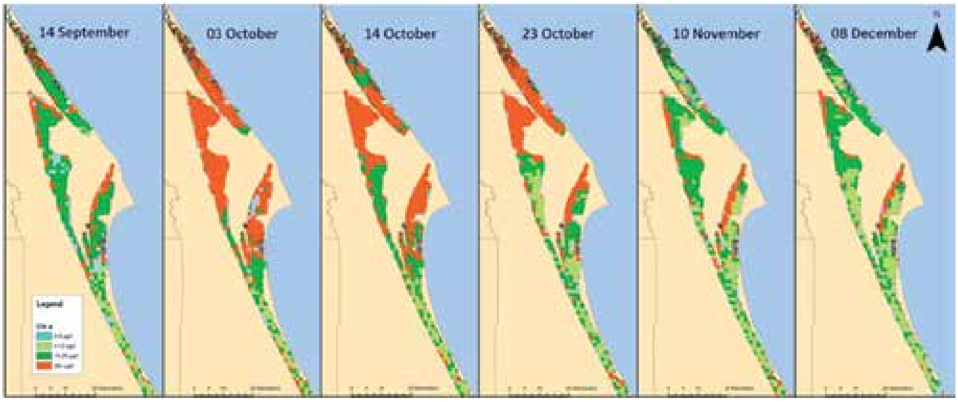

Figure 6.
Indian River Lagoon chlorophyll a *concentrations for 2011 (September–December 2011). The concentrations are estimated using medium resolution imaging spectrometer normalized difference chlorophyll index (image source: [29]).*

Variable	Coefficient	Standard error	t-statistic	Probability	Robust SE	Robust probability	VIF
Intercept	1.032	0.531	1.943	0.053	0.571	0.071	
Precipitation	0.009	0.005	1.967	0.050	0.005	0.060	1.001
LDI	0.692	0.071	9.780	<0.0001	0.085	<0.0001	1.001

Table 1.
A table of the ordinary least squares model variables.

much the independent variables explain the variation in the dependent variable. In relation to the multiple R^2 the Adjusted R^2 accounts for the model complexity. The multiple R^2 the Adjusted R^2 for this tests shows a small R^2 between the variables (R^2 = 0.15). The OLS regression also tests for the model significance with the Joint F-statistic and Joint Wald statistic to support the significance of R^2 values (**Table 2**).

The Koenker's BP statistic tests for nonstationary and heteroscedasticity. The null hypothesis is that the dependent and independent variables have a consistent relationship in geographic space, thus being stationary [33]. The Koenker's BP statistic shows significant existence of nonstationary trends between runoff depth and LDI (p = 0.004). Therefore, the model significance was interpreted based on the Joint Wald statistic (p < 0.0001) which also indicates that the relationship was statistically significant. However, the overall measure of how well the explanatory variables explained the variation in the runoff depth from the OLS analysis was relatively small (R^2 = 0.15). The Jarque-Bera statistic tests for model bias that can arise form nonstationary data, misspecification of independent variables, and skewed residuals [30]. In this case, the Jarque-Bera statistic shows no significant model bias (p = 0.064). A Global Moran's Index was performed on the residuals of the output file to test for the assumption of no spatial autocorrelation or clustering in the data. The Global Moran's Index showed statistically significant clustering rejecting the null hypothesis that the data are randomly distributed spatially within a global assumption (Moran's I = 0.07, p < 0.0001). Therefore, the OLS results should not be used to adequately interpret relationship between the explanatory variables and runoff depth.

4.8 Geographically weighted regression

Due to the detection of nonstationary and/or heteroscedasticity in the datasets, a GWR was used to adequately assess the relationship. The Global Moran's Index and

Anselin Local Moran's Index was performed to test for clustering and local patterns of spatial association [37]. The Global Moran's I indicated that the standard residuals produced from the GWR were significantly dispersed indicating the absence of spatial autocorrelation (Moran's I = −0.025, p = 0.111). The algorithm calculated an index for every feature, and 96% of the local p-values were not significant ($p > 0.05$). The validation for choosing the GWR also can be justified by the smaller AICc produced (AICc = 1522.83) compared to the OLS (1573). The R^2 for the GWR increased ($R^2 = 0.35$) with a lower adjusted R^2 of 0.26. As previously stated, the GWR accounts for nonstationary data that contain local trends for the relationship between the variables. Local trends within the dataset relationships were inevitable due to the complexity of different LC/LU within urban communities. The locally weighted regression coefficients can be seen on the coefficient raster produced by the GWR analysis (**Figure 8**). The coefficients show that LDI influences runoff in locations with more impervious surfaces and higher runoff depths, and forested land cover that consists of low LDI values and low runoff. The coefficients increase from blue to yellow to red, indicating higher relationships between the two variables.

Table 3 shows statistical values generated from the model according to the optimal sampling distance for nearest neighbors (bandwidth). The sampling kernel type for the GWR was fixed, and therefore provides the bandwidth in meters. The Residual Squares is the sum of squared residuals that represent the distance between the observed and estimated values. Therefore, the data are more related when this value is smaller. With a strong influence from bandwidth, the Effective Number is a measure of the complexity of the model that is used to calculate other variables within the GWR model, and it is useful when compared to other models. The sigma is the estimated standard deviation for the residual sum of squares, which shows

Number of observations:	**564**	**AICc**	**1573.001**
Multiple R-squared	0.151	Adjusted R-squared	0.147
Joint Wald statistic	67.250	Prob(>chi-squared), (2) df:	<0.0001
Koenker (BP) statistic	10.963	Prob(>chi-squared), (2) df:	0.004
Jarque-Bera statistic	5.500	Prob(>chi-squared), (2) df:	0.064

Table 2.
Statistical diagnostic results from the ordinary least squares regression.

Variable name	**Values**
Bandwidth	11228.83 m
Residual squares	406.15
Effective number	66.62
Sigma	0.90
AICc	1522.83
R-squared	0.35
Adjusted R-squared	0.26
Dependent field	0.00
Explanatory field	1.00

Table 3.
Results from the geographic weighted regression analysis.

that the standard deviation of the observed values for runoff depth were relatively close to the predicted values calculated for the regression model (σ = 0.90).

5. Discussion

5.1 Spatially continuous PRC of the IRL and Halifax River watersheds

The goal of this research is to calculate spatially continuous potential runoff coefficient (PRC) and runoff depth. In order to demonstrate how spatial and temporal variation in PRC can be estimated within a given estuarine drainage area, this study calculated PRC as a proportion of rainfall becoming surface runoff and calculated the runoff depth that is the amount of rainfall converted to runoff.

The average PRCs increase from forest, grass, agriculture, bare soil, and to impervious. Ideally, forested areas would have the highest interception of precipitation because of high percent cover of vegetation. Forested areas also have an increase in absorption from the abundance of extensive rhizome systems in the substrate. Areas of grass may have high percent cover of vegetation, but the interception of storm water may not as efficient due to the small biomass of plants. The classification image shows that forest (27.4%) and grass (24.7%) are the most dominant land covers within the IRL watershed. Forests mostly cover the northern section of the IRL watershed and the Halifax River watershed westward of coastal cities. The higher PRC values are located along the Halifax River and IRL in more developed urban communities such as Daytona Beach, Melbourne, and Palm Bay, Florida. Throughout the state of Florida, St. Augustine grass (*Stenotaphrum secundatum* [Walt.] Kuntze) is a popular turf grass used for urban lawns. This rhizome structure of this grass is dense, but relatively short in length which increases yields in runoff and shoreline erosion. Regardless of specific lawn grass, runoff coefficients are higher than forest cover. The recommended runoff coefficient value table for Georgia Stormwater Management also shows different values for grass covered lands based on the soil texture and slope [38]. However, there is only one value for forested areas despite the slope and texture. Although different from forests PRCs used in this study, a change in land cover can impact runoff yields particularly in areas of dense vegetation.

Impervious surfaces make up 15.3% of the study area much of which is located along the coastlines. Based on the National Atlas of the United States Spatial Data collected from the Florida Geographic Data Library (FGDL), there is a total of 40 cities within the IRL watershed. For this study, the ten coastal communities with the highest cover of impervious surface were included: Palm Bay, Port St. Lucie, Melbourne, West Melbourne, Daytona Beach, Port Orange, Ormond Beach, New Smyrna Beach, Titusville, and Fort Pierce. The cities of the most impervious surfaces are Palm Bay with ~50,554 acres of impervious surfaces, and Port St. Lucie with ~73,959 acres of impervious cover.

5.2 Temporal variation in runoff depth

The runoff depth varies with changes in LC/LU and intensity of precipitation. The estimated average runoff depth for the IRL ranges from 2.5–141.5 cm for the 11-year interval. The runoff depth throughout the study area fluctuates among the years (**Figure** 7), due to the changes in precipitation. With PRC values, the areas with potential nonpoint source pollution can be used as target locations for management or mitigation. Runoff depth values above the 11-year mean varied across the area and amongst the years. Runoff deviation from the mean indicated

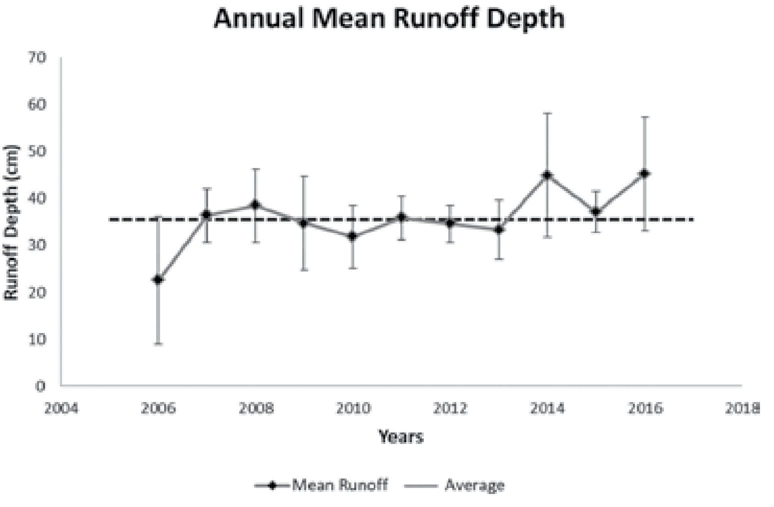

Figure 7.
The mean of the total runoff depth for each year with standard error bars for standard deviation. The dotted line represents the average 11-year runoff depth (μ = 35.89 cm) (created in Microsoft Excel 2010).

that heavy runoff depth values above the 11-year mean are years of 2008, 2014, 2015, and 2016. Causes for runoff differences can be contributed to fluctuations in climatic and annual weather patterns for rainfalls. Climatic and temporal trends have been related to changes in the IRL water quality such as El Niño years linked to declines in salinity levels in 1997, and the extended period of La Niña drought events that persisted in autumn of 2006 and summer 2007 [3]. The precipitation data for the IRL were low quantities in 2006 and 2007, and a gradual increase to 2016. The runoff depth appeared to be above the 11-year mean (35.89 cm) throughout the watershed for the years of 2014 and 2016. These are the years of strong El Niño events during which recurrent algal blooms occurred in IRL. La Niña events in Florida have shown nitrate levels to higher in ground water than in streams, which results that nutrients in aquifers accumulates from fertilizer, septic tank effluent, and animal wastes [39, 40]. The average runoff depth for 2006 was the lowest of the years, with 2016 being the highest.

Nutrient loads vary with different land use. For example, golf courses are suspected to be a major contribution to nutrient loading in waterways aside from agricultural lands. Recorded nitrate and phosphorus concentrations significantly increased at the outflow locations from the inflow concentrations for the Morris Williams Municipal Golf Course in Austin, TX [41]. Above average runoff depths in such locations can be monitored as an indicator for early warnings of algal blooms.

5.3 Linear regression between runoff depth, precipitation, and land development

Developed land within the IRL watershed contains impervious surfaces consisting of roads, parking lots, and also vegetated lots that are highly altered by human development. Precipitation undoubtedly contributes to runoff quantities, but LC/LU, and development can influence runoff yields. The regression analyses were used to test the relationship between runoff and development, as well as between runoff and precipitation. The OLS regression (**Tables 1** and **2**), the test to analyze if precipitation is an important factor for determining areas and timing with high runoff contribution, could not be adequately assessed due to spatial autocorrelation (Moran's I = 0.07, $p < 0.0001$). However, the results appear to be marginally significant at the 95% confidence interval ($p = 0.05$; robust $p = 0.06$). The LDI showed to be a significant ($p < 0.0001$) variable at explaining a significant amount of variation in runoff depth. Presence of significant spatial autocorrelation using the Global Moran's I is based on the assumption of stationary data. In this case there will be clustering of standard residuals from heteroscedasticity, thus indicating a local model such as GWR is more appropriate. The Global Moran's Index indicated no spatial autocorrelation with a negative index and rejecting the null hypothesis at with 95% confidence (Global Moran's I = −0.025, $p = 0.111$).

Although the runoff depth was determined by precipitation, LC/LU can have a higher impact on the quantities of runoff. Empty grass lots within urban communities can have compacted soil from earlier construction activity which may decrease infiltration rates up to 70% in the central Florida region [42]. The runoff coefficients for the agricultural land surfaces include the effects of compacted soil from heavy machinery. Based on the coefficient raster generated from the GWR analysis, LDI values for forested and impervious areas may account for most of the linear relationship between development and runoff (**Figure 8**). The local trends between rainfall and runoff on smaller time intervals may have a strong linear relationship. However, the mean rainfall values may have reduced the weights in local rainfall-runoff relationships. This outcome also can be noticed within the 11-year mean runoff OLS regression from the existence of local relationships between runoff and the independent variables.

Precipitation estimates along the 251-kilometer IRL estuary and ~ 35-kilometer Halifax River varies within locations, with changing LC/LU as a factor. Areas with lower rainfall can have a higher runoff yield than areas with higher precipitation over forested areas that were assigned lower runoff coefficients. As a result, areas consisting of more human disturbance have a linear relationship with more runoff. Urban communities are often primary targets for some studies to analyze rainfall-runoff by enhancing methods to estimate the DCIA in developed catchments [43]. Based on the global trends of urbanization within coastal areas, stronger rainfall-runoff relationships have positive correlations with the increase of impervious cover percentages for urban zones within separate countries [44]. The purpose of choosing LDI was to indicate the contributions of surface runoff from vegetated lands affected by urban development. To further explain this relationship, future research should assess stormwater runoff using the impervious percentage images created by the USGS. The percentage of imperviousness can also be compared to increases in runoff depth.

5.4 Runoff depth during the 2011 super algal bloom

The IRL ecosystem recently suffered from a recurrence of algae blooms since 2011 which are heavily influenced by anthropogenic stressors within its watershed, such as surrounding developed land with possible higher surface runoff [8]. Based on a visual comparison; the runoff depth was higher prior to the algal bloom events between 2011 and 2016 particularly near the areas of recorded high Chlorophyll *a* concentrations (**Figures 3**–**6**). It is important to note that the monthly runoff reflects precipitation estimates collected at the end of the month. Therefore, the runoff depth map for March should be visually compared to the chlorophyll *a* concentrations in April 2011.

Although there is no available MERIS NDCI calculations collected throughout the summer, there was an increase of runoff to 10–18 cm in May and June for the Banana River (**Figures 5** and **6**). The increase may explain the 48.62 μg/L spike in chlorophyll a May 2011 from April 2011. Based on the estimated concentrations by MERIS NDCI and water quality samples from SJRWMD, the algal bloom became higher on the 14 September 2011 with the highest concentrations in October [29].

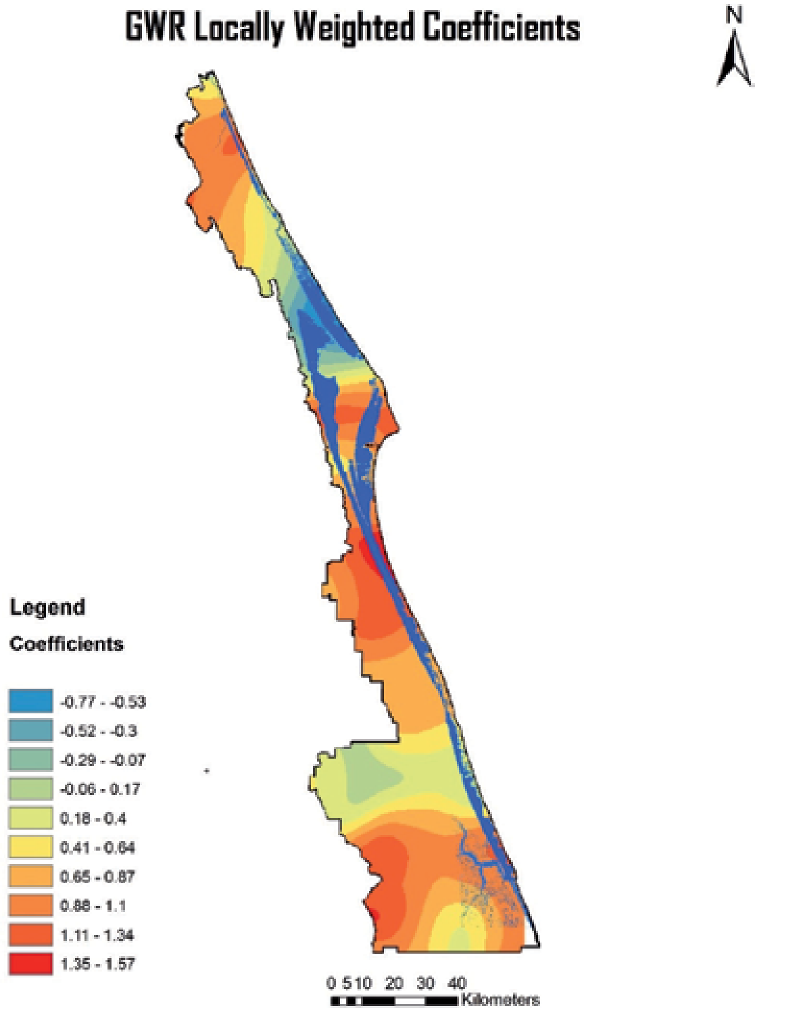

Figure 8.
The map above shows the geographically weighted regression locally weighted coefficients throughout the study area.

The runoff depth for October 2011 showed the high runoff with values above 15 cm in the southern IRL and Northern IRL. Subsequently, concentrations of chlorophyll a gradually decreased throughout October, and further dropped in November and December. Results also indicate that there were also smaller contributions of runoff during those months with decreasing trends. Visual comparisons between the chlorophyll *a* and runoff depth indicate that there may be a correlation positive association between the two variables for 2011. However, further analysis including statistical measures should be performed to assess the relationship.

5.5 Implication for coastal water management

Delineation of PRCs and runoff depths can provide a geographic depiction for assessing lands of interest to implement sustainable developmental designs and structures. In this study, runoff coefficients were calculated for each pixel regardless of surrounding pixel values. Therefore, computational methods used in this study to determine runoff depth were not assessed using methods to incorporate Directly Connected Impervious Areas (DCIA). DCIAs are areas that are considered to be hydraulically connected to the conveyance system according to the Southwest Florida Water Management District Resource Regulation Technical Guide [45]. Other study estimated runoff volumes in various sub-basins of rivers and tributaries within the IRL watershed using DCIA and non-DCIA methods [46]. Runoff from such studies use a measure called the Soil Conservation Survey Runoff Curve Number. The overall runoff was calculated from the sum of the DCIA and non-DCIA runoff, while runoff coefficients were derived by dividing the generated runoff by the total rainfall for the stations which was listed as "C values". While this approach can be used to determine Total Maximum Daily Loads (TMDLs) for nutrients, PRCs from this study can be used to emphasize exact locations within the watershed that are suitable for LC/LU management practices.

Direct surface runoff into waterbodies can be significantly affected by impervious surfaces in close proximity. In other scenarios, runoff from developed lands may travel through vegetation before entering into a waterbody. The harmful effects of surface runoff from and on urban communities call for a need of more stringent regulations, and more efficient coastal urban planning and management. This approach of stormwater management provides a long term adaptation plan to be proactive to the future impacts from climate change. Delineation of potential runoff coefficients and runoff depths can provide a geographic depiction for assessing lands of interest to implement sustainable developmental designs and structures. Mean runoff depth and runoff coefficient values can be used to determine areas of high runoff to apply green infrastructure within a watershed. "Green Infrastructure" is the practice of utilizing natural vegetated areas for runoff treatment by mimicking natural stormwater flow paths, and is composed of many low impact development (LID) designs [47]. Developed land within the IRL watershed contains impervious surfaces consisting of roads, parking lots, and also vegetated lots that are highly altered by human development.

Precipitation undoubtedly contributes to runoff quantities, but LC/LU, and development can influence runoff yields. The regression analyses were used to test the relationship between runoff and development, as well as between runoff and precipitation. The OLS regression, the test to analyze if precipitation is an important factor for determining areas and timing with high runoff contribution, could not be adequately assessed due to spatial autocorrelation (Moran's I = 0.07, $p < 0.0001$). However, the results appear to be marginally significant at the 95% confidence interval ($p = 0.05$; robust $p = 0.06$). The LDI showed to be a significant ($p < 0.0001$) variable at explaining a significant amount of variation in runoff depth. Presence of significant spatial autocorrelation using the Global Moran's I is based on the assumption of stationary data. In this case there will be clustering of standard residuals from heteroscedasticity, thus indicating a local model such as GWR is more appropriate. The Global Moran's Index indicated no spatial autocorrelation with a negative index and rejecting the null hypothesis at with 95% confidence (Global Moran's I = −0.025, $p = 0.111$).

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Mitigation of stormwater runoff often includes developing more sustainable development strategies within urban communities. An aggregation of developmental designs for combating runoff in an urban community showed reductions in runoff, and also projected expansions in bare soil, impervious cover, and soil alteration will lead to higher runoff volumes [48]. As with vegetated and undeveloped surfaces within riverine systems, the hydrological changes in volume and base flows are reduced with this hybrid design. In reference to GIS approaches to correlating surface runoff to LCLU, urban areas and bare land also corresponded to the degradation of stormwater quality [49].

6. Conclusion

The PRCs for the IRL were applied to land surfaces based on soil, land cover, and slope. These coefficients were used as ratios to determine the runoff depth per pixel within the IRL using precipitation data. After calculating the runoff depth for an 11-year period (2006–2016), it was found that the recent years (2014, 2016) were above the average 11-year runoff matched years of strong El Niño. The runoff deviation from the 11-year mean was also calculated per pixel for each year and highlighted higher runoff quantities closer to the shore of the IRL within the watershed. It is well known that impervious surfaces decrease infiltration, thus increasing runoff yields. Even with vegetated landscape, highly developed land can have poor infiltration from compact soil. The linear regression analysis showed that land development has a significant relationship with runoff depth, and there are local trends between the variables. During the 2011 super algal bloom, the months of March and April 2011 showed increases in runoff, which matched the areas with higher chlorophyll *a* mapped with MERIS in the Mosquito Lagoon in the Northern IRL [29]. In October 2011, extremely high concentrations were detected from MERIS and sampled from St. Johns River Water Management District; this research also calculated high runoff depth concentrations, delineated in the IRL watershed for October 2011. Based on these analyses, the output of this research can possibly delineate areas within the coastal communities that experience higher runoff, and help locate more suitable areas for stormwater parks, green infrastructure, and sustainable stormwater structures. Future research can include using the indices such as LDI to further correct the runoff coefficients for a particular watershed. PRCs can be applied to other watersheds of coastal ecosystems for as a visual reference, or used as a parameter for more advanced hydrologic modeling.

Acknowledgements

This publication was made possible by the National Oceanic and Atmospheric Administration, Office of Education Educational Partnership Program award (NA16SEC4810009). Its contents are solely the responsibility of the award recipient and do not necessarily represent the official views of the U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Conflict of interest

There is no conflict of interest.

Author details

Philip W. Bellamy and Hyun Jung Cho*
Bethune-Cookman University, Daytona Beach, Florida, USA

*Address all correspondence to: choh@cookman.edu

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Chapter 6

Autonomous Systems for the Environmental Characterization of Lagoons

Monica Rivas Casado, Marco Palma and Paul Leinster

Abstract

This chapter reviews the state of the art in robotics and autonomous systems (RAS) for monitoring the environmental characteristics of lagoons, as well as potential future uses of such technologies that could contribute to enhancing current monitoring programmes. Particular emphasis will be given to unmanned aerial vehicles (UAVs), autonomous under water vehicles (AUVs), remotely operated underwater vehicles (ROVs) and (semi-)autonomous boats. Recent technological advances in UAVs, AUVs and ROVs have demonstrated that high-resolution data (e.g. 0.4 cm imagery resolution) can be gathered when bespoke sensors are incorporated within these platforms. This in turn enables the accurate quantification of key metrics within lagoon environments, such as coral morphometries. For example, coral height and width can now be estimated remotely with errors below 12.6 and 14.7 cm, respectively. The chapter will explore how the use of such technologies in combination could improve the understanding of lagoon environments through increased knowledge of the spatial and temporal variations of parameters of interest. Within this context, both advantages and limitations of the proposed approaches will be highlighted and described from operational, logistical, and regulatory considerations. The chapter will be based on recent peer-reviewed research outputs obtained by the authors.

Keywords: emerging technologies, robotics, autonomous systems, environmental monitoring, UAVs, autonomous underwater vehicles, ROVs, semi-autonomous boats

1. Introduction

Lagoons are shallow bodies of water separated from larger bodies of water by barrier reefs, coral reefs, sandbars or other natural barriers such as shingle or rocks (**Figure 1**). Monitoring of lagoons is a regulatory requirement in Europe under the Water Framework Directive [1]. These requirements need to be interpreted alongside those of other directives such as the Nitrates Directive, Habitats Directive and the Marine Strategy Framework Directive and the EU strategy on adaptation to climate change [2, 3]. Implementation of these regulatory requirements has increased the focus on characterizing lagoon environments and in developing periodic and routine monitoring programmes (e.g. [4]), with government across the European Union having to reconsider their approach to lagoon monitoring.

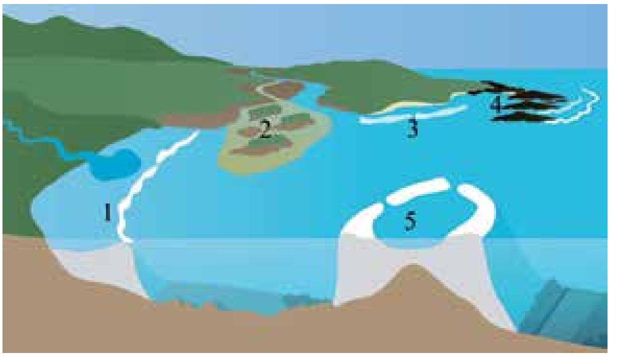

Figure 1.
Schematic diagram depicting different types of lagoon environments. (1) sandbar coastal lagoon; (2) river delta and tidal lagoon; (3) coastal coral reef lagoon; (4) archipelago's lagoon; (5) atoll coral reef lagoon. Modified from IAN image library, Tracey Saxby (ian.umces.edu/imagelibrary/).

For example, Scotland's common standards for saline lagoon habitat monitoring were abandoned in 2008 as they were not considered to be fit for purpose and were not in accordance with these new regulatory requirements [3]. The development of periodic and routine monitoring programmes has required consideration of how to increase the spatial and temporal understanding of lagoon environments and has resulted in increased spatio-temporal coverage, resolution, larger data sets and more sophisticated data analysis approaches [3, 5].

The range of parameters that potentially could be monitored is wide and varied [4, 6]. **Table 1** summarizes the key parameters that are typically monitored to characterize lagoon environments [1]. These include biological, physico-chemical and hydromorphological parameters. Traditional monitoring methods rely on visual observation or direct manual measurements of these key parameters [1]. In general, such methods are highly time-consuming and costly. They can also require destructive sampling and are therefore limited in the spatial extent within which they can be implemented.

Remote sensing techniques based on satellite imagery have been used to overcome some of these limitations (e.g. [7–9]). Satellite imagery enables the monitoring of large extents. However, the resolution provided by satellite imagery is, in many cases, not sufficient to characterize a lagoon environment to the required level of detail. Information derived from satellite imagery cannot be used for physical measurements of water quality and does not enable characterization of the sub-surface properties of lagoons in the deepest areas.

Recent technological advances within the area of robotics, autonomous systems and machine learning have been identified as potential solutions to overcome the limitations mentioned above. Both robots and autonomous systems have been identified by the UK government as one of the eight great technologies [10] where the UK will be global leaders. Robots and autonomous systems that are able to monitor the environment independently of human control could revolutionize lagoon monitoring in the next decades. Such technologies have already been used in a diverse range of environments, with some authors reporting some applications in lagoons [11]. Both robots and autonomous systems require bespoke algorithms that enable them to carry out their tasks, from path planning during autonomous navigation to the analysis of the data collected. Machine learning methods enable the development and implementation of such algorithms. Machine learning techniques have already been successfully used in multiple environments to detect fish species automatically from imagery collected with underwater cameras [12] and to predict trophic status indicators in coastal lagoons [13].

Parameter	Description	
Biological	Phytoplankton	Changes in phytoplankton composition indicate changes in the dynamics of the lagoon. Changes in nutrients, salinity or environmental stressors have an impact on the primary production. Key metrics look at the presence of harmful algal species, species configuration of assemblages, phytoplankton variation over time, growth and biomass [14, 15]
	Other aquatic flora	This includes floating (emergent) and submerged plants. The key parameters used to describe other aquatic flora include community structure, taxonomic composition, abundance, coverage, diversity and species richness
	Habitat	Habitat characterization focuses on the quality and diversity of the habitat present within the lagoon and surrounding areas. Key metrics include species composition, species coverage gain/loss, habitat alteration, complexity, patchiness and stabilization [14]
	Macro-invertebrates	Abundance and diversity of macro-invertebrates are ecological indicators of water-level fluctuations and human pressures. Taxonomic composition, abundance, species richness, community structure and diversity indexes are key parameters
	Fish	Fish community composition (diversity and structure), abundance and seasonality are the key parameters used to characterize fish communities in lagoons. Changes in these parameters are indicators of environmental change and anthropogenic impact
Physico-chemical	Salinity	Salinity patterns provide information about the vertical and horizontal stratification of water in the lagoon, tidal patterns and the rate of saline and fresh water ingress-egress
	Temperature	Temperature measurements provide information about the temporal and spatial variation patterns in the lagoon and the occurrence of thermoclines. It also provides information about the influence of insolation and evaporation processes
	pH	An indicator of acidification and algal activity
	Oxygen	Oxygenation levels in lagoons are an indication of primary production and general organic matter consumption
Hydromorphological	Tidal range	The tidal range is the difference in water level between high tide and low tide. The tidal range is an indicator of the likely patterns of saline and fresh water ingress-egress
	Hydrology	Hydrological characterization focuses on quantifying existing hydrological processes within lagoons. These include evaporation, insolation, internal circulation (saline and freshwater ingress-egress, groundwater), groundwater input and mixing processes, amongst others
	Morphology	Quantity, structure and substrate of the bed, depth variation and continuity and structure of the intertidal zone are key morphological parameters. More detailed characterizations look at the properties of the barrier, backbarrier stratigraphy, absence/presence of tidal inlet [16] and detailed bathymetry

Table 1.
Key parameters used for lagoon characterization based on the water framework directive [1].

The aim of this chapter is to review applications of recent technological advances within the context of lagoon environmental monitoring and define the implications for future remote sensing-based monitoring of these environments and the associated management strategies. In particular, this chapter reviews reported uses of robotics and autonomous systems for the characterization of lagoon ecosystems. It also highlights future applications of such technology and interprets the findings within the context of lagoon management and protection. The first section highlights how unmanned aerial vehicles, autonomous underwater vehicles and autonomous on-water platforms have been used to enhance existing lagoon environment monitoring practices. The second section describes the implications of the use of such technology for survey design, their potential to provide continuous information in time and space and the need for tailored data processing methods. The last section identifies some of the advantages and limitations of these remote sensing monitoring methods within the context of environmental management and current practice.

2. Robots and autonomous systems

2.1 Background

In the last decade, the uptake of robotics and autonomous systems (RAS) for environmental monitoring has increased significantly. The low cost and availability of some of the technologies in the market have facilitated the integration of RAS solutions within the environmental sector. Perhaps the most significant uptake of RAS relates to unmanned aerial vehicles (UAVs) and autonomous underwater vehicles (AUVs). UAVs are small aircraft controlled remotely (i.e. with no human pilot on board). When equipped with specific sensors, they enable on-demand and generally high-resolution data collection. This overcomes some of the limitations of more traditional remote sensing methods such as satellites. Their capabilities also enable the collection of information under low cloud cover, thus increasing the operational window for environmental monitoring.

A wide range of sensors are currently available in the market for integration on existing off-the-shelf platforms (**Figure 2**). These sensors include multispectral, thermal, hyper-spectral and high-resolution red, green and blue (RGB) cameras and water quality probes. RGB cameras are the most accessible and therefore currently the most used sensor for environmental monitoring. However, recent advances in sensor miniaturization (e.g. [17]) facilitate the integration of combined sensors on a single platform, enabling RGB imagery to be coupled with other sources of information.

2.2 Unmanned aerial vehicles

Within the context of lagoon characterization, UAVs have been used to assess the preferred locations and distribution at a fine scale of blacktip reef sharks and pink whiprays within a coral lagoon and reef systems off French Polynesia (Morea) [11]. This study focused on the assessment of the differences in species presence along reef habitats such as fringing, channels and sandflats. Density estimates of both species were estimated from the video footage recorded with a GoPro Hero 3+ Silver Edition camera fitted to a DJI Phantom II UAV quadcopter. The study highlighted the usefulness of UAVs to detect statistically significant differences in species densities across lagoon habitats [11].

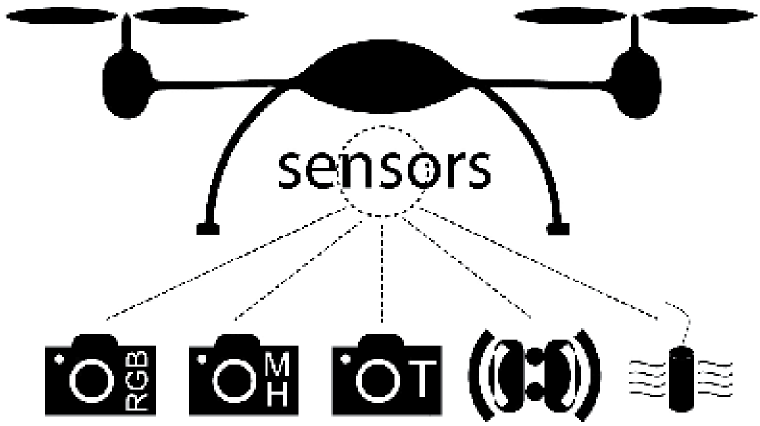

Figure 2.
Schematic diagram showing an array of sensors that can be integrated to drone platforms [i.e. red, green and blue (RGB) camera, multispectral camera, thermal camera, hyper-spectral camera, laser scanner, conductivity-temperature-depth probe].

UAVs have also been used to make water surface elevation (i.e. orthometric water height above mean sea level) and bathymetry observations in lagoons of the Yucatan Peninsula (Mexico) [18]. In Ref. [18], the authors used a DJI hexacopter Spreading Wings S900 UAV equipped with an RGB high-resolution camera (Sony DSC-RX100) and lower-resolution fish-eye lens Eken H9 camera to characterize water surface elevation. The UAV was enabled to control a tethered sonar sensor (Deeper Smart Sonar PRO + Deeper, UAB, Vilnius, Lithuania) able to map the bathymetry of the lagoons. The information thus gathered enabled the estimation of water depth. The authors reported the technology to be accurate and fit for purpose, with errors less than 7 cm for water surface elevation estimation and less than 3.8% of the actual water depth. The study also highlighted the flexibility and low cost of the technology and its capacity to monitor remote areas that are difficult to access by human operators.

Lally et al. [19] reviewed the latest advances in UAV technology (platforms, payload and probe integration) for water sample capture and physico-chemical analysis. The potential of UAVs to gather water samples in lagoons is still unexplored. To date and to the authors' knowledge, only a few examples exist of this application of the technology [19] but none within lagoon environments. Multiple limitations still curtail the uptake of the technology and include water samples are too small to be representative, restrictive drone technology, low rate of sample collection and low reliability [19]. For the technology to be transferable and cost-effective for lagoon characterization, a range of enhancements are required such as increased payload capability, increased battery endurance, beyond visual line of sight operation and real-time physico-chemical measurement [19].

2.3 Autonomous underwater vehicles, ROVs and on-water platforms

It is evident that the use of the technology for water sample collection would be of benefit to managers and conservationists alike, especially within a regulatory context where water quality assessment of such ecosystems is required on a regular basis. In England, for example, there are 52 coastal saline lagoons defined in Special Protection Areas or Special Areas of Conservation, with an additional 28 lagoonal water bodies identified under the Water Framework Directive [6]. All these lagoons and lagoonal water bodies require monitoring, assessment and reporting of the ecological quality. The use of autonomous or semi-autonomous UAVs to gather water samples could de-risk the overall activity, provide samples from inaccessible locations (increased representativeness) and increase the cost-effectiveness of the monitoring programme.

A faster route to achieve autonomous water sampling capability is the use of autonomous or semi-autonomous on-water platforms (**Figure 3**). Small boats with autonomous capability will overcome some of the limitations highlighted for UAV technology. In addition to water quality parameters, the capability of on-water platforms could be expanded to include factors such as water depth, bathymetry mapping, underwater habitat and emergent/submerged vegetation assessment. This would facilitate the temporal and spatial collocation of sampling for multiple variables. Recent studies have looked at their use within the context of freshwater ecosystem monitoring [20]. For example, Vandrol et al. [20] presented a structure-from-motion-based approach for the characterization of habitat and morphology in rivers for small boats capable of navigating autonomously along rivers. The methodology presented could also be transferred to lagoon environment characterization. Fornai [21] presented the small-size autonomous surface vessel (ASV) able to perform water column monitoring with a bespoke sampling probe (**Figure 3**). The autonomous solar-powered vessel "BUSCAMOS-RobObs" equipped with side scan sonar, sub-bottom sonar, laser systems, ultrasound sonar, depth metres, a multi-parametric probe and a GPS for collecting georeferenced oceanic data has been tested at the coastal lagoon system of Mar Menor (Spain) [22] (**Figure 3**). Low-budget and portable autonomous vessels have also been proved to be efficient with the collection of bathymetry and other variables in remote and dangerous coastal areas [23] (**Figure 3**).

Characterization of the euphotic and epipelagic zones can be achieved with both autonomous underwater vehicles (AUV) and remotely operated underwater vehicles (ROVs) (**Figure 4**). AUVs are robots able to travel underwater at different depths without the need of input from an operator. Remotely operated underwater vehicles (ROVs) are a variant of this type of robot. ROVs are directed by an operator via a remote control or an umbilical. Both AUVs and ROVs have been used for lagoon environment monitoring. For example, AUVs have been used in the Mar Menor (Murcia, Spain) coastal lagoon in different studies. The Mar Menor lagoon is separated from the Mediterranean Sea by a 20 km long dune cord that acts as a barrier to seawater ingress and ensures the protection of

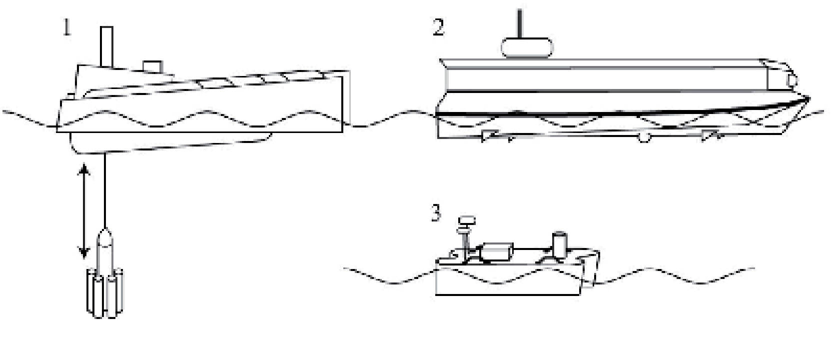

Figure 3.
Schematic diagram showing multiple autonomous surface vessels (ASV) used in coastal areas and lagoon systems. (1) ASV equipped with a winch system for autonomous water column sampling [21]; (2) the solar-powered ASV equipped with a large range of sensors is able of self-mooring [22]; (3) the affordable and portable size ASV used in coastal surveys in Greenland [23].

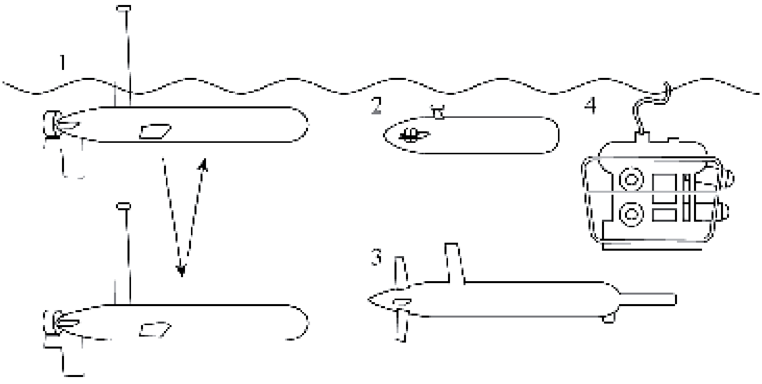

Figure 4.
Schematic diagram showing multiple autonomous underwater vehicles (AUV) and a remotely operated vehicle (ROV). (1) Guanay II [27]; (2) SPARUS [28]; (3) Seacon [26]; (4) general remotely operated vehicle (ROV).

the characteristics of both environments. In [24], the AEGIR [25], Seacon [26], Guanay II [27] and SPARUS AUV [28] were deployed in the Mar Menor lagoon to better understand the ingress-egress of marine and freshwater into the environment. The multiple AUVs were equipped with probes to capture real-time measures of salinity. Similarly, in the Indian River Lagoon (Florida, USA) [29], AUVs have been used to collect spatially dense water quality data to study the spatial variability of conditions related to algal blooms. The Indian River Lagoon extends across three estuaries for over 160 miles. Phytoplankton blooms are frequent within the lagoon and are well known to have an ecological impact on the three estuaries. The AUV was used to measure water quality parameters that provide indicators of algal activity, temperature, conductivity, pH, dissolved oxygen, turbidity, total chlorophyll and phycocyanin fluorescence. In [30], the authors developed an AUV system able to track a leopard shark tagged with an acoustic Lotek MM Series transmitter along the SeaPlane Lagoon (Los Angeles, USA). The AUV was fitted with a stereo-hydrophone and receiver system able to detect acoustic signals. Further applications of AUVs exist in marine environments [31], many of which could be transferred to lagoon environments. Predicted improvements of the technology, such as enhanced hovering capability, long endurance and rapid response capabilities [31], will facilitate further monitoring applications in lagoon environments.

2.4 Concluding remarks

The use of RAS for lagoon environmental monitoring has proved to be successful for multiple variables. The cost-effectiveness of such methods is yet unknown and needs to be understood in relation to comprehensive and more integrative monitoring programmes. The capabilities provided by RAS could further benefit lagoon environment monitoring via the integration of different platforms—e.g. UAVs, AUVs, ROVs and bespoke sensors. The technology readiness level of such approaches is still constrained by a number of factors, such as the miniaturization of sensors, but initial conceptual models have already been tested [32, 33]. Successful design of integrated solutions will require a significant degree of collaboration between experts from different disciplines, including engineers, biologists, ecologists, environmental scientists, marine scientists, data analysts and software developers. Future developments and investment should focus on further advancing the technology towards achieving an integrated system that enables the collection of collocated spatio-temporal information of all the parameters required for lagoon characterization (**Table 1**).

3. Implications for survey design

Standardization of monitoring protocols across lagoons, although a EU regulatory requirement [34], is challenging because of the complex and varied range of conditions encountered across such environments. Identification of the best location where specific samples of water quality, habitat or phytoplankton are to be taken is usually difficult to determine due to the spatio-temporal variability present within and between lagoon environments and a priori lack of knowledge of the conditions within the lagoon. Recent studies have looked at developing statistically robust sampling protocols to address this gap in knowledge. The use of robotics and autonomous systems introduces continuous monitoring capability. This makes survey design easier by prioritizing continuous data collection over point sampling. From a statistical perspective, such approaches to data collection enables the estimation of unbiased measures of dispersion and central tendency, with less intensive requirements on determining where point sample should be taken. This is of special relevance when trying to disentangle the effects that multiple factors (e.g. management practice) have on the quality of the lagoon.

Palma et al. [35] studied the effect of sampling design on coral reef characterization when collecting high-resolution (0.4 cm) RGB imagery with semi-autonomous water vehicles (**Figures 5** and **6**). The authors were interested in determining seascape metrics that would provide information about the configuration of coral reefs in Ponta do Ouro Partial Marine Reserve (Mozambique) and the morphology of the site (**Table 1**). A range of sampling scales (quadrats of size 0.5 m × 0.5 m, 2 m × 2 m, 5 m × 5 m, 7 m × 7 m) and densities (from 1 to 100 quadrats) were compared. Results showed that sampling scales equal to or coarser than 5 m × 5 m and sampling densities equal to or larger than 30 were most effective along the 1655 m^2 case study area. The study highlighted that special attention needs to be given to the design of coral reef monitoring programmes, with decisions being based on

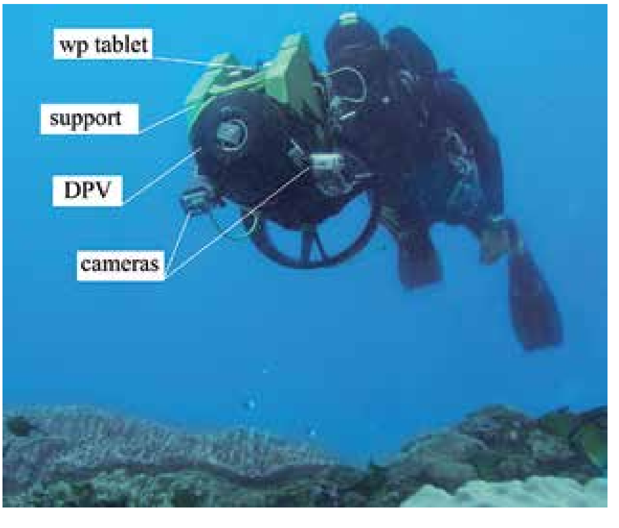

Figure 5.
The driver propulsion system (DPV), a remotely operated vehicle (ROV), equipped with a waterproof (wp) tablet and cameras. The tablet is used to coordinate data collection and steer vehicle direction.

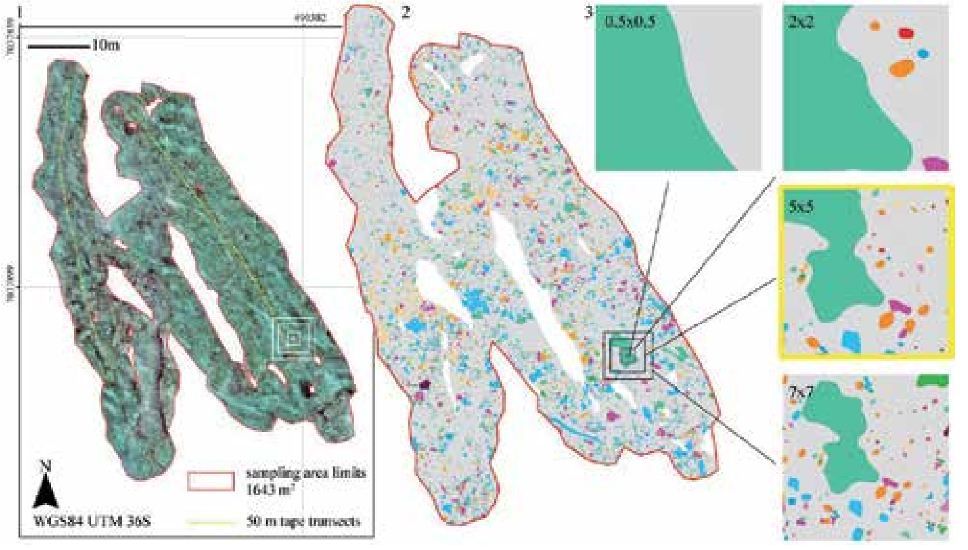

Figure 6.
Coral reef area sampled at Ponta do Ouro partial Marine Reserve in Palma et al. [35]. The image shows the different sampling strategies compared in the study (0.5 m × 0.5 m, 2 m × 2 m, 5 m × 5 m and 7 m × 7 m). Each sampling strategy depicts a different spatial configuration of the number and coverage of species (colored polygons) present within the area.

the seascape metrics and statistics being determined. Although the Ponta do Ouro Partial Marine Reserve is not classed as lagoon, the results obtained are transferable to lagoon environments.

More recent studies, also transferable to lagoon environments, have looked at the combined use of structure-from-motion (SfM) approach and ROV to map coral reefs and reduce the need for destructive sampling. In particular, Palma et al. [36] developed a framework for wide-scale benthic monitoring which is transferable to lagoon environments. The authors estimated population structure, morphology and biomass automatically from imagery collected with a (i) a GoPro Hero4 Black Edition (Woodman Labs, Inc., San Mateo, CA, USA) recording maximal resolution still images (4000 pixels × 3000 pixels) and (ii) a Sony Alpha NEX7 Digital Camera (Sony Corporation, Minato, Tokyo, Japan) recording full high-definition (1920 pixels × 1080 pixels) videos mounted on a ROV—the driver propulsion system (DPV) (**Figure 7**). The point clouds generated with both cameras contained more than 6.5 million points. Both the point cloud and the high-resolution imagery collected enabled the estimation of coral morphometries, such as height, width and planar surface of coral colonies. With the methodology proposed in [36], the error in coral height estimation was always <12.6 cm. For coral width estimation, the error was always <14.7 cm, whereas for the estimation of the planar surface, the error was 533 cm^2. Palma et al. [36] were also able to develop the methodology further to estimate coral ash free dry weight (AFDW) from the imagery collected based on the planar surface estimated. AFDW is the biomass weight present within the coral after oxidation of the organic component occurs at high temperatures. Eq. (1) is specific for *Paramuricea clavata* [37]. The results provided information on the overall health of coralligenous habitats within the Marine Protected Area of Portofino (Punta del Faro, Italy). The technology enabled sampling of 52 m^2 within 6 minutes, with data analysis requiring under 10 hours of post-processing work:

$$AFDW = A \cdot 0.0047 \cdot 0.1515 \quad (1)$$

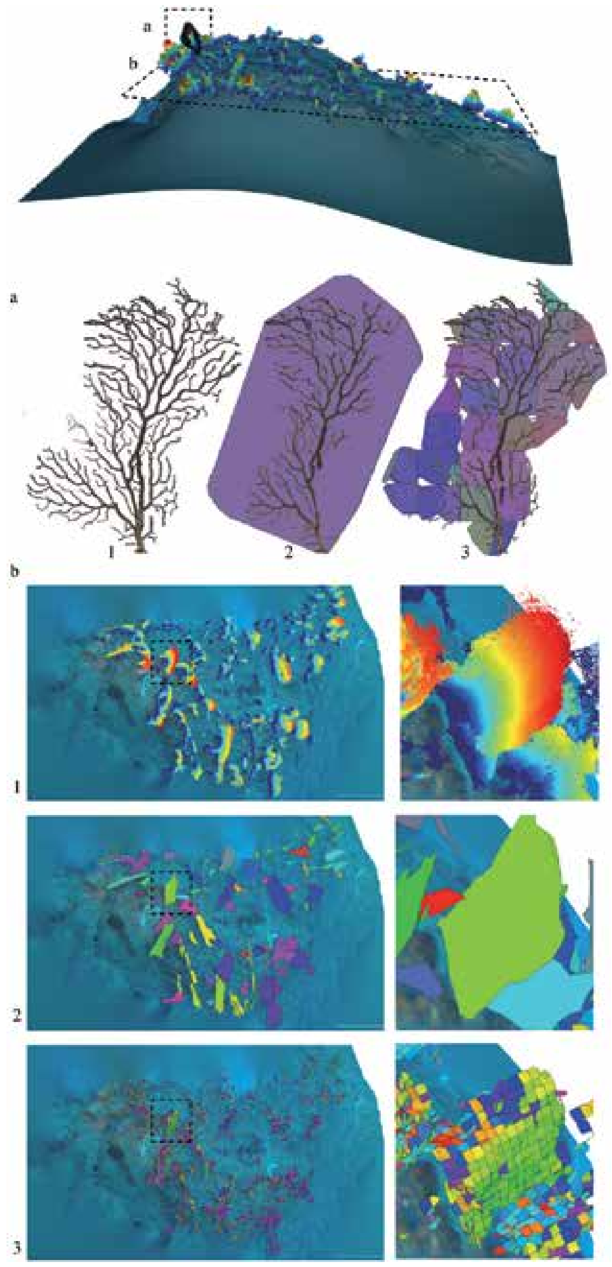

Figure 7.
Image depicting the structure-from-motion methodology developed by Palma et al. [36] to sample corals without the need for destructive sampling. Overall view of the sampled area within the marine protected area of Portofino (Punta del Faro, Italy); (a) detailed view of a scanned coral branch and the automated estimation of its surface area; (b) sequence of images showing the implementation of the estimation of the surface area of corals on-site using SfM methods: (b1) point cloud generation, (b2) delineation of outmost boundary and (b3) estimation of the coral surface area via a small set of polygons.

Technological advances in RAS and data processing algorithms enable more comprehensive data sets to be produced that facilitate more informed management decisions. The increased quality and quantity of data collected provides a robust foundation for the use of more advanced statistical methods than the estimation of measures of central tendency and dispersion.

4. Management considerations

4.1 Key challenges

Remote sensing approaches including the use of satellites, UAVs, remote-controlled boats and underwater vehicles provide the potential for significant advances in the understanding of the environmental characteristics and functioning of lagoons. They can facilitate a better understanding of the temporal and spatial variation of environmental quality parameters, of habitat extent and condition, of risks, pressures and resultant responses and of the effectiveness of mitigation measures. They can contribute to coordinating and implementing nature-related policies [2], to the standardization of monitoring programmes ([34]) and to identifying environmental management priorities. They could also be used to better understand climate change impacts.

Recent studies [2] have highlighted the need to increase research and technology development (RTD) to enhance current lagoon management practices. For example, current understanding of the functioning and ecological quality of European lagoons is currently impaired by limited and incomplete data sets [2] such as lack of water quality measurements, gauging records, climate stations or water level stations. Further data weaknesses identified included insufficient water quality data in spatial and temporal dimensions for lagoon model calibration and validation. Based on a total of four case study areas, the work by Stålnacke et al. [2] concluded that effective lagoon management critically depends on high-quality data in geospatial format. Such data can be obtained with the remote sensing RAS solutions described in previous sections. However, there are several challenges to the deployment of remote sensing approaches and their widespread uptake by those responsible for the management and oversight of lagoons. Many of the techniques are still predominately the domain of the research community. There is as yet no purpose driven overarching monitoring and surveillance protocol for lagoons into which the use of remote sensing can be easily positioned. Thought has to be given to the use that will be made of the data that will be collected. For example, is it being collected because it is now possible to collect it or it will inform and improve the management of a lagoon.

Remote sensing approaches clearly have an important role to play in the baseline assessment of a lagoon enabling detailed characterizations of habitats, morphology and quality. They can then be used to determine how these parameters vary within and between years including the impact of climate change. In addition, they can enable a better assessment of the condition of a lagoon, the pressures, responses and effectiveness of interventions, than existing methodologies. Whether such detailed characterizations are needed for all lagoons will be for individual managers and organizations to determine.

There are few agreed protocols for the collection and interpretation of data using these techniques. This can limit their use in demonstrating compliance with legislative requirements. However, if remote sensing techniques do gain greater utilization in terms of routine monitoring including for legislative purposes, then this will significantly increase data transfer and storage capabilities and requirements. These monitoring approaches generate significant quantities of data that will have to be managed—the transfer and storage of this data could be a challenge. Agreed data collection and analysis protocols would facilitate the exchange of information and enable intercountry comparisons to be made.

These technologies produce information that has not routinely been available previously [31, 38], for example, spatial and temporal variations in a range of water quality parameters obtained using on-water platforms with a variety of probes [39]. Such information will enable modeling outputs to be ground-truthed and better management decisions to be made. Although this information will enable a greater understanding of lagoons, it will require expenditure that previously was not required. Business cases will therefore need to be made to justify expenditure on initial characterization studies and then for routine surveillance. Such capital and revenue requirements could form a barrier to entry of these techniques into routine use. It may take a significant time before these techniques have widespread uptake by wildlife trusts, government agencies and regulatory bodies.

Some of the techniques will substantially reduce the cost of data collection and improve the health and safety of those collecting the information such as the use of small boat-mounted ACDP sensors to measure flow. However, for others it was not possible to collect the type of information that can now be gathered such as the spatial distribution of water quality parameters. To collect such information would therefore result in costs that were not previously incurred. Additional funding will therefore be necessary, and the case is made as to why such information is useful and justifies the level of expenditure proposed.

4.2 Technology acceptance

Technological uptake and integration in standard monitoring programmes will depend upon the factors highlighted in previous sections as well as the cost-effectiveness of the technology and the acceptance of the results produced by government agencies.

There could be resistance to the use of such systems because of the associated cost or initial capital investment. In addition, some people will resist the introduction of new technologies. Innovation is not always welcomed. There can be a level of conservatism in people working in a science or technical area to new approaches. It is not the way that they were taught to do things, and efficiencies can lead to some people losing their jobs or having to do something else. For example, the use of UAVs may be constrained by concerns that the technology can be used to violate individuals' privacy, their link to war-fare and the risk of collision with aircraft [40, 41]. Technological advances occur very fast within the context of RAS. However, the rate-determining step in their uptake can be the associated business and governance processes.

Technology acceptance and adoption models could be used to determine the key factors that will drive the uptake of remote sensing RAS monitoring solutions [42]. These models consider internal antecedents of behaviour-like attitudes, values and intentions, norms, incentives and institutional constraints to provide an estimate of the likelihood of technology uptake. Further research is required to better understand how the uptake of RAS-based remote sensing technology for lagoon environment monitoring can be facilitated.

4.3 Concluding remarks

Lagoons have been difficult environmental features to characterize and assess with the typically used monitoring approaches. They are extensive, and their characteristics vary spatially and temporally. Remote sensing approaches and RAS developments therefore provide new opportunities to better understand and assess lagoon environments. They also provide the means of better understanding what management approaches work in practice and assessing the effectiveness of interventions. They can also be used to inform the design of routine monitoring programmes.

However, there are real challenges in translating research and development and investigative approaches into repeatable and robust monitoring techniques that can be used on a routine and standardized basis for regulatory and compliance purposes. There will therefore need to be a concerted effort if the clear benefits that the developing remote sensing and RAS technologies provide are to be realized in the management of lagoon environments. The risk of not using such techniques and approaches is that the lagoon environments will continue to suffer environmental degradation.

Conflict of interest

The authors declare no conflict of interest.

Author details

Monica Rivas Casado[1*], Marco Palma[2] and Paul Leinster[1]

1 Cranfield University, Bedfordshire, UK

2 Università Politecnica delle Marche, Ancona, Italy

*Address all correspondence to: m.rivas-casado@cranfield.ac.uk

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Chapter 7

Process-Based Statistical Models Predict Dynamic Estuarine Salinity

Christina L. Durham, David B. Eggleston and Amy J. Nail

Abstract

Climate change is increasing variation in freshwater input and the intensity of this variation in estuarine systems throughout the world. Estuarine salinity responds to dynamic meteorological and hydrological processes with important consequences to physical features, such as vertical stratification, as well as living resources, such as the distribution, abundance and diversity of species. We developed and evaluated two space-time statistical models to predict bottom salinity in Pamlico Sound, NC: (i) *process* and (ii) *time* models. Both models used 20-years of observed salinity and contained a deterministic component designed to represent four key processes that affect salinity: (1) recent and long-term fresh water influx (FWI) from four rivers, (2) mixing with the ocean through inlets, (3) hurricane incidence, and (4) interactions among these variables. Freshwater discharge and distance from an inlet to the Atlantic Ocean explained the most variance in dynamic salinity. The final *process* model explained 89% of spatiotemporal variability in salinity in a withheld dataset, whereas the final *time* model explained 87% of the variability within the same withheld data set. This study provides a methodological template for modeling salinity and other normally-distributed abiotic variables in this lagoonal estuary.

Keywords: estuaries, space-time model, spatial covariance, freshwater inflow, process-based model, salinity

1. Introduction

Estuarine salinity responds to dynamic meteorological and hydrological processes [1] with important consequences to physical features, such as vertical stratification, as well as living resources, such as the distribution, abundance and diversity of species [2–5]. For example, relatively low mixing and subsequent salinity stratification can lead to hypoxia in areas where organically-rich sediments are not adequately re-oxygenated, causing emigration of mobile fauna and degradation of ecosystem functions [5–9]. Rapid salinity changes, such as those associated with large rainfall events or tropical cyclones, can cause death of postlarval stages that are sensitive to unusually low salinities [10], and mass seaward migration and subsequent hyper-aggregation of mobile, commercially important species that can result in (1) shifts of juveniles from primary nursery areas protected from trawling to secondary non-nursery areas vulnerable to fishing pressure [11], (2) overharvest of adults due to increases in fishery catchability [12], or (3) bias fishery-independent surveys that leads to over-inflated population abundance estimates [12]. Thus, the need to accurately predict the spatiotemporal dynamics of salinity is unprecedented. The specific goals of this study were to: (1) evaluate several statistical models to hindcast and forecast salinity in the second largest estuary and largest lagoonal estuary in the United States—Pamlico Sound, North Carolina, USA, and (2) assess salinity observations, predictions, and standard errors under five hydrologic scenarios characteristic of historic and future climate changes.

Pamlico Sound (PS) is a relatively shallow estuary with a mean depth of 4 m and a maximum depth of 7 m. PS circulation is dominated by wind-driven currents and freshwater input [13, 14]. Seasonal cyclonic storms are also an important climatological component of the PS system. Since 1996, over three tropical storms or hurricanes have passed within 300 km of the North Carolina coast per year [10]. Given the important role that salinity plays in the abiotic and biotic system components of estuaries, and the likelihood that global climate change will increase the frequency of extreme weather events (e.g., floods, droughts, hurricanes—[9, 15, 16]), there is a critical need for models that can accurately forecast spatiotemporal variation in salinity (e.g., [17]). A recent review by Iglesias et al. [17] highlights the strengths of applying numerical modeling tools to characterize morpho-hydrodynamic processes in estuarine and coastal systems. *Numerical methods* can include a large variety of models and techniques, such as finite element, finite difference, finite volume, or Eularian-Lagrangian models (e.g., [17–19]). Complex, three-dimensional numerical models used for simulation and forecasting of dynamic estuarine salinity can require significant effort and computation time that is beyond the capabilities of many local management agencies. Local management agencies sometimes require a quick turnaround time for long-term simulations or short-term forecasts of estuarine salinity conditions, which could be produced using location-specific statistical models. Therefore, the goals of this study were to (1) develop and evaluate two types of *statistical models* of bottom salinity in PS, and (2) apply the best models to produce sound-wide retrospective maps of bottom salinity based on observational data. Bottom (as opposed to surface) salinity was chosen as the variable of interest because it characterizes habitats of mobile demersal species that are important members of benthic food webs, and that are the targets of valuable commercial and recreational fisheries. Hereafter, the term 'salinity' will always refer to bottom salinity unless otherwise noted.

1.1 Statistical models to predict dynamic salinity

Producing retrospective salinity maps based on observational data does not require a statistical model based on hydrological mechanisms that affect salinity; it is possible to perform individual spatial interpolations for each time period of interest using an ordinary kriging model or a universal kriging model with a simple spatial trend. Predicting salinity under a hypothetical set of conditions, however, does require a model that can 'learn' about hydrological mechanisms based on retrospective data (e.g., [20, 21]). Thus, the more comprehensive goal of this study was to produce retrospective maps of salinity by developing a space-time statistical model in which the mean function represents the hydrological mechanisms that affect salinity, and a spatial covariance function makes up the difference between the observed salinity data and the mean function's salinity prediction.

To create such a model, we constructed explanatory variables that accounted for the effect of riverine freshwater inflow (FWI), distance to inlet sources of oceanic saltwater, and hurricane incidence on salinities at different locations in PS. We used a forward-selection process to choose which of these variables to keep in the model. Standard errors based on the covariance function allowed for assessment of strengths and weaknesses of the representation of the hydrology in the mean function. Since an additional goal of this study was to provide a template for researchers to build process-based models of normally-distributed estuarine variables, we considered only models that could be fit using procedures in the SAS® software package, yet can be adopted to R-statistical software.

Other process-based models of PS salinity in the literature—all of which are differential-equation-based deterministic models—provided important insights into how different variables influenced spatiotemporal salinity variation in PS ([22, 23], and others). However, these models ultimately lacked the spatial resolution and/or coverage of the entire area of interest of this study, and none quantified uncertainty at every space-time prediction location. For example, Xu et al. [24] predicted surface and bottom salinity, and temperature at 30-second intervals over a spatial grid with varying cell size (200–800 m^2) in the Pamlico River Estuary (PRE), a PS tributary, using a customized extension of the Environmental Fluid Dynamics Code [25] to incorporate FWI from major tributary rivers, as well as tide and wind effects on circulation. Although this model incorporated environmental variation and produced salinity predictions suitable to assess long-term space-time trends, the PRE makes up only 18% of the area of PS. Predicting salinity across the entire PS using this model would require spatial domain expansion and re-parameterization, and such extensions are not planned (J. Lin, NC State University, pers. comm. on behalf of Xu et al. [24]).

Though we are unaware of researchers that have constructed space-time statistical models of salinity in PS, there are examples of applying statistical models for spatial prediction of salinity in other estuaries. For example, Rathbun [26] used independent multiple linear regression models with spatially-correlated errors to predict salinity and dissolved oxygen (DO) in Charleston Harbor, SC over a two-week time period in 1988 as a function of spatial coordinates and distance to the estuary mouth. Chehata et al. [27] performed three-dimensional spatial interpolation of salinity and DO measurements in Chesapeake Bay. Qiu and Wan [20] developed a salinity model based on time series analyses of salinity data for the Caloosahatchee River Estuary, Florida, USA. The structure of their model consisted of an autoregressive term representing the system persistence and an exogenous term accounting for physical drivers including freshwater inflow, rainfall, and tidal water surface elevation that cause salinity to vary. The model was calibrated and validated using up to 20 years of measured data collected they found that the time series model offers comparable or superior performance compared with its 3-D, numerical counterpart. This model has been used as a tool for water resources management projects relating to ecosystem restoration and water control in south Florida [20]. Similarly, Ross et al. [21] examined the response of salinity in the Delaware Estuary, USA to climatic variations using statistical models and long-term (1950-present) records of salinity from the U.S. Geological Survey and the Haskin Shellfish Research Laboratory. The statistical models included non-parametric terms and were robust against auto-correlated and heteroscedastic errors. After using the models to adjust for the influence of streamflow and seasonal effects on salinity, several locations in the estuary showed significant upward trends in salinity. Insignificant trends are found at locations that are normally upstream of the salt front. The models indicate a positive correlation between rising sea levels and increasing residual salinity, with salinity rising from 2.5 to 4.4 psu per meter of sea-level rise. The results suggest that continued sea-level rise in the future will cause salinity to increase regardless of any variation in fresh water influx [21]. Urquhart et al. [28] present the results of multiple statistical models that predicted daily, gridded surface salinity at 1 km resolution across Chesapeake Bay, USA as a function of surface reflectance estimates of salinity from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS), onboard the Aqua platform satellite. Eight statistical methods were tested, and sea surface salinity was accurately predicted via remote sensed products with an accuracy that was more than sufficient for many physical and ecological applications [28].

None of these previous studies, however, attempted to explicitly represent the hydrological processes by which fresh and saltwater mixing affects estuarine salinity. In this paper, we describe the development of candidate explanatory variables to represent mechanisms affecting PS salinity and how that development led to consideration of two fundamentally different mean functions. We then describe the forward selection process by which candidate variables were chosen to be retained in the models, and how candidate covariance functions were selected to pair with each mean function. Next, we examined maps of salinity observations, predictions, and standard errors under five hydrologic scenarios, analyzed these results, and provided overall implications of the findings.

2. Methods and results

2.1 Data and notation

We used bottom salinity values measured by the North Carolina Division of Marine Fisheries (NC DMF) Pamlico Sound Trawl Survey Program 195 (*the survey*) every June and September from 1987 to 2006. The survey is conducted only in June and September each year. Designed to assess species abundance at depths over 2 m, the survey uses a weighted stratified random sampling design. For each time period, coordinates of stations are randomly generated within each of seven water body strata, with more stations allocated to larger strata, for a total of 54 stations per time period. Hereafter, we denote with S the spatial domain that includes all points sampled within the seven strata mentioned over the entire 1987–2006 temporal domain. **Figure 1** shows the geographic location of each sampling station in S. Salinity was measured using a YSI-85 multi-function meter at the beginning of each trawl and recorded along with depth and spatial reference coordinates. All spatial coordinates used in this analysis were converted from decimal degrees to northings and eastings in nautical miles (nmi) from a reference point (the origin in **Figure 1**) located southwest of S at 34.6°N, −77.1°W. Salinity is always reported using the Practical Salinity Scale.

The temporal domain contains $T = 40$ time periods, or month/year combinations, indexed by the subscript t, so that $t = 1, \dots, T$. A time period is approximately 2.5 weeks long, the time it takes to sample all stations. Since locations of the 54 stations sampled in each time period differed slightly, and since some data were missing in each time period, let n_t represent the number of sites in time period t. Site refers to a specific spatial location nested within a particular time period and is indexed using the subscript i where $i = 1, \dots, n_t$. The dataset included $N = 2100$ total observations of salinity, where $N = \sum_{t=1}^{T} n_t$. Denoted with sal_{it} observed salinity at site i in time period t.

The fresh water influx (FWI) data represented watersheds of the Neuse, Pamlico, Roanoke, and Chowan rivers, which comprise 80% of the land draining into PS [29]. FWI observations were average daily river discharge rates collected by one

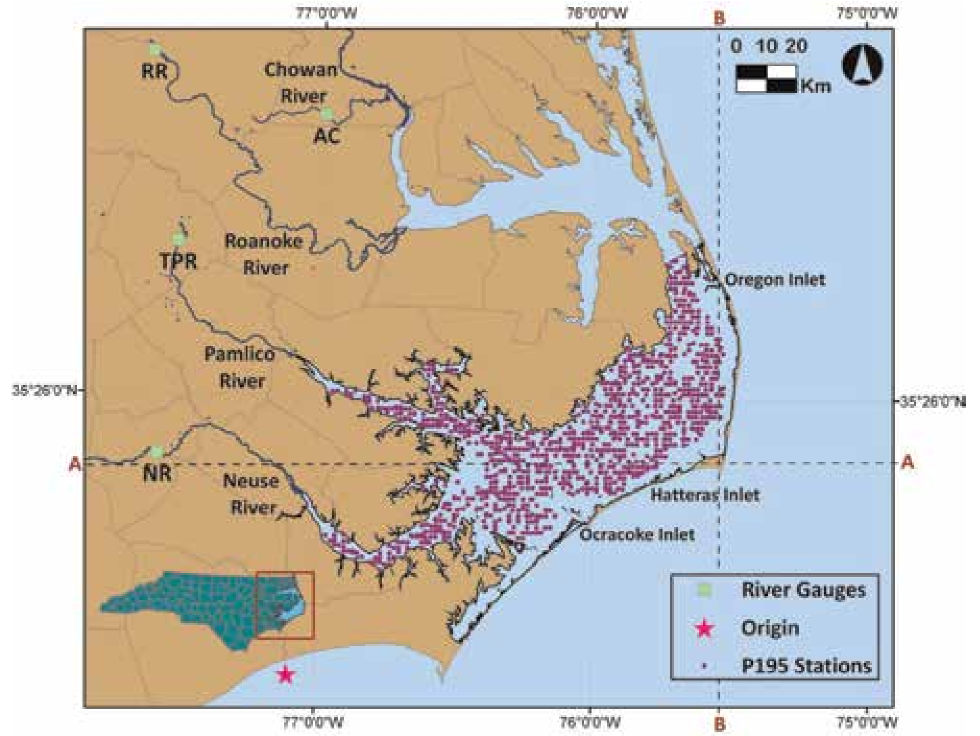

Figure 1.
Pamlico Sound, NC and the Chowan, Roanoke, Pamlico, and Neuse Rivers. Green squares show the four river gauge stations used in this study. Purple dots indicate all P195 trawl survey sample stations for the 1987–2006 time domain. The pink star indicates the reference point from which northings and eastings were calculated. As referenced in Section 3.5, Parallel A is located at 35° 16′ N latitude and meridian B is at 75° 42′ W longitude.

US Geological Survey (USGS) gauge station per tributary (**Figure 1**): Neuse River (NR) station 02089500 in Kinston; Tar-Pamlico River (TPR) station 02083500 in Tarboro; Roanoke River (RR) station 02080500 in Roanoke Rapids; and Ahoskie Creek (AC) station 02053500 in Ahoskie, which gauges Chowan River inflow. Discharge rates in ft^3/s for every day during the time domain (7305 days) were downloaded from the USGS Water Resources website for the state of North Carolina (USGS 2009) and were converted to m^3/s. For each river, the gauge chosen was the furthest downstream gauge that recorded data over the entire temporal domain.

2.2 Candidate explanatory variables

The creation of explanatory variables reflects the modeling context—the objectives, the geographical features of the spatial domain, and the space-time coverage and resolution of the data—but the general thought process can be modified by other researchers in a different context. We index the term *it* as any variable that varies in both space and time, and with *t* any variable that varies over time but is constant over *S* within a time period.

2.3 Freshwater influx indices

Sixty-one days is the average freshwater residence time of the four major rivers flowing into PS [30–32], accounting for the temporal lag between the upriver gauging of freshwater and the delivery of that water to S. Therefore, we defined the long-term metric $2moFWI\_r_t$ for river r and time period t where $r = 1, \dots, 4$, and $t = 1, \dots, T = 40$ as the average daily discharge rate in the 61 days prior to m_t, the first day of the survey in time period t. Because Ramus et al. [33] calculated a seven-day residence time for the Neuse and Pamlico Rivers after Hurricanes Dennis and Floyd deposited 1 m of rainfall in eastern NC less than 2 weeks before the September 1999 survey, we defined the short-term metric $1wkFWI\_r_t$, by averaging daily discharge rates in the 7 days prior to m_t .

Since freshwater from river r in time period t should have more of an effect on sal_{it} the closer site i is to the river, a unique measure of the influence of $1wkFWI\_r_t$ and $2moFWI\_r_t$ for each site was formed by dividing each by $dist\_r_{it}$, $r = 1, \dots, 4$, the distance separating the gauge on river r from site i within time period t:

$$1wkFWII\_r_{it} = \frac{1wkFWI\_r_t}{dist\_r_{it}}, \text{ and } 2moFWII\_r_{it} = \frac{2moFWI\_r_t}{dist\_r_{it}} \tag{1}$$

The coordinates of each gauge station were used to calculate distance because the gauge was the location of the $1wkFWI\_r_t$ and $2moFWI\_r_t$ observations. Like all distances in this study, $dist\_r_{it}$ represents distance "as the crow flies" as opposed to water-path distance. Though the superiority of using water-path distance when modeling water-quality variables in stream and estuarine systems seems intuitive, results from studies that compare these two distance metrics are inconclusive. For example, Gardner et al. [34] found more accurate predictions of stream temperatures when models incorporated water-path distance, but only when this distance was modified and weighted by stream order. Peterson and Urquhart [35] predicted various nutrient concentrations in 17 Maryland rivers and concluded that using water-path distance works well when modeling certain nutrients, but not others, and that the crow-flies distance appeared to be the most suitable distance measure overall. Comparing the accuracy of predictions of water quality parameters generated from two different multiple linear regression models containing the explanatory variable "distance to inlet mouth", Little et al. [36] found that predictions from models using water-path distance were no more accurate than those from models using crow-flies distance. None of these studies demonstrated marked predictive improvement using water-path distance, therefore we used crow-flies distance from each of the four river gauges to each of 2100 sample stations and over 6000 prediction locations.

The plot in **Figure 2** of sal_{it} against Roanoke River $2moFWII\_r_{it}$ typifies the relationships between salinity and each of the eight $1wkFWII\_r_{it}$ and $2moFWII\_r_{it}$ variables. Larger values of the metric are associated with smaller values of salinity, but groups of observations have different slopes. Closer examination revealed that the different groups corresponded to different time periods. We attempted to account for the different slopes in two ways, first by considering the 28 pair-wise interactions among the $1wkFWII\_r_{it}$ and$2moFWII_r_{it}$ and second by considering 39 time-period indicator variables defined as

$$timeper\_1_t = \begin{cases} 1 & \text{if } t = 1 \\ 0 & \text{otherwise} \end{cases}, \dots, timeper\_\tau_t = \begin{cases} 1 & \text{if } t = \tau \\ 0 & \text{otherwise} \end{cases}, \dots, timeper\_39_t = \begin{cases} 1 & \text{if } t = 39 \\ 0 & \text{otherwise} \end{cases}$$

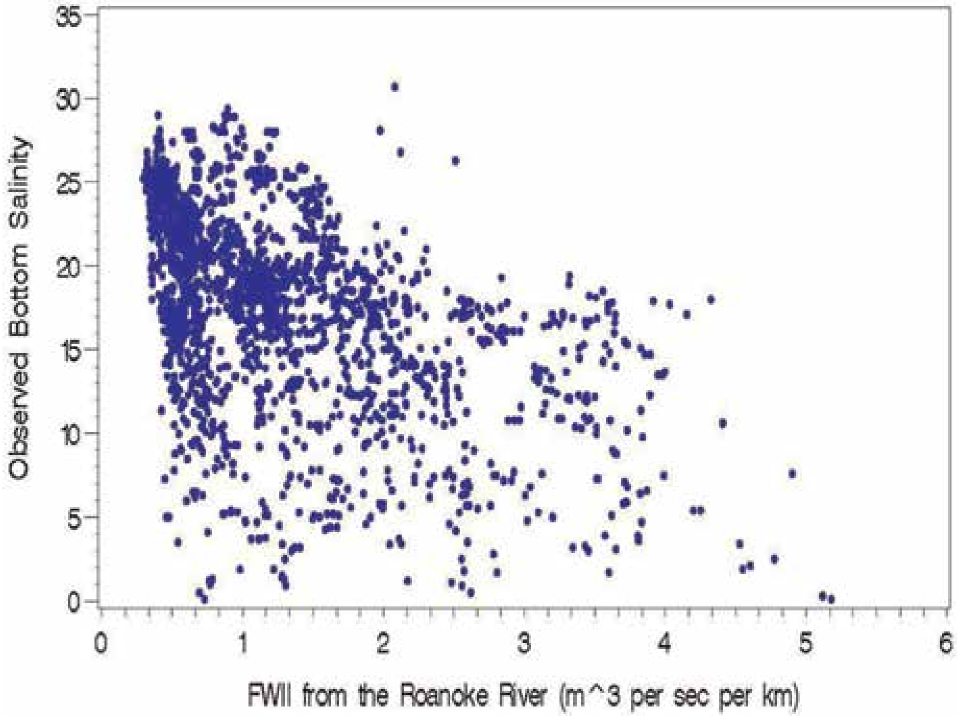

Figure 2.
Observed bottom salinity (psu) vs. the Roanoke River two-month relative freshwater influx index ($2moFWII\_r_{it}$) in $m^3\ s^{-1}\ km^{-1}$ from 1987 to 2006. Groups of values within the same time period exhibit relationships with different slopes.

(A fortieth indicator variable was not used because it would create a non-full-rank design matrix, and the effect for the fortieth time period can be derived using the intercept.) This latter consideration led to the creation of two distinct mean function models: the *process* and *time* models. The first has process variables only, and the second has process variables in addition to the time-period indicator variables to address the possibility that salinity is affected by some aspect of physical phenomena that is not accounted for by any other variable in the model.

2.4 Saltwater mixing and tidal signal

Although salinity on the inner-continental shelf of the U.S. Southeast Atlantic coast exhibits some spatial variability near PS [37], we follow Xie et al. [38] and assume constant open ocean salinity. This assumption allows for modeling the effect of ocean water mixing as a function of only the distance to inlet, as opposed to distance interacting with the salinity of the ocean water, from each spatial location in the sound to each of the major PS inlets: Oregon, Hatteras, and Ocracoke. Exploratory analyses reveal that models using a single variable (distance to the nearest inlet) rather than three variables (distances to each of the three inlets), explains the same amount of variability in salinity when other explanatory variables are also included. Therefore, we consider for inclusion in subsequent models the variable $closest\_inlet\_dist_{it}$, defined to be the distance separating site i, sampled in time period t, from the center of the most proximate inlet.

2.5 Wind speed and direction

A prevailing wind field that is north/northeast from March to August and south/southwest from September to February is the primary driver of currents in PS [39]. Thus, wind speed and direction were incorporated into the modeling process using the categorical variable $month_t$, where

$$month_t = \begin{cases} 1 & \text{if } t \text{ is in Sept} \\ 0 & \text{if } t \text{ is in June} \end{cases}$$

is used to examine the effects of seasonal wind patterns on the spatial distribution of salinity.

2.6 Evaporation and direct precipitation

Holding other factors constant, sound-wide salinity in time periods that experience more evaporation of water from the surface of PS would likely be higher than those in time periods that experienced less evaporation, but no evaporation data were available for the space-time domain of interest. Salinity in time periods for which there was more direct precipitation into *S* should be lower than those in lower-precipitation time periods, however precipitation data were only available at two weather stations on the edges of PS from which information about individual spatial locations within PS would be difficult to infer. Giese et al. [40] found that direct precipitation constitutes only 8% of mean PS freshwater input, thus the signal from riverine FWI should dominate in explaining salinity variability. Therefore, we did not include evaporation or direct precipitation variables in our models.

2.7 Spatial coordinates

Estuarine salinity varies over space such that functions of spatial coordinates might explain variability in salinity not accounted for by the other variables. Scatterplots of salinity versus easting and northing suggested that salinity is quadratic in the former and cubic in the latter. The quadratic function of easting can be explained by examining a west-to-east path through PS along the 35° 16′ N parallel (A in **Figure 1**): salinity should initially increase, reach a maximum at the saltwater plume near Ocracoke and Hatteras Inlets, and decrease again on the other side of the plume in the waters on the western shore of Hatteras Island near Buxton, NC. The cubic function of northing is best described by examining a north-to-south path along longitude of 75° 42′ W (B in **Figure 1**), where salinity should increase traveling south from Albemarle Sound, reach a local maximum near Oregon Inlet, decrease continuing past the saltwater inlet plume, and increase again as the Hatteras Inlet saltwater plume is reached. Thus, $easting_{it}$, $easting^2_{it}$, $northing_{it}$, $northing^2_{it}$, and the interactions $northing_{it} * easting_{it}$, $northing^2_{it} * easting_{it}$, $northing_{it} * easting^2_{it}$, and $northing^2_{it} * easting^2_{it}$ are considered as explanatory variables. All coordinates are centered before they are squared or cubed by subtracting the mean over all observations.

2.8 Hurricanes

Hurricanes can rapidly introduce large volumes of freshwater to estuaries via riverine influx, push large volumes of saltwater in through inlets via storm surge, and alter circulation patterns through abrupt changes in wind speed and direction [7, 10]. Hurricanes can also open new inlets to PS, which can alter current flow and increase saltwater intrusion [41]. The variable $1wkFWII\_r_{it}$ should capture variability in salinity due to hurricane-produced FWI. Three additional variables may account for non-FWI-related variability in salinity due to hurricane passage. These variables are unique to a given time period t but are constant over all sites i within t. The continuous variable $inverse\_days\_survey_t$ is the reciprocal of the number of days between the most recent hurricane and m_t, except when there is no hurricane within the 61 days, and then it takes the value zero. The categorical variable $category_t$ equals the category of the most recent hurricane rated on the Stafford-Simpson scale $(1, \dots, 5)$, but if no hurricane made landfall in the 61 days prior to m_t, it takes the value zero. Finally, the discrete variable num_storms_t equals the number of hurricanes making landfall in NC in the 61 days prior to m_t.

2.9 Variable selection

Section 3 identifies 46 candidate explanatory variables for the process model mean function: $1wkFWII\_r_{it}$ and $2moFWII\_r_{it}$ (8), plus selected pair-wise interactions (explained below) (24); spatial coordinates, their powers, and specified interactions (9); $closest\_inlet\_dist_{it}$; $month_t$; and hurricane variables $inverse\_days\_survey_t$, $category_t$, and num_storms_t. For the time model, there were an additional 39 time period indicator variables. Some variables—in either model—may be redundant. There is overlap among the hurricane variables, and spatial coordinates may not be necessary if other variables explain more variability in salinity. The set of variables included in the final model(s) should balance goodness-of-fit with parsimony. We first describe the variable-selection process for the process model, then for the time model.

2.10 Process model

The results of eight separate ordinary least squares linear regression models of salinity make up the rows **Table 1**. The first five consist of an intercept and a single explanatory variable: $closest\_inlet\_dist_{it}$, $category_t$, $inverse\_days\_survey_t$, num_storms_t, and $month_t$. The sixth and seventh contain an intercept plus, respectively, the sets of four short and long-term freshwater influx indices $\{1wkFWII\_r_{it}, r = 1, \dots, 4\}$, and $\{2moFWII\_r_{it}, r = 1, \dots, 4\}$. We treated the short and long-term sets of indices as groups assuming that if an index evaluated for one river is meaningful, then it is also meaningful for other rivers. We discuss the eighth row in Section 4.2.

Adjusted R^2 is a modification of R^2 that penalizes the number of explanatory variables. While R^2 increases as more variables are added to a model, adjusted R^2 increases only if the added variable decreases the error sum of squares enough to offset the loss in error degrees of freedom.

The model with the long-term freshwater influx indices had the largest adjusted R^2 at 0.38, followed by the model with the distance from the nearest inlet (0.34), and the model with the short-term FWI indices (0.27). None of the other four models explained more than 5% of the variability in salinity. We chose the model with the long-term freshwater influx indices as the base upon which to build the mean function.

To this base model we added the variable $closest\_inlet\_dist_{it}$ since the model containing this variable had the second-best performance, thus beginning a forward-selection process. Each time we added a variable or set of variables to the model, we kept it in the model if the new adjusted R^2 exceeded the old. Variables

Explanatory variable or set of explanatory variables	Adj R^2
$closest\_inlet\_dist_{it}$	0.34
$category_t$	0.049
$inverse\_days\_survey_t$	0.035
num_storms_t	0.029
$month_t$	0.015
$1wkFWII\_r_{it}, r = 1, \dots, 4$	0.27
$2moFWII\_r_{it}, r = 1, \dots, 4$	0.38
$timeper\_\tau_t, \tau = 1, \dots, 39$	0.41

Table 1.
Adjusted R^2 for the eight initial linear regression models. All regressions include an intercept plus the variables listed.

from the seven initial models were then added in order of decreasing adjusted R^2. Following this procedure, the mean trend model grew to contain 10 variables —$\{2moFWII\_r_{it}, r = 1, \dots, 4\}$, $closest\_inlet\_dist_{it}$, $\{1wkFWII\_r_{it}, r = 1, \dots, 4\}$, and $inverse\_days\_survey_t$—with adjusted R^2 0.57.

Because the effect of FWI from one river on a given location in PS could change based on the FWI from another river during the same time period, we evaluated the addition of the 6 pair-wise interactions among the four $1wkFWII\_r_{it}$, the 6 pair-wise interactions among the four $2moFWII\_r_{it}$, and the twelve interactions between the $1wkFWII\_r_{it}$ and the $2moFWII\_r_{it}$, excluding interactions of one river's $1wkFWII\_r_{it}$ with its own $2moFWII\_r_{it}$. Despite a decrease in error degrees of freedom by 24, adjusted R^2 was 0.66, so the set was retained.

Spatial coordinate variables were evaluated last in groups according to their polynomial order, with squared and cubic terms added before interactions. We considered these variables last because we wanted to include them only if they explained additional variability in the response after more interpretable variables were included. We determined that including all variables except $northing_{it}^2 * easting_{it}^2$ increased the adjusted R^2. The final process model mean function thus had an adjusted R^2 of 0.73 and included the following: $\{2moFWII\_r_{it}, r = 1, \dots, 4\}$; $closest\_inlet\_dist_{it}$; $\{1wkFWII\_r_{it}, r = 1, \dots, 4\}$; $\left\{1wkFWII\_r_{it} * 1wkFWII\_q_{it}, r \neq q\right\}$; $\left\{2moFWII\_r_{it} * 2moFWII\_q_{it}, r \neq q\right\}$; $\left\{1wkFWII\_r_{it} * 2moFWII\_q_{it}, r \neq q\right\}$; $inverse\_days\_survey_t$; $easting_{it}$, $easting_{it}^2$, $northing_{it}$, $northing_{it}^2$, and interactions $northing_{it} * easting_{it}$, $northing_{it}^2 * easting_{it}$, and $northing_{it} * easting_{it}^2$.

2.11 Time model

To build the time model, we followed the same procedure described above, selecting for the base of the mean function a set of time period indicator variables because a linear regression of sal_{it} on these variables had an adjusted R^2 of 0.41 (**Table 1**). (Note that such a model is equivalent to fitting an ANOVA model using the time periods as groups.) Again, we added other sets of explanatory variables in order of decreasing adjusted R^2. Before evaluating interactions, the mean trend time model had an adjusted R^2 of 0.78 and contained 48 variables: $\{timeper\_\tau_t, \tau = 1, \dots, 39\}$, $\{2moFWII\_r_{it}, r = 1, \dots, 4\}$, $closest\_inlet\_dist_{it}$, and $\{1wkFWII\_r_{it}, r = 1, \dots, 4\}$. When interactions among the $\{timeper\_\tau_t, \tau = 1, \dots, 39\}$ and the$\{2moFWII_r_{it}, r = 1, \dots, 4\}$ were added, the model was not full rank (not all columns in the design matrix were linearly independent). Because we created this second model to evaluate these interactions, we removed the $\{1wkFWII\_r_{it}, r = 1, \dots, 4\}$, the most recent variable addition, to include them. This new model, including the interactions, became the base since its adjusted R^2 (0.89) was larger than that of the previous mean trend time model (0.78). After investigating spatial coordinate variables, the final mean trend time model (below) had an adjusted R^2 of 0.91 and included 204 variables: $\{timeper\_\tau_t, \tau = 1, \dots, 39\}$, $\{2moFWII\_r_{it}, r = 1, \dots, 4\}$, $closest\_inlet\_dist_{it}$, $\{timeper\_\tau_t * 2moFWII\_r_{it}; \tau = 1, \dots, 39; r = 1, \dots, 4\}$, $easting_{it}$, $easting^2_{it}$, $northing_{it}$, and $northing^2_{it}$. To avoid confusion later, note that the adjusted R^2 of 0.73 for the process model and 0.91 for the time model were based on fitting each model to the full dataset. In the next section, we report R^2 (not adjusted R^2) based on a cross-validation dataset.

2.12 Modeling spatially correlated error

The variable selection analyses above used ordinary least squares (OLS) regression to model salinity as a function of explanatory variables. That model can be written as

$$sal_{it} = \beta_0 + \beta_1 x_{1it} + \beta_2 x_{2it} + \cdots \beta_P x_{Pit} + \varepsilon_{it}, \ \ t = 1, \dots, 40, \ \ i = 1, \dots n_t \tag{2}$$

where x_{pit} represents the value of the p^{th} explanatory variable at space–time location it, for $p = 1, \dots P$, where P is the total number of explanatory variables. $\beta_0, \beta_1, \dots, \beta_P$ represent the intercept and regression coefficients, and deviations from the mean trend ε_{it} are assumed to be independent and identically distributed $\varepsilon_{it} \sim N(0, \sigma^2)$ with mean 0 and variance σ^2. The model can be equivalently written as $sal_{it} = \boldsymbol{x}_{it}^T \boldsymbol{\beta} + \varepsilon_{\iota\tau},$, where $\boldsymbol{x}_{it}$ is the $(P+1) \times 1$ vector containing the values of the explanatory variables at space-time location it, and $\boldsymbol{\beta}$ represents the $(P+1) \times 1$vector of regression coefficients. The same model written in matrix form is

$$\boldsymbol{Y} = X\boldsymbol{\beta} + \boldsymbol{\varepsilon}, \ \ \boldsymbol{\varepsilon} \sim N\left(\boldsymbol{0}, \sigma^2 I\right), \tag{3}$$

where bold print indicates vectors so that $\boldsymbol{Y}$, $\boldsymbol{\varepsilon}$, and $\boldsymbol{0}$ are $N \times 1$ vectors containing, respectively, all observations of salinity in the space–time domain, all deviations from the mean function, and all zeros. X is the $N \times (P+1)$ design matrix whose rows represent space-time locations and whose columns contain the values of the explanatory variables (with a column of ones for the intercept), and I is the $N \times N$ identity matrix. Since a histogram of salinity observations is somewhat symmetric and bell-shaped, use of the normal distribution is justified.

Rarely, however, does the assumption of independent and identically distributed errors hold for observations of natural phenomena associated with locations in space and time. While it is intuitive that values of salinity located close together in space should be similar, it is also generally the case that the deviations from the mean function of observations located close together are similar. That similarity is referred to as spatial covariance, and the spatial covariance between deviations from the mean trend at two locations within the same time period can be modeled as a function of the distance separating them. Including in the overall model both a deterministic mean function and a spatial covariance function allowed predictions of salinity at locations where there were no observations.

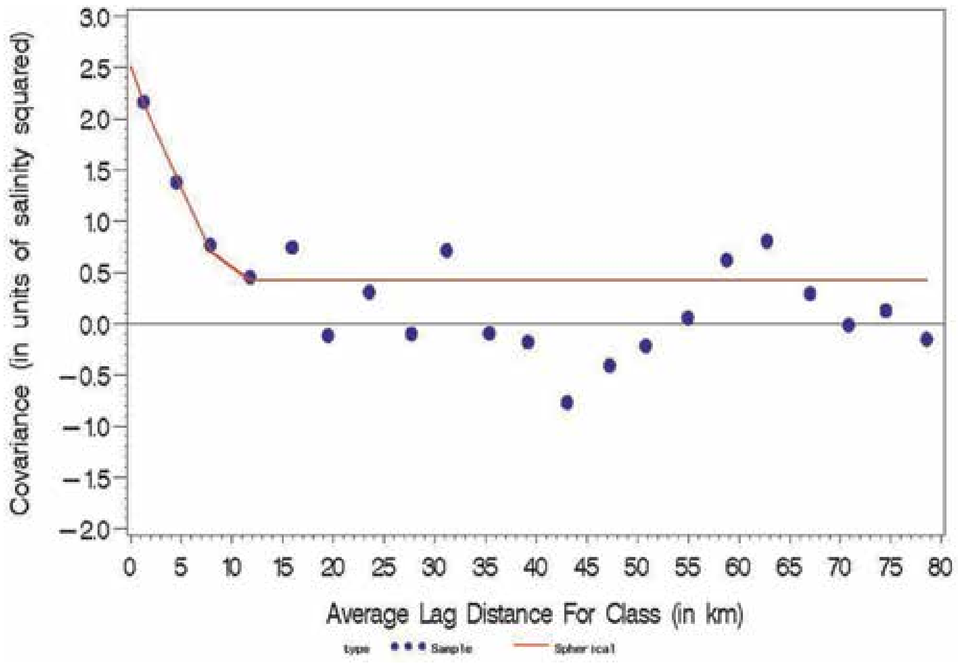

Figure 3.
Sample covariogram for June 1994 calculated from process model residuals (blue dots). The solid red line illustrates a spherical covariance function fit to the covariogram. Covariance is in units of salinity squared.

Valid covariance functions ensure that the covariance matrix will be positive definite, which, in turn, ensures that variances will be non-negative. Each covariance function has a shape defined by a range parameter, a partial sill, and sometimes a nugget effect. Appendix Table A1 gives formulas for determining spatial covariance according to the exponential, Gaussian, and spherical covariance functions, each with and without a nugget effect. **Figure 3** shows an example of the spherical covariance function—the solid red line—fit to a sample covariogram—the blue dots—of deviations from the process model for June 1994. The range parameter—θ for the exponential and Gaussian covariance functions, ρ for spherical—is related to the distance that must separate two sites before their deviations are independent, where independence corresponds to a covariance of zero or virtually zero. In **Figure 3**, the range is approximately 10 km. In the absence of a nugget effect, the partial sill σ^2 is the value of the covariance at distance zero—that is, it is the variance of deviations from the mean—and in **Figure 3** this value is approximately 2.5 squared units of salinity. In the presence of the nugget σ_n^2, there is a discontinuity in the covariance function at distance zero, so that the intercept is slightly greater than the limit of the smooth part of the function as distance approaches zero. In this case, the variance of the deviations is equal to the sum of the partial sill and nugget: $\sigma^2 + \sigma_n^2$. It may be the case that variance is higher when values of deviations are higher. Since covariance parameters represent physical quantities that may change over time, we used the capabilities of SAS® Proc Mixed to allow a different partial sill and range parameter for each time period.

Model (3), modified to include spatial correlation, becomes

$$\boldsymbol{Y} = X\boldsymbol{\beta} + \boldsymbol{\varepsilon}, \quad \boldsymbol{\varepsilon} \sim N(\mathbf{0}, \Sigma), \tag{4}$$

where Σ represents the $N \times N$ block-diagonal covariance matrix

$$\Sigma = \begin{bmatrix} \Sigma_1 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \Sigma_2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \Sigma_T \end{bmatrix},$$

where zero matrices for off-diagonal elements indicate that deviations in one time period are not correlated with those in another. We make this assumption partially due to the long time span separating June and September, but also because no SAS® procedure has the capacity to model such space-time correlation while at the same time allowing every time period to have different spatial covariance parameters and allowing a mean function to be fit. Diagonal elements $\Sigma_1, \Sigma_2, \ldots, \Sigma_t \ldots, \Sigma_T$ are individual spatial covariance matrices for each time period with dimensions $n_t \times n_t$, and elements $[\Sigma_t]_{ij} = Cov\{\varepsilon_{it}, \varepsilon_{jt}\}$ representing the spatial covariance between sites i and j in time period t.

Understanding how predictions of salinity and prediction standard errors are generated from this model will make the results and analysis in Sections 6 and 7 easier to understand. To predict salinity at space–time locations where it is not observed, the following results are needed. Superscripts differentiate between locations where salinity is observed and unobserved. Model (4), represents observations of salinity (by virtue of the dimensions of the vectors and matrices), but we model salinity observations and unobserved values of salinity at other space-time locations using a similar model, the joint distribution of unobserved and observed salinity, given by

$$\begin{pmatrix} \boldsymbol{Y}^o \\ \boldsymbol{Y}^u \end{pmatrix} \sim N\left\{ \begin{pmatrix} X^o\boldsymbol{\beta} \\ X^u\boldsymbol{\beta} \end{pmatrix}, \begin{pmatrix} \Sigma^o & \Sigma^{ou} \\ \Sigma^{uo} & \Sigma^u \end{pmatrix} \right\}. \tag{5}$$

Here, $\boldsymbol{Y}^o$ represents the $N \times 1$ vector of salinity observations, and, letting N^u represent the number of space-time locations at which we want to predict salinity, $\boldsymbol{Y}^u$ represents the $N^u \times 1$ vector of unknown values of salinity at these locations. All the symbols in (5) have the same meaning as in (4), except for the distinction between observed and unobserved locations. The $N \times N^u$ matrix Σ^{ou} contains the cross-covariance between observed and unobserved locations. Thus,

$$\Sigma^{ou} = \begin{bmatrix} \Sigma_1^{ou} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \Sigma_2^{ou} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \Sigma_T^{ou} \end{bmatrix},$$

and $\Sigma^{uo} = (\Sigma^{ou})^T$. The elements $\left[\Sigma_t^{ou}\right]_{ij} = Cov\left\{\varepsilon_{it}^o, \varepsilon_{jt}^u\right\}$ also come from the spatial covariance function.

Let $\boldsymbol{\psi}$ represent the vector that contains all spatial covariance parameters for every time period—either 80 or 81 parameters depending on whether a nugget effect is used. Standard normal distribution theory gives the distribution of unobserved salinity $\boldsymbol{Y}^u$ conditioned on knowing the values of observations $\boldsymbol{Y}^o$ and all of the parameter values:

$$\boldsymbol{Y}^u | \boldsymbol{Y}^o, \boldsymbol{\beta}, \boldsymbol{\psi} \sim N\left\{ X^u\boldsymbol{\beta} + \Sigma^{uo}(\Sigma^o)^{-1}(\boldsymbol{Y}^o - X^o\boldsymbol{\beta}), \quad \Sigma^u - \Sigma^{uo}(\Sigma^o)^{-1}\Sigma^{ou} \right\}. \tag{6}$$

The pipe symbol (|) means "given" or "conditioned on knowing the values of" the terms following the pipe symbol. The terms before the comma represent the mean of the multivariate normal distribution, which is used for the salinity prediction, and the terms after the comma represent the variance-covariance matrix, which is used for prediction standard errors. Salinity predictions are the sum of the mean trend, $X^u\boldsymbol{\beta}$, and the spatial interpolation of observation deviations from the mean trend, $\Sigma^{uo}(\Sigma^o)^{-1}(\boldsymbol{Y}^o - X^o\boldsymbol{\beta})$. If the deviations $(\boldsymbol{Y}^o - X^o\boldsymbol{\beta})$ are large for a given time period, then the partial sill σ_t^2 will be large for that time period, so that diagonal elements of Σ^o and Σ^u will be large. For a given location, the prediction standard error is the diagonal element of the matrix $\Sigma^u - \Sigma^{uo}(\Sigma^o)^{-1}\Sigma^{ou}$. If the diagonal elements of Σ^o and Σ^u are large, then the diagonal elements of $(\Sigma^o)^{-1}$ are small, and the prediction standard error is a large number minus a small number. That is, the prediction standard error will be high for time periods in which observation deviations from the mean function are large. When observation deviations from the mean trend are small, the reverse is true, and prediction standard errors tend to be low for that time period.

The salinity predictor

$$X^u\boldsymbol{\beta} + \Sigma^{uo}(\Sigma^o)^{-1}(\boldsymbol{Y}^o - X^o\boldsymbol{\beta}) \tag{7}$$

is an *exact predictor*: the prediction of salinity at a site where there is an observation will exactly equal the observation. For this reason, to determine which spatial covariance function to use, we randomly selected 10% of the observations to withhold as a cross-validation dataset, the *test dataset*; the remaining 90% we term the *base dataset*. For every combination of the two mean functions—process and time—and the six spatial covariance functions in Appendix Table A1, we fit model (4) to the base dataset, and predicted salinity values at the space–time locations of the test dataset using the results given in (5) and (6). When the model predicted salinity to be less than zero, we set the prediction equal to zero before calculating the following statistics. Predictions of negative values could be avoided using a truncated normal distribution, but SAS® Proc Mixed does not permit specification of this distribution. The root mean squared error (RMSE) of predictions—with the same units as salinity—are given in **Table 2**, along with the slope, intercept, and coefficient of determination (R^2) from a regression of actual salinity values in the test dataset on predictions of them. If predictions were perfect, this regression would have slope equal to one, intercept equal to zero, and R^2 equal to 1.

Salinity predictions are better when a spatial covariance function is combined with either mean function. For example, of the time models, the exponential covariance function with a nugget produced predictions with the lowest RMSE (2.1), slope closest to one (0.92), and intercept closest to zero (1.55). Comparing process models, the exponential and spherical, each with and without a nugget, performed equally well, and better than the time models. To select the best model from this group of four, we examined statistics based on how well the model fit the base dataset. The model with an exponential covariance function with a nugget had the lowest AIC (7580.0) and BIC (7711.7) and was thus chosen as the final model. It explained 89% of variability in the test dataset and generated predictions with RMSE 2.0.

Next, we fit this model using the full dataset, and produced retrospective maps of salinity predictions and standard errors at evenly spaced 1 nmi (1.85 km) increments for each time period. Forty-two salinity predictions—less than 0.1% of the total number of predictions—were negative and set to zero.

	Model type	−2 log likelihood	AIC	BIC	RMSE (psu)	Slope/β_1	Intercept/β_0	R^2
Process	IID	9935.9	9937.9	9943.5	2.9	0.98	0.84	0.74
	Exponential	7430.7	7584.7	7714.7	2.0	0.95	1.03	0.89
	Exponential + σ^2_n*	7424.0	7580.0	7711.7	2.0	0.96	0.96	0.89
	Gaussian	8198.0	8356.0	8489.5	2.3	0.94	1.37	0.84
	Gaussian + σ^2_n*	7532.0	7686.0	7816.0	2.1	0.94	1.15	0.87
	Spherical	7570.0	7722.0	7850.4	2.0	0.95	1.07	0.88
	Spherical + σ^2_n*	7571.6	7727.6	7859.3	2.0	0.96	0.93	0.89
Time	IID	7077.5	7079.5	7084.9	2.6	0.83*	3.47*	0.83
	Exponential	Infinite						
	Exponential + σ^2_n	6217.1	6367.1	6493.7	2.1	0.92*	1.55*	0.87
	Gaussian	6281.0	6433.0	6561.3	2.2	0.90*	1.98*	0.86
	Gaussian + σ^2_n*	6214.0	6366.0	6494.4	2.2	0.91*	1.90*	0.86
	Spherical	6199.6	6315.6	6479.9	2.2	0.91*	1.86*	0.86
	Spherical + σ^2_n	6201.3	6357.3	6489.1	2.2	0.91*	1.86*	0.86

Process and time mean functions with no spatial covariance (IID) and with each of six covariance functions were used. The symbol "σ^2_n" indicates that a nugget was included. Stars (*) indicate rejection of the appropriate null hypothesis at the α = 0.05 level of significance: H_{01}: σ^2_n = 0; H_{02}: β_1 = 1; H_{03}: β_0 = 0. The exponential plus nugget process model is highlighted as it was chosen as the best model of PS salinity for our modeling context.

Table 2.
Summary statistics comparing salinity observations in the test dataset to predictions based on fitting models to the base dataset.

2.13 Examining freshwater influx scenarios

To examine variations in the spatial distribution of salinity under drought, average, and flood conditions, we classified freshwater influx from each river within each time period ($1wkFWI\_r_t$ and $2moFWI\_r_t$) as LOW if it fell below the 25th percentile of observed FWI across all time periods, MODERATE if it fell between the 25th and 75th percentiles, HIGH if it fell between the 75th and 95th percentiles, and FLOOD if it fell above the 95th percentile. Next, we classified one-week and two-month FWI for the entire time period as LOW (or HIGH) if at least two rivers exhibited low (or high) inflow, MODERATE if at least three rivers exhibited moderate inflow, and FLOOD if at least one river exhibited extremely high (>95th percentile) inflow. These classifications are mutually exclusive, though some of the 40 time periods did not fall into any of them. The first two columns of **Table 3** list the 16 combinations of classifications, and the third column shows the classification and salinity rank for each time period. Time periods were ranked 1–40 by mean predicted salinity (1 = highest mean salinity; 40 = lowest).

Moderate-to-moderate FWI. June 2005 (**Figure 4**) experienced moderate FWI in both the 2 months and 1 week prior to the survey in PS with predicted salinity ranked 37th—the lowest of the moderate-to-moderate time periods. Legend colors for model predictions in the left pane and observations in the upper right pane of **Figure 4** (as well as **Figure 5A** and **B, 6A** and **B**) are based on percentiles of the distribution of observed salinity across all time periods: minimum to 5%; 5–10%; 10–25%; 25–50%; 50–75%; 75–90%; 90–95%; and 95% to maximum. From the left pane of **Figure 4**, predicted salinity in June 2005 increased moving east across PS,

2mo_FWI$_{rt}$	*1wk_FWI$_{rt}$*	**Time periods and mean predicted salinity rank (mmyy, r)**
Flood	Flood	**(0603, 40)**, **(0999*, 30)**
	High	none
	Moderate	(0687, 28), (0689, 27)
	Low	None
High	Flood	(0903*, 39), (0690, 29)
	High	(0904*, 32)
	Moderate	(0698, 38), (0693, 36), (0697, 35)
	Low	None
Moderate	Flood	(0996*, 33)
	High	(0696, 26), (0900, 24)
	Moderate	**(0605, 37)**, (0989, 31), (0601, 26), (0600, 22), (0604, 21), (0688, 16), (0990, 13), (0692, 10)
	Low	(0694, 17)
Low	Flood	(0987, 18)
	High	(0695, 6)
	Moderate	(0905, 20)
	Low	(0997, 15), **(0699, 12),** (0901, 8), (0902, 7), (0993, 5), **(0602, 4),** (0988, 3), (0994, 1)

Only time periods that fit each scenario as defined in Section 6 are listed; the remaining 7 time periods were not classified. Boldfaced time periods are examined in Section 6. Stars (*) indicate time periods in which hurricanes occurred within the 61 days prior to the survey.

Table 3.
Sixteen combinations of 2mo_ and 1wk_FWI$_{rt}$ classifications; time periods that exhibit each set of conditions; and mean predicted salinity rank (1 = highest).

reaching a maximum just south of Oregon Inlet. We note the same east-west salinity gradient when comparing this pane to the June 2005 map of observed salinities (top right pane), indicating that prediction maps typically mirror trends seen in observation maps. The area of highest predicted salinity corresponds to a lone purple observation of 26.5 just south of Oregon Inlet (**Figure 4**). Plumes of relatively higher salinity are evident in the vicinity of all three ocean inlets (**Figure 4**).

The lower right pane of **Figure 4** (as well as **Figure 5A** and **B, 6A** and **B**) displays prediction standard errors (SE) with the same units as salinity. The same eight percentile groups classify colors on the SE legend, here based on the distribution of prediction standard errors across all time periods. The transition from low SE at sample sites to higher SE moving away from sample sites reflects the fact that the exact predictor (6) reproduces observations, so confidence intervals closer to sample sites are narrower than those further away.

This spatial trend in SEs is further illustrated by comparing locations of high SE in the same time period, which are also consistent over time. High SEs occur between the mouths of the Neuse and Pamlico Rivers and along a margin of varying width following the outline of the Outer Banks, areas within which sampling does not occur (**Figure 1**). We note here that because SEs increase as distance from sample site increases, we chose to generate only interpolated (and not extrapolated)

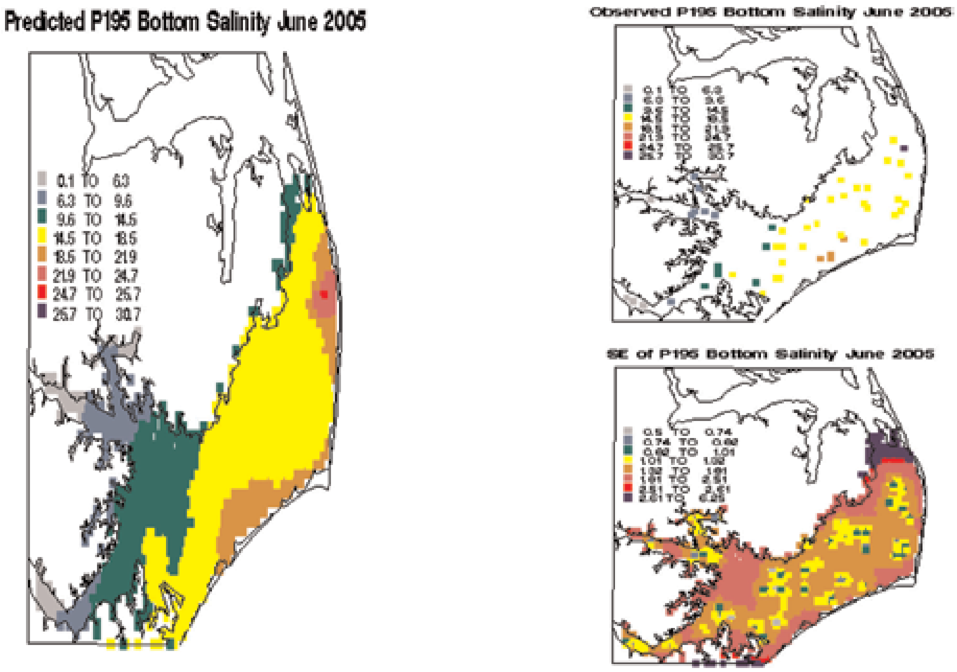

Figure 4.
Salinity model predictions (left), prediction standard errors (bottom right), and P195 survey observations (top right) for June 2005, classified as moderate-to-moderate FWI.

salinity predictions. In June 2005, as in all other time periods, predictions were generated only for locations within *S*, which does not extend either to Albemarle Sound or to the heads of the Neuse and Pamlico Rivers (**Figure 4**).

Low to low FWI in early and late-stage drought. June 1999 (**Figure 5A**) and June 2002 (**Figure 5B**)—which mark early and late stages of North Carolina's 1998–2002 drought [42]—experienced low long- and short-term FWI with predicted salinity ranking 12th and 4th, respectively. At every point in PS, predicted salinity in these two time periods was higher than in June 2005, and predicted salinity was much higher in June 2002 than June 1999, though both have similar values for $1wkFWI\_r_t$ and $2moFWI\_r_t$ variables from three of the four tributary rivers. The difference may be due to (1) the fact that in the fourth river, the Roanoke, $1wkFWI\_r_t$ and $2moFWI\_r_t$ in June 1999 were twice their values in June 2002, or (2) that by June 2002, NC had been experiencing drought conditions for 4 years (186 weeks) as opposed to less than one (30 weeks) and that this cumulative FWI deficit became more pronounced over time.

Though June 2002 salinity observations have a larger mean and greater variability, the majority of prediction standard errors are less than 1.01. In June 1999, however, SEs fell between 1.01 and 1.81 at all prediction locations except those that were very close to observations. This result shows that the conditions affecting salinity in PS were better represented by the mean function in June 2002 than they were in June 1999.

Flood to flood FWI—with and without hurricanes. FWI was extremely high in September 1999 (**Figure 5A**) as a result of the 500-year floods produced by Hurricanes Dennis and Floyd that occurred 24 and 12 days before the survey, respectively. In June 2003 (**Figure 5B**), extremely high FWI was due to an eight-month period of above-average precipitation totals prior to the survey. Though these are

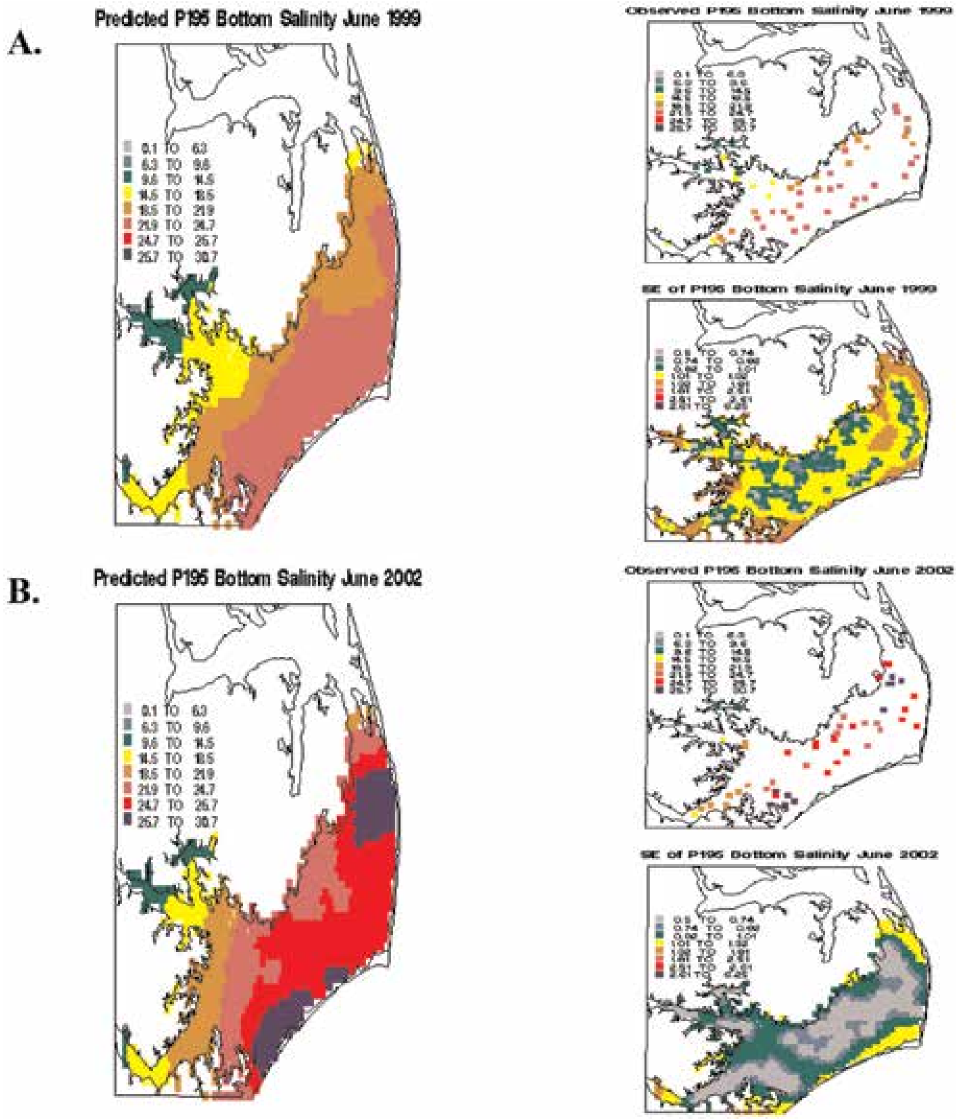

Figure 5.
Salinity model predictions (left), prediction standard errors (bottom right), and P195 survey observations (top right) for June 1999 (A) and June 2002 (B), both classified as low-to-low FWI.

the only two time periods categorized as flood-to-flood, predicted salinity in September 1999 ranks a surprisingly high 30th, while in June 2003 it ranks 40th. Observed and predicted salinity for these two time periods are lower than those in the low-FWI time periods of June 1999 and 2002, but in September 1999, salinity was higher at most prediction locations, and more variable, than in moderate-FWI June 2005. Water at locations near the two southerly inlets to PS was more saline in September 1999 than in these same locations during moderate-FWI of June 2005 likely due to storm surge-generated inlet plumes. Salinity at locations near the Neuse and Tar-Pamlico Rivers was similar to that in June 2005. Standard errors were lower sound-wide in June 2003 than in September 1999. SEs in September 1999 were highest sound-wide relative to the other four time periods examined (**Figures 5** and **6**).

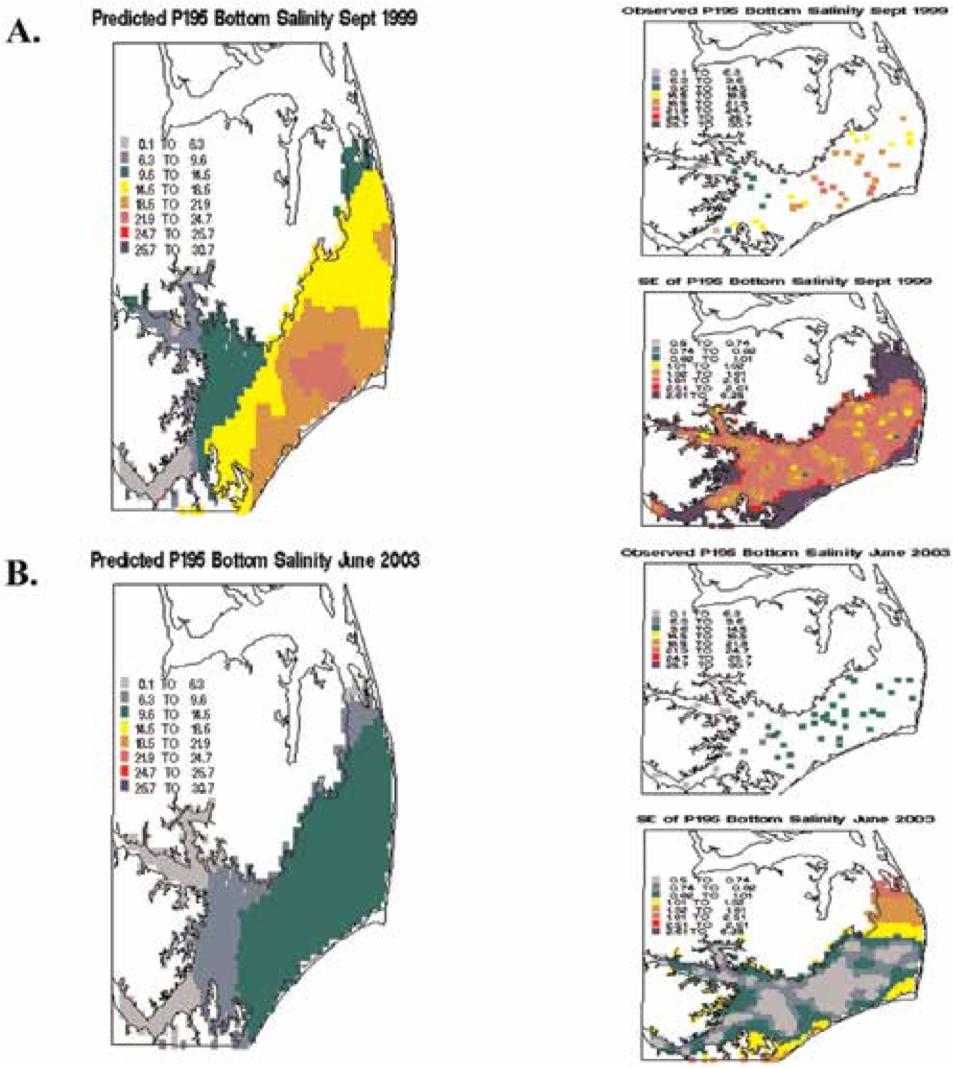

Figure 6.
Salinity model predictions (left), prediction standard errors (bottom right), and P195 survey observations (top right) for September 1999 (A) and June 2003 (B), both classified as flood-to-flood FWI.

3. Discussion

Because water exchange between lagoonal estuaries and the open ocean can be relatively restricted, there is a relatively high potential in systems like PS for changes in precipitation patterns and storm frequencies associated with global climate change to result in changes in salinity patterns and subsequent ecosystem alterations. Changes in precipitation will affect the amount and timing of river flow, which will impact nutrient cycling, estuarine flushing rates, and salinity. Increased storm activity may open new inlets, which would alter current flow, increase tidal action, and allow a greater influx of seawater that carries with it both different chemical signals and mobile species. Salinity is therefore a practical estuarine characteristic to use to study the impacts of these changes, as both effects mentioned above include enhanced water exchange that impacts overall estuarine salinity content [43, 44].

We developed and evaluated two statistical models, using the best model to hindcast salinity in PS. The process mean function combined with the exponential covariance with a nugget explained 89% of the variability in a test dataset with a RMSE of 2.0 and produced relatively accurate retrospective salinity maps under a wide range of freshwater influx and system-state scenarios. Much of this accuracy was due to allowing the range and partial sill parameters of the spatial covariance to be time-period specific. We then examined variations in the spatial distribution of salinity under varying freshwater influx (FWI) conditions such as drought, average FWI, and flood conditions, and identified the following patterns. In years with moderate FWI, the salinity gradient increased from west to east in PS as expected, and was highest adjacent to the major inlets, with highest salinities near Oregon Inlet. In years with low FWI indicative of drought conditions, the overall mean and variance in salinity increased in PS. In years with floods, salinities displayed a high degree of spatial variation, with salinities being lower near the tributaries as expected, yet also displaying occasional sharp increases in salinity near inlets due to influx of ocean water into PS via the major inlets.

3.1 Improvements to model predictions

For retrospective prediction purposes, model improvements could focus on improvements to the mean trend, the covariance, or both, and such improvements could be evaluated using the test dataset. A reasonable goal might be to increase R^2 to 0.93 or to reduce RMSE to 1.5. Improvements for the purpose of prospective prediction of salinity under hypothetical, unobserved conditions, a situation in which spatial covariance among observation deviations cannot be used, would entail improving the mean function exclusively. Locations and time periods with high SEs highlight conditions not well-represented by the current mean function. A reasonable goal here would be to produce a model for which all values of SE fall beneath the current median (1.32).

Mean function. The mean function alone explained over two-thirds of the variability in salinity in both process and time models. While this is a noteworthy accomplishment, there remains room for multiple improvements. High SE values in **Figure 5A** show that the mean function is unable to capture the interaction between high FWI in September 1999 and hurricane storm surges. One hurricane explanatory variable, $inverse\_days\_survey_t$, remained in the final process model. Its parameter estimate was positive, reflecting that strong hurricane winds push more saltwater into PS through inlets than would enter under typical seasonal wind conditions, but alone it explained only 4% of salinity variability in the full dataset. The $inverse\_days\_survey_t$, variable did not differentiate between a year in which a single hurricane passed within 12 days of the survey and a year in which such a hurricane followed another that passed 12 days earlier. A future effort might attempt to account for cumulative build-up of storm surge on observed PS salinities.

Though $closest\_inlet\_dist_{it}$ alone explained a third of the variability in salinity over all time periods, variability in inlet-plume size across **Figures 3–5** suggests that this distance metric should be modified based on wind speed and direction, using more finely resolved wind information than the $month_t$ variable. Devising a way to use the u and v components of wind to interact with $closest\_inlet\_dist_{it}$ could allow both the size and the direction of the inlet plume to vary such that east-to-west winds create different plume sizes and shapes than winds from the southeast-to-northwest. Considerable exploratory analysis would be needed to determine what pre-survey time lag should be considered to affect observed survey salinities.

Differences in both salinity values and SE estimates between early-stage drought during June 1999 and late-stage drought during June 2002 suggest accounting for effects of FWI over a longer duration than 61 days. Doing so might explain differences in salinity patterns seen in time periods with similar one-week and two-month FWI conditions. Molina [45] calculated an 11 month mean residence time for freshwater in PS. We could incorporate this effect by adding a third freshwater influx index to the mean function or by adding an autoregressive component to the model so that salinity in a given time period was a function of mean salinity in the previous time period. The first option would be tedious from a data-manipulation standpoint, but much easier from a mathematical model-fitting standpoint, because SAS® Proc Mixed could still be used. The second option necessitates a change in the covariance function, as we can no longer assume that salinity deviations from the mean function at a given space-time point were independent in time. This second option would also require specialized hand-written code, as no current SAS® Proc allows such a dynamic space-time model to be fit.

Differences in salinity patterns between June 1999 and June 2002, our two low-to-low FWI time periods, could be attributed to differences in FWI from the Roanoke River, one of the two northern rivers whose connection to PS is indirect. This observation warrants further investigation into the calculation of the FWII indices; namely, an investigation of water-path distance as a possible substitute for crow-flies distance between river gauges and sites in PS. Although we did not find a study that demonstrated marked predictive improvement using water-path distance under all circumstances ([36, 46], and others), it would be interesting in future work to compare differences in PS salinity predictions using both distance methods. Recall that Gardner et al. [34] noted more accurate predictions of stream temperatures when models incorporated water-path distance, but only when this distance was further modified and weighted by stream order. It might be the case that water-path distance out-performs crow-flies distance in predicting estuarine salinity when care is taken to make all explanatory variables as meaningful as possible. Development of an automated procedure for calculating water-path distances similar to the one used in [47] would make such an investigation more practically feasible.

Covariance function. Two mutually-exclusive improvements to the covariance function, as implemented in SAS® Proc Mixed, could be investigated: using either the Matern covariance function or an anisotropic covariance function to achieve greater flexibility in each time period. The Matern covariance function has a smoothing parameter in addition to partial sill and range parameters. When the smoothing parameter takes the value of 0.5, the Matern covariance function is the same as the exponential covariance function—as the smoothness parameter approaches infinity, the covariance function approaches the Gaussian covariance function. Using the Matern covariance function is thus equivalent to allowing a third parameter to determine which two-parameter covariance function is appropriate, as opposed to using the same two-parameter covariance function for every time period. The computational cost of this flexibility is high—in a similar model with only four separate groups of covariance parameters, compared to the 40 groups in this paper—co-author Amy Nail experienced computation time of 2 h (versus a 2 min run time using the two-parameter exponential covariance function here). The added computational burden is due to the complex nature of the Matern covariance function and to the necessity of estimating one additional covariance parameter per time period (for a total of 40 additional parameters).

Another way to achieve flexibility while still specifying a single covariance function for every time period, would be to allow an anisotropic covariance function. Geometric anisotropy allows for different range parameters in different directions. For example, if the water current in PS were flowing directly north-to-south, two points separated by a north-to-south vector might have more similar values of salinity than would two points separated by a west-to-east vector of the same length.

Fortunately, the parameterization of a geometric anisotropic covariance function is such that if anisotropy were unnecessary, the parameters would take values that effectively result in an isotropic covariance function. The cost of this added flexibility is the need to estimate two additional covariance parameters per time period, for a total of 80 additional parameters. Computation time might be less here than for Matern, since anisotropic covariance functional forms are less complex.

4. Conclusions

We created a statistical model combining a process mean function with an exponential spatial covariance function with a nugget to predict salinity in a lagoonal estuary. This model can generate predictions of bottom salinity for Pamlico Sound, NC that are more spatially-resolute than any previous bottom salinity predictions encountered in the literature for this system. The salinity maps produced using the model are useful for researchers to build an intuitive understanding of salinity dynamics under PS conditions covered by these 40 time periods. Salinity predictions can also be used to inform future analyses including, but not limited to, the examination of historical distribution patterns of estuarine species relative to salinity variability and the prediction of salinity changes under various global climate change scenarios.

Acknowledgements

We thank the North Carolina Division of Marine Fisheries and the United States Geological Survey for providing datasets used in this study. We also thank editor A. Manning for helpful comments that improved the manuscript. Funding for this project was provided by the Environmental Defense Fund (Program Manager Pam Baker), North Carolina Coastal Recreational Fishing License Program (Grant No. 2010-H-004), North Carolina Sea Grant (R12-HCE-2) and the National Science Foundation (OCE-1155609) to D. Eggleston. A. Nail was supported as a VIGRE Postdoctoral Fellow by NSF grant DMS 0354189.

Appendix

See **Table A1**.

Name of covariance function	$\mathrm{Cov}\{\boldsymbol{\varepsilon}_{\mathrm{ti}}, \boldsymbol{\varepsilon}_{\mathrm{tj}}\} =$	
	With nugget effect	**Without nugget effect**
Exponential	$\sigma_{n_t}^2 I(d_{ij}=0) + \sigma_t^2 \exp\left(\frac{-d_{ij}}{\theta_t}\right)$	$\sigma_t^2 \exp\left(\frac{-d_{ij}}{\theta_t}\right)$
Gaussian	$\sigma_{n_t}^2 I(d_{ij}=0) + \sigma_t^2 \exp\left(\frac{-d_{ij}^2}{\theta_t^2}\right)$	$\sigma_t^2 \exp\left(\frac{-d_{ij}^2}{\theta_t^2}\right)$
Spherical	$\sigma_{n_t}^2 I(d_{ij}=0) + \sigma_t^2 \left[1 - \left(\frac{3d_{ij}}{2\rho_t}\right) + \left(\frac{d_{ij}^3}{2\rho_t^3}\right)\right] \mathrm{I}(d_{ij} \le \rho_t)$	$\sigma_t^2 \left[1 - \left(\frac{3d_{ij}}{2\rho_t}\right) + \left(\frac{d_{ij}^3}{2\rho_t^3}\right)\right] \mathrm{I}(d_{ij} \le \rho_t)$

Note: For all models, $\sigma_{n_t}^2, \sigma_t^2 > 0$, *and* $\theta_t \ge 0$, $-\infty < \rho < \infty$, *and* d_{ij} *is the distance separating sites i and j.*
Note: I(statement) = 1 if statement is true and 0 otherwise.

Table A1.
Formulas for the three spatial covariance functions used in this analysis.

Author details

Christina L. Durham[1], David B. Eggleston[1]* and Amy J. Nail[2]

1 Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC, United States

2 Department of Statistics, North Carolina State University, Raleigh, NC, United States

*Address all correspondence to: eggleston@ncsu.edu

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Section 4

Bio-processes

Chapter 8

Subtropical Coastal Lagoon from Southern Brazil: Environmental Conditions and Phytobenthic Community Structure

Leticia Donadel and Lezilda Torgan

Abstract

The chapter is about the study of environmental conditions and the structure of the benthic diatoms community in Peixe Lagoon, which is inserted in a National Park in southern Brazil. The study was carried out covering four seasons from 2011 to 2012. The system is shallow (<60 cm) located parallel to the coastline, and it is connected to the ocean through a single channel, which occurs naturally or through human action. In this lagoon, during the study, the water temperature ranged between 15.3 and 32.1°C, and the dissolved oxygen presented higher value in the winter (12.5 mg.L^{-1}) and lower value in the summer (7.5 mg.L^{-1}). The lagoon ranged from mesotrophic to hypereutrophic conditions. The salinity varied between 1.3 and 36.2%, and these variations were mainly related to meteorological conditions. The community of diatoms in Peixe Lagoon is composed by 62 taxa distributed in 30 genera composed largely of marine, brackish, and few freshwater species. Among the attributes of the community, composition better reflects the environmental variations. The opening and closing of the channel, salinity, temperature, and the action and direction of the wind are variables influencing the dynamics of the microphytobenthic community.

Keywords: environmental variables, diatoms, community attributes, microphytobenthos, system dynamic

1. Introduction

The shallow coastal lagoons are low depth water column mixing systems in which phytoplankton and microphytobenthos communities, microscopic eukaryotic photosynthetic algae, and cyanobacteria which live on the seabed [1] play a key role in the primary production and recycling of matter and nutrients. The role of microphytobenthos is quite important where macrophytes are absent and light radiation penetrates down to the bottom [2].

Microphytobenthos are composed of a set of microorganisms distributed in very diversified taxonomic groups, among which the diatoms are an important and often dominant component in estuarine and shallow coastal environments. These algae have varied adaptive strategies for adhesion and migration on different substrates, and there is a very large number of species sensitive to environmental changes.

Traditionally, benthic diatoms are classified according to the substrate in which they live. Those that live on thin sediment are called epipelic and those that live on sandy substrate are called epipsammic [3].

Diatoms studies in coastal lagoon were mainly concentrated in the world's largest water bodies, the Baltic, Black, and Caspian seas, which are ecosystems impacted by the anthropogenic actions and global climate changes. The eutrophication happened due to the increased nitrogen and phosphorus loads during the last century, and the increase in water temperature related to climate was detected by the changes in subfossil diatom assemblages. The accumulation of heavy metals from surrounded waters can be monitored due to the capacity of these algae to accumulate metals attached to the outside of the cell wall. There is an excellent literature review about these and other impacts; see the Snoeijs and Weckström chapter [4]. We can also find excellent information about the composition, spatial distribution of modern diatom assemblages, diversity, production, and ecology of the sediment-inhabiting diatoms in the estuaries [5–11]. In the smaller shallow lagoon from the east coast of Uruguay (South America) the diatoms studies were used to infer the paleosalinity, trophic and climate changes in relation to the sea level variation [12–16].

So far, most studies concentrated on phytoplankton at Patos Lagoon [17–24], Tramandaí-Armazém Lagoon [25–29], and Peixe Lagoon [30–34]. Regarding microphytobenthic, studies were limited to salt marshes and to the Patos Lagoon estuary [35–43].

The knowledge of the diatoms at Peixe Lagoon began with investigations on diatom assemblages in current and fossil sediments that allowed paleoenvironmental reconstruction. It demonstrated that the lagoon behaved as a deeper and more extensive lagoon system connected to the ocean by one or more permanent linking channels during the Holocene [44]. Later, studies were carried out on the taxonomic composition of diatoms in the marginal sediment of the lagoon. One study emphasizes the genus *Diploneis* Ehrenb. ex Cleve, rich in species [45]. Another investigation highlights the occurrence of *Cocconeis sawensis* Al-Handal et Riaux-Gobin, recently described for saline lakes in southern Iraq as an epiphyte in *Chara* sp. Linnaeus (1753: 1156). It was also recorded on an island in the South Pacific and epizoic on manatee in Florida Bay, USA [46]. The other species of the community were described, illustrated, and compiled with information on ecology and distribution in these coastal systems [47].

Studies about phytoplankton in subtropical coastal lagoon from south of Brazil showed that the structure and dynamic of the phytoplanktonic community were regulated by hydrological factors (inflow-outflow of continental and coastal waters in the system) as well as by meteorological conditions (wind and rainfall) and limnological variables (temperature and salinity) [18, 19, 33]. We have a set of factors that can act simultaneously while being difficult to recognize a main factor. Our question is to know if the structure and dynamic of the benthic diatoms in the Peixe Lagoon are related with these same factors. In order to answer this question, the study objectives were: (1) to know the composition of the diatoms community; (2) to verify the community structure and its spatial and temporal variation; and (3) to relate the variations of the community to environmental variables over an annual cycle.

In this chapter, firstly, we present information about the geographic, environmental, and climatic features where the Peixe Lagoon is situated. To be a case study, the methods are also included. Secondly, we describe the physical and chemical conditions of the lagoon and the benthic diatoms composition. Thirdly, we present and discuss the environmental variables related to the composition and spatial and temporal variation of the community attributes. Finally, we review the relationships of organisms occurring in plankton and sediment that should not be overlooked in studies in shallow coastal lagoons.

2. Study area

Peixe Lagoon is the only intermittent lagoon of the extreme south of Brazil and it is situated in the Lagoa do Peixe National Park (31°00′46″ S; 51°09′51″ W and 31°29′00″ S; 50°46′31″ W). This park is recognized by the Ramsar Convention as a Wetlands site, as well as an area of the UNESCO Atlantic Forest Biosphere Reserve, an Important Bird and Biodiversity Area (IBA) and a designated a site of international importance by the Western Hemisphere Shorebird Reserve Network (WHSRN). The coast is characterized by a microtidal regime, with a mean amplitude of 0.45 m [48].

Peixe Lagoon is a shallow, elongated system (35 km long and 1 km wide), parallel to the coastline (**Figure 1**) connected to the Atlantic Ocean through a single narrow channel (chocked lagoon) (**Figure 2**). The channel occlusion occurs due to deposition of sand caused by the predominance of the north and northeast winds [49, 50]. The connection with the ocean usually occurs during winter and spring, when the precipitation becomes more pronounced and the marshes and fields marginal to the lagoon are flooded. During these periods, an artificial opening of the channel is carried out by means of machines, since a natural opening only occurs sporadically [50]. The margins of the lagoon are covered by salt marshes vegetation dominated by *Paspalum vaginatum* Sw., *Cotula coronopifolia* L., *Sporobolus montevidensis* (Arechavaleta) P.M. Peterson & Saarela (= *Spartina densiflora* Brong), *Hydrocotyle bonariensis* Lam., *Androtrichum trigynum* (Spreng.) H. Pfeiff., *Bacopa monnieri* (L.) Wettst., and *Juncus acutus* L. [51]. The surface sediments at the bottom are essentially sandy. On the sites with greater depth of the lagoon, the sediments are thinner, with addition of silt and clay [49].

The system is located in subtropical climate where the rainfall is distributed throughout the year. In the period of studies, the highest rainfall (145.8 mm) occurred at the end of the fall (June 2011), decreasing in the following months and then increasing (131.2 mm) in early spring (October 2011). November had the lowest cumulative precipitation (23.0 mm). The average monthly temperature varied between 12.6 and 18°C in the autumn/winter seasons and between 18.3 and 24.4°C in spring/summer (**Figure 3**).

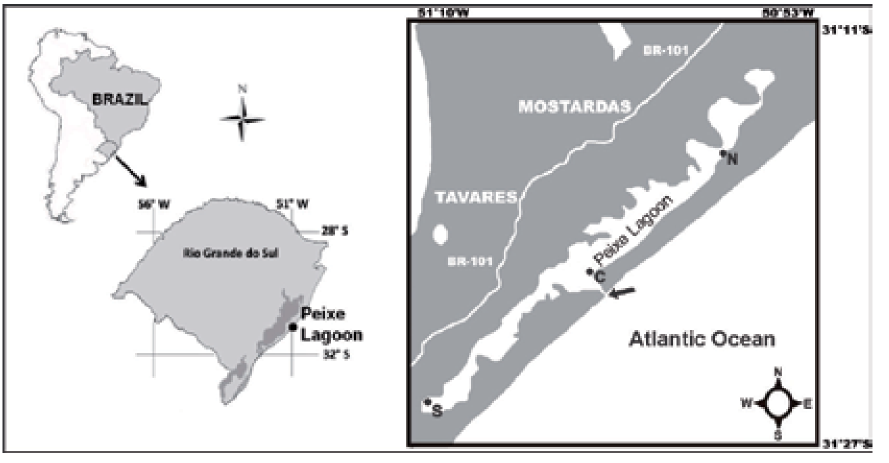

Figure 1.
Location of Peixe Lagoon area in the state of Rio Grande do Sul, southern Brazil, the sampling stations (North = N, Center = C, South = S) and the channel of connection with ocean (arrow).

Figure 2.
Aerial view of the Peixe Lagoon channel. Source: Lagoa do Peixe National Park (PNLP).

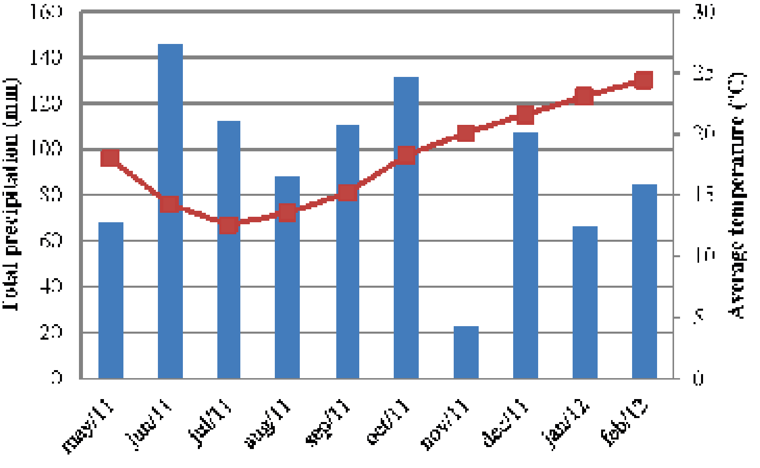

Figure 3.
Total precipitation (mm) and average monthly temperature (°C) recorded by the meteorological station of Mostardas/RS. Source: National Institute of Meteorology (INMET).

3. Methods

3.1 Sampling

The study was based on samples collected at three sampling stations in the lagoon. North (**Figure 4**) is close to a narrow channel that interconnects the northernmost sealed bodies with a central portion of the lagoon; Center (**Figure 5**) is next to the channel that connects to the ocean; and South (**Figure 6**) is at the south end of the lagoon. Sampling occurred in the four seasons, fall (June 2011), winter (August 2011), spring (November 2011), and summer (February 2012). During the first sampling, in the fall, the channel was closed. It was open days before winter sampling and remained open for the remainder of the sampling period. For the diatoms analysis, sediment samples were collected at depths of 2 cm with a spatula, at the lagoon margin, and packed in glass pods for transport to the laboratory.

3.2 Abiotic variable

Conductivity (mS.cm^{-1}), salinity, pH, water temperature (°C), dissolved oxygen—DO (mg.L^{-1}), and oxidation-reduction potential—ORP (mg.L^{-1}) were

Figure 4.
Sampling station: North.

Figure 5.
Sampling station: Center.

Figure 6.
Sampling station: South.

measured with a HORIBA U52 probe. Depth and water transparency (cm) were measured with a Secchi disk. Precipitation, wind velocity, and wind direction data were obtained from the National Institute of Meteorology—INMET.

Laboratory analyses were performed as follows: total phosphorus—TP ($mg.L^{-1}$) by absorptiometry reduction of ascorbic acid, total nitrogen—TN ($mg.L^{-1}$), according to the Kjeldahl method (NBR 10560-1988, 13796-1997), and total silicate ($mg.L^{-1}$) with the silicomolybdate method [52]. The classification of salinity was based on the Venice System [53]. Trophic level was determined by the modified system of Vollenweider [54].

3.3 Diatom analysis

The sediment samples (1g) were dried in an oven and cleaned with potassium permanganate and hydrochloric acid according to the Simonsen technique [55]. For light microscopy (LM) analyzed, a Zeiss Axioplan Microscope (Carl Zeiss, Oberkochen, Germany) was used. The relative abundance of the taxa was carried out in slides seeking the minimum sample efficiency of 80% [56]. Species richness was estimated by the number of taxa present in the samples. The specific diversity was assessed using Shannon index (H′) [57] and Evenness equitability (E). The analysis of variance (ANOVA) was applied to test the significance among the community attributes, since the data presented a normal distribution. The PAST® software was used for these analyzes. The relationship between biotic and abiotic variables with canonical correspondence analysis (CCA), PC-ORD® version 6.08 was used. For the construction of the biotic matrix, only species with a frequency equal to or >5% were considered in at least one sample unit and for the abiotic matrix, 10 environmental variables were included (**Table 1**). The data were transformed into log10(x + 1) in order to normalize the variances [58]. The Monte Carlo permutation test was carried out to verify the significance of the ordination axes.

	Fall			Winter			Spring			Summer		
	N	C	S	N	C	S	N	C	S	N	C	S
Depth	65	25	25	60	20	40	50	30	30	50	25	42
Secchi	65	15	25	40	20	0	60	25	30	30	25	12
Temp	15.5	17.2	[illegible]	17.0	15.6	17.4	28.5	26.1	26.3	29.8	32.1	31.6
pH	7.9	7.6	8.4	7.6	8.0	7.7	7.9	8.2	8.6	8.1	8.5	8.2
ORP	275	282	262	230	201	259	273	205	202	211	198	214
DO	10.1	10.3	12.3	12.3	11.5	12.1	10.7	9.8	9.3	7.6	9.0	9.4
Salin	31.2	28.3	30.8	4.5	17.0	1.5	7.1	26.2	10.0	37.9	36.0	21.5
Cond	[illegible]	39.4	[illegible]	8.1	27.8	2.5	12.1	41.6	18.5	52.0	54.6	43.5
Sil	9.8	[illegible]	1.1	17.0	18.0	17.4	[illegible]	[illegible]	6.6	9.8	[illegible]	[illegible]
PT	0.03	0.07	0.08	0.15	0.12	0.06	0.08	0.13	0.07	0.07	0.05	0.06
NT	0.6	0.16	0.43	0.87	0.68	0.90	0.01	0.09	0.02	0.55	0.65	0.56

Table 1.
Physical and chemical variables analyzed in Peixe Lagoon in the four seasons, from June 2011 to February 2012, in the North (N), Center (C), and South (S) sampling stations. Depth (cm); Secchi = Secchi transparency (cm); temp = temperature (°C); ORP = oxide-reduction potential (mV); cond = conductivity ($mS.cm^{-1}$); DO = dissolved oxygen, salin = salinity (ppt); sil = silica ($mg.L^{-1}$); PT = total phosphorus ($mg.L^{-1}$); NT = total nitrogen ($mg.L^{-1}$).

4. Environmental conditions

The lagoon has a mean depth (<60 cm) and the Secchi disk depth generally coincides with the total depth. The water temperature varies between 15.3 and 17.6°C in the colder seasons (fall and winter) and from 26.1 to 32.1°C in the hottest seasons (spring and summer). The pH varies from 7.6 to 8.8 and the oxidation-reduction potential as well as the dissolved oxygen present similar trends, with higher values in the cold seasons and lower in the hot seasons (**Table 1**).

In relation to nutrients, total phosphorus varies between 0.03 and 0.08 $mg.L^{-1}$ in fall and summer at 0.12–0.15 $mg.L^{-1}$ in winter and spring, from eutrophic to hypereutrophic conditions. Total nitrogen presented higher values (0.68–0.90 $mg.L^{-1}$) in winter (mesoeutrophic conditions), with a decline in spring (0.01–0.09 $mg.L^{-1}$) and elevation in the summer (0.55–0.65 $mg.L^{-1}$), changing to mesotrophic conditions. Silica concentrations are higher in winter sampling (mean of 17.5 $mg.L^{-1}$). When the channel of connection with ocean was open, the total nitrogen concentrations at all stations elevated as well as the total phosphorus in the north and center in winter. This may have been due to the water runoff from the land around the lagoon, used for livestock (**Table 1**).

The salinity demonstrated outstanding spatial and seasonal variations. These variations were mainly related to the meteorological conditions. Spatially, the salinity varies between 1.3% in the South station in the winter (oligohaline zone) and 36.2% in the Center during the summer (euhaline zone). The station with the highest salinity variation is the North (4.5% min./winter and 34.9% max./summer), followed by the South station (1.3% min./winter and 29.5% max./summer). The Center station maintained higher values of salinity in all the climatic seasons due to its proximity with the ocean. Seasonally, salinity has the highest values in summer and the lowest in winter. These low values can be attributed to the action of the wind, predominantly northeast, that propelled the waters from the Ruivo Lake which are less saline, to the Peixe Lagoon [33]. In the summer, the decrease of the precipitation and intensity of the wind causes the outstanding increase of the salinity. This dynamic was also observed in the system from 1991 to 1996 [50]. The South station of the lagoon presents less marine influence, therefore, lower salinity.

The variation of water levels of the lagoon is also strongly controlled by the winds regime, both intensity and direction, as well as precipitation. In the periods of predominant south wind (fall) and low precipitation (spring), the lowest levels of depth were observed. The Center is located next to the connection channel with the ocean and has a low average depth (30 cm). It is constantly saline (poly to euhaline zone). Due to the predominant northeasterly winds for most of the year, the water body of the lagoon is pushed to the west bank. The variation of the intensity of the winds can vary in the periods of day and night, causing great extensions of marginal sediment to be exposed and to be submerged again in a matter of hours [50].

The wind velocity during the period of studies had the lowest averages in the fall. It intensified in the following months of winter, with a peak in August

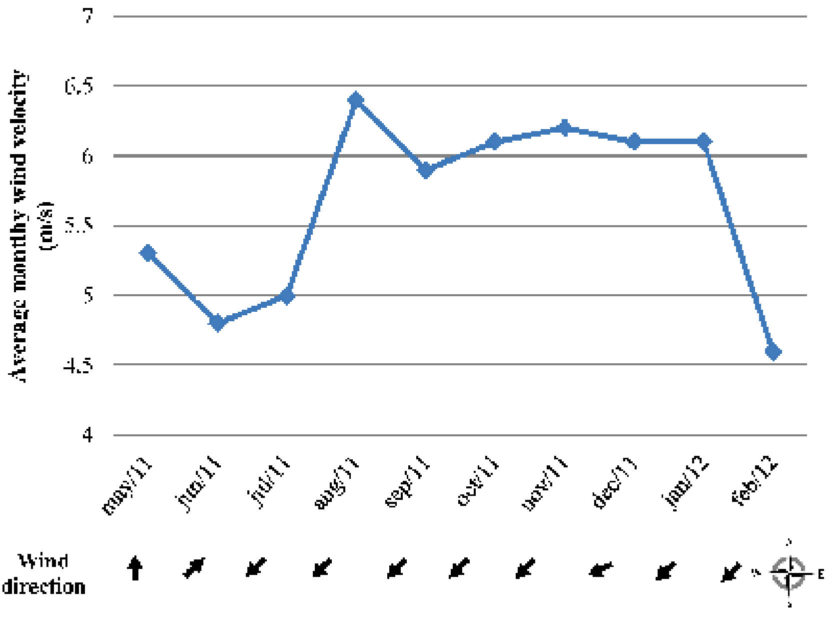

Figure 7.
Average monthly wind velocity (m/s) and predominant monthly wind direction (arrows indicate direction). Data recorded by the Meteorological Station of Mostardas/RS. Source: INMET.

(6.4 m/s). A sharp decrease occurred in February 2012 (4.6 m/s). The predominant direction of the wind in the fall was south and southwest, shifting northeast in July and in the following months (**Figure 7**).

5. Benthic diatoms composition

The diatoms community in Peixe Lagoon is composed by 62 taxa distributed in 30 genera composed largely of marine, brackish, and few freshwater species (**Table 2**). Similar results were recorded in an area adjacent to this study [28], where a total of 73 predominantly benthic and brackish taxa were found.

The genera with the greatest number of taxa are *Amphora* Ehrenberg ex Kützing, *Nitzschia* Hassall, and *Diploneis* Ehrenberg ex Cleve. The freshwater species that probably tolerate the wide variation of salinity are *Amphora ectorii*, *Cocconeis neodiminuta*, *C. euglypta*, *Chamaepinnularia truncate*, *Diploneis aestuari*, *D. didyma*, *Nitzschia palea*, *N. scalpelliformis*, *N. frustulum*, *N. vitrea* var. *salinarum*, and *Planothidium delicatulum*. More than 50% of taxa are cosmopolitan, and the remaining are restricted to a large extent to South America. An aspect to be highlighted is

	FALL			WINTER			SPRING			SUMMER		
TAXA	N	C	S	N	C	S	N	C	S	N	C	S
[illegible]	-	-	X	-	-	-	-	-	-	X	X	X
[illegible]	-	X	-	-	-	-	X	-	-	-	-	-
[illegible]			X				X					
[illegible]	X	X	X	X	X	X	X	X	X	X	X	X
[illegible]	X		X				X		X	X	X	
[illegible]	X			X			X			X	X	
[illegible]	-	-	-	-	-	-	X	-	-	-	-	-
[illegible]	-	-	-	-	-	-	-	-	-	-	X	-
[illegible]			X									
[illegible]	X											
[illegible]										X		
[illegible]		X			X							
[illegible]	-	-	X	-	-	-	-	X	-	-	X	-
[illegible]		X								X		
[illegible]	-	-	X	-	-	X	-	-	X	-	-	-
[illegible]	-	-	X	-	-	X	-	-	-	-	-	-
[illegible]								X			X	
[illegible]								X			X	
[illegible]	-	-	-	-	X	-	-	-	-	-	-	-
[illegible]	X	-	X	X	X	-	-	X	-	-	X	-
[illegible]		X		X	X							
[illegible]	-	-	-	-	X	-	X	-	-	X	-	-
[illegible]	X		X	X			X					
[illegible]	X	-	-	-	-	-	X	-	-	-	-	-
[illegible]	X			X						X		
[illegible]		X	X			X	X		X			X
[illegible]	X			X	X		X	X		X	X	
[illegible]	-	-	-	X	-	-	-	-	-	-	-	-
[illegible]			X			X			X	X		X
[illegible]									X	X	X	X
[illegible]	-	-	-	-	X	-	-	-	-	-	-	-
[illegible]	X	X	X			X				X		
[illegible]	-	-	X	-	-	-	-	-	-	X	-	-
[illegible]	X			X								
[illegible]												X
[illegible]			X	X								
[illegible]	X	-	-	-	-	-	-	-	-	X	X	-
[illegible]		X										
[illegible]		X			X		X			X		
[illegible]	X	-	-	-	-	-	-	-	-	-	-	-
[illegible]		X		X		X	X			X	X	
[illegible]	-	-	-	-	-	-	X	-	X	-	-	-
[illegible]	X			X								
[illegible]	-	-	-	-	-	-	-	-	-	-	-	X
[illegible]	-	-	-	-	-	-	-	-	-	-	-	-
[illegible]	X	-	-	-	-	-	-	-	-	-	-	-
[illegible]			X				X	X		X	X	
[illegible]	-	-	-	-	-	-	-	X	-	-	X	-
[illegible]	X	-	-	X	-	-	-	-	-	X	-	-
[illegible]								X		X	X	
[illegible]	-	X	X	-	X	-	-	-	X	-	-	-
[illegible]			X				X	X				
[illegible]				X			X			X		
[illegible]			X									
[illegible]	X			X								
[illegible]			X									
[illegible]	-	-	X	-	-	X	-	-	-	-	-	-
[illegible]		X			X					X	X	
[illegible]										X		
[illegible]	-	-	X	-	-	-	-	-	-	-	-	-
[illegible]	X			X			X			X		
[illegible]	-	-	-	-	-	X	-	-	-	-	-	-
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 2.
Distribution of the diatoms at the North—N, Center—C, and South—S in the four seasons of the year in Peixe Lagoon, from June 2011 to February 2012.

the predominance of birraphid and monoraphid diatoms, which are organisms that have raphe. This structure is a selective characteristic of the epipelic species [59–63] because it promotes the movement of organisms in search for better light and humidity conditions, since it allows the secretion of polymeric substances produced by their cells.

6. Structure of the community *versus* environmental conditions

6.1 Spatial and temporal variation

The community attributes (richness, diversity, and evenness) showed a decreasing spatial gradient from the North to the South stations. The specific diversity ranged between 2.3 bits/ind. at North and 0.4 bits/ind. at South and the evenness varied between 74 and 20% at North and South stations.

Seasonally, in fall, without connection with the ocean, the community attributes presented the highest values. After the channel opening, the richness was similar in winter and spring, rising in the summer. The values of evenness and diversity increased from winter (0.6–1.7 bits/ind.) to summer (0.8–2.3 bits/ind.) (**Figure 8**). However, these attributes did not differ significantly between the seasons and the station sampling.

6.2 Diatoms composition related to environmental variables

The composition of the diatoms and the physical and chemical variables of the water in the canonical correspondence analysis (**Figure 9**) of the abundant species (25 species with more than 5% abundance) can better demonstrate the community dynamics in the system.

The sampling units of the South station are grouped on the negative side of axis 1. They were related to the lower values of conductivity and salinity. The species associated with this axis were *Cocconeis sawensis*, *Fragilaria eichhornii*, *Cocconeis euglypta*, *Fallacia florinae*, and *Halamphora coffeaeformis*. In this axis, it is also possible to observe the separation of the sampling units from the North, mainly due to the difference in temperature between hot and cold seasons, in fall and winter months. The related species were *Nitzschia scalpelliformis*, *Luticola simplex*, *Ehrenbergia granulosa*, *Rhopalodia runrichiae*, *Diploneis smithii*, and *D. didyma*. The sampling units of the Center station are grouped on the positive side of axis 2, where higher values of salinity and temperature were observed in the hotter seasons, as well as the lower values of silica and ORP. The species *Opephora pacifica*, *Catenula adhaerens*, and *Opephora* aff. *mutabilis* were related to this axis (**Figure 10**).

During the study, we observed periods with higher and lower marine influence, due to the opening of the channel. In fall, the only season in which the channel was closed, the composition of diatom species was distinct in the north and south of the lagoon. The south and south-west quadrant wind might also have been an influence factor for the distinction of community composition.

After the channel opening, it is possible to observe the difference in the composition of the community at the southern portion in relation to the north and center portions of the lagoon. The species highlighted in the south (*Cocconeis sawensis*, *C. euglypta*, *Fallacia florinae*, and *Halamphora coffeaeformis*) are found in brackish and marine waters, with the exception of *C. euglypta*, a characteristic species of freshwater, but it supports high conductivity water [64]. So, the marine influence appeared as one of the main factors affecting spatial diatom composition and spatial distribution in the lagoon.

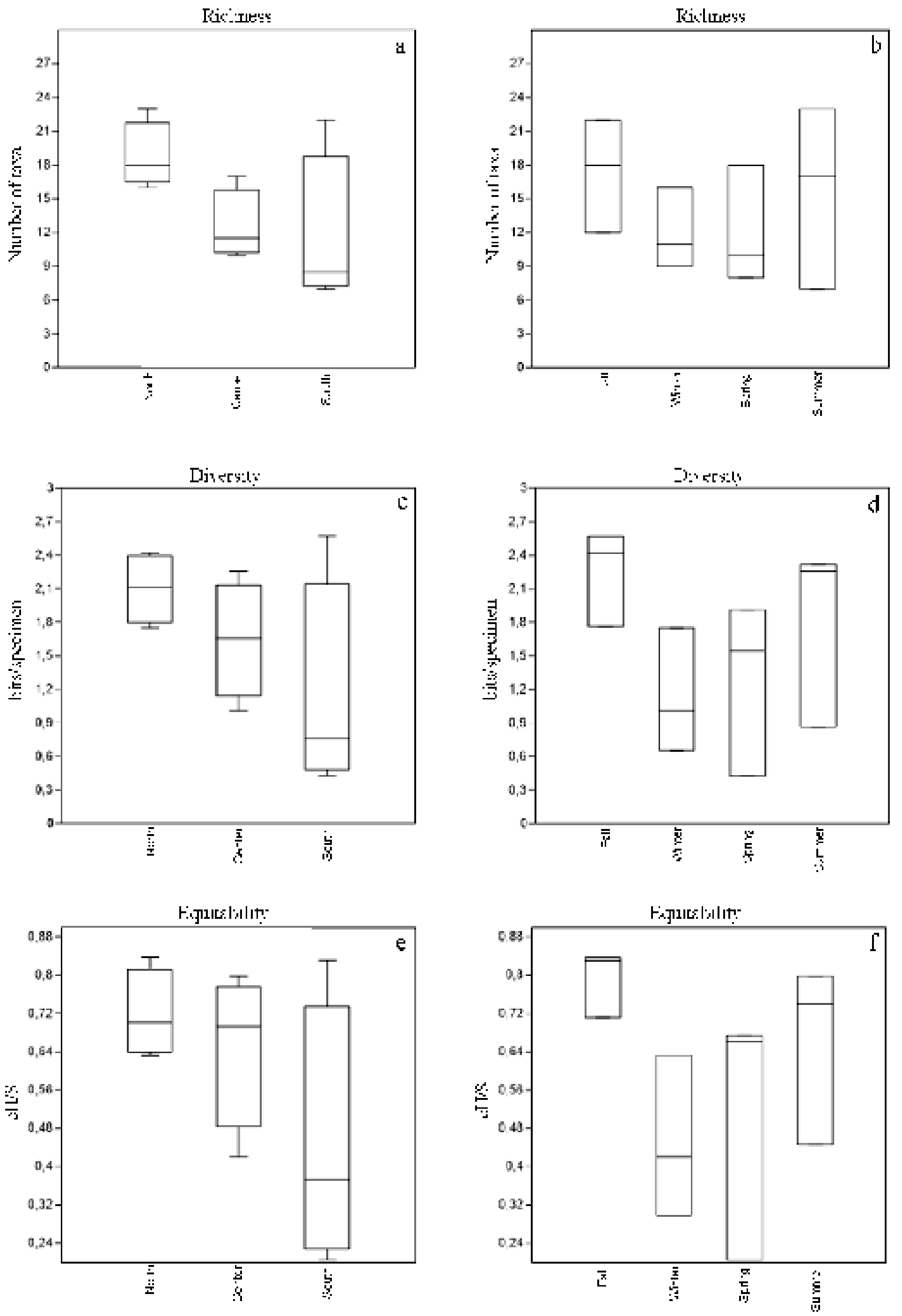

Figure 8.
(a–f) Distribution of community attributes related to sampling stations and the seasons of the year in Peixe Lagoon from June 2011 to February 2012.

However, the salinity cannot be considered as the only driving force that determines the composition of diatom species in environments with marine influence in subtropical and temperate regions. Temperature is also considered a very important environmental factor [11]. In Peixe Lagoon, the temperature difference between hot seasons (spring and summer) and cold seasons (fall and winter) also differentiated

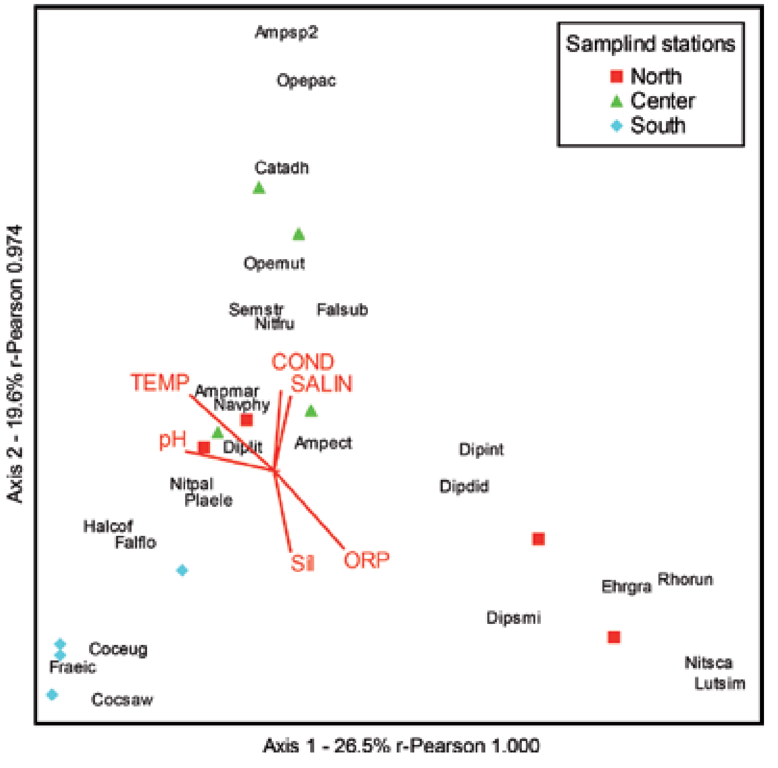

Figure 9.
Canonical correspondence analysis (CCA) of the abundant species in the sampling stations and seasons fall, winter, spring, summer in Peixe Lagoon. For legends of the variables, see **Table 2**. *Amphora ectorii (Ampect), A. maracaiboensis (Ampmar), Amphora sp.2 (Ampsp2), Catenula adhaerens (Catadh), Cocconeis euglypta (Coceug), C. sawensis (Cocsaw), Diploneis didyma (Dipdid), D. interrupta (Dipint), D. litoralis (Diplit), D. smithii (Dipsmi), Ehrenbergia granulosa (Ehrgra), Fallacia florinae (Falflo), F. subforcipata (Falsub), Halamphora coffeaeformis (Halcof), Luticula simplex (Lutsim), Navicula phylleptosomaformis (Navphy), Nitzschia frustulum (Nitfru), N. palea (Nitpal), N. scalpelliformis (Nitsca), Opephora aff. mutabilis (Opemut), O. pacifica (Opepac), Placoneis elegantula (Plaele), Rhopalodia runrichiae (Rhorun), Seminavis strigosa (Semstr), Fragilaria eichhornii (Fraeic).*

the composition of the species. *Diploneis interrupta*, *D. didyma*, *D. smithii*, *N. scalpelliformis*, and *Luticola simplex* were related to the colder seasons. This was also observed for species of *Diploneis* in the sediment of sublittoral zone of the Gulf of Trieste [65]. *Catenula adhaerens*, *Nitzschia frustulum*, *Opephora aff. mutabilis*, *O. pacifica*, and *Seminavis strigosa* were related to the sampling units with higher temperatures and salinities.

6.3 Diatoms related to sediment

Another important factor regarding diatom distribution is the sediment characteristic [66, 67]. In the Center and South stations, the surface of the Peixe Lagoon is essentially covered by sandy sediments, in which we find *Campylosira cymbelliformis*, *Catenula adhaerens*, *Dimeregramma minus*, and *Staurophora soodensis* species usually associated with sand grains.

In deeper sites of the lagoon, such as near the North, the sediments are thinner, with addition of silt and clay [49]. In this station, where muddy sand is present, we observed more clearly the seasonal variation of the diatom community. This site also showed highest diversity (1.7–2.4 bits/ind.) and richness (16–26 táxons) and the presence of more exclusive epipelic species; among these are the following: *Caloneis permagna*, *Luticola simplex*, *Nitzschia dissipatoides*, *N. scapelliformis*,

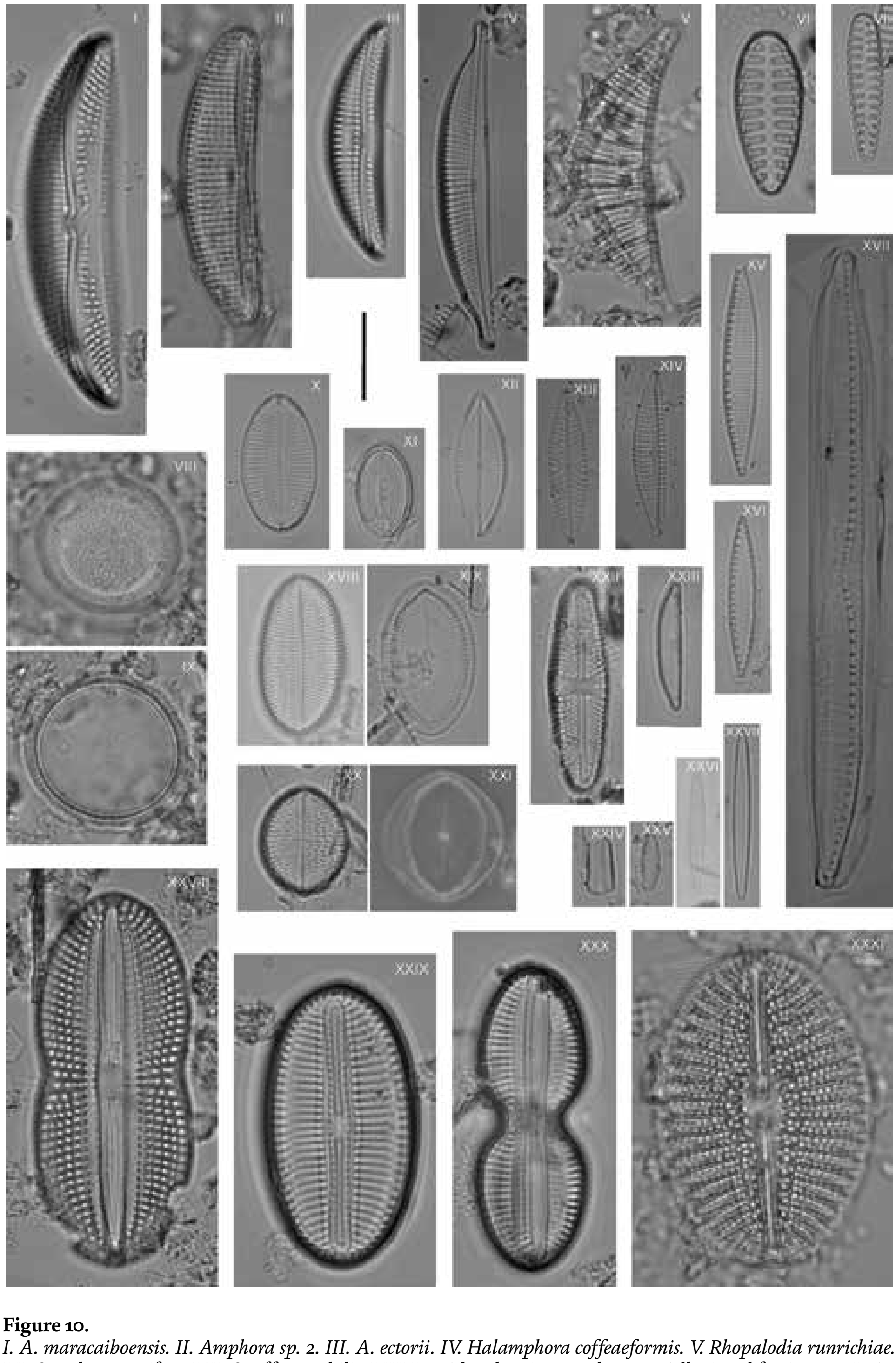

Figure 10.
I. A. maracaiboensis. II. Amphora sp. 2. III. A. ectorii. IV. Halamphora coffeaeformis. V. Rhopalodia runrichiae. VI. Opephora pacifica. VII. O. aff. mutabilis. VIII,IX. Erhembergia granulosa. X. Fallacia subforcipata. XI. F. florinae. XII. Placoneis elegantula. XIII. Navicula phylleptosomaformis. XIV. Seminavis strigosa. XV. Nitzschia frustulum. XVI. N. palea. XVII. N. scalpelliformis. XVIII,XIX. Cocconeis euglypta. XX,XXI. C. sawensis. XXII. Luticola simplex. XXIII. Catenula adhaerens. XXIV-XXVII. Fragilaria eichhornii. XXVIII. Diploneis didyma. XXIX. D. litoralis var. clathrata. XXX. D. interrupta. XXXI. D. smithii. Scale bar = 10 μm.

N. vitrea var. *salinarum*, *Rhopalodia runrichiae*, and *Terpsinöe americana* (**Table 2**). In agreement with other studies, the epipsammic fraction appeared to be much more stable than epipelic assemblage [9, 67].

7. Sediment and water interaction

We expected to find planktonic forms in the sediment due to the low depth of the lagoon and because of the fact that the sediment usually integrates planktonic and periphytic taxa [3]. The absence of planktonic forms could be explained by the hydrographic processes that tend to transport nonliving, unattached forms out of the system, similar to estuaries [67]. Furthermore, the location of the sampling stations, since the material was collected on the lagoon margin, was outside the water surface. However, it is known that in periods with decreasing wind intensity, water tend to return flooding areas that had been exposed [50]. A few planktonic species in the sediment were also recorded in a study of microphytobenthos in the Gulf of Trieste, Europe, although the collections were made in submerged sediment [65].

Comparing with an earlier study about phytoplankton at Peixe Lagoon, with sampling performed during the same period, *Asterionellopsis glacialis* (Castracane) Round, *Chaetoceros gracillis* Pantocsek, and *Skeletonema potamos* (Weber) Hasle were found in abundance in plankton samples. In this study, however, these species were not found in the sediment; whereas *Diploneis didyma*, a highlighted species found in benthos, was also present in the plankton. The species *Cocconeis sawensis* was recorded at the southern benthos of the lagoon, and it was also observed in the plankton and epiphyton in association with the macroalgae *Cladophora* sp. in the fall and winter seasons [33, 46]. This suggests that in shallow environments, the plankton receives a greater contribution of benthic species than the opposite. Similar results were found in shallow estuarine zone of Patos Lagoon [19].

Estuary and shallow coastal waters develop the process of resuspension whereby sediment particles with diatoms enter the water column. Examination of diatoms in the water revealed that 75% of frustules belonged to pennate forms and we concluded that flooding tides were responsible for a net transport of epipelic diatoms from the mudflat to a salt marsh. The resuspension of the diatoms can be the source of the chl *a* peak in the plankton [68]. So, this organism may greatly augment the primary production in water [69, 70]. Other investigations have showed large number of benthic diatoms in the water column [71, 72]. The wind, flooding tides, and tidal inducing waves and currents are the causes of this process.

8. Conclusions

In the Peixe Lagoon, the benthic diatoms were present in high diversity. Among the attributes of the community, the taxonomic composition best responded to the environmental variables. The quantitative attributes did not show significant relationships. The connection with the ocean, salinity, rainfall, wind action, and temperature were strongly related to the spatial and seasonal variation of the composition of the diatom community in this lagoon system. These organisms substantiate their use as indicators of environmental variations, mainly regarding salinity and temperature in subtropical coastal systems.

Acknowledgements

We thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico-Programa de Capacitação em Taxonomia (CNPq-PROTAX) for the financial support and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for a doctoral grant to the first author and to CNPq for Productivity Grant to the second author. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001.

Author details

Leticia Donadel* and Lezilda Torgan
Postgraduate Program in Botany, Department of Botany, Federal University of Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil

*Address all correspondence to: leticiadonadel@yahoo.com.br

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Chapter 9

Lagoons Reefs of Alacranes Reef and Chinchorro Bank: Ocean Reef of Mexican Atlantic

Daniel Torruco, M. Alicia González-Solis and Ángel Daniel Torruco González

Abstract

Coral reef lagoons are one of the parts of the reef with the largest biotopes, making it an area with great inequalities. Under this perspective we try to compare the lagoons of the biggest ocean reefs in Mexico, which despite belonging to the Mexican Atlantic depend on two different systems: Alacranes Reef of the Gulf of Mexico and Banco Chinchorro of the Mexican Caribbean. From the results the proportion of living substrate is higher were obtained in Banco Chinchorro; however, the richness of species and diversity is greater in Alacranes (58 versus 39 species and 4.44 versus 4.38 bits/ind., respectively). *Lobophora variegata* (algae) is the only species whose dominance was proportionately consistent in both reefs; the similarity of sites identifies specific zones of the lagoons in both reefs, in the space the species are distributed close to the center of the axes, but many remain solitary or assembled in pairs. Despite the differences between the reefs according to the community descriptors, the location of the sites and their position in relation to the wind are relevant to the understanding of the dynamics of the lagoons.

Keywords: lagoon reefs, macroalgae, invertebrate coral reef, Atlantic reef, natural protected areas

1. Introduction

Coral reefs are one of the most diverse communities on the planet and the most diverse in the marine environment; they occupy less than 1% of the bottom of the ocean but are inhabited by 25% of all the marine species currently present [1]. In the Caribbean, coral reefs emerged about 27–30 million years ago in the mid-Oligocene, reaching outstanding development during the Miocene and part of the Pliocene (23–2.5 million years) due to the enrichment of species from the Pacific Ocean to the closure of the Isthmus of Panama [2], which confers it to be one of the oldest environments of the Earth [3].

It is built by living beings of the Scleractinia group that are the main builders and that rise from the bottom to the surface and that by its dimensions and physical structure, influence the environment. Its inhabitants are very diverse and have specific adaptations to each part of this system; therefore, the system has high sensitivity to external agents and an enormous complexity. They are systems located between the tropics, with high temperatures of 18–28°C, surrounded by clear oligotrophic waters, with high oxygenation, and a salinity of 35 parts per thousand [4].

In addition to the high diversity in which these ecosystems live and develop, they are very productive marine communities. They play a critical role as habitat and protection areas of approximately 10–20% of the world's fisheries [5, 6].This great system consists of sections that confer zoning. These sections can or will not be presented according to the type of reef in question, providing a distinctive and unique trait to each one. In our case, we will focus on the description of one of these sections, the reef lagoon, and we will do this by confronting the two largest reefs in Mexico, Alacranes Reef and Chinchorro Bank, both of them belong to the Atlantic Ocean, but their structures, characteristics, and components are different.

Both reefs have been studied under different aspects ranging from shipwrecks, [5] ecology [6, 7], biology [8], sociology [9], and paleontology [10], which gives us an idea of the importance of these ocean reefs to the country in relation to the exploitation of its natural resources, conservation, and even its importance in the delimitation of the territorial sea and consequently its sovereignty.

One of the fade questions, however, was: are these reefs subject to the same ecological-environmental pressures and controllers even though they belong to two different ocean systems? To get closer to this response, we try to put the reader in context by making a wide description of each reef highlighting its ecological, fishing, and tourist importance, showing the results obtained through two sampling periods in the lagoon in particular and discussing them in relation to the southern, central, and northern areas of each of them, the leeward and windward zones and above all their membership in one or another ocean system.

One of the objectives of this research is to determine whether there are differences in the processes that occur in a given area of the reef, and this will lead to different ideas about whether it is possible to propose conservation and management plan differentials; different surveillance efforts, in the case of protected areas; differences in the natural resources exploitation, etc. That is the importance of this study. In the biological-ecological sense, there are also a number of objectives such as identifying the most important species in the structure of the lagoon community, knowing the dominant species in each area, and determining whether there is a substitution of species in each time period and above all knowing how stability is in the broader sense of this area of the reefs, recognizing that corals can be under such pressure that they can suffer disease and even death when the ambient conditions change rapidly without giving time to acclimatization. Around the world there is concern about coral reef conditions, especially because of the multiple problems they face such as coastal development and alterations by human influence that lead to a higher rate than estimated. Solutions to this problem can only be given through a vigorous drive for scientific research, particularly ecological and necessarily multidisciplinary that proposes informed procedures with firm scientific foundations. Fortunately, there are national and international efforts to preserve the health of reefs by restraining their arguments and procedures in scientific discoveries; we are sure that our contribution will serve as a further support to the efforts of conservation of these reefs.

2. Material and methods

In this section we will present the study areas, the general characteristics of each reef, as well as the methodology used to obtain the data and the subsequent numerical analysis.

2.1 Study area

Both reefs are oceanic and the largest in Mexico and are marine protected areas: Alacranes reef with the National Park status and Chinchorro Bank as a biosphere reserve.

The physiographic reef structure makes it possible to recognize two sections, windward and leeward, and at least four main areas, South Lagoon, Central Lagoon, North Lagoon, and reef crest that border each reef.

2.1.1 Alacranes reef

Their geographical location is 22°23′N, 89°41′W, and 135 km off coast of Port Progreso on the Yucatan Shelf. This reef is the largest and most complex of the series of reef lying along the edge of the Campeche Sound. The reef has the form of the atoll with northwest trend, due in part by winds and strong westerly currents. Its sub-oval pattern of outer reefs encloses shallow lagoon, and relationship to the Campeche Sound characterizes it as a shallow lagoon shelf atoll [11, 12]. The surrounding waters are 52 m deep. The lagoon reef maximum depth is 20 m in the north. We recognize a semicircular well-developed windward reef on the eastern side and leeward margin less sharply defined belt of reef growth. The windward reef forms a continuous barrier along the north, east, and southeast. The leeward side is characterized by small patch reefs and submerged sandbars. The lagoon is filled with microatolls giving a reticular pattern. There are five sand cays on the leeward rim of the reef: Bird or White Island, Isla Chica, Pérez Island, Dead Island, or Deserter and Banished Island. The total area recorded for the five islands is 530.407 m^2, representing 1.7% of the area [13]. By virtue of the intense dynamics of the islands, their shape and dimensions can vary from the order of meters or tens of meters in short periods of time [11]. All cays are very low with maximum height of 3–4 m. A *Thalassia testudinum* seagrass bed and other algae are frequent in the lagoon reef. The cays are important site for nesting seabirds and nesting green turtles. Sharks are abundant in shallow waters; the management program [5] reported 116 bird species, 136 fishes, 24 species of shark, and 34 coral species. The reef is currently visited by fishermen who collect queen conch and other shells. Lobsters and grouper are also taken, mainly by skin diving and spear gun. The tourism is more and more frequent. The area has frequent climatological disturbance (winds of the north and hurricanes). The area has a forbidden period for the conch and lobster for the Fish Secretary decree.

2.1.2 Chinchorro Bank

Their geographical location is 18°47′–18°23′N, 87°14′–87°27′W, and 24 km off coast of southeastern Quintana Roo, México, between Xcalak and the Ubero and about 100 km north from Turneffe Island in Belize. This reef is part of the Great Atlantic Reef Belt (second world barrier). Chinchorro has an area of 53.379 ha. It is a kidney-shaped prominence and is separated from the mainland by a 1000-m-deep channel [14]. The current is very strong (often over two knots). There are four cays: Cayo Norte (two mangrove-covered islands with an area of 2645.2 ha, destined for the protection of the reef); Cayo Centro, the largest, is a mangrove island with few little inner lagoons with an area of 1263.76 ha, comprises the entire cay and adjacent waters; and Cayo Sur (or Lobos), the smallest (300 m long), is a sandy bank, the only close to the windward margin of the atoll, with 678.53 ha, destined mainly to the protection of the elkhorn corals; all the cays represent 5.82% of the total area of the reserve [15]. The reef has an area of 1443.6 km^2; lagoon reef maximum depth is

21 m in the south, 3–4 m near Cayo Centro, and 2 m in the north. A *Thalassia testudinum* seagrass bed and garden eels, sometimes at high densities, are found in the reef lagoon. The reef lagoon extends for several tens of kilometers west of the bank and is extremely productive [13]. Under its waters the first thing we identify are sponges, fans and sea whips, and isolated colonies of stony corals and a huge diversity of multicolored reef fishes or small fish that are by hundreds hidden under the rocky cavities of where they come out and create a lively silver spot. However, the diversity and abundance of someone groups (e.g., the management program [14] reports 95 species of Cnidaria, 35 sponges, 96 birds, 11 reptilian, 135 algae, and 104 species of mollusk), the main fauna inhabiting this tropical ecosystem is practically unknown (cichlid, crocodiles, etc.). Some of this species have never been described; maybe others are relict species, and others are a complex of subspecies interacting biologically and ecologically between them. Aggregation of the queen conch (*Strombus gigas*) and spiny lobsters (*Panulirus argus*) and abundance of large fish are frequent; turtles probably occur too. Cayo Centro is an important breeding site for frigate birds (*Fregata magnificens*) and olivaceous cormorant (*Phalacrocorax olivaceous)*. The area is fished for queen conch (*Strombus gigas*) and lobster (*Panulirus argus*) by fishermen from Xcalac and Chetumal; there are three fishery cooperatives with 60–70 elements each one; the current disturbance for fishing is probably small, because of a forbidden period for the Fishery Secretary decree [14]. There are two lighthouses and many wrecks. The reef is gradually becoming popular with scuba divers who make 4- to 5-day trips from Cancún, Cozumel, and Quintana Roo coasts. The area has frequent climatological disturbance (winds of the north and south and hurricanes) (**Figure 1**).

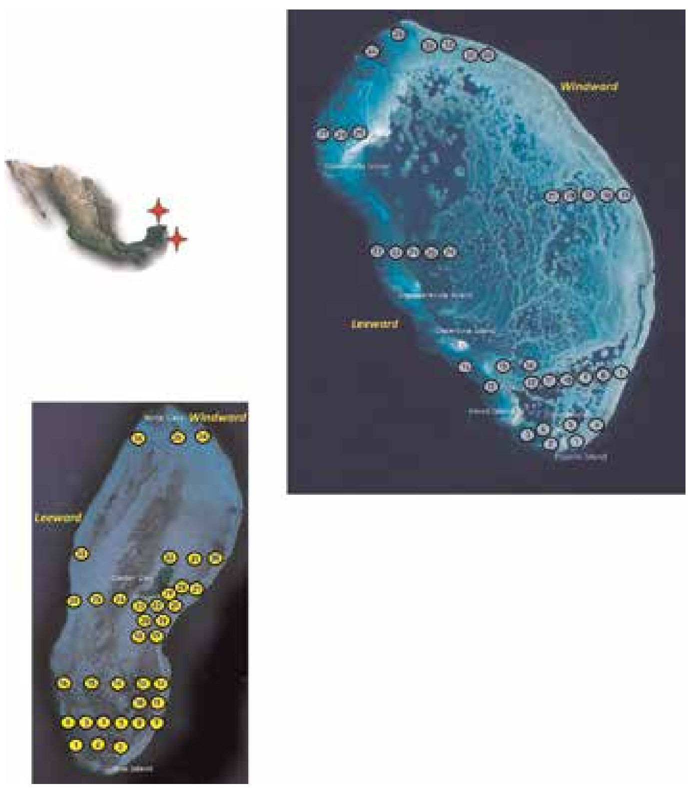

Figure 1.
Sampling sites in both oceanic reefs.

2.2 Methods

2.2.1 Sampling

The sampling was developed in two periods with a 2-year interval (2015–2017), for each reef. Each reef complex was divided into three main areas: north, central, and south. We established 35 sites for Alacranes reef and 36 stations for Chinchorro Bank, positioned with GPS (Garmín inReach Explorer+). The stations were distributed in the following ways: 16 sites in the southern zone of both reefs; 10 and 17 for Alacranes and Chinchorro, respectively, in the central zone and 9 and 3 for Alacranes and Chinchorro, respectively, in the north zone. The differences between the south and central areas with the northern area were mainly the difficulty and risks of navigating the low sand and shallow depths.

Two 20-m-long randomized photographic transects [16] for each site, transect consisted of 20 photographs that covered each one an area of (56 × 34 cm) 1904 cm^2, were used [17]. The photographs were taken with a Nikonos V camera, and the total number of photographs analyzed was 2802 (533.5 m^2); 38 photographs were disposed by out of focus. To obtain the coverage of the species, each photograph was superimposed on a grid with 10 cm^2 divisions for the coverage calculation. In parallel with the photographic transects, a selective collection of species was carried out for their precise identification in the laboratory and to serve as a basis for photointerpretations. The bibliography used depended on the phylum [18–23].

2.2.2 Data analysis

The coralline coverage data matrix for each reef was used in different numerical analyses. A single matrix was formed by reef, where the most common community parameters were determined in the sites, with the purpose of obtaining a robust quantitative descriptive synthesis: the dominance was determined by the index of the importance value [24]; its formula is as follows:

$$IVI = A\% + F\% \tag{1}$$

where A—relative abundance, F—relative frequency

and biological diversity was quantified with the Shannon-Wiener index [25] whose expression is

$$H' = -\sum_{i=1}^{S} p_i \log p_i \tag{2}$$

where p_i is the proportion of the abundance of the species ***i***.

The sites were classified with the Bray-Curtis similarity index, using the flexible union criterion with a β = 0.25 [26]; the coefficient has the following equation:

$$d_{i,k} = \frac{\sum_{i=1}^{Z} \left|X_{i,j} - X_{i,k}\right|}{\sum_{i=1}^{Z} \left(X_{i,j} - X_{i,k}\right)} \tag{3}$$

where j, k—objects ***j*** and ***k*** that are evaluated, ***i*—i**-ésimo descriptor, Z—number of descriptors, $d_{j,k}$—affinity value determined as geometric distance, $X_{i,J}$—descriptor value ***i*** in the entity ***j***.

A main coordinate analysis was used for spatial distribution of the species [27].

3. Results

3.1 Biodiversity

Biodiversity is a characteristic of nature and a property of living beings. It is a highly complex and nonlinear system, which is produced from a complex dynamic of interactions between living beings and their nonliving supports (physical, chemicals, etc.) through different contexts of time, geography, and cultures. The reef system is among the most biodiverse, equated with the tropical rain forest and linked to the ecological services provided by this interaction that finally integrates the environment and reflects the sensitivity of these services with concerning the depletion and disappearance of resources, communities, and populations. In this case we present the results obtained when investigating two lagoons of Atlantic Ocean reefs.

In both reefs the nonliving substrate generally has a higher percentage (**Figure 2**); however, in some places living coverage exceeds the substrate. On the other hand, on the Alacranes reef, only three sites are given this situation also in the southern part (**Figure 2A**). Some areas of the Chinchorro Bank, especially the southern part, show greater coverage than inert substrate (**Figure 2B**). Generally, the tendency for Alacranes reef is a decrease in living coverage from the south to the north, and consequently an increase of the substrate does not live in that

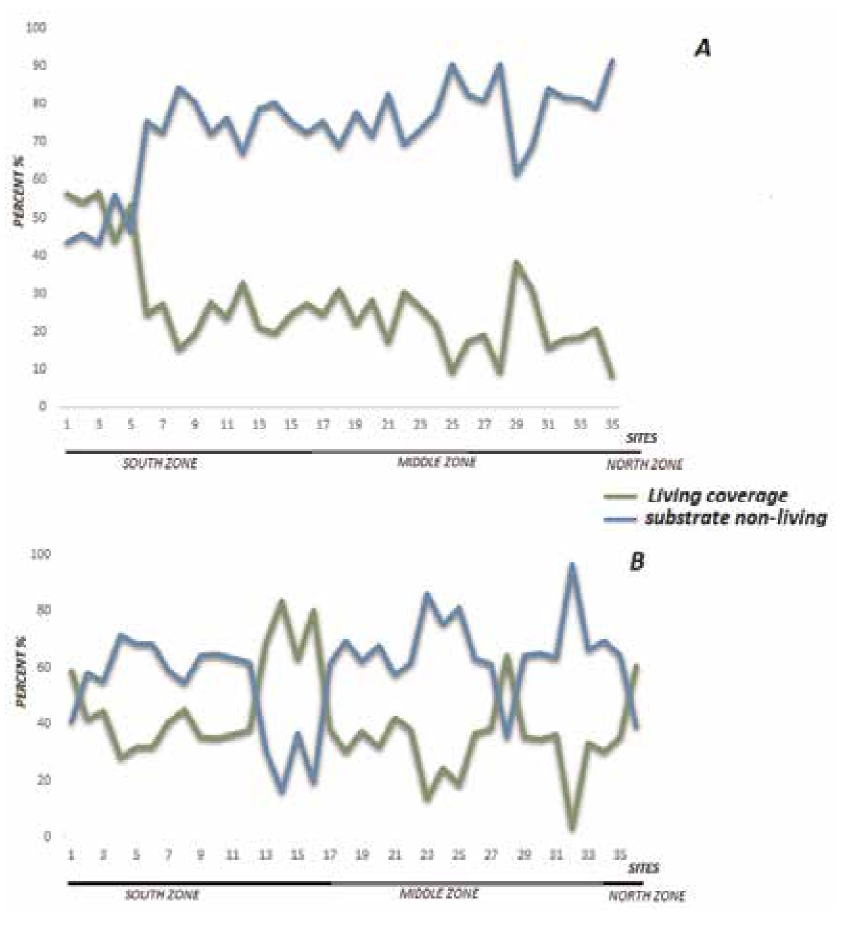

Figure 2.
Live coverage and inert substrate percentages in the reef lagoons. (A) Alacranes reef, (B) Chinchorro Bank.

direction. Chinchorro Bank shows a similar tendency to Alacranes, where there is a descent from the south to the north, only that the trend slope is lower. The living substrate increases also from the south to the north with a similar slope.

In relation to the organisms collected in the reef lagoons, three phyla with 70 species were registered, the disposition of the groups in each reef is presented in **Table 1**, and in the annex the presence of the species in each lagoon is recorded.

Even though some species are presented in both reefs, the dominance percentage of the five most representative species is shown in **Figure 3**; they show that the dominance percentage of *Orbicella annularis* for Chinchorro Bank is higher and that for Alacranes reef decreases until the fourth place. On the other hand, the alga *Lobophora variegata* is presented in the second place in Chinchorro Bank but rises to the first in Alacranes reef; however, the dominance percentage is similar.

The richness of species is lower in Chinchorro, since the sites that present the greatest richness reach only seven species, while in Alacranes most sites are between 15 and 20, reaching in the southern area up to 40 species (**Figure 4A, D**). Diversity in Chinchorro Bank goes from 0 (one species) to 2.4 bits/ind., while in the Alacranes reef, it goes from 1 to 4.3 bits/ind. (**Figure 4B, E**). Equitability has similar behavior to diversity in both reefs, reaching 0.9 as its maximum value (**Figure 4C, E**).

Table 2 seeks to gather the general information of the two ocean reefs, their origin, presenting the totals in terms of their size, as well as the parameters of total diversity that are presented in both lagoons.

Groups	Alacranes reef	Chinchorro Bank
Algae	11	8
Sponges	18	4
Hydrozoa	2	2
Hard corals	18	16
Soft corals	9	9
Total	58	39

Table 1.
Species number per group registered in Alacranes reef and Chinchorro Bank lagoons.

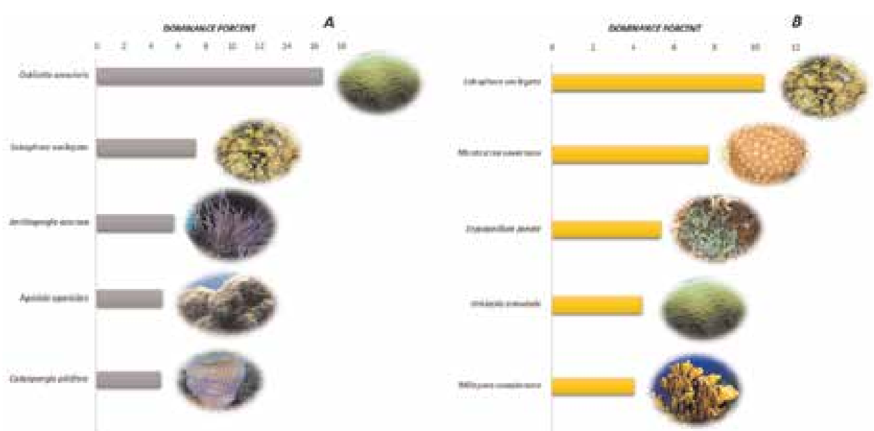

Figure 3.
The five species with the highest percentage of dominance. (A) Alacranes reef, (B) Chinchorro Bank lagoons.

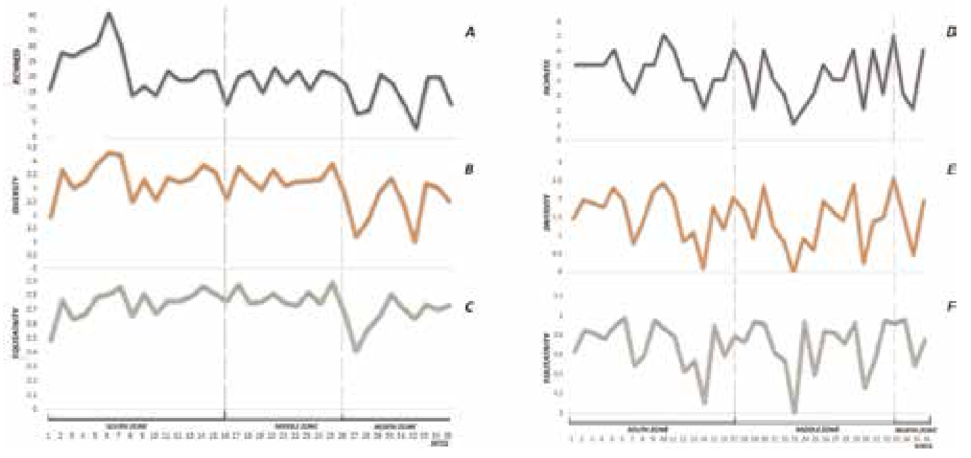

Figure 4.
Richness (A, D), diversity (B, E), and equitability (C, F) in the lagoons of Alacranes (ABC) and Chinchorro (D,E,F) reefs. The three areas are south, central, and north.

Attribute	Alacranes reef	Chinchorro Bank
Origin	Pleistocene-Cretaceous	Cenozoic: Pliocene-Pleistocene
Area (km^2)	300	1443.6
Islands	5	4
Island area [km^2]	0.53	5.82
Insular percentage	1.7	0.40
Lagoon area [km^2]	299.755	533.79
Surrounding water depth (m)	52 m	+500 m
S (species no.)	58	39
H′ (bits/ind.)	4.44	4.38
H'_{max} (bits/ind.)	5.85	5.25
H'_{min} (bits/ind.)	0.127	0.308
J′	0.759	0.834

Table 2.
Alacranes reef and Chinchorro Bank characteristics.

3.2 Site affinity

The similarity given by the Bray-Curtis index, of the Alacranes Reef, forms seven groupings: The first is formed by two sites in the northern area. The second clusters more sites (11), which are distributed throughout the reef; however, at lower levels, sites of the same area or at least contiguous areas such as stations 8, 12, and 18 are associated. The third group joins two stations: one from the central zone and the other from the north.

The four clusters include five stations that although they identify some area, some site of another area is joined as is the case of sites 19, 20, 21, and 23, elements of the central zone to which site 28 of the north zone is joined. The fifth group relates eight sites, showing an association that completely identifies the area in the south. The sixth cluster has five sites, most of them from the south zone and only one from the north zone (site 29). The seventh group has only two sites: one of the south zone and one of the north (**Figure 5A**).

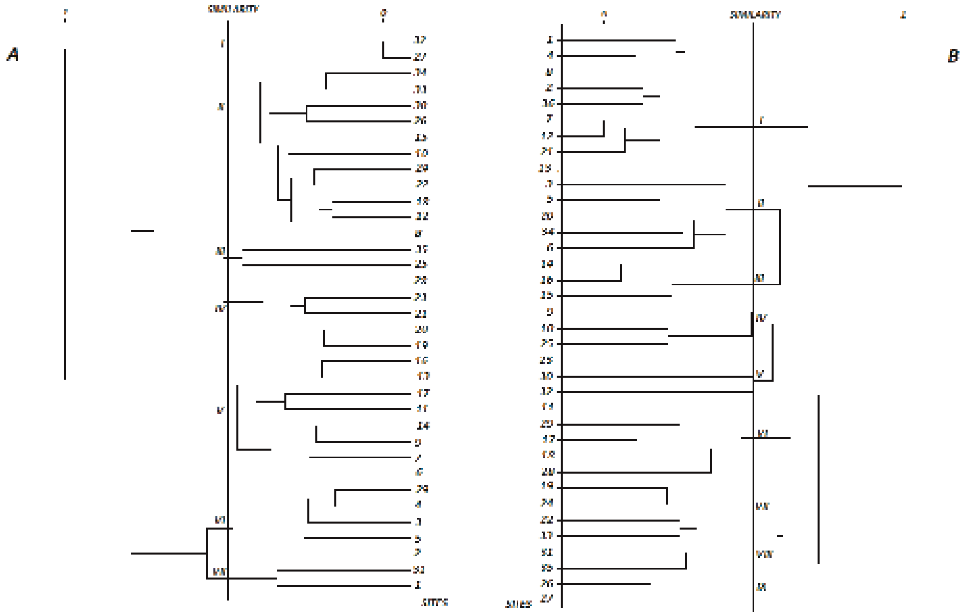

Figure 5.
Sites similarity given by the Bray-Curtis index. (A) Alacranes reef, (B) Chinchorro Bank lagoons.

The Chinchorro Bank sampling sites form nine groups at a level of 50%. The largest of them includes eight stations, of which six belong to the south zone, one to the central part on windward, and one of the north zone in leeward. Group II gathers five sites of which three are in the south zone, one in the central part on windward, and one in the north area in leeward. The third cluster is exclusive to the southern zone. Cluster IV is made up of two sites in the south windward area and one in the center of the central area. Group V has three exclusive sites in the middle area, two of them close to the island of Cayo Centro and one of them on the windward edge. The sixth cluster has five stations, almost all of them from the middle area, except for a site located in the south area. Group VII has four locations, close to each other in the central area except for one of them located in the leeward area. The eighth cluster is formed by two stations in the central zone and the other in the north. The last group consists of two sites in the central area, one on the windward edge and the other in the leeward (**Figure 5B**).

3.3 Spatial species distribution

In relation to the spatial distribution of species of Alacranes reef, there were 58 species (flora and fauna) that also form, most of them, a large conglomerate close to the three axes of coordinates. There were paired associations as in the case of *Amphimedon compressa* with *Stephanocoenia intersepta*, *Siderastrea siderea*, and *Millepora alcicornis*, among others; *Antillogorgia bipinnata*, *Porites astreoides*, *Agaricia agaricites*, *Dictyota* sp., *Acanthophora spicifera*, and *Isophyllia sinuosa* move away from any grouping (**Figure 6A**).

In Chinchorro Bank, it has to be generally presented that for 39 species most of them cluster at the origin of the three axes, forming a large group. The species *Halimeda incrassata* and *Lobophora variegata* show a very close relationship, while the species *Callyspongia plicifera*, *Antillogorgia acerosa*, *Agaricia agaricites*, *Orbicella annularis*, *Eunicea mammosa*, *Eunicea flexuosa*, and *Gorgonia flabellum* are out of any conglomerate (**Figure 6B**).

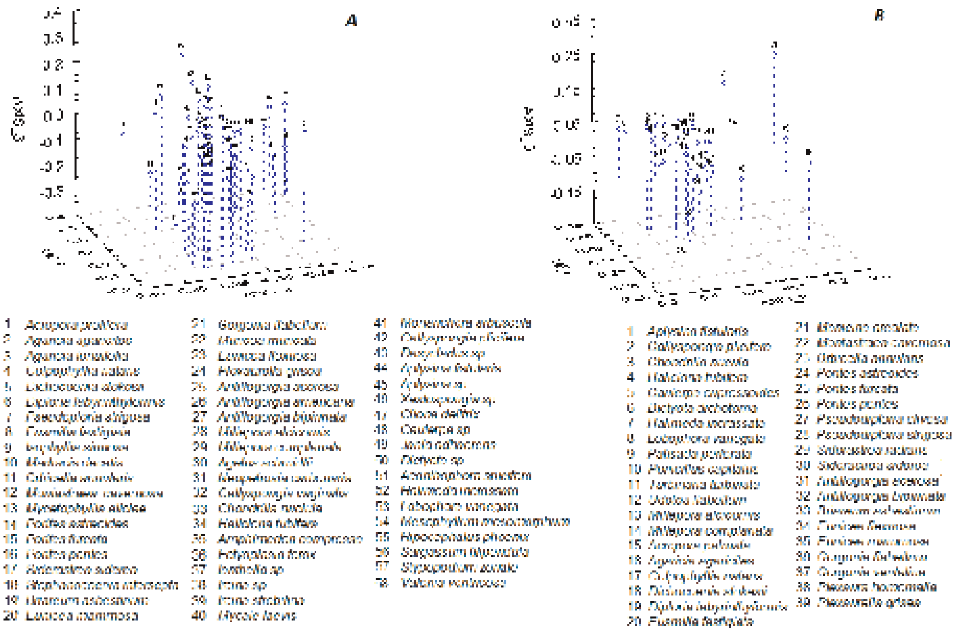

Figure 6.
Spatial ordination of the species found in the reef lagoons. (A) Alacranes reef, (B) Chinchorro Bank.

4. Discussion

4.1 Biodiversity

The marine benthic communities have been evaluated from different points of view, which respond to their distribution, interests, or incidental events. The most common assessments are those focused on establishing the community structure and distribution patterns of temperate and boreal zones [28, 29], while in the tropical coastal zone are the evaluations focused on determining the response of these communities to changes caused by seasonal fluctuations and/or physico-chemical or structural modifications of the environment, by natural or anthropogenic sources [30–32]. Precisely, an indicator related to environmental services is biodiversity. It is essential to know the ecological characteristics of reefs and coralline communities, because it allows to identify the stability of these ecosystems as well as the manifestations that these present in the face of natural and anthropogenic disturbances. The most obvious indication of the effect of natural and anthropogenic disturbances on coral systems is the death of corals. However, if the damage is not massive, sometimes there is a change of species, in which other types of coral species or various organisms in the bottom, such as carbonated or fleshy algae, arrive and occupy the position of the species that originally resided in the site, causing the so-called phase change [33, 34]. Consequently, the functions of the system are affected, since the corals that arrive are not always so efficient to produce carbonate, to generate sediments or sands, and above all, to give food or refuge to other species, so even if there is live coral, the environmental service is not the same.

Meanwhile, environmental variability is one of the two forms of environmental change, with alterations in the intensity or frequency of stochastic events [35, 36]. Its raise is associated with the increment in disturbances and variability of resources, imposing challenges that have a greater influence on biological communities, than those generated by changes in the average environmental condition (the second form of environmental change). In turn, environmental variability has been conceptually used to frame all possible values that may exhibit the physical and chemical characteristics of a benthic habitat [37, 38].

Alacranes reef can be considered as the most studied coral complex of the Mexican seas due to its extraordinary characteristics, which place it within the most extensive and important coralline masses of the country [39]. The reef was described for more than a century [40] but, until the late 1950s, began to be studied more or less constantly, mainly by foreigners [41]. Alacranes has a vast history of shipwrecks and has been a point of attraction of visitors since colonial times [42].

The Yucatan Peninsula is a platform of sedimentary origin, constituted by a karstic Quaternary complex. It is the most recent emersion area in the country, and its growth is associated with sediment coastal transport processes and marine transgression and regression cycles. Therefore, Alacranes is of recent formation, originated by the biological action of the corals with the gradual deposit of calcareous material during the Pleistocene and Cretaceous, favored by the slow immersion of the Yucatan Peninsula [43]. Alacranes sits on a terrace of 51–64 m that is supposed to be carved during the descent eustatic sea level at the end of Wisconsin or at the beginning of the transgression Holocene (11,000 years ago), hence began the modern reef growth, arriving some 5000 years, both the reef and the sea level, to its current values [44]. The area is a platform reef of approximately 300 km^2, which rises 50 m from the seabed. According to several investigations [45], it is known that the pattern of currents and the contribution of nutrients for the Alacranes reef come from the upwelling process that originates in the eastern end of the Yucatecan platform. The current of the Caribbean, as it passes through the Yucatán Strait and ascends on the platform, contributes high values of nutrients and therefore a high productivity [46]. Thanks to this contribution, there are commercial fisheries of lobster (*Panulirus argus*) and the groupers (*Epinephelus* sp.) [47]. The general state of conservation of the reef can be considered good [48].

Alacranes is a resting area for migratory birds that cross the Gulf of Mexico; particularly one of the islands of the Alacranes reef is considered one of the most important breeding areas in the world for the bird *Sula dactylatra*. Thus, it is considered an important area for the conservation of birds of the country [49], especially with a record of 110 species between accidental and permanent residents in the reef. In the reef environment, the management program has registered 34 species of corals, some of which are considered species under special protection [50] —in this assessment we report 28. According to the Alacranes bathymetric characterization, the slope of windward descends to an average of 55 m of depth; in the north part there is a marked inflection of the profile in comparison of the areas center and south, where the slope descends gently. The windward slope is the only site on the Alacranes reef where the stony corals of the genus *Orbicella*/*Montastraea* are not dominant. The dominance corresponds to *Siderastrea radians*. One of the characteristics of this area is the high density of soft corals or octocorals; the dominant genus is *Pseudopterogorgia*, although *Gorgonia flabellum* is also frequent and reaches large size. In addition to these, the genera *Eunicia*, *Plexaura*, and *Plexaurella* are represented in this part, like the one reported by other studies [42, 51]. The barrier reef is physiographically one of the most conspicuous elements of the system, and like any barrier reef, in turn is divided into outer barrier, west in the case of Alacranes, reef crest, and inner barrier [52]. The outside is the one that is exposed to the prevailing winds and the persistent swell train. Along the barrier at different points, it reaches the surface. The notorious dominance of the *Palythoa caribbeaerum* colonial anemone extends to the areas of the crest and the inner barrier. In the shallow part, between three and four meters of depth, the Hydrozoa *Millepora alcicornis* is frequent, like *Gorgonia flabellum*. In this area, the hard corals are represented by *Porites asteroids*, *Pseudodiploria strigosa*, *Acropora palmata*, and *A. cervicornis*, mainly. In the southern part of the barrier, *Acropora prolifera*, a rare species in the Caribbean reefs, is located. The reef crest reaches up to 400 m wide and marks the maximum growth of the reef and is only interrupted by two channels of flow and reflux tidal in the area known as the flooded. The boundary between the crest and the inner barrier is not clearly defined, but it can be said that it starts in the area where the swell train begins to disappear. In the inner barrier, in the closest part to the crest, *Acropora palmata*, *A. cervicornis*, *Porites porites*, *P. astreoides*, and *Millepora alcicornis* are the corals competing with *Palythoa*. To the west the inner barrier comprises the meadows of seagrass and the canals near the barrier. Of these components, the seagrass meadows play an important role in the system [53]. They are presented in shallows of sandy bottoms covered by meadows of *Thalassia testudinum*, *Cymodocea manatorum*, and *Diplanthera wrightii* whose roots and rhizomes form a dense plot that functions as a sediment trap and stabilizes the substrate. Associated with the meadows are presented corals *Manicina areolata*, *Oculina diffusa*, and *Porites porites*. The reef plateau is the most complex area of reef lagoon and includes shallow seagrass meadows, pinnacular reefs, and microatolls, as well as an intricate network of canals, the result of these morphological structures that rise abruptly from 12 to 15 m deep, until almost reaching the surface. *Orbicella annularis* is dominant and accompanies *M. cavernosa*, *Pseudodiploria strigosa*, *Colpophylia natans*, *Porites porites*, *P. astreoides*, and *Stephanocoenia intersepta*.

For its biological characteristics, the reserve of Chinchorro Bank is a natural laboratory, practically unaltered, partially known, and even unknown in many of its aspects, to develop innovative scientific research and quality focused both on the execution of floristic and faunal inventories that enrich and update existing ones, as well as to understand in detail the biological and ecological relationships and processes that develop there. Due to Chinchorro Bank's geographical isolation and its position in the hurricanes and tropical storms route, it is important to establish mechanisms to facilitate the knowledge of the prevailing meteorological conditions to increase the safety degree of visitors and fishermen. Unlike other Mexican reefs, Banco Chinchorro does not develop on a continental or insular shelf but on a deep underwater crest (more than 400 m deep about 30 km out coast), which rises like a pinnacle [54, 55]. Little is known of its origin; we have the theory that in the past, the reef complex was formed by separation and derives from a portion of the continental coastal area, possibly in the Cenozoic era in the late Tertiary period or early Quaternary (in the Pliocene-Pleistocene age). The separate fraction of the coastline contained a fringe or marginal reef and coastal lagoons with typical fauna. The detachment of part of the coast was possibly of a single plate, which took with it a large reservoir of ancient water which possessed characteristics of a continental mass of water, which has maintained its characteristics with the contribution of the rains. Due to its geographical position in the Western Caribbean and their influence in the Gulf Stream, it is an intermediate point compared to other reef systems located downstream in the Lesser Antilles, which allows it to receive larvae of these distant places and in turn export larvae of different organisms generated in Chinchorro to systems located upstream, like Cozumel, Alacranes reef, and the keys of Florida, among others [56].

The Chinchorro Bank is of great ecological importance due to the high diversity of organisms that are there. By remaining practically isolated for a long time, some areas are unchanged, allowing for a comparable study with other similar ecosystems. Banco Chinchorro is nominated by UNESCO as a World Heritage Site and as a Ramsar site for the protection of migratory birds and wetlands. It was recently designated as the Man and Biosphere (MAB) site [50]. The fauna inventoried by the management program [14] is dominated by local and migratory birds that use the keys permanently or during the time of migration to rest and feed. Ninety-six species of birds are registered. Several of them registered in NOM-059-ECOL-1994 as subject to special protection, for example, the blue-winged teal (*Anas discors*) and the roadside hawk (*Buteo magnirostris*). The brown heron (*Ardea herodias*) is considered rare. For example, the blue-winged teal (Anas discors) and the road hawk (*Buteo magnirostris*), the brown heron (*Ardea herodias*) is considered rare, the stork (*Mycteria americana*) and the rabies or rabihorcado (*Fregata magnificens*) as it is known in the locality where, according to fishermen's reports, this bird reached great abundance they have the category of threatened. Within the reptiles, the American crocodile (*Crocodylus acutus*) is listed as endangered, although apparently in the bank, this species is abundant.

The known composition of the coral taxa is represented by hexacorals, octocorals, and hidrozoarios with 95 species reported [14]; in this assessment we report 31. Among the Scleractinian *Orbicella annularis*, *M. cavernosa*, *Porites astreoides*, *Agaricia tenuifolia*, *A. agaricites*, *Acropora palmata*, and *A. cervicornis* dominate, while of the gorgonian the dominant ones correspond to *Eunicea mammosa*, *Gorgonia flabellum*, *P. americana*, *Briareum asbestinum*, and *Plexaura flexuosa*. The hidrozoarios are represented by *Millepora complanata* and *M. alcicornis* like the report by other investigation [57]. The macroinvertebrates are conspicuous elements of the coral reef; they are even organisms of great scientific, tourist, and commercial interest, but little is known of those that are presented in the reserve. The available records, which are not exhaustive, correspond to 35 species of sponges, 78 gastropods, 26 bivalves, and 6 crustaceans [14]. For Chinchorro Bank, faunal and floristic inventories with which it is counted in the reserve are partial. It is not known the composition of zooplankton, phytoplankton, microzoobenthos, and microphytobenthos, among others, as well as taxonomic groups of which there are no records such as the case of echinoderms, jellyfish, anemones, crustacean by marine fauna, and arachnids, insects, and mammals for terrestrial fauna is not known.

With the high values of diversity in Alacranes reef, one would think that it is the most diverse and most conserved reef; however, the high coverage values in Chinchorro Bank belie that assumption. It is very important to mention that the coverage composition of benthic organisms is a variable that determines total biodiversity or specific group biodiversity, such as benthic organisms, invertebrates, or reef fish [58]. Both lagoons have hard and soft corals in different proportions, but abundance has a high variation in soft corals. This may be related to the high colonization capacity of soft corals which adhere to different types of substrate.

The south part of Chinchorro Bank recorded the highest diversity of benthic groups, but Alacranes reef was in the north. Density and percentage of live coral coverage, particularly reef building corals in these areas, are slightly over the average recorded in coral reefs from the Mesoamerican Reef [59]. It is possible that these corals enhance considerably the growth of new colonies, which will make possible the persistence of reefs and the habitat they provide to other species. In the north of Chinchorro and the south of Alacranes, it is highly probable that sedimentation condition will affect and reduce the live coral coverage, since this condition persists for a period; about 7% of coral coverage in this area could be lost because it is well known that sediments damage coral polyp tissues by abrasion and asphyxia.

4.2 Site affinity

There are distinct morphological variations between leeward and windward sectors. A shallow and extensive reef flat is a common feature in most of leeward part of these reefs. Coralline algae are quite abundant in these flats, and rubble of coral skeletons in ample dead beds of hard corals is evident. With both data sets, the classification analysis leads to effectively recognizing the quantitative differences between the different zones. It extracts subjective considerations and discovers the importance of the ecological attributes identified in the field. However, in some cases the factors that originate the distribution patterns are not clearly discovered, since the analysis conducted suggests that significant changes with the depth occurs in the populations and shows that the different parts of the same reef system can be subjected to different pressures and combinations in the selection process, even in physiographical areas related to the frequency and intensity of disturbance by the wave.

The affinities between the sites showed strong identities toward identifying areas with particular characteristics such as windward, leeward, and the reef ridge; however, the inclusion of some site of the reef plain in these groups can be caused by the depth and the type of biotope that develops there (availability of free substrate, coral fragments, etc.) as happens in other reef sites [60]. Chinchorro Bank presented a greater number of groupings, showing particular areas with strong characterization, where slight changes in some parameters is sufficient for the index to detect and separate them; Alacranes gathers more sites in its clusters, which would allow to think that their affinities are maintained in a larger area.

4.3 Spatial species distribution

In stable ecological systems, it is possible to recognize the dynamic state in which all the interactions and variations of a community are centered and nullified at a point of equilibrium to which all the components of the community are directed after a disturbance, allowing the community to be recognized as an entity based on its attributes [61–63], which are the total abundance of species, the total abundance of the dominant species, the biomass of the community, and the composition of species [64, 65]. With the analysis of Main Coordinates, it's possible to identify a community for the species that most influence its community spatial structure [66]; however, this community could present different points of stability, in which the dominance of different species is present, which they present specific equilibrium points, providing different levels of resistance to disturbances, as could create the differences between windward and leeward levels. In both reefs and analysis strategies, the species that takes advantage of the largest amount of resources for its benefit and consequently is the most dominant is *Orbicella annularis*, which is similar to that reported for the Netherlands Antilles [67], on both reefs was a species that separates from any grouping, being more evident in Chinchorro Bank. However, in areas with a certain degree of disturbance, the scheme changes dramatically, and other species replace *O. annularis* in its dominance. In the first case, when solid substrate is available, the gorgonians are those that have more aggressiveness and in the second when missing a solid substrate, the group of sponges has some advantage. In fact, these data confirm what was partially found by other research [68–70] who defined areas or biotopes with strong ecological differences. Coral reefs in the Caribbean and Gulf of Mexico have a similar coral biota. Nevertheless, there is a reduction in the number of common Scleractinian coral species from the Alacranes reef to Chinchorro Bank. Coral species richness, however, does not seem to decrease drastically as it does with gorgonians [71].

5. Conclusions

The conclusions of this research are as follows:

- The two lagoons have different dynamics.

- The proportion of live coverage in Chinchorro Bank is higher than in the Alacranes reef.

- While the richness is greater in the lagoon of the Alacranes reef, the magnitude of the Chinchorro Bank lagoon may result in an undervaluation due to insufficient sampling.

- The abundance-rich ratio of species given by diversity is similar in both lagoons.

- *Orbicella annularis* is the coral that is among the five most dominant species in both lagoons.

- In the lagoons there were site affinities, especially at the edges, that faithfully identify windward and leeward areas, which allow to infer the importance of this element and what originates in relation to wave force, oxygenation, etc.

- The analyses show areas with large ecological differences in the lagoons.

By virtue of its insular nature and the scarcity of freshwater, both reefs have remained safe from major alterations. Alacranes reef and Chinchorro Bank are a distant paradise that still have abundant fishing resources and diverse underwater life to marvel, as well as the possibility of discovering hidden secrets kept by the sea and time. However, we must consider and not forget that the overexploitation of resources can deplete the productivity of this place, which until now is one of the last places where coral reefs and memories of other times remain intact. The knowledge obtained from these systems must serve to conserve their natural resources, with special emphasis on endemic species, threatened, endangered, special protection, and those of current and potential economic importance, as well as preserving the reef landscape and its natural elements, for the enjoyment, recreation, exploitation, and elevation of the quality of life of social groups and visitors and for future generations. It should also encourage the conduct of research and studies that broaden and deepen this knowledge and contribute to the development of methods and alternatives for the sustainable use of resources.

The benchmarks of reefs in Mexico are changing, and they need to be redefined frequently to update them, in order for the management tools to be more effective and accurate; we hope that this contribution will go in that direction of conservation and maintenance of these magnificent ecosystems.

Acknowledgements

We would like to extend our thanks to the National Council of Science and Technology for the support given to the realization of several projects in which this field work is included. Likewise, we thank the Marine Secretariat and the fishermen of several cooperatives, for the transfer of personnel and students to the different reefs and to all the people and institutions that contributed resources, time, and knowledge to carry out this research.

Appendix

			Alacranes reef lagoon																																		
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**1**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
		Species																																			
Algae	1	*Acanthophora spicifera (M.Vahl) Børgesen, 1910*	+	+		+	+	+	+				+			+			+			+			+			+			+	+	+		+	+	
	2	*Caulerpa* sp. *J.V. Lamouroux, 1809*					+							+							+						+			+		+			+		
	3	*Dictyota* sp. *J.V. Lamouroux, 1809*	+	+	+	+	+	+	+	+		+		+		+			+			+			+			+			+	+	+		+	+	+
	4	*Halimeda incrassata (J.Ellis) J.V. Lamouroux, 1816*	+	+	+			+	+				+		+		+				+	+			+	+			+	+	+			+	+	+	+
	5	*Jania adhaerens J.V.Lamouroux, 1816*	+				+	+	+	+			+		+			+		+		+		+		+	+								+		+
	6	*Lobophora variegata (J.V.Lamouroux) Womersley ex E.C.Oliveira, 1977*	+	+	+	+	+	+	+	+	+	+		+			+			+				+		+		+			+	+	+		+	+	
	7	*Mesophyllum mesomorphum (Foslie) W. H. Adey, 1970*	+		+	+		+			+		+			+			+		+		+			+							+		+	+	+
	8	*Rhipocephalus phoenix (J.Ellis & Solander) Kützing, 1843*					+	+	+						+					+															+		
	9	*Sargassum filipendula C. Agardh, 1824*		+				+	+			+												+								+					+
	10	*Stypopodium zonale (J.V.Lamouroux) Papenfuss, 1940*		+			+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+				+	+	+
	11	*Valonia ventricosa J. Agardh, 1887*					+	+		+																			+		+				+		
Sponge	12	*Agelus schmidtii Wilson, 1902*							+							+				+				+				+			+						
	13	*Aplysina fistularis (Pallas, 1766)*			+	+		+	+																									+		+	
	14	*Aplysina* sp. *Nardo 1834*			+	+	+	+		+		+			+			+				+				+						+					
	15	*Amphimedon compressa Duchassaing & Michelotti, 1864*			+	+					+			+			+			+			+			+	+										
	16	*Callyspongia plicifera (Lamarck, 1814)*		+		+		+	+										+			+			+					+						+	
	17	*Callyspongia vaginalis (Lamarck, 1814)*				+		+												+																	

			Alacranes reef lagoon																																		
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**1**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
		Species																																			
	18	*Chondrilla nucula Schmidt, 1862*		+				+			+					+			+			+			+			+			+						
	19	*Cliona delitrix Pang, 1973*			+				+							+			+			+				+				+							
	20	*Dasycladus* sp. *C. Agardh, 1828*				+		+	+	+				+			+			+			+			+			+								
	21	*Ectyoplasia ferox (Duchassaing & Michelotti, 1864)*				+		+				+			+			+			+					+			+	+		+					
	22	*Ianthella* sp. *Gray, 1869*					+			+				+			+			+				+				+									
	23	*Ircinia strobilina (Lamarck, 1816)*	+	+	+								+			+				+				+											+		
	24	*Ircinia* sp. *Nardo, 1833*			+				+		+					+					+						+									+	
	25	*Haliclona tubifera (George & Wilson, 1919)*		+	+	+	+	+		+			+			+			+				+			+					+						
	26	*Mycale Laevis (Carter, 1882)*	+	+		+		+								+			+			+				+	+										
	27	*Monanchora arbuscula Duchassaing & Michelotti, 1864*				+	+	+			+		+			+																	+				
	28	*Neopetrosia carbonaria (Lamarck, 1814)*	+					+					+				+			+				+			+								+		
	29	*Xestospongia* sp. *Laubenfels, 1932*			+	+	+							+			+			+				+				+									
Hydrozoa	30	*Millepora alcicornis Linnaeus, 1758*		+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+							+		+	+			+	+	
	31	*Millepora complanata Lamarck, 1816*																			+	+	+	+	+	+	+	+	+	+				+	+	+	
Hard corals	32	*Acropora prolifera (Lamarck, 1816)*						+			+									+		+	+	+					+	+					+	+	
	33	*Agaricia agaricites (Linnaeus, 1758)*		+		+	+		+				+	+			+			+		+	+	+		+	+	+									
	34	*Agaricia tenuifolia Dana, 1848*		+							+				+	+	+									+	+	+									+
	35	*Colpophyllia natans (Houttuyn, 1772)*				+									+				+					+	+	+	+	+				+	+		+	+	
	36	*Dichocoenia stokesii Milne Edwards & Haime, 1848*			+		+								+							+	+									+				+	

			Alacranes reef lagoon																																		
			1	2	3	4	5	6	7	8	9	10	1	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
		Species																																			
	37	*Diploria laberynthiformis (Linnaeus, 1758)*		+	+	+	+	+	+						+		+						+		+	+	+				+	+	+			+	+
	38	*Isophyllia sinuosa (Ellis & Solander, 1786)*				+		+	+				+				+		+	+	+	+	+	+	+		+	+								+	
	39	*Eusmilia fastigiata (Pallas, 1766)*			+	+	+		+				+	+	+																						
	40	*Madracis decactis (Lyman, 1859)*					+						+																								+
	41	*Montastrea cavernosa (Linnaeus, 1767)*	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+			+	+	+				
	42	*Mycetophyllia aliciae Wells, 1973*				+		+									+			+				+			+									+	
	43	*Orbicella annularis (Ellois & Solander, 1786)*	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+				+	+			+	
	44	*Porites astreoides Lamarck, 1816*	+	+		+		+							+	+			+		+		+		+		+				+	+	+			+	
	45	*Porites furcata Lamarck, 1816*	+	+	+			+						+		+			+			+					+				+				+		
	46	*Porites porites (Pallas, 1766)*				+		+	+		+		+				+			+				+			+	+			+				+		
	47	*Pseudodiploria strigosa (Dana, 1846)*	+	+	+		+	+	+			+			+		+		+	+		+				+		+			+	+			+	+	
	48	*Siderastrea siderea (Ellis & Solander, 1786)*	+	+	+	+	+	+	+	+	+			+	+	+						+	+	+	+			+			+	+	+		+		+
	49	*Stephanocoenia intersepta (Lamarck, 1816)*						+																							+						+
Soft corals	50	*Antillogorgia americana (Gmelin, 1791)*		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+			+	+	+	+	+	+	+			+	+	+					
	51	*Antillogorgia acerosa (Pallas, 1766)*		+	+	+	+					+	+	+							+		+			+					+						
	52	*Antillogorgia bipinnata (Verril, 1864)*		+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+											+	+					
	53	*Briareum asbestinum (Pallas, 1766)*		+				+																													
	54	*Eunicea flexuosa (Lamouroux, 1821)*	+	+			+	+	+																												
	55	*Eunicea mammosa Lamouroux, 1816*			+		+	+	+																												
	56	*Gorgonia flabellum Linnaeus, 1758*		+	+		+	+	+		+		+	+		+	+	+	+		+	+	+	+	+		+			+							
	57	*Muricea muricata (Pallas, 1766)*			+		+	+	+			+	+		+		+	+	+																		
	58	*Plexaurella grisea Kunze, 1916*		+			+		+																												

DOI: http://dx.doi.org/10.5772/intechopen.88662

			Chinchorro Bank lagoon																																			
		Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Algae	1	*Caulerpa cupressoides (Vahl) C,Agardh, 1817*																															†					
	2	*Dictyota dichotoma (Hudson) J.V.Lamouroux, 1809*													†																							
	3	*Halimeda incrassata (J.Ellis) J.V. Lamouroux, 1816*													†		†																†	†				
	4	*Lobophora variegata (J.V.Lamouroux) Womersley ex E.C.Oliveira, 1977*														†	†	†															†					
	5	*Palisada perforata (Bory de Saint-Vicent) K.W. Nam, 2007*												†		†																		†				
	6	*Penicillus capitatus Lamarck, 1813*													†																			†				
	7	*Turbinaria turbinata (Linnaeus) Kuntze, 1898*												†																	†	†						
	8	*Udotea flabellum (J.Ellis & Solander) M.A. Howe, 1904*																†															†					
Sponges	9	*Aplysina fistularis (Pallas, 1766)*																			†																	
	10	*Callyspongia plicifera (Lamarck, 1814)*					†														†	†						†					†				†	†
	11	*Chondrilla nucula Schmidt, 1862*																															†					
	12	*Haliclona tubifera (George & Wilson, 1919)*					†																		†										†			
Hydrozoa	13	*Millepora alcicornis Linnaeus, 1758*		†																																		
	14	*Millepora complanata Lamarck, 1816*																		†										†	†							
Hard corals	15	*Acropora palmata (Lamarck, 1816)*											†																	†	†							
	16	*Agaricia agaricites (Linnaeus, 1758)*	†			†				†	†		†									†	†					†	†		†				†			†
	17	*Colpophyllia natans (Houttuyn, 1772)*			†												†																					
	18	*Dichocoenia stokesii Milne Edwards & Haime, 1848*										†	†																									

			Chinchorro Bank lagoon																																			
		Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	19	*Diploria laberynthiformis* (Linnaeus, 1758)										+																										
	20	*Eusmilia fastigiata* (Pallas, 1766)							+																													
	21	*Manicina areolata* (Linnaeus, 1758)																									+											
	22	*Montastrea cavernosa* (Linnaeus, 1767)			+		+															+													+			
	23	*Orbicella annularis* (Ellois & Solander, 1786)	+	+	+	+	+	+	+	+			+	+	+		+	+				+	+												+	+		+
	24	*Porites astreoides* Lamarck, 1816		+			+	+																							+							
	25	*Porites furcata* Lamarck, 1816	+			+	+	+	+	+																												
	26	*Porites porites* (Pallas, 1766)			+								+	+					+	+							+			+								
	27	*Pseudodiploria clivosa* (Ellis & Solander, 1786)										+							+																			
	28	*Pseudodiploria strigosa* (Dana, 1846)	+								+							+										+								+		
	29	*Siderastrea radians* (Pallas, 1766)				+				+	+								+													+						
	30	*Siderastrea siderea* (Ellis & Solander, 1786)																				+				+									+	+		
Soft corals	31	*Antillogorgia acerosa* (Pallas, 1766)		+							+	+									+		+	+		+		+							+		+	+
	32	*Antillogorgia bipinnata* (Verril, 1864)			+			+																														
	33	*Briareum asbestinum* (Pallas, 1766)				+																																+
	34	*Eunicea flexuosa* (Lamouroux, 1821)								+																		+	+									
	35	*Eunicea mammosa* Lamouroux, 1816		+								+							+					+			+		+									+
	36	*Gorgonia flabellum* Linnaeus, 1758	+									+	+						+	+									+		+							
	37	*Gorgonia ventalina* Linnaeus, 1758																	+	+		+								+								
	38	*Plexaura homomalla* (Esper, 1794)										+												+											+			
	39	*Plexaurella grisea* Kunze, 1916									+									+			+															

Author details

Daniel Torruco[1]*, M. Alicia González-Solis[1] and Ángel Daniel Torruco González[2]

1 Research Center and Advance Studies of the National Polytechnic Institute, Merida, Yucatan, Mexico

2 Vizcaya of the Americas University, Merida, Yucatán, Mexico

*Address all correspondence to: dantor@cinvestav.mx

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ISBN 978-1-78985-953-9
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