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Speciality : Climate Change and Biodiversity

Mangrove degradation and its effects on estuarine fisheries: case study of Tanbi Wetland National Park, The Gambia

ADAM CEESAY

Public defense: 7th October, 2016

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REPUBLIQUE DE COTE D'IVOIRE
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Ecole doctorale pour le Changement Climatique et Biodiversité

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THESE

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Spécialité : Changement Climatique et Biodiversité

Dégradation des mangroves et ses effets sur les pêcheries en milieu estuarien : cas du Parc National des Zones Humides de Tanbi, La Gambie

ADAM CEESAY

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Professeur	Tidou Abiba Sanogo	Université Jean Lorougnon Guédé	Président
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DEDICATION

This is dedicated to my mum for believing in me all through. It is said that trust is earned, but with her everything was already given unconditionally. And that was the only motivation I needed to focus on what was important and to stay away from everything else that was not. I pray for her long life, good health and all the happiness in the world.

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I would like to express my gratitude to my supervisor, Prof. Koné Tidiani for all the time and effort spent assessing this scientific work. Thanks to my co-supervisor Dr. Ebrima Njie for all the encouragement and guidance during my PhD tenure. I am also grateful to Dr. Amadou Camara for his help during the formulation of my research proposal; to Prof. Allassane Ouattara for all the tips on water quality monitoring; to Drs. Mathieu Koné and Kanvaly Dosso for taking the time to read through it all and to Uncle Lamin Sanneh for helping me acquire some of the reagents used during this research.

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LIST OF ACRONYMS

ANOVA – Analysis of Variance

BAC – Brikama Area Council

BCC – Banjul City Council

CO_2 – Carbon dioxide

CRR – Central River Region

CPUE – Catch per Unit Effort

DO – Dissolved oxygen

DPWM – Department of Parks and Wildlife Management

DWR – Department of Water Resources

EEZ – Exclusive Economic Zone

ETM – Enhance Thematic Mapper plus

GBA – Greater Banjul Area

GBoS – Gambia Bureau of Statistics

GDP – Gross Domestic Product

GHE – Greenhouse Energy

GHGs – Greenhouse gases

GIS – Geographical Information Systems

GOTG – Government of The Gambia

GRP – Graduate Research Program

ITCZ – Intertropical Convergence Zone

IUCN – International Union for Conservation of Nature

IPCC – Intergovernmental Panel on Climate Change

KM – Kanifing Municipality

LDCs – Least Developed Countries

LRR – Lower River Region

MDS – Multidimensional Scaling

MSS – Multi-spectral Sensor

NAPA – National Adaptation Plan of Action

NARI – National Agricultural Research Institute

NBR – North Bank Region

NDVI – Normalized Difference Vegetation Index

NEA – National Environment Agency

O_2 - Oxygen

PCA – Principal Components Analysis

PRCM – Regional Partnership for Coastal and Marine conservation in western Africa

SUME – Sahelian Upwelling Marine Ecoregion

TM – Thematic Mapper

TWNP – Tanbi Wetland National Park

UNESCO – United Nations Educational, Scientific and Cultural Organization

URR – Upper River Region

USAID – United States Agency for International Development

US EPA – United States Environmental Protection Agency

USGS – United States Geological Survey

WAMER – West African Marine Ecoregion

WR – Western Region

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FOREWORD

The research work presented here is in partial fulfillment of a doctorate degree in Climate Change and Biodiversity from the Félix Houphouët-Boigny University, Cote d'Ivoire. The doctorate program was sponsored by the German Federal Ministry for Education and Research (BMBF) and administered by the Graduate Research Program on Climate Change and Biodiversity within the project of the West Africa Science Service Center for Climate Change and Adapted Land Use (WASCAL). Entailed in this research is a comprehensive assessment of the long-term ecosystem changes in Tanbi Wetland National Park (TWNP) as well as the corresponding short-term/seasonal changes in hydrology and fish assemblage. Based on established mangrove ecosystems assessment protocols from globally renown institutions including (but not limited to) the United States Environmental Protection Agency (EPA), France's International Research and Development Institute (IRD) and the Ramsar Convention; this research brings home to The Gambia a new approach to marine environmental monitoring. It is hoped that this research will serve as a baseline document for future ecological assessments within the highly-treasured mangrove ecosystems of the River Gambia. It is undoubtedly the first multi-decadal ecosystem assessment of its kind for The Gambia and the Sahelo-Sudan as a whole that took an integrated approach of both natural and anthropogenic factors. The findings of this research highlighted existing conservation gaps in The Gambia and provides very useful recommendations for addressing them to ensure greater success in managing this Ramsar wetland of international importance. Notwithstanding, it takes into account the wetland's function as a livelihood source for the poor and vulnerable coastal communities in The Gambia.

ABSTRACT

Climate-induced ecosystem changes were studied in Tanbi Wetland National Park (TWNP) in conjunction with the major land use types i.e. agriculture, settlement, tourism, oyster processing, completely fragmented and partially fragmented zones. To study hydrological changes in TWNP in The Gambia, in-situ analyses of physico-chemical parameters and nutrient build-up were conducted during the peak discharge period of the River Gambia in 2013 and repeated during the peak dry season in 2014. Mangrove vegetation dynamics was assessed by remote sensing, using Landsat images of decadal time series covering 1973 – 2012. To assess seasonal changes in the fish assemblage in relation to the hydrological changes, fish were sampled at all the land use types using a seine net during the rainy and dry seasons. A questionnaire-based assessment of local knowledge on climate-induced ecosystem changes was also conducted. Average salinity in TWNP was 24.5 and 35.8 ppt for the rainy and dry seasons respectively. Mangrove vegetation cover declined by 6% while grassland increased by 56.4% from 1973-2012. 43 fish species from 25 families were recorded from 2013-2014. Fish species richness declined by 16% and abundance by 35% as the seasons changed from rainy to dry. Fish bio-ecological categories were dominated by estuarine species of marine origin (Em) (47%) throughout the year, 2014. Multidimensional Scaling (MDS) of the environmental variables indicated salinity as the main water variable influencing fish species richness in TWNP. Local awareness about the climate change concept was high (70%). However, local adaptation practices to climate-induced ecosystem changes were low (50%). Based on the low percentage loss in vegetation cover, this research concludes that except at the completely fragmented zone, the impacts of human activities on mangrove vegetation in TWNP are negligible. It also demonstrates that the decline in the fish assemblage is due to local extinctions caused by seasonal hyper-salinity.

Key words: TWNP, River Gambia estuary, climate change, adaptation, land use.

RESUME

Les modifications écosystémiques d'origine climatique ont été étudiées dans des zones partiellement et complètement fragmentées dans Parc National de Tanbi (PNT) (Gambie) en corrélation avec les principaux types d'utilisation des terres (agriculture, occupation, tourisme, traitements des huîtres. Pour étudier les changements hydrologiques dans le PNT, l'analyse des paramètres physico-chimiques et de l'accumulation des nutriments ont été faites pendant la crue du fleuve Gambie en 2013 et durant la saison sèche en 2014. L'étude diachronique des mangroves a été faite avec des images Landsat de 1973-2012 par intervalle de 10 ans. Les variations saisonnières de la diversité de l'ichtyofaune ont été évaluées en fonction des variations hydrologiques. Pour ce faire, les poissons ont été capturés dans toutes les catégories d'utilisation des terres à l'aide d'une senne pendant les deux saisons. De plus, une enquête des connaissances locales sur la variation des écosystèmes causée par le climat a été abordée. La salinité moyenne dans le PNT était de 24,5 et 35,8 ppt respectivement pour la saison pluvieuse et sèche. La couverture des mangroves a diminué de 6% alors que celle de la savane herbeuse a augmenté de 56,4% entre la période 1973-2012. 43 espèces de poisson appartenant à 25 familles ont été recensées pour l'année 2014. Leur diversité et abondance ont diminué de 16% et 35% respectivement lors de la saison pluvieuse et de la saison sèche. Durant l'année, les catégories bioécologiques des poissons ont été dominées à 47% par les espèces estuariennes d'origine marine. Le positionnement multidimensionnel des variables environnementales a indiqué que la salinité est la principale variable environnementale influençant la richesse spécifique de poissons dans le PNT. La connaissance locale sur le concept de changement climatique était élevée (70%). Cependant, les techniques d'adaptation était faible (50%). Sur la base du faible pourcentage de perte de couverture végétale, la présente recherche indique, qu'excepté la zone où la végétation de mangrove est fortement fragmentée, il y a un faible impact humain sur le PNT. Elle confirme aussi que le déclin de la richesse spécifique des poissons est dû à l'hyper-salinité saisonnière.

Mots clé : PNT, Estuaire Fleuve Gambie, Changement Climatique, Adaptation, Utilisation des terres.

INTRODUCTION

The Gambia is the smallest country in mainland Africa **(Jallow *et al.,* 1999)**. The country is blessed with the River Gambia, which divides the country into two parts, running through its entire length and covering 20 percent of the land area **(Wood, 2000)**. The River Gambia has its source in the Fouta Djallon highlands (Guinea Conakry) and empties into the Atlantic Ocean **(PRCM, 2011)**. It is one of the greatest sources of employment, food and aesthetics to The Gambian people **(National Environment Agency, 2010)**. It is also one of the world's last rivers that is yet to be impounded and as such, experiences minimum to no pollution from either industries or agriculture **(Albaret *et al.,* 2004)**. In this natural state, the river is fringed by about 45,000 hectares of luxuriant mangroves that grow to heights of up to 40 meters **(Saenger & Bellan, 1995)**, comprising seven out of the eight true mangrove species reported in West Africa **(Corcoran *et al.,* 2007)**.

In relation, The Gambia's coastal waters cover about 80 km along the Atlantic coast **(Leeney & Downing, 2015)** and are reported to be one of the richest marine ecosystems within the West African Marine Eco Region (WAMER) **(Lee *et al.,* 2009)**. This coast is home to about 672 fish, 74 reptile, 33 amphibian, 10 mollusc and 6 crustacean species **(IUCN, 2010)**. Many small-bodied mammals are found here, e.g. the cane rat (*Thryonomys swinderianus* (Temminck, 1827)) and the spotted-necked otter (*Hydrictis maculicollis* (Lichtenstein, 1835)); as well as larger-bodied ones such as the vulnerable West African manatee (*Trichechus senegalensis* (Link, 1795)) **(IUCN, 2010)**. Because of this, coastal biodiversity is very important to The Gambian economy, supporting the fisheries and tourism sectors which contribute 12% and 8% of national Gross Domestic Product (GDP) respectively **(CIA World Fact Book, 2014; United Nations, 2014)**.

The recent global interest on how climate change impacts aquatic ecosystems has brought to light the need for more information on tropical mangrove estuaries **(Schlenk & Lavado, 2011)**. As a delicate meeting point between marine and fresh waters, tropical mangrove estuaries serve as a natural buffer zone and nursery ground for both marine and riverine fishes **(Vannucci, 2001)**. This situation is even more pertinent when considering the River Gambia estuary. Like The Gambian part of the Atlantic Coast, the River Gambia estuary is home to many vulnerable organisms such as the Nile crocodile (*Crocodilus niloticus* (Laurenti, 1768)). The River Gambia estuary serves as a suitable abode to many endemic African birds e.g. the sacred African ibis (*Threskomis aethiopicus* (Latham, 1790)) and is also a suitable destination for winter migration by European birds e.g. yellow-billed Stork (*Mycteria ibis* (Linnaeus, 1766)) **(Wood, 2000)**.

The major economic activities in and along the River Gambia include agriculture, fishing, and tourism. Agriculture for instance, contributes about 19% of The Gambia's GDP **(CIA World Fact Book, 2014)**, while the fisheries sector contributes about 12% of the GDP, employing both Gambian and foreign nationals **(United Nations, 2014)**. Fish products are a principal component in the Gambian diet, and thus provides more than 50% of the total animal protein intake **(Gordon *et al.,* 2013)**. Tourism is also a major contributor of The Gambia's GDP (now contributing 18.9%) and employs an appreciable number of Gambians who are involved in safaris, sports fishing, dolphins and bird watching **(Dia, 2012)**. Besides these, the single major GDP contributor is the service sector contributing over 50% **(National Environment Agency, 2010)**.

With a coastline of 80 km, a continental shelf area of 4000 km^2 and an Exclusive Economic Zone (EEZ) of 10,500 km^2 **(FAO, 2007)**, the Gambian waters form an indispensable part of the Sahelian Upwelling Marine Ecoregion (SUME) / West African Marine Ecoregion (WAMER) (Figure 1). Its coastal area is biologically very productive due to nutrient-rich seasonal upwelling and fluvial outflow; hence the biological productivity and richness in pelagic and demersal fisheries resources **(FAO, 2007)**. Considering the fish species that have been identified in The Gambia, along with several species of cetaceans including the bottle-nosed dolphin and humpback whale, and also four species of endangered marine turtles **(Lee *et al.,* 2009)**, the ecological uniqueness cannot be overemphasized.

The River Gambia itself has undergone numerous changes within the last couple of decades; both in the quantity and quality of its ecosystems services. Most of these changes are believed to be caused by uncontrolled human activities such as overfishing **(Lee *et al.,* 2009)**. Even though it is the only remaining undammed river in West Africa, the River Gambia has undergone many natural ecological changes as well, e.g. reduced seasonal flooding and increased salinity, leading to alteration of fish community structure **(Louca *et al*., 2008)**. The above has led many scientists to believe that most of the ecosystem changes are in fact climate-induced. For example, **Huq *et al*. (2003)** suggested that a 1% change in rainfall can cause up to 3% change in river runoff. This can have deleterious consequences on fish populations, local communities and socio-economic groups that are dependent on riverine resources. Seasonal sea water intrusion in the river Gambia now goes up to 240 km inland **(Leeney & Downing, 2015)** and river discharge gets as low as $4.5m^3s^{-1}$ during the peak dry season **(Belhabib *et al.,* 2013)**.

The overall health of an estuary is influenced by a multitude of factors, most of which are interdependent **(Albaret, 1999)**. Such factors include floods (depending on force and duration) **(Lee *et al.,* 2009)**, a change in the balance of physico-chemical parameters **(Blaber *et al.,* 2000)**. For example, salinity and nutrient influx, presence, abundance and state of mangroves **(Panfili *et al*., 2004)** as well as land use/human activities occurring in it e.g. infrastructure, agriculture and industry **(Albaret, 1999)**. All of these are influenced by and interact with changes in climate variables such as rainfall, atmospheric temperatures and sea level rise. For instance, using the estuaries of Senegal, Gambia and Fatala in Guinea as a case study, **Baran (2000)** discovered that fish species richness in West African estuaries is principally influenced by hydrological variability between the dry and the flood seasons.

Mangrove estuaries of the River Gambia are one of the unique ecosystems that are undergoing a serious decline in both the quality and quantity of services it provides for its dependents. The Tanbi Wetland National Park (TWNP) is one example of such estuaries. Due to its ecological richness and importance to The Gambia's socio-economy, this park was designated a Ramsar wetland of international importance in 2007 **(The Ramsar Convention on Wetlands, 2012)**. Covering about 6300 hectares, the TWNP connects the three main urban municipalities and councils i.e. Banjul City Council (BCC), Kanifing Municipality (KM) and Brikama Area Council (BAC) **(Satyanarayana *et al.,* 2012)**. The wetland supports over 41% of the national population **(National Environment Agency, 2010)**. The site once boasted of some of the most luxuriant mangroves, supporting numerous forms of aquatic wildlife and attracting thousands of nature lovers in the tourism sector **(IUCN, 2010)**, and serving as one of the most important breeding and over-wintering sites for diadromous fishes in the West African region **(Lee *et al.,* 2009)**.

The changes in global climate for the past three decades are however beginning to affect the life forms within the wetlands in The Gambia. The TWNP for instance is one of The Gambia's five coastal ecosystems that are most sensitive to sea level rise and it was predicted that a 2m increase in sea level will cause its complete inundation **(Dia, 2012)**. Like in most West African mangrove estuaries, the mangroves of the TWNP have been growing slower **(Maniatis, 2005)**. This type of poor growth in mangrove vegetation points to the occurrence of the climate-induced mangrove dwarfism **(Alongi, 2009)**. Such occurrence of mangrove degradation has been reported in many tropical mangrove estuaries in other parts of the world where it was believed to be due to long-term changes in hydrology **(Kathiresan, 2002; Austin *et al.,* 2010)**.

The perceived changes in hydrological regimes and their role in mangrove degradation are eventually bound to affect the health and survival of other estuarine organisms, especially fish assemblages **(Albaret *et al.,* 2004)**. This phenomenon has not been well studied within the WAMER, but may have immeasurable impacts on livelihoods of coastal communities. Although many studies have been done on the effects of climate change on fish assemblages or distributional range of marine fishes focusing on a regional scale (mostly in the developed world), such information is very scanty for Africa. Especially in the Sub-Saharan part where estuarine fish assemblages are reported to be highly resilient, despite exposure to vast hydrodynamic variations and stress **(Villanueva, 2015)**. For the least developed countries such as The Gambia, such studies are almost non-existent.

Meanwhile, fisheries is the single most important source of animal protein, foreign exchange and also a key source of revenue for economic and social development within The Gambia and the West African Marine Eco Region (WAMER) as a whole **(Lee *et al.*, 2009)**. This situation calls for an urgent assessment of climate-induced ecosystem changes in the River Gambia estuary, its impacts on fish assemblage and local fisheries as well as socio-economics of the coastal communities and how these interact with human activities such as land use change. This is necessary for better formulation and implementation of sustainable national and sub-regional development plans. Thus, it is herein hypothesized that the seasonal variations in water quality of the River Gambia estuary, accompanied by loss of mangrove vegetation and decline in fisheries are a result of long-term changes in climate variables; exacerbated by human impacts through land use change. Therefore, the main question this research aims at answering is as shown below:

- How does climate change affect the estuarine hydrology, mangrove vegetation and fisheries of the TWNP?

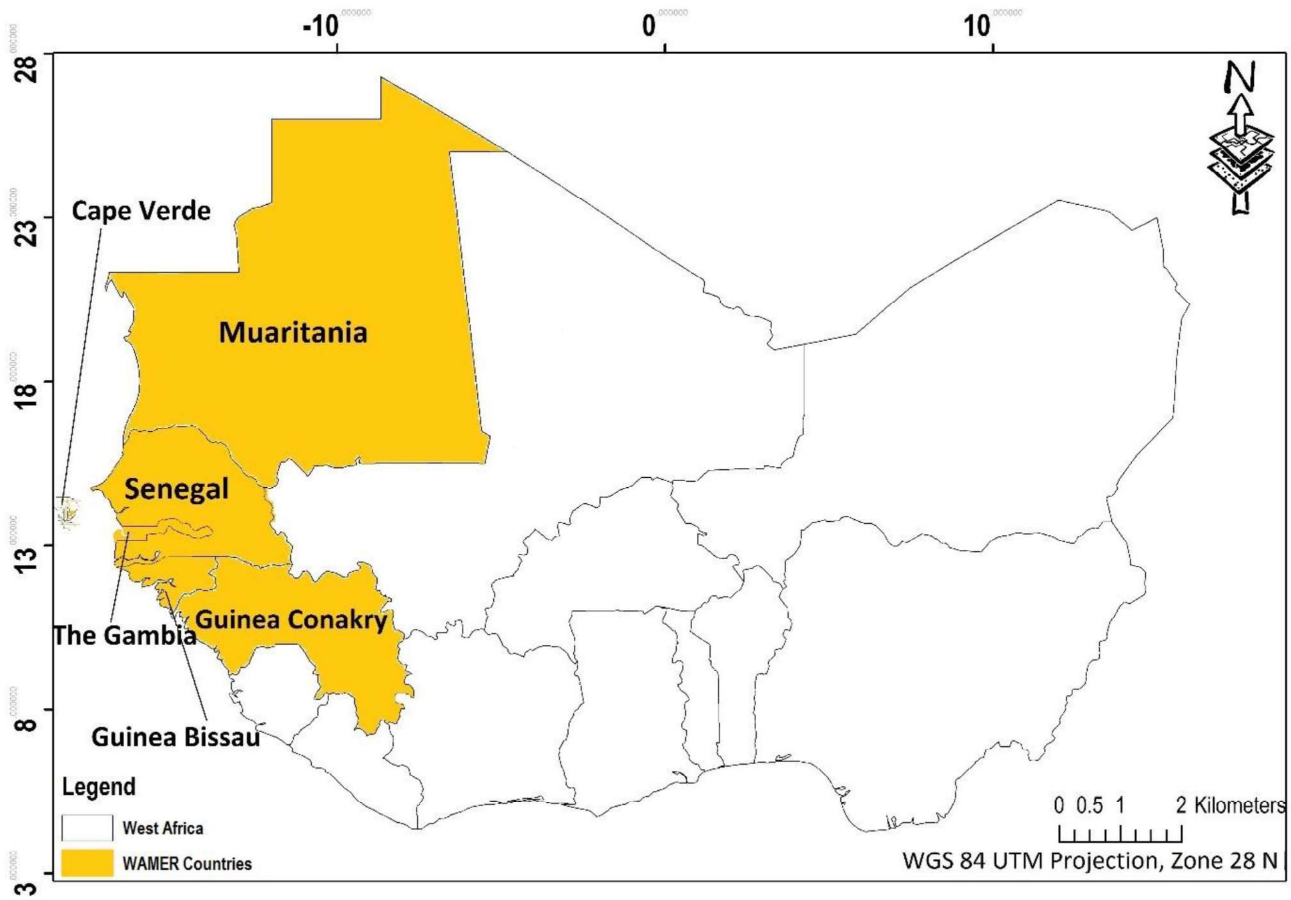

Figure 1. The member countries of the West African Marine Eco Region (WAMER), area in yellow (Adapted from **Lee *et al.*, 2009**).

Problem identification

The Gambia has an area of 11,300 km^2 **(Jallow *et al.,* 1999)**. It has a population of 1,782,893 and one of the fastest population growth rates (2.6%) in Africa **(Lee *et al.,* 2009)**. Like most of the Least Developed Countries (LDCs), The Gambia's economy is a natural resource-based one with rain-fed agriculture as its mainstay **(CIA World Fact Book, 2014)**. The country has five major administrative regions. Due to the importance of the River Gambia in the sustenance of the aforementioned economic activities the administrative regions were named in reference to their proximity to the River Gambia. These regions include: North Bank Region (NBR), Central River Region (CRR), Upper River Region (URR), Western Region (WR) and the Lower River Region (LRR) **(National Environment Agency, 2010)** (Figure 2).
Located 13º28 N and 16º34 W, The Gambia has a flat terrain with the highest peak less than 100m above sea level **(Jallow *et al*., 1996)**, with Banjul (the capital city) only about 0.5m above sea level **(Jallow *et al.,* 1999)**. This situation has created suitable conditions for seasonal floods, especially along the fringes of the River Gambia and leading to the formation/expansion of the lateral mangrove channels of the estuary **(Vidy *et al.,* 2004)**. Such geographical and ecological conditions have contributed towards making the exploitation of aquatic biodiversity an appealing venture, thus leading to destructive practices e.g. over-fishing and mangrove logging for fuel wood, as well as agricultural and touristic purposes **(Dia, 2012)**.

Like most Sub-Saharan countries however, productivity of rain-fed agriculture has registered a drastic drop due to a decline in rainfall and prolonged dry seasons following the Sahelian drought in the early 1970s **(Mertz *et al.,* 2011)**. Overall, annual rainfall in The Gambia has decreased by 30% between 1950 and 2000 alone, remaining at a range of 850 mm to 1200 mm, the bulk of which occurs in August causing heavy floods in one-third of the country **(Dia, 2012)**. Long-term rainfall pattern for Banjul is shown in Figure 3. The impacts of the decline in rainfall and recurrent dry spells are further amplified by the unyielding atmospheric temperatures during the past four decades **(Hutchinson, 1985; McSweeney, 2012)**.

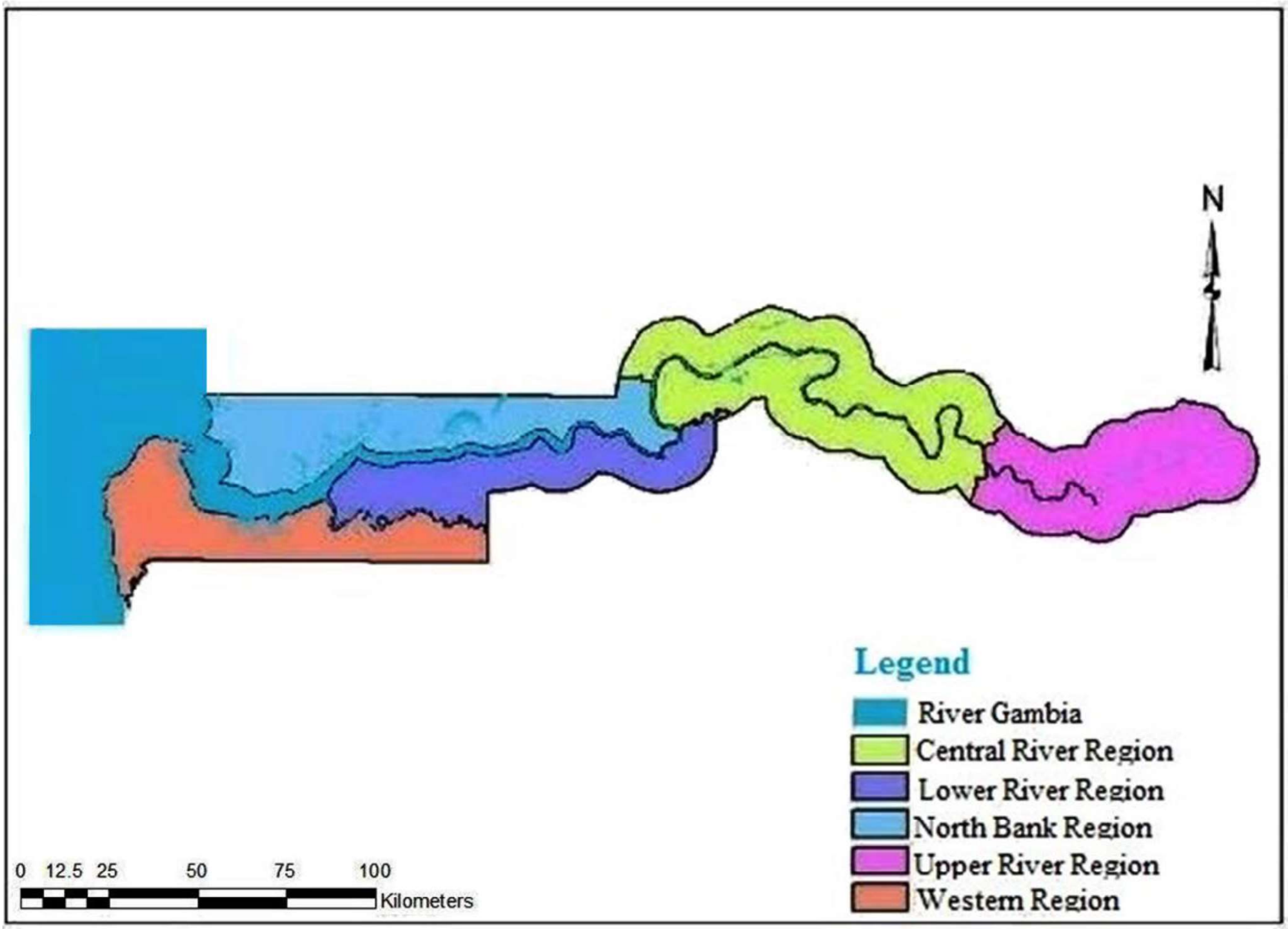

Figure 2. Map of The Gambia showing the five administrative regions (Adapted from: **National Environment Agency, 2010**).

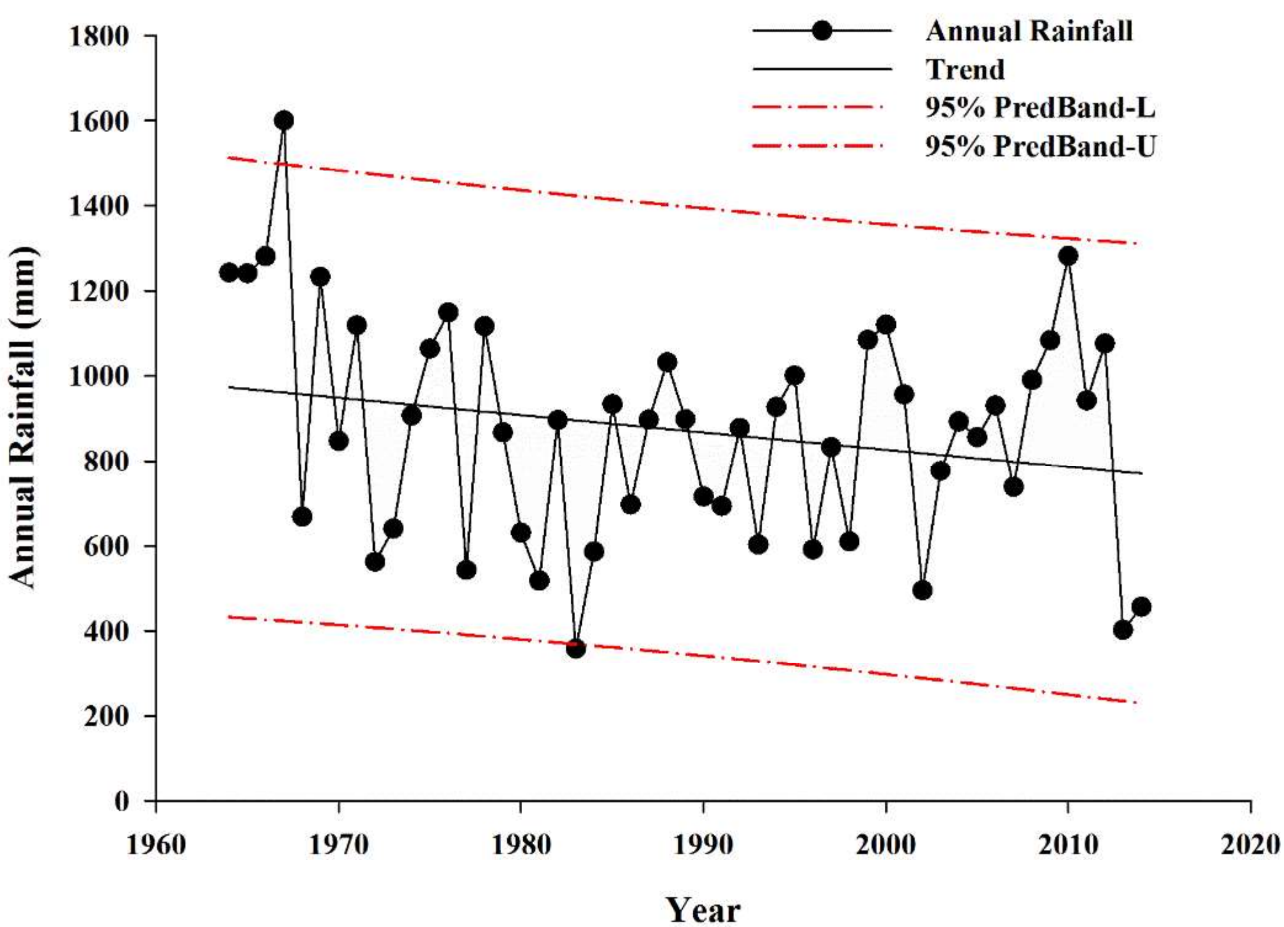

Figure 3. Long-term rainfall pattern for Banjul, 1964 – 2014 (Source: **The Gambia Meteorological Bureau, 2015**).

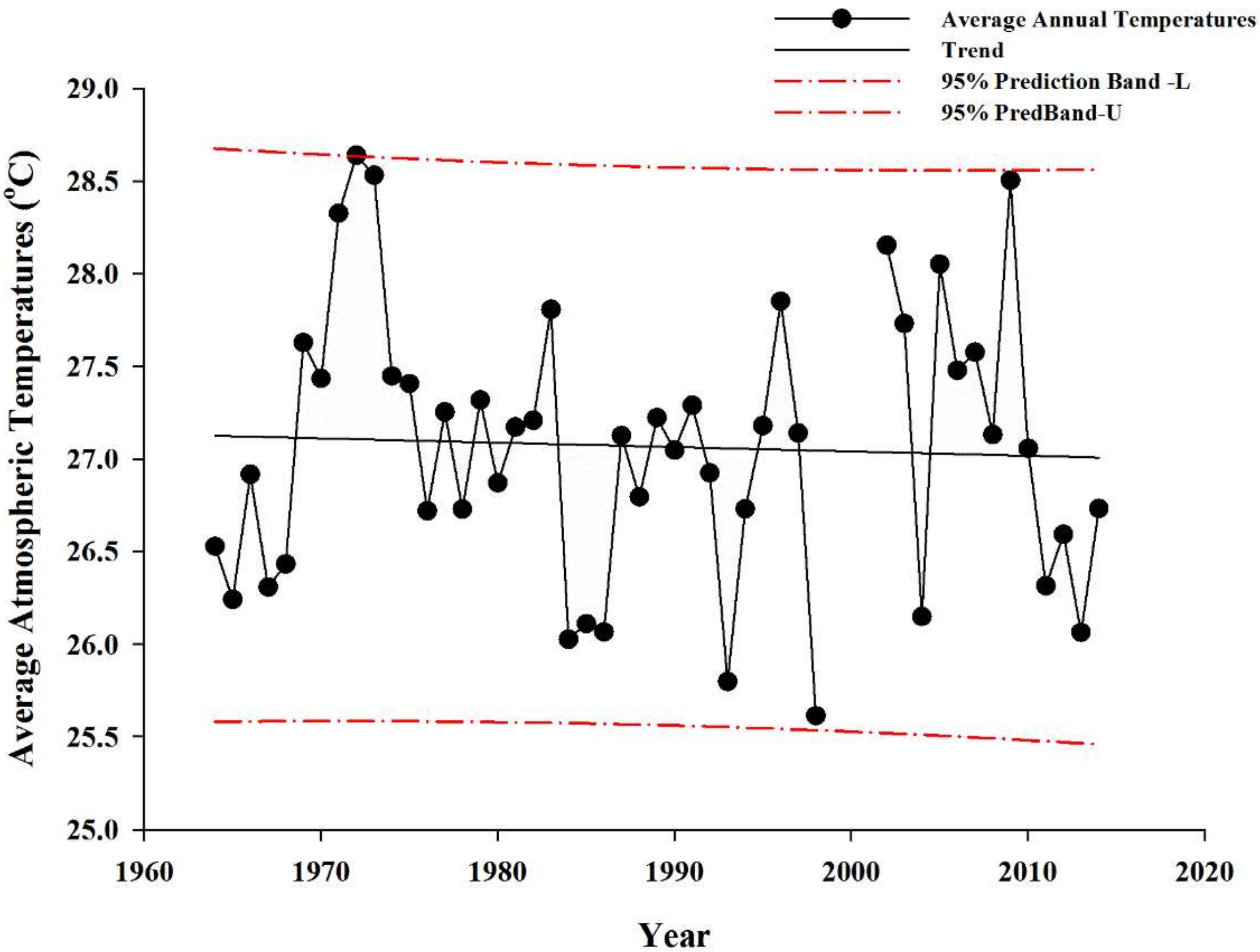

Figure 4. Long-term atmospheric temperatures for Banjul, 1964 – 2014 (Source: **The Gambia Meteorological Bureau, 2015**).

A result of the situation above was an increase in soil salinity and acidity, as well as a corresponding area expansion of the tannes at the expense of mangrove forests **(Marius, 1982)**. Due to this situation, many of the farmers from rural communities are obliged to migrate to the urban areas in search of better jobs and alternative resources e.g. coastal resources **(National Environment Agency, 2010)**. The annual rate of increase in urban population is now almost twice (4.1%) that of the national level (2.6%) and as a result, over 63% of the population now lives in the Greater Banjul Area (GBA), which is only 16% of The Gambia's total land area **(National Environment Agency, 2010)**. The pressures exerted by the socio-economic activities of such a population could be overwhelming for the natural resources available, in this case estuarine biodiversity **(Baran, 2000)**.

Nonetheless, in a recent ethnoecological study of the TWNP, **Satyanarayana *et al.* (2012)** reported that the impacts of the socioeconomic activities are well within the carrying capacity of the park. However, in a similar study on the same site **Maniatis (2005)** expressed that it is quite unlikely to find a mangrove ecosystem that is flanked on three sides by development, serving as an extensive hub for the major economic activities such as fishing, rice growing, tourism etc.; yet remaining intact over time. These two contradicting findings have triggered the need for more clarity in the status of the mangrove ecosystem under the effects of climate and land use change. Thus, it is hoped that this research would fill the existing information gap.

Like most estuarine systems in the world, the coupled effects of human activities and climate change have taken a serious toll on the stability and the ecosystems services of the River Gambia estuary **(McSweeney, 2012)**. The increase in atmospheric temperatures, sea level rise and low freshwater discharge into the estuaries due to declining rainfall have led to great losses in mangrove vegetation during the past three decades **(Spalding *et al.,* 1997)**. The resultant ecosystem changes e.g. long-term inundation and increase in tidal amplitudes have had great implications for coastal organisms **(Castellanos-Galindo & Krumme, 2015)**, for example local extinctions of fish species **(Blaber *et al.,* 2000)**. In addition, during a comparative assessment of the vulnerability of mangroves to climate change, **Ellison (2015)** reported that sea level rise is the major climate variable impacting mangroves and mangrove ecosystem processes in the tropics Table I.

Table I. Exposure components of climate change impacts on mangroves, processes affected, and sensitivity outcomes (Adapted from **Ellison, 2015**).

Exposure components	**Processes affected**	**Sensitivity components**
Rising sea level	Forest health Forest productivity Recruitment Inundation period Accretion rates	Forest mortality, dieback from the seaward edge, migration landward, depending on sediment inputs, topography and lack of barriers.
Increased waves, wind and extreme storms.	Forest productivity Recruitment Accretion rates	Forests damaged or spatial area changed, surface elevation change, erosion or excess sedimentation.
Increased air and sea temperatures.	Respiration Photosynthesis Forest productivity	Reduced productivity at low latitudes and increased winter productivity at high latitudes.
Enhanced CO_2.	Photosynthesis Respiration Biomass allocation Forest productivity	Increased productivity, subject to limiting factors of salinity, humidity, nutrients. Soil elevation increase.
Increased rainfall and fresh water availability.	Sediment input Groundwater Salinity Productivity	Increased accretion and maintenance of surface elevation, increased ground water, diversity, productivity and recruitment.
Reduced freshwater availability.	Sediment inputs Groundwater Salinity Photosynthesis Forest productivity	Reduced ground water, diversity, photosynthesis, productivity and accretion. Mangrove migration landward, species changes.

In connection, as of 1989 tidal amplitude around Banjul reached a mean of 2.9m from an initial mean of 2m in the early 1980s due to sea level rise **(Jallow *et al*., 1999)**. Another estuarine phenomenon resulting from sea level rise is seasonal hyper-salinity, which has become frequent within the Sub-Saharan mangrove estuaries, including The Gambia **(Darboe, 2002)**. Because of these frequent fluctuations in the water quality parameters, slow growth/ mangrove dwarfism and death are common sights in the estuaries of The Gambia **(Marius, 1982; Sandbrink & Meijeren, 2010)**. These are indicated by the presence of numerous mangroves with a uniform height of less than 3m and root stumps of the red mangrove, *Rhizophora mangle* (Linnaeus, 1753) and black mangrove, *Avicennia germinans* (Linnaeus, 1764) (Figure 5 and Figure 6).

It has been reported that countries with high rates of mangrove loss usually register great decline in fisheries, as nursery grounds become unstable **(Lubbers *et al.,* 1990; McKee, 1996)**. Similarly, recent reports on fisheries stocks show a decline in fish catches in and around TWNP **(Lee *et al.,* 2009)**. Between 2006 and 2011 alone, the annual fish landings for the three local communities (Banjul, Bakau and Jeshwang) surrounding TWNP have declined by 36%, 13% and 7% respectively **(The Gambia Fisheries Department, 2011)**. The size and number of fish caught, as well as oysters and cockles usually harvested from the mangrove pneumatophores have also become smaller; forcing most of the Banjul-based harvesters to move to the North Bank where Catch per Unit Effort (CPUE) is more stable **(Lee *et al.,* 2009)**.

All these highlight the effects of hyper-salinity caused by the coupled impacts of climate change and socio-economic activities on mangrove, leading to great losses in estuarine biodiversity within The Gambia **(Lee *et al.,* 2009)**. Variations in hydrological regime and deteriorating vegetation have been the factors proven to impede the entry of larvae and juveniles of marine species into the estuaries of The Gambia during the dry season **(Darboe, 2002)**. This trend if continued will lead to drastic shifts in fish populations, consequences of which will be gruesome on people's livelihoods, biodiversity conservation aims as well as The Gambia's economy as a whole.

Figure 5. *Rhizophora mangle* (Linnaeus, 1753) (red mangroves) of uniform height ($\leq$ 3 m) in Tanbi Wetland National Park in The Gambia in 2014.

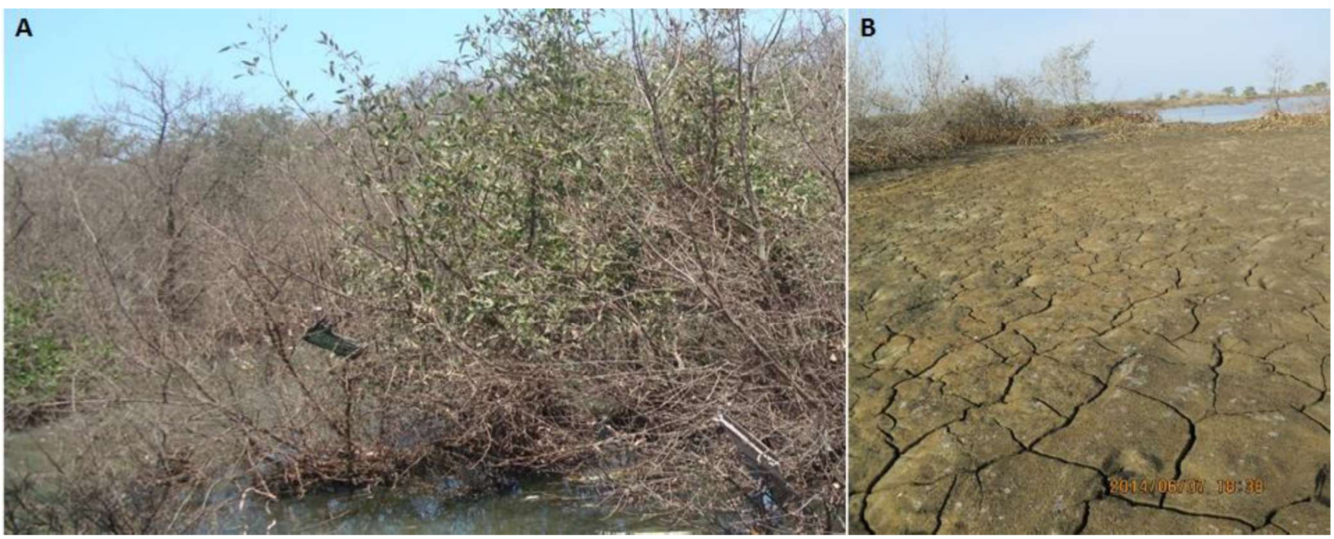

Figure 6. Massive death of *Avicennia germinans* (Linnaeus, 1764) (black mangrove) (A) and salt deposits (B) caused by salt water intrusion and evaporation during the dry season in Tanbi Wetland National Park in The Gambia in 2014.

Justification

The need for policy makers and urban planners to lay hands on scientific research that makes predictions and recommendations for successful implementation of desired environmental programs cannot be overemphasized. This will positively influence decision-making for proper biodiversity conservation and adaptation to climate change by offering substantial mindset shift for full recognition of the fundamental role of ecosystems as life-supporting systems **(Mertz *et al.,* 2009; Munang *et al.,* 2010)**. Although a lot of work has been done at national, regional and global levels, there is still a substantial information gap concerning the assessment of changes in mangrove habitats especially for the coasts of West Africa. These areas are under serious threat due to the fact that population densities are high and industrial development is taking center stage **(Corcoran *et al.,* 2007)**.

As such, the research proposed herein will contribute towards bridging the information gap by providing on-the-ground status information and useful recommendations for timely intervention/conservation of mangrove ecosystems such as the TWNP in The Gambia. Loss of aquatic biodiversity in The Gambia has been attributed to climate factors such as change in tidal regimes and shifts in salinity gradient **(Jallow *et al.,* 1996)**. As early as 1982, mangrove deaths of over thousands of hectares were reported in The Gambia, the cause believed to be a minor (<5 centimeters) but rapid (<6 weeks) change in the hydrological regime **(Blasco *et al.,* 1996)**. This period is believed to be part of a recurrent trend of droughts which has existed for more than thirty years beginning with the Sahelian drought in 1972 and causing numerous adverse ecological and human effects **(Hutchinson, 1985)**. Overexploitation, pollution and coastal erosion have also been incriminated. Thus, the main ecological challenge for coastal and marine zones of The Gambia is to safeguard and conserve the biodiversity and ecological assets **(The Gambia Government, 2007)**. To this end, the present research work was undertaken to contribute with strong scientific findings to the conservation and management of biodiversity in mangrove estuarine ecosystems of The Gambia.

Moreover, information available on the state of the River Gambia estuary is disjunctive at best, making its incorporation into conservation plans/activities a nearly impossible task. As a result, national projects aimed at training local communities in sustainable mangrove utilization have not been able to slow down the deterioration trend of mangroves in The Gambia **(National Environment Agency, 2010)**. These projects advocate for rational utilization of resources in order to minimize human impacts, while seemingly overlooking the fact that biomass levels of the mangrove habitats are also tied to climatic variation **(Williams & Rota, 2011)**. Hence, measures such as controlling fishing effort only limits fishers' incomes without really solving the problem of biodiversity loss **(O'Reilly *et al.,* 2003)**. This research can contribute toward solving this problem by shedding light on the carrying capacity of the mangrove estuaries of TWNP.

Besides, the only comprehensive pilot study conducted on the intended study site (TWNP) was done in 2005 to determine mangrove species composition and socio-economic impacts on the wetland integrity. It reported negligible changes in mangrove vegetation due to human intrusion **(Maniatis, 2005)**. The aforementioned pilot study has set a strong foundation for further research, which needs to be built upon to seal the information gaps concerning the factors responsible for the progressive biodiversity losses in TWNP. The current research proposed here shall fill that gap by further studying the synergistic impacts of land use change and climate change and variability.

Research aim

The main aim of this research work is to investigate the effects of climate-induced hydrological changes on mangrove and the implications for estuarine fisheries in The Gambia, based on the dynamics of vegetation cover, seasonal water quality and dwelling fishes.

Bearing in mind the biodiversity conservation problems highlighted previously, this research seeks to answer the following questions:

- What is the role of seasonal variability in the long-term changes in hydrological regime of the estuarine ecosystem?
- What are the main drivers of vegetation change in the mangrove estuary of TWNP?
- How does seasonal variability of water quality affect fish assemblage in the mangrove estuary of TWNP?
- How does local knowledge/the lack of it affect conservation efforts under a changing climate?

In order to generate the appropriate protocol for answering the research questions mentioned above, various hypotheses were formulated based on literature as well as preliminary field observations concerning the intended study site. These hypotheses were as follows:

1. During the past four decades, there has been a noticeable degradation in the mangrove vegetation cover within TWNP.
2. Changes (short and long-term) in climate variables affect the balance of physico-chemical parameters in the mangrove estuary of TWNP.
3. Seasonal variability plays a significant role in shifts of estuarine fish assemblage/community structure in TWNP.

4. Socio-economic groups can serve as an important source of information on observed ecosystem changes in fragile mangrove estuaries.

In relation, specific objectives were formulated corresponding to the hypotheses and research questions mentioned above. The specific objectives of this research were as stipulated below:

1. To assess vegetation dynamics of TWNP for the past four decades (1973 – 2012).
2. To study the seasonal changes in physico-chemical parameters of the TWNP.
3. To assess the effects of seasonal fluctuations in water quality/physico-chemical parameters on the fish assemblage in TWNP.
4. To assess local knowledge on climate-induced ecosystem changes and document local adaptation strategies.

CHAPTER I – LITERATURE REVIEW

1.1. The earth's energy balance

As explained by **Bastian (2012)**, the earth receives its energy from the sun in the form of shortwave radiation (sunlight). When this sunlight makes its way through the atmosphere, a part of it is reflected back into space, and the other part penetrates to warm the earth's surface. Part of this is reradiated in the form of infrared (longwave radiation) back into space. Greenhouse gases (GHGs) such as carbon dioxide (CO_2) released from the burning of fossil fuels form a blanket in the atmospheric layer, trapping infrared radiation and re-emitting it back to the earth; thereby causing warming **(Bastian, 2012)**. The upward shift in global temperatures as a result of the heat trapped by these GHGs is referred to as the greenhouse effect (GHE) **(IPCC, 2007)**. When driven to extremes, the GHE can interfere with important life processes such as the carbon cycle **(IPPC, 2014)**. Although under natural conditions, carbon is exchanged through the various reservoirs of life with a balanced exchange between the biosphere, atmosphere and the world's oceans **(IPPC, 2014)**.

Prior to the industrial revolution, atmospheric concentration of GHGs was at equilibrium and thus, negligible amounts of infrared heat were trapped by these gases. But the uncontrolled release of CO_2 (and other GHGs that absorbs longwave radiation) from anthropogenic activities have resulted in the earth retaining more heat than it is releasing. In the past 100 years, the continued release of carbon has tipped the carbon cycle into trapping more heat in the stratosphere and creating a cumulative energy imbalance that warms the earth's atmosphere, surface and oceans **(Doney *et al.,* 2012)**. As a result, average global temperatures have increased by 0.85^{o}C between 1975 and 2012; meaning an increase of about 1^{o}C every century **(Bastian, 2012)**. Fourteen out of the fifteen hottest years in meteorological history occurred between the year 2000 and now, with the past three decades being record warmest **(Trenberth *et al.,* 2007)**.

Even though, certain warming periods were recorded from the early deglaciation periods, these were explained by natural activities such as super-volcano eruptions, resultant extinction triggers or by deglaciation events activated by orbit cycles **(Bastian, 2012)**.

The second greatest driver of climate change is deforestation. Since plants absorb and store CO_2 and release oxygen (O_2) through the process of photosynthesis, their indiscriminate removal releases their stored carbon dioxide without the necessary vegetation to absorb the released CO_2, thus increasing the atmospheric CO_2 **(Chmura *et al.,* 2003)**. Global CO_2 concentration increased from 280ppm during the pre-industrial period to 398ppm in the year 2014 **(IPCC, 2014)** i.e. an increase of 42%, half of this increase occurred during the last three decades; increasing at a rate of ≥2.0ppm each year between 2000-2009. According to **Bastian (2012)** "when we add all the CO_2 increase in the atmosphere to the observed increase in the oceans, the sum is approximately equal to all of the coal, oil and natural gas burnt since the 19th century".

1.2. The global climate

Climate change has been dubbed the single greatest threat to humanity, and as such ignoring it will only magnify its predicted global ramifications. Even with the different schools of thought on the degree of change, there is a general consensus that our planet is warming at an unprecedented rate consistent with the increase in fossil fuel burning and mass deforestation **(Bastian, 2012)**. For instance, global surface temperatures increased by about 0.85ºC over the past 100 years; 0.55ºC of which occurred during the past 30 years **(Mertz *et al.,* 2009; IPCC, 2014)**. The years 1995 to 2006 were the warmest years of global surface temperatures ever recorded since 1850, with arctic temperatures increasing twice more than the global average **(IPCC, 2007)** and Africa, Asia, and Latin America having registered a temperature increase of 0.5ºC to 1.0ºC within the same period **(Trenberth *et al.,* 2007)**. Africa alone has registered an increase of 0.7ºC within the 20th century and is predicted to register a decadal increase of up to 0.5ºC for the next century **(Diop *et al.,* 2010)**.

With oceans absorbing about 80% of the heat added to the climate system **(IPCC, 2007)**, sea level rise followed a similar trend to surface temperatures. Between the last glaciation and the Holocene, global sea level rose by approximately 80m **(Clark *et al.,* 2012)**; at an annual rate of 1.8mm between 1961 and 2003, and then doubling up to 3.1mm between 1993 and 2003 **(IPCC, 2007)**.

Precipitation has also registered serious declines, especially in tropics from 10ºS to 30ºN since the 1970s **(Trenberth *et al.,* 2007)**; contrary to the increasing wetness in South America and northern and central Asia, the Sahel, southern Africa, and parts of southern Asia have been getting drier since 1970 **(Dai *et al.*, 2004)**.

Even though all the changes above are occurring at a global scale, the impacts of climate change are foreseen to be more severe in poor developing countries where atmospheric temperatures are already high, national dependence on rain-fed agriculture (which is directly affected by climate change) is heavy and the high levels of poverty preventing proper adaptation **(Mertz *et al.,* 2009)**. In these countries, climate variability and change will enhance heat and moisture stresses and contribute to an already long list of existing problems **(Schmidhuber & Tubiello, 2007)**. Hence there is need for more adaptation, because no matter how well we manage to reduce the growth in emissions, the inertia in the climate system will lead to climate change and result in impacts on natural and managed systems **(IPCC, 2007; Mertz *et al.,* 2009)**.

1.3. Marine biomes and climate change

Climate change is one of the greatest drivers of change in marine ecosystems and evidence of observed climate change impacts is strongest and most comprehensive for natural systems. The rate of global warming and the melting of ice sheets caused global mean sea level to continue rising during the Holocene, causing large disturbances and range shifts in marine ecosystems **(Clark *et al.,* 2012)**. The global trend in sea level rise may further aggravate the problems of coastal erosion and flooding, with impacts on coastal settlements and infrastructure **(IPCC, 2007)**. Similar predictions were made with regards to the ecological impacts in coastal habitats such as mangroves, seagrass beds and coral reefs, as species struggle to adapt to changing conditions **(Diop *et al.,* 2010)**. For instance, vegetation growth in a marine ecosystem is mostly dependent on physical conditions such as sea level and inundation duration **(Kirwan & Mudd, 2012)**. Thus, there is a strong relationship between sea level rise and declining vegetation in marine biomes i.e. mangroves and sea grass beds **(UNEP, 2010)**.

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of both quantity and quality, and as a result many marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to ongoing climate change **(IPCC, 2014)**.

As global atmospheric temperatures increase, it is accompanied by melting of the ice caps and poses great impacts on species distribution as marine species respond to ocean warming by shifting their latitudinal range as the integrity of marine ecosystems become increasingly affected **(Cheung *et al.,* 2009)**. For example, the increase in sea surface temperatures has been reported to cause large-scale coral mortality by bleaching in the coasts of Eastern Africa **(Diop *et al.,* 2010)**. In addition, marine biomes serve as the world's biggest carbon sink **(Chmura *et al.,* 2003)**. Acidification of ocean waters through the increasing dissolution of atmospheric CO_2 is thus another cause for global concern in marine biomes **(Chen, 2008)**. An average global decrease of 0.1 units of pH has been recorded for the world's oceans due to the increasing uptake of anthropogenic carbon since 1750 **(IPCC, 2007)**. A continuation of this trend was predicted to cause detrimental interruptions in physiological processes such as spawning of finfish, formation of exoskeletons in crustaceans etc., leading to great alterations in ocean food webs and a decline in global marine fisheries **(Blaber, 2013)**. The effects of such disturbances on distribution of fish species are reportedly already being observed in the form of local extinctions, species invasions and turnover, leading to a destabilization of the current global species richness of marine fishes **(Cheung *et al.,* 2012)** (Figure 7).

1.4. Mangroves and estuarine fisheries

Mangroves are unique tropical and subtropical plants that are specially adapted to thrive in inundated and saline intertidal zones **(Sremongkontip *et al*., 2000)**. Based on their ability to cope with high salt concentration and regular inundation, mangroves form the primary features within estuarine and marine ecosystems **(Kathiresan & Bingham, 2001; Syed *et al.,* 2001)**. Mangrove estuaries are regarded as one of the world's most productive natural ecosystems **(Alongi, 2009)** as they provide unique ecosystems services including: carbon fixation, storage and mineralization; serving as nursery grounds for aquatic fauna; shoreline protection, and also their land-building capacity **(Lee *et al*., 2014)**. Due to their location between land, seas and rivers, mangrove estuaries act as a buffer zone **(Dahdouh-Guebas *et al*., 2005; Dia, 2012).**

Mangroves have been extensively studied globally and as of the year 2010, 8000 publications have been indexed on mangrove studies, indicating an ever increasing global interest in these unique vegetation **(Lee *et al*., 2014)**. Mangrove ecosystems have undergone immense changes due mostly to direct human activities such as agricultural and industrial expansion. These were initially labeled the main culprits for mangrove degradation, mostly because losses in mangrove vegetation have been higher in areas where human populations and urbanization are high **(Manson *et al.,* 2005)**. Globally, mangrove coverage has declined from 198,000 km^2 in 1980 to 150,000 km^2 in 2012 **(Van Lavieren *et al*., 2012)**. This decline can now be attributed to the impacts of both natural and anthropogenic processes **(Spalding *et al*., 1997)**. Of the remaining global mangrove coverage, one fifth of it is found in sub-Saharan Africa, and 70% of this is found in 19 countries in West Africa **(Diop *et al.,* 2010).** Mangrove distribution for West Africa is shown in Figure 8.

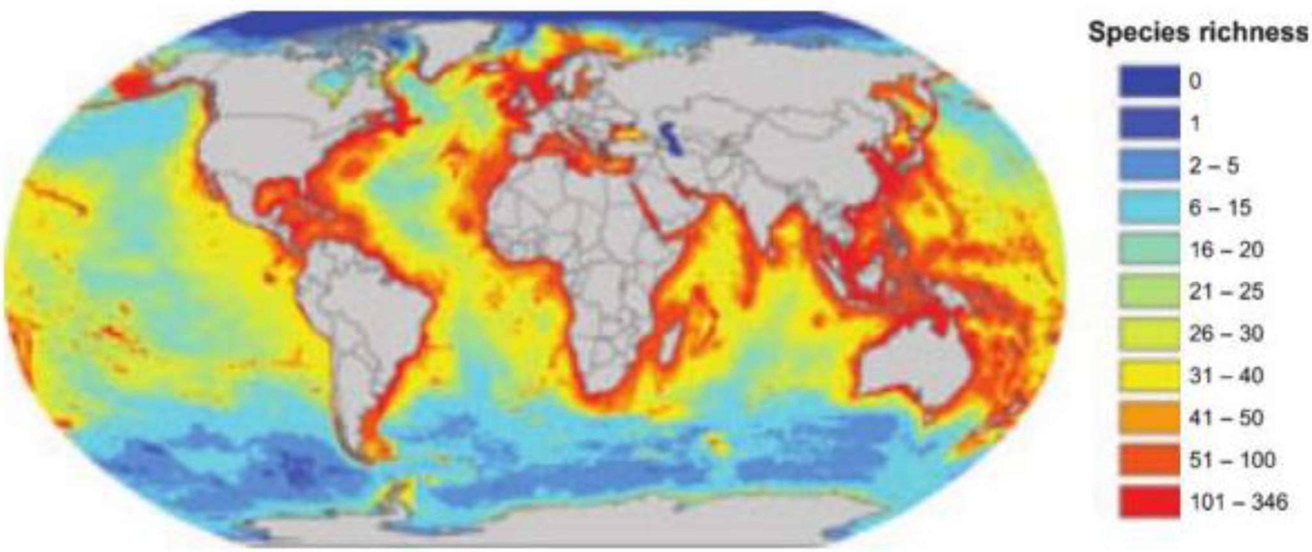

Figure 7. Global distribution of species richness in marine fishes and invertebrates (Source: **Cheung *et al.*, 2009**).

Figure 8. Mangrove distribution in West Africa (Source: **Crow & Carney, 2013**).

Notwithstanding, research focus has recently been shifting towards natural causes of global mangrove loss i.e. climate change. The effects of changes in climate variables such as sea level rise have been reported to be one of the major threats to mangrove estuarine health as it strengthens the occurrence of salt intrusion/hyper-salinity in the usually moderately brackish mangrove ecosystems **(Panfili *et al.*, 2004)**. Changes in rainfall pattern on the one hand cause major ecological disturbances within mangrove estuaries, as river flow declines with insufficient rains and on the other hand wetlands get seasonally flooded with excess rains; thus increasing their vulnerability to natural variability **(Schlenk & Lavado, 2011; Villanueva, 2015)**. In addition, human stressors add to this vulnerability **(Ellison, 2015)**. In this situation, mangrove ecosystems continue to be transformed, degraded and overwhelmed as their natural environment continues to deteriorate **(Van Lavieren *et al.*, 2012)**.

The recent changes in climate form a synergistic relation with the impacts of socio-economic activities such as agriculture, leading to drastic changes in hydrology/physico-chemical parameters in mangrove estuaries and reduced habitat integrity (hyper-salinity) **(Panfili *et al.*, 2004)**. **Austin *et al.* (2010)** also suggested that modest changes in rainfall and temperature caused significant reductions in mean annual runoff and increased stream salt concentrations in Murray-Darlin Basin (Australia), resulting in loss of vegetation. Such drastic changes in hydrology were also reported to induce stunting of *Avicennia marina* (Forssker, 1907) stands and denaturing of terminal buds in *Rhizophora mangle* (Linnaeus, 1753) seedlings in the USA **(Kathiresan, 2002)**. Hence there is a general consensus that mangrove estuaries are inadvertently one of the world's most delicate ecosystems. For proper functioning of mangrove estuaries, a healthy vegetation (mangrove) is prerequisite, as the relationship between ecosystems health and the quality and quantity of services they provide is a delicate one **(Williams & Rota, 2011)**. **The U.S. Fish and Wildlife Services (1999)** reported that mangroves improve water quality and clarity by filtering upland runoff and trapping waterborne sediments/debris and at the same time recycling and maintaining the nutrient mass balance of the estuarine ecosystems. **Vannucci (2001)** also suggested that mangroves serve as a sink of carbon, heavy metal pollutants and other toxic compounds, making their regulatory role very vital for cushioning the effect of seasonal variability on estuarine waters, as well as for the dwelling fauna.

Therefore, a vibrant mangrove cover is necessary for providing favorable ecosystem conditions and services. As the release of GHGs has continued at an alarming rate these past few decades, the role of mangroves as carbon fixers in the tropics is increasingly being recognized **(Alongi, 2009)**. Thus, the degradation of mangroves can destabilize the estuarine physico-chemical balance and stall important biological and biochemical processes such as photosynthesis, decomposition and nutrient uptake, spawning activities and consequently growth and reproduction of dwelling fauna **(Jallow *et al*., 1999)**. If left unchecked, mangrove degradation can thwart global efforts in reversing the current trend of GHGs in the atmosphere, as CO_2 assimilation rates are twice higher in mangroves than in regular tropical forests **(Alongi, 2009)**.

In addition to the above, unsustainable land use practices could spell doom for third-world countries with low adaptive capacity such as The Gambia. Current research shows that fish provides 20% of the total animal protein intake in Africa **(Williams & Rota, 2011)**. The estuaries of West Africa in particular exhibit fish production ranging around 15 to 16 tons/km^2/year **(Blaber, 2013).** However, this amount is only a reality under ideal hydrological stability. For instance, **Panfili *et al.* (2004)** reported reduced maturity size for the cichlid *Sarotherodon melanotheron* (Rüppell, 1852) in the estuaries of The Gambia and Senegal due to progressive hyper-salinity and as a result, lower tonnage per unit area. This species can only withstand hyper-salinity by limiting its growth, reducing maturity size and lowering its fecundity level **(Panfili *et al*., 2004)**.

Consequently, the need for assessment of ecosystem change in mangrove estuaries while taking account of both natural and anthropogenic factors cannot be overstated **(Munang *et al*., 2010)**. This will provide appropriate recommendations for the rational use of mangrove estuaries in accordance with the global stride towards sustainable development. It will also increase resilience of coastal communities against the immediate impacts of seasonal variability as well as the long-term effects of climate change **(Peh & Lewis, 2012)**.

1.5. The case of the Sahel and Sahelo-Sudan

The Sahelian zone in West Africa is one of the poorest regions in the world and also has one of the world's fastest population growth rates **(McSweeney, 2012)**. The area is characterized by high variability in rainfall with a generally declining trend and ever increasing atmospheric temperatures since the famous Sahelian drought in the 1960s and 1970s **(Dai *et al*., 2004)**. With a 30% decline in rainfall with the past four decades **(Dai *et al*., 2004)**, this area has seen the adverse effects of long-term changes in seasonal pattern as a result of the latitudinal movement of the Inter-Tropical Convergence Zone (ITCZ) **(Hutchinson, 1985)**, manifesting in the form of desert encroachment, salt intrusion into previously arable agricultural land **(Prince *et al.,* 2007)** and hyper-salinity in many estuaries **(Villanueva, 2015).**
Such phenomenon is much more visible in the estuarine ecosystems of the Sahel where evaporation rates are as high as 5mm per day **(Pagés & Citeau, 1990)**. As a result, average salinity levels in many Sahelian estuaries have risen exponentially since the late 1960s, ranging from 35 ppt to more than a 100 ppt **(Pagés & Citeau, 1990; Panfili *et al.,* 2004)**. This in the long run led to the drying up of many lakes and the formation of many inverse estuaries e.g. the Sine-Saloum and Casamance inverse estuaries in Senegal **(Savenije & Pagés, 1992; Ecoutin *et al.,* 2010**; **Azzoug *et al*., 2012)**.
Located along the western part of the Atlantic coast, waters of this area are characterized by semi-diurnal tides with ranges that are locally variable but generally small **(Blasco *et al*., 1996)**. With the increase in projected sea level rise and reduced runoff, mean tidal height increases **(Jallow *et al.,* 1996).** Mangrove estuaries found within this climate zone are at an extreme ecological disadvantage, as they experience the impacts of climate change for the Sahel in the form of prolonged droughts as well as extensive floods from its Sudanian source. Hence, this climate zone is aptly named the Sahelo-Sudan **(Baran, 2000)**. The changes in rainfall pattern along this zone are believed to be from an eastward shift of convective activity typical of an El Niño-like event and disrupting normality within the ITCZ **(Blunden & Arndt, 2015)**.
The River Gambia estuary is found within the Sahelo-Sudanian climate zone, an area that is reported to have an average annual rainfall of less than 600mm, and annual rainy seasons lasting from 45 to 90 days **(Huq *et al.,* 2003)**. The annual number of rainy days in this area were reported to show a decrease over time in proportion to the decrease in actual rainfall and as result, The Gambia had registered a 40% decline in annual rainfall between 1956 and 1982 alone **(Hutchinson, 1985)**. Climate change manifestations similar to those of the Sine-Saloum and Casamance are beginning to surface in the River Gambia estuary, due to long-term variability in seasonal extremes within the Sahel and Sahelo-Sudan climate zones **(Savenije & Pagés, 1992)**. This situation has led to an unstable ombrothermic scenario

for The Gambia and inevitably causing a poor mixing power between rain water/runoff and sea water intrusion, within the estuaries of the River Gambia **(Belhabib *et al.*, 2013)** (Figure 9).

1.6. The River Gambia

The River Gambia has its source in Fouta Djallon (Guinea Conakry) and runs a length of about 700 miles **(Wood, 2000)**. It is one of the largest rivers in West Africa and comprises of two distinct habitat types: estuary at its mouth and freshwater further upstream **(Wood, 2000)**. It is regarded as a unique Nilo-Sudanian river due to its lack of any substantial habitat alterations and is not subjected to fishing pressure or human-related water pollution **(Reichard, 2008)**. This river is fringed by mangrove swamps, creeks and gallery forests and this created very diverse habitats which serve as home to about 1500 species of plants, 80 species of mammals, 330 species of birds, 26 species of reptiles, and 150 species of freshwater fishes **(Wood, 2000; Reichard, 2008)**.

The river supports a wide range of socioeconomic activities, with the most prominent ones being agriculture, fishing, and tourism **(National Environment Agency, 2010)**. Its estuarine part is of utmost importance to local livelihoods and is also considered to be a reference ecosystem for comparisons during research in other tropical estuaries subjected to natural and artificial perturbations **(Simier *et al.*, 2006)**. Notwithstanding, the estuarine part has recently begun to show signs of major climatic stress and these have been observed in more frequent occurrences of salt intrusions **(Lee *et al.,* 2009)**, retardation of growth in its major mangrove species (*Rhizophora mangle* and *Avicennia germinans*) **(Maniatis, 2005)** and disappearances of important fish species **(Leeney & Downing 2015)**.

In relation to the situation above, sites such as the Tanbi Wetland National Park (TWNP) located in the estuarine zone at the mouth of the River Gambia stand the risk of losing characteristic ecological traits which are the basis for its recent designation as a Ramsar wetland of international importance in the year 2007, if the trend of natural deterioration persists **(IUCN, 2010; The Ramsar Convention on Wetlands, 2012)**.

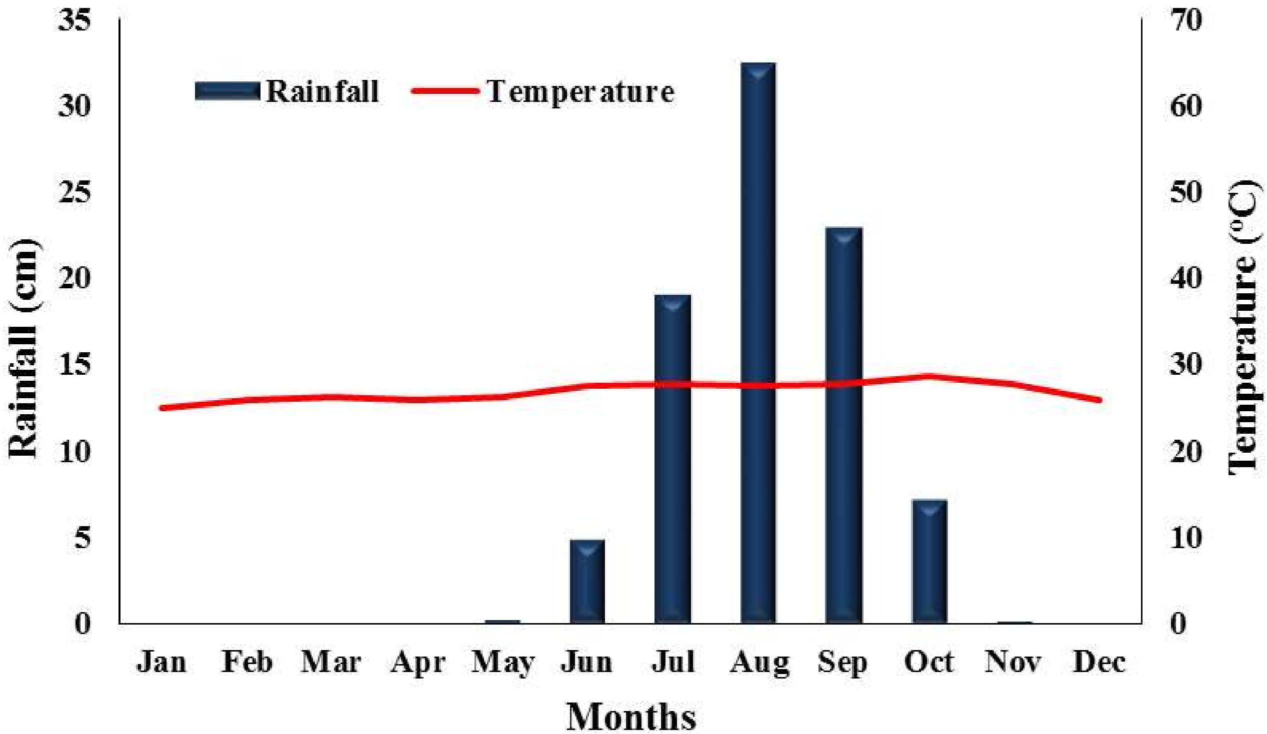

Figure 9. Ombrothermic diagram for Banjul (1964-2014) (Source: **The Gambia Meteorological Bureau, 2015)**.

CHAPTER II – MATERIALS AND METHODS

2.1. MATERIALS

2.1.1. Study site

The Tanbi Wetland National Park (TWNP) is a lowland area with a mean altitude of 1 to 1.6m above sea level, extending between 13º23N – 16º34W and 13º26N – 16º38W**(Lee *et al*., 2009)**. With an area of about 6304ha, the TWNP is flanked on the Southeast by the River Gambia and to the Northwest by the Atlantic and the Greater Banjul Area (GBA) in the Southwest **(Hirani, 2005;The Ramsar Convention on Wetlands, 2012),** as well as the capital city Banjul on the East **(Satyanarayana *et al.,* 2012)**. Located in the Sahelo-Sudanian climate zone, TWNP has a long dry season (October – June) and a short rainy season (June – October) **(Camara, 2012)**. Prominent land use types include: agricultural lands and dumping grounds; settlement areas; ubiquitous oyster processing zones with locally constructed oyster smoking pens; cruising boat docks for river excursions and so on **(Crow & Carney, 2013)**.

Mangroves in TWNP are comprised of *Rhizophora mangle* (Linnaeus, 1753) (red mangrove), *Avicennia germinans* (Linnaeus, 1764) (black mangrove), *Laguncularia racemosa* (Gaertner, 1807) (white mangrove) and *Rhizophora harrisonii* (Leechman, 1918) **(Maniatis, 2005)**. Common fish species previously reported in TWNP are *Ethmalosa fimbriata* (Bowdich, 1825), *Sardinella maderensis* (Lowe, 1838), *Sarotherodon melanotheron* (Rüppell, 1852) and *Oreochromis niloticus* (Trewavas, 1983) as well as the shrimp *Paneaus notialis* (Pérez Farfante, 1967) and oyster *Crassostrea gasar* (Deshayes, 1830) **(Baran, 2000; Darboe, 2002)**. The location of TWNP and the sampling stations are shown in Figure 10.

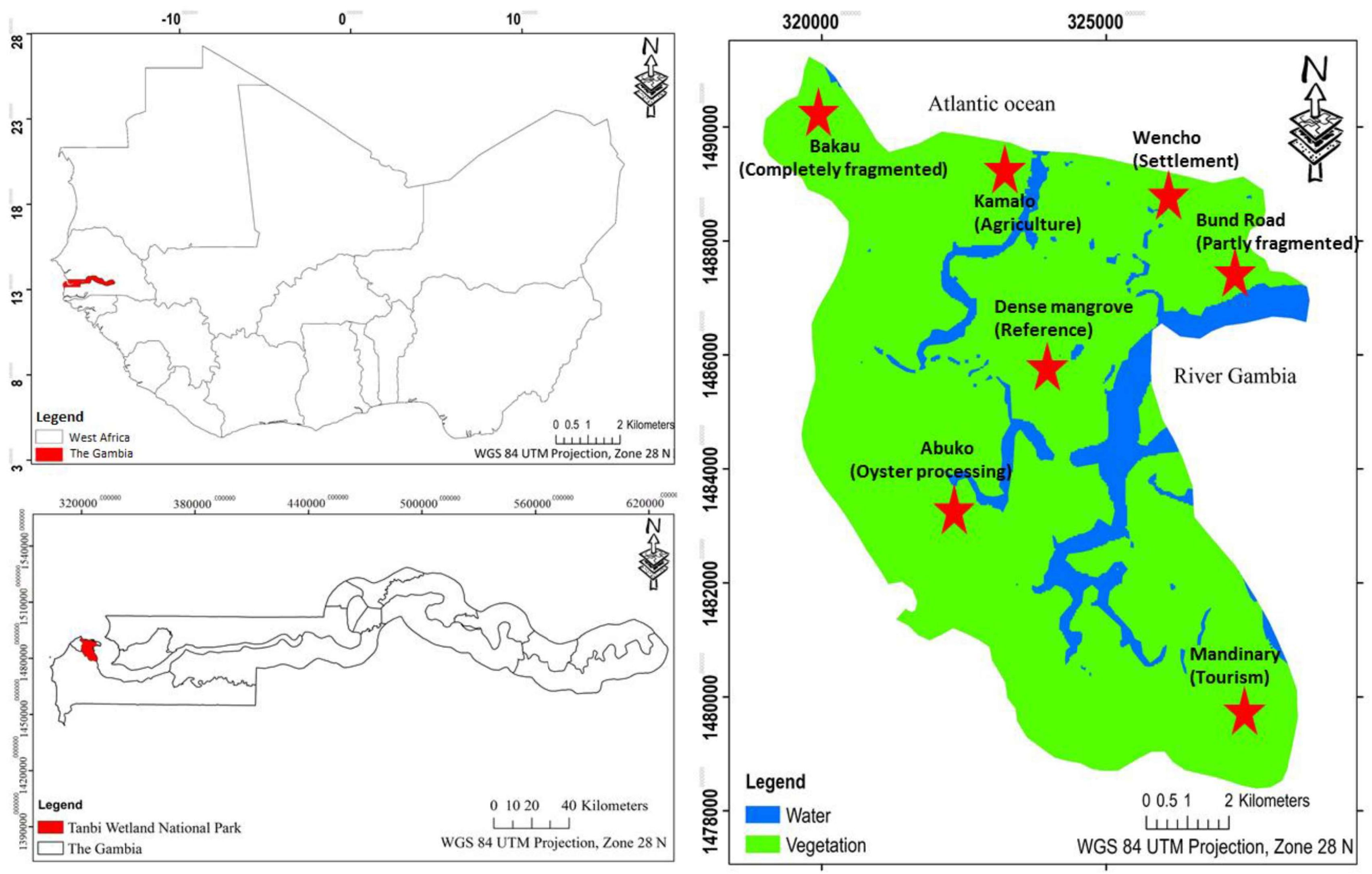

Figure 10. Location of The Gambia in West Africa and Tanbi Wetland National Park in The Gambia, with the sampling stations marked (red star).

2.1.2. Materials for water quality / environmental studies

For collection of water samples, 336 Polyethylene bottles of 500ml capacity were used for each season. Annual tide tables were acquired from the Gambia Maritime Unit for peak tidal forecasts prior to sampling. Laboratory grade disinfectant and foil paper were purchased for preparing sampling bottles and to eliminate the effect of light on water samples to be collected. Coolers / ice boxes were also purchased for temporary sample storage and transport to and from the field.

For analyses of physico-chemical parameters, the following devices were acquired: YSI Pro-plus watermeter for in-situ analysis of salinity, pH, dissolved oxygen (DO) and temperature; HACH turbidity meter for laboratory analysis of turbidity (HACH 2100P). NitraVer® 5 and PhosVer® 3 reactive reagent pillow packs were bought for use with a HACH spectrophotometer (DR/2010) during nutrient (nitrate and phosphate) analyses.

For chlorophyll a (chl-a) analysis, Whatman microglass fiber filters of 25mm diameter and 0.7µm porosity were procured for filtration of water samples. For extraction of filtered samples, 90% acetone solution was prepared. An Eppendorf centrifuge 5804 was borrowed for centrifugation of chl-a specimens and 0.1 N HCl (Hydrochloric acid) prepared for acidification before reading. A spectrophotometer (Perkin Elmer LAMBDA 25 UV/Vis system) was secured for reading concentrations of pigments in the resultant supernatants. A Cold storage unit of -80ºC was also borrowed for storing filtered samples.

2.1.3. Materials for mangrove vegetation dynamics studies

Satellite images of the TWNP based on a decadal time series (Landsat 1973, 1984, 1995, 2002 and 2012). Shapefiles of the study area with the administrative boundaries were obtained from the World Database on Protected Areas (http://old.unep-wcmc.org/world-database-on-protected-areas_164.html) and from the National Environment Agency in The Gambia. In addition, field data describing the different land use/land cover types was also acquired.

Field equipment used include a handheld Global Positioning System (GPS) receiver (Garmin eTrex 30), a digital camera (Canon G16 cyber-shot) and data collection forms formulated by the researcher. For software needs, ENVI 5.1 and ArcGIS 10.2 were installed for image analysis and mapping.

2.1.4. Materials for fish assemblage studies

A seine net of 100m x 4m, with mess size of 14 mm was procured. The net was leaded at one side and fixed with floaters on the other side to ensure a complete coverage of the entire water column. A sixperson capacity rowboat with the same fisherman aided by a four-man research team was used to deploy the fishing net at all sampling sites.

A polythene spread of 6m x 2m was used to sort fish caught at the various sampling sites. Polyethylene barrels were used for transporting catches to the laboratory. Two weigh scales were used in weighing the fishes caught: ACP-200 Digital Pocket Scale (0.01 – 200g capacity) for weighing fishes at fingerling stage and an H-110 Digital Hanging Scale (0.02 – 50kg capacity) for weighing fishes above 200g. A storage unit set at 4ºC was used for short-term (3 days maximum) storage of fish specimens and a 10% formalin solution used for long-term storage. A 3-piece SE handheld magnification set (2x, 6x and 9x capacity) was used for proper viewing of fishes' physical features and a DR dissection kit used in clipping fish body parts for ease of identification.

The fish identification keys software program **(Paugy *et al.,* 2003)** developed by the Institute for Research and Development (IRD) was acquired for identifying fresh and brackish water fishes of West African waters. In addition, textbook versions of the fish identification keys (The Fresh and Brackish Water Fishes of West Africa), Volumes I **(Lévêque *et al.,* 1990)** and II **(Paugy *et al.,* 2003)** were used for verification. The Fishbase website (http://www.fishbase.org) was also used to verify reported occurrences and or endemism of the identified fish species. In addition, Windows Estimates software version 7.5 program was installed for computations of fish species similarity indices for fish captured at different sampling stations.

2.1.5. Materials for social studies

Printed forms of the questionnaires were used for gathering the social studies information. These questionnaires were formulated to feature sustainability issues such as long-term (herein, four decades) ecosystem changes in TWNP. In addition, climate change matters and their relationship with socio-economic setup were also included based on the four categories below:

- Ecosystem changes in TWNP (physical changes in terms of water quality, soil, vegetation and fisheries).
- Climate change (as understood by the socioeconomic groups in TWNP).
- Economic status (as recorded in increase/decrease in daily earnings of the socioeconomic groups in TWNP.
- General observations (focusing on general understanding of the subject matter by the local people that are gainfully employed in TWNP).

Drawing boards, flipcharts and markers were also used for illustrations where necessary during the social studies interviews.

2.2. METHODS

2.2.1. Ecological concept model for mangrove estuaries

An ecological concept model was formulated to show the intricate relationship between the mangrove vegetation, water quality condition and fish community structure. The model is adapted from **Rudnick *et al.* (2005)** and it takes into account the various components and the delicate ecological balance of an estuary. **Rudnick *et al.* (2005)** stipulated that since estuaries are a meeting zone between fresh and marine water, they could be affected by various drivers of change, as well as multiple stressors. For example, sea level rise, agriculture and settlement activities, as well as excessive fishing and recreation. Therefore, it is necessary for all research work within estuaries to take into account how these factors interact to affect water quality condition, mangrove community, fish community, benthic grazers and fish-eating birds. The focus of this research was on the former three components i.e. water quality condition, mangrove and fish community (Figure 11).

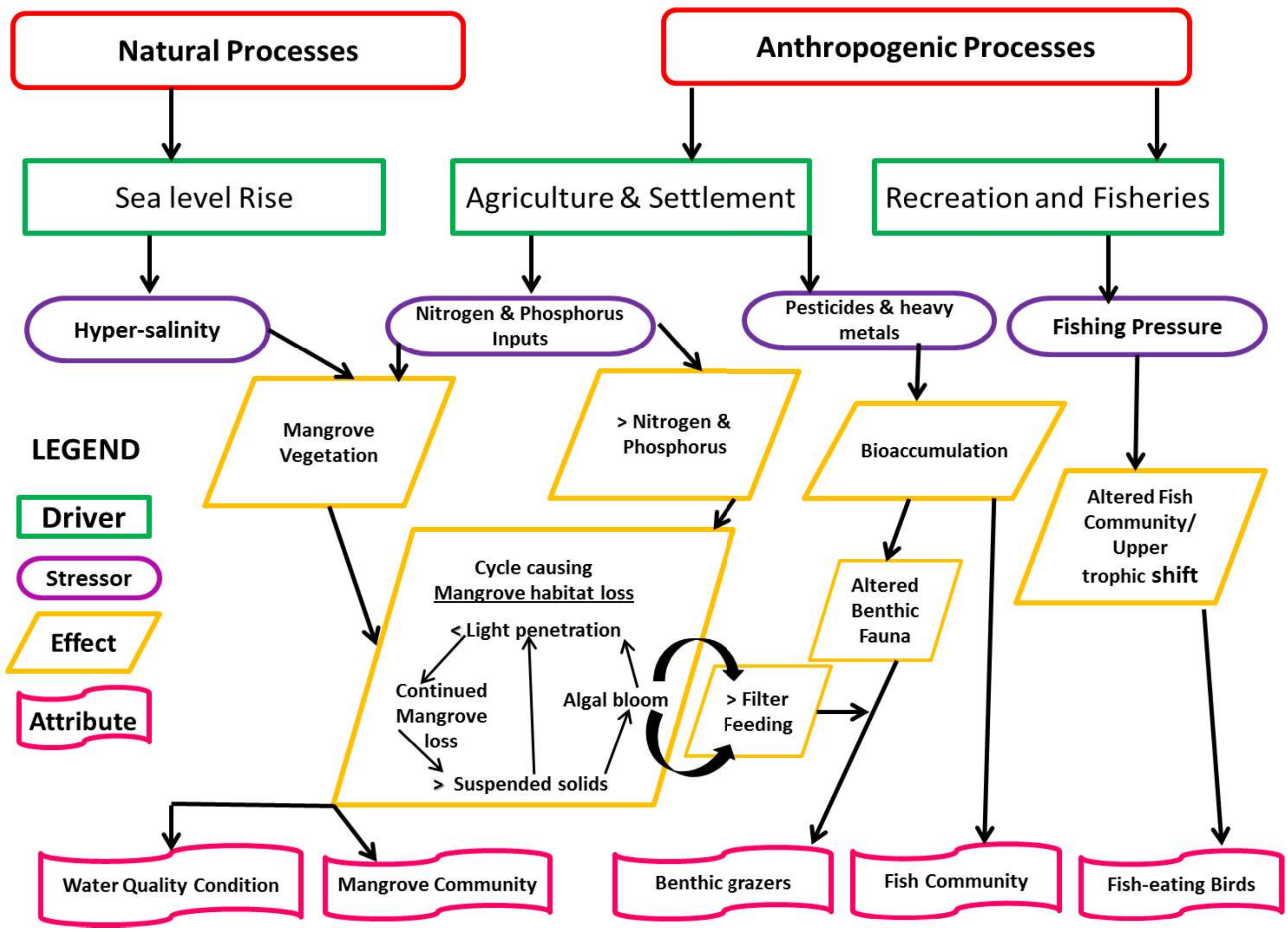

Figure 11. Ecological concept model for a mangrove estuary (Adapted from: **Rudnick *et al.,* 2005**).

2.2.2. Sampling design

Based on the increasing number of researchers advocating for an integrated research approach towards monitoring ecosystems change **(Turner *et al.,* 1994)**, as well as the reported trade-offs and synergies between climate change and anthropogenic activities **(Munang *et al.,* 2010)**, sampling design was based on the major land use/land cover types in TWNP. Seven sampling stations were identified as representative of the major land use types in TWNP and they include the following:

- Dense mangrove (reference zone).
- Kamalo (agriculture zone).
- Wencho (settlement zone).
- Abuko (oyster processing zone),
- Mandinary (tourism zone).
- Bund Road (partially fragmented zone).
- Bakau (completely fragmented zone).

Details of the sampling stations and their respective coordinates are shown in Table II.

For correlation with satellite imagery on mangrove vegetation studies and to ensure a uniform representation of the hydrological regime of the study area, a straight-line-transect method was used, according to recommendations of **Kathiresan (1990)** for sampling environmental/water quality parameters. Three transects were set perpendicular to the water source at each sampling point (adapted from **Louca *et al*., 2008**). In each transect, four plots were set to give 12 plots per land use type (Figure 12).

Table II. Sampling stations, land use types and their GPS coordinates in Tanbi Wetland National Park in The Gambia.

Sampling Point	Land Use Type	GPS Coordinates
Dense mangrove	Untouched (reference zone)	13.4295N – 16.6312W and 13.4306N – 16.6318W
Kamalo	Agriculture zone	13.4676N – 16.6338W and 13.4671N – 16.6349W
Abuko	Oyster processing zone	13.4097N – 16.6475W and 13.4106N – 16.6481W
Mandinary	Tourism zone	13.3824N – 16.0038W and 13.3831N – 16.0098W
Wencho	Settlement zone	13.4580N – 16.5965W and 13.4592N – 16.5989W
Bakau	Completely fragmented zone	13.4694N – 16.6643W and 13.4693N – 16.6642W
Bund Road	Partially fragmented zone	13.4524N – 16.5878W and 13.4531N – 16.5886W

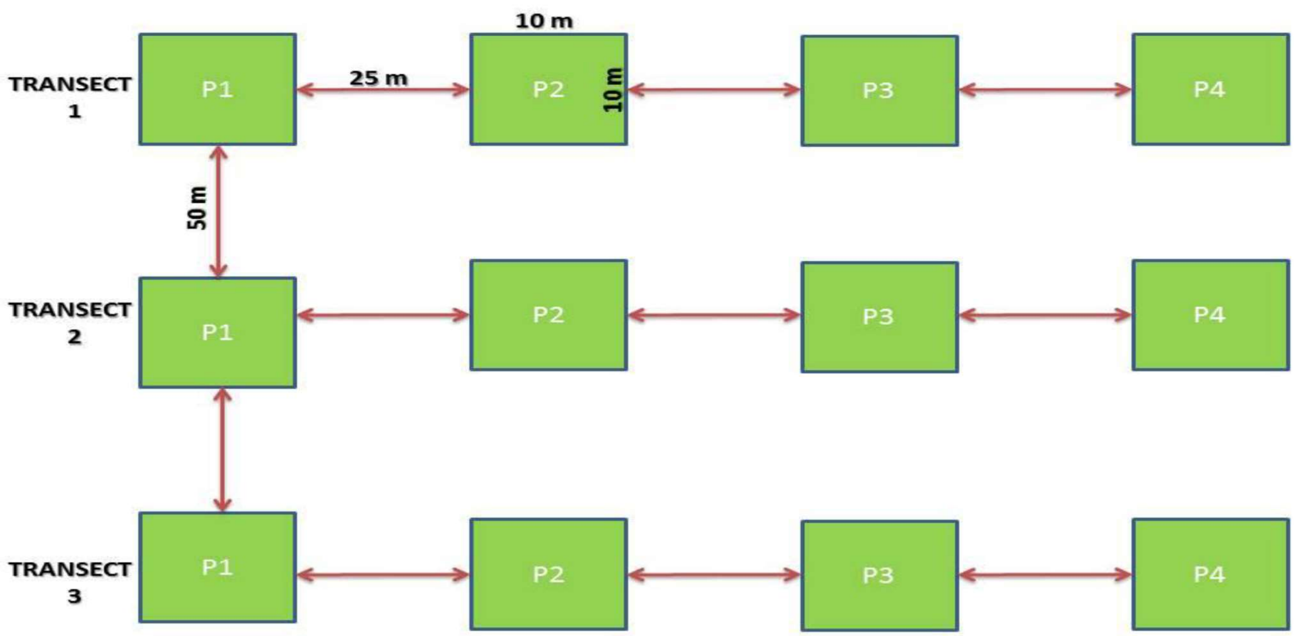

Figure 12. Sampling design used (Adapted from **Kathiresan, 1990; Louca *et al.,* 2008**). P: plot.

2.2.3. Environment / water quality analysis

There are five water quality parameters deemed most important for influencing diversity of aquatic organisms (both flora and fauna) and they include: salinity, dissolved oxygen, temperature, pH and turbidity **(California Environmental Protection Agency, 2010)**. These factors interact at ecosystem level to provide a suitable abode for all living things dwelling within a given aquatic body **(Rudnick *et al.,* 2005)**. Since estuaries are a meeting point for fresh and marine waters, its most important environmental variable is salinity **(US EPA, 2006)**. Thus, a balance in the influx of both fresh and marine water sources is important for a stable estuarine ecosystem **(Rudnick *et al.,* 2005)**. Factors influencing salinity in estuaries include rainfall, evaporation, sea level rise and most importantly freshwater runoff **(Panfili *et al.,* 2004**). The River Gambia for instance, has an important catchment basin and a freshwater flow that pushes back the salinity frontier to near the river mouth in the rainy season and dilutes the saline tides in the dry season **(Marius, 1982)**. This, together with uniform temperature is believed to be the reason mangroves in the upper parts of the River Gambia grow to amazing heights of 20 – 40 m **(Saenger & Bellan, 1995; Spalding *et al.,* 1997)**.

Temperature is another important factor that supports aquatic life by fueling the chemical and biological processes e.g. photosynthesis and nutrient decomposition, thus it is a key determinant for primary and secondary productivity within mangrove estuaries **(Kathiresan & Bingham, 2001)**. As a result of the above, temperature has a major influence on the stability of other life-supporting variables e.g. the rate of dissolved oxygen (DO) depletion in aquatic ecosystems **(Guillard *et al.,* 2012)**.

DO is relied upon by aquatic organisms for respiration **(Portner & Peck, 2010)**. However, because of the fact that DO in water is influenced by multiple factors e.g. temperature and water flow rate, it is a volatile variable that requires constant monitoring **(US EPA, 2006)**. An increase in water temperature for instance results in higher evaporation rates leading to loss of DO, while a decrease may lead to a more stable DO supply for dwelling fauna **(Ireland Environmental Protection Agency, 2001)**. Likewise, fast moving rivers may absorb more atmospheric oxygen than slower-moving ones **(US EPA, 2006)**. In comparison, no other environmental variable of ecological importance to estuarine and coastal marine ecosystems around the world has changed as drastically as DO has in response to land use change since the 19th century **(Diaz, 2001)**. Over the long run, this has led to loss of fisheries, loss of biodiversity and alteration of food webs within many estuaries **(Diaz, 2001)**.

Using the above as basis, the environmental phase of this research was centered on the following water quality variables: salinity, dissolved oxygen, pH, water temperature and turbidity, in accordance with recommendations for the River Gambia estuary **(Albaret *et al.,* 2004)**. Research during the past decade also confirms that nitrogen and phosphorus are the chief culprits in eutrophication/nutrient over-enrichment in coastal waters, which leads to oxygen depletion, especially around highly populated coasts **(Howarth *et al.,* 2000)**. In order to feature the effects of such stressors resulting from human activities such as agriculture and settlement, nutrient levels (nitrate and phosphate) were also measured according to methods of **Sandbrink & Meijeren (2010)**.

Based on the initially identified sampling design, water samples were collected diagonally at a depth of 10 – 25cm from 3 points at each plot to give 36 water samples per sampling site (n=36). Since no significant vertical stratification has been reported in water quality variables of the river Gambia estuary **(Darboe, 2002; Albaret *et al*., 2004; Guillard *et al*., 2012)** all water samples were collected at high tides between the hours of 6am and 12pm for measurement of water quality variables i.e. salinity, dissolved oxygen, pH, water temperature and turbidity, as well as for nutrients (nitrogen and phosphate) and chlorophyll a (chl-a). Physico-chemical parameters i.e. salinity, dissolved oxygen, temperature and pH were all analyzed in-situ using a YSI proplus water meter. Salinity was reported in parts per thousand (ppt), dissolved oxygen in milligrams per liter (mgl^{-1}) and temperature in degrees Celsius (^{o}C). In order to feature the effects of distance from the open coast on salinity levels at the various sampling stations, specific site distances were measured using the internet-based mapping tool **(Google free map tools, 2016)**.

At the same time water samples for nutrients (nitrate and phosphate) and turbidity analyzes were collected in clear polyethylene bottles, wrapped in foil and stored in ice boxes for transport to the laboratory (Figure 13). Nitrate analysis was done based on the HACH protocol of cadmium reduction **(HACH Company, 2005a**), while phosphate was analyzed based on the ascorbic acid method **(HACH Company, 2005b)**. The results of the nutrient analysis were expressed in milligrams per liter (mgl^{-1}). Turbidity was analyzed with a HACH turbidity meter (HACH 2100Q) and results expressed as nephelometric turbid units (NTU).

Figure 13. Water samples collected in polyethylene bottles, foiled and ready for storage.

To assess chlorophyll a content, 12 water samples (each of 500ml) were collected at each sampling point using foiled polyethylene bottles, stored on ice and transported to the laboratory. Using Whatman fibre glass membrane filters (diameter 25 mm and porosity 0.7 µm), these samples were filtered in subdued light, wrapped in foil and stored at -20^{O}C until further analysis. Using the fluorescence method (spectrophotometry) based on the EPA protocol 445.0 **(Arar & Collins, 1997)**, chl-a pigments were extracted from the filter samples using a 90% acetone solution. An Eppendorf centrifuge 5804 was used for centrifugation of chl-a specimens. This was followed by acidification of the supernatant to 0.003 N HCl with 0.1 N HCl acid. The concentrations of pigment in the centrifuged samples were read using a spectrophotometer (Perkin Elmer LAMBDA 25 UV/Vis system). Finally, the chlorophyll a content was calculated as follows:

$$CS,c = \frac{\text{CE, c } x \text{ Extract Volume (L) } x\ DF}{\text{Sample Volume (L)}}$$

Where, CS,c = corrected chlorophyll a concentration (µg/L) in the whole water sample,

CE,c = corrected chlorophyll a concentration (µg/L) in the extract solution analyzed,

DF = dilution factor,

Extract volume = volume (L) of extract prepared before dilution

For representation of the complete seasonal cycle, sampling for the environmental studies was done during the peak discharge period of the River Gambia (September – December, 2013) and repeated during the peak dry season (April – July, 2014).

2.2.4. Mangrove vegetation dynamics

2.2.4.1. Image selection and acquisition

The satellite images used in this study were Landsat images. These were downloaded from the United States Geological Survey (USGS) website (http://glovis.usgs.gov/). The images were selected based on availability for the study site's path and row i.e. 205/051 from different Landsat sensors as shown in Table III.

Table III. Characteristics of the satellite images used in vegetation dynamics study.

Image	Path/Row	Acquisition date	Landsat #	Image type	UTM Zone
1973	205/051	Feb 21, 1973	1	MSS	28N
1984	205/051	March 18, 1984	5	TM	28N
1995	205/051	May 09, 1995	5	TM	28N
2002	205/051	May 20, 2002	7	ETM+	28N
2012	205/051	May 15, 2012	7	ETM+	28N

2.2.4.2. Image processing

The aforementioned images were pretreated in preparation for vegetation analysis. This stage involves radiance calibration of the images and the extraction (sub-setting) based on the frame of the study area. After this, the 2012 image was stripe-corrected using the gap-fill method suggested by the USGS and according to methods of **Scaramuzza *et al.* (2004)**. These stripes were caused by digital malfunctions of the Landsat 7 sensor in 2003. After this, a Principal Component Analysis (PCA) and Normalized Differential Vegetation Index (NDVI) calculation were performed to create new components for the images. These together with the original bands were used to create the false color composites of the study site's land cover, according to methods of **(Thu & Populus, 2007)**.

The analysis of these false color composites was based on the principle that each land use/land cover type has a specific spectral reflectance. This is indicated in the color of that particular vegetation, characterized by its phenology and structure. With this, two sets of false color composites were generated i.e. the false color images of ETM+1/4/5/7 (A) and ACP1/ACP3/NDVI (B). Based on the clarity of the resultant images, the false color composite PCA1/PCA3/NDVI (B) was more accurate as opposed to the classic false color image ETM+1/4/5/7 (A) in discriminating major components such as mangrove and swamp areas. Therefore, the most discriminative colors were retained to support the ground-truthing stage which is necessary for confirmation of the different types of land use/land cover (Figure 14).

After this, a sample of 84 ground control points representative of the different land use/land cover types were selected and their geographical coordinates recorded to ease location in the field. For illustration of the different land use/land cover, representative pictures were also taken of each one during the fieldwork (Figure 15 to Figure 19).

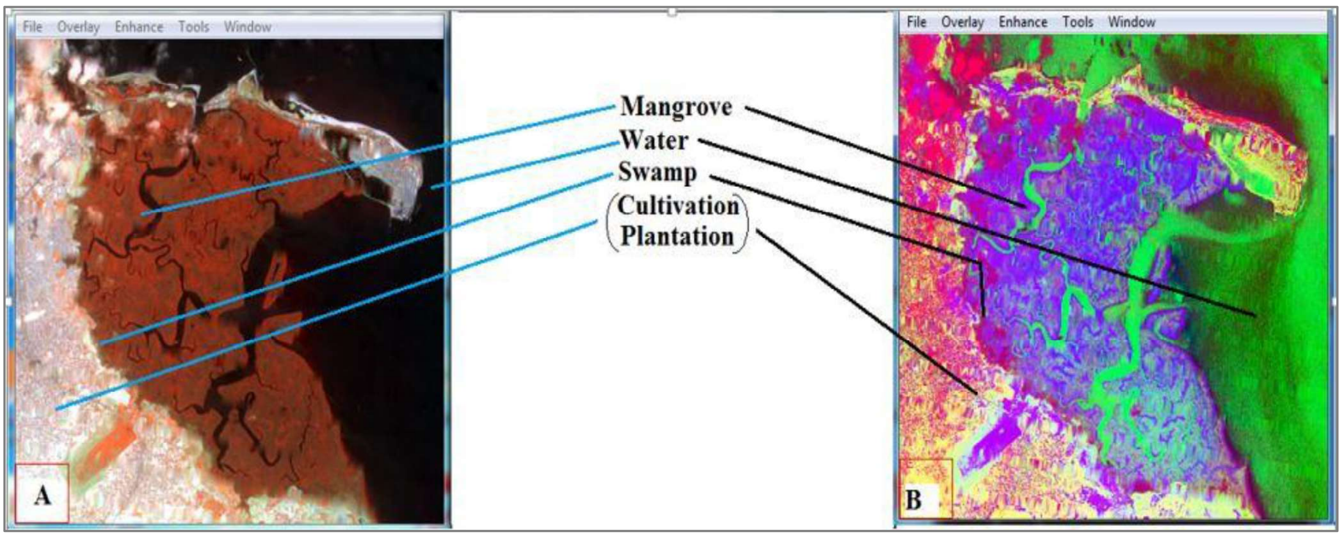

Figure 14. False color composites of Tanbi Wetland National Park, ETM+1/4/5/7 (A) and ACP1/ACP3/NDVI (B).

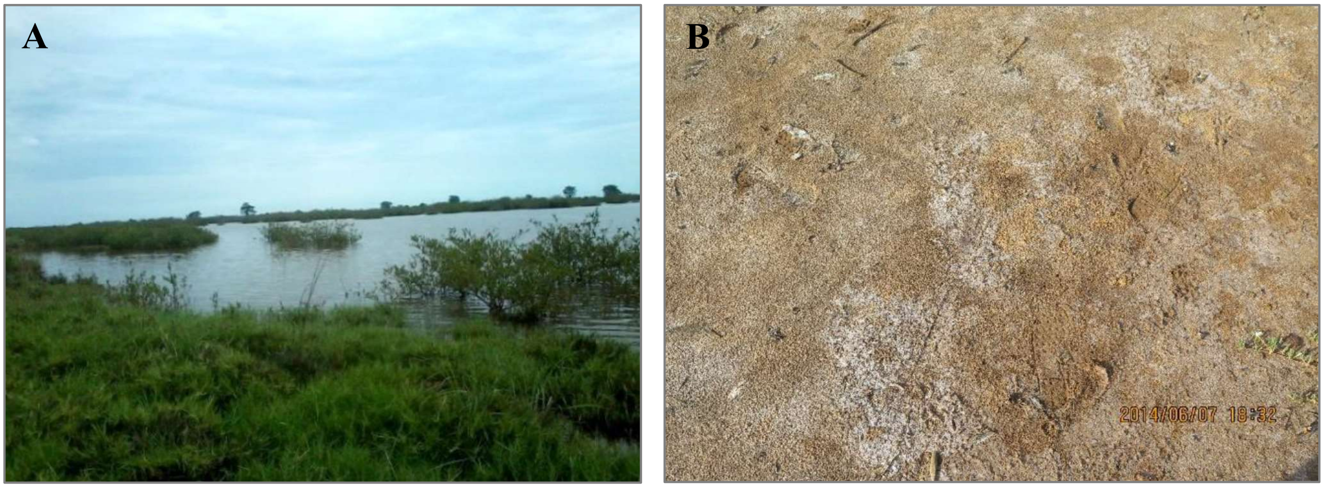

Figure 15. Pictorial view of the prominent land use/land cover features in Bakau (completely fragmented zone).

A: vegetation cover mostly comprises mangrove associate grasses during the rainy season, B: view of the dry hypersaline bare grounds in Bakau during the dry season, 2014.

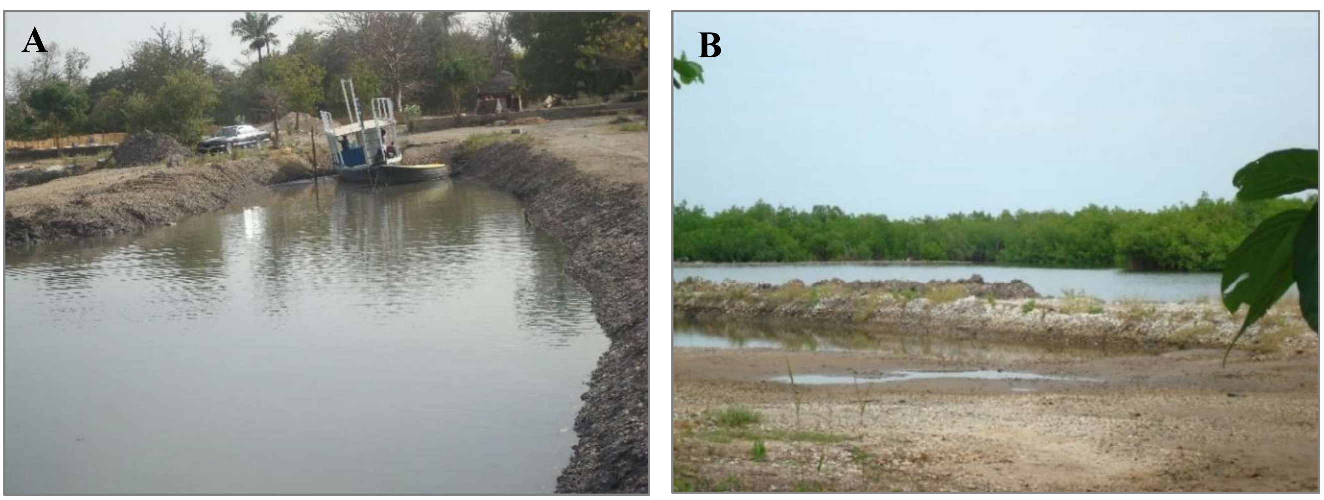

Figure 16. Pictorial view of the prominent land use/land cover features in Mandinary (tourism zone), 2014.

A: locally carved out docking channel for small tourist boats, B: walk-bridge made from oyster shells.

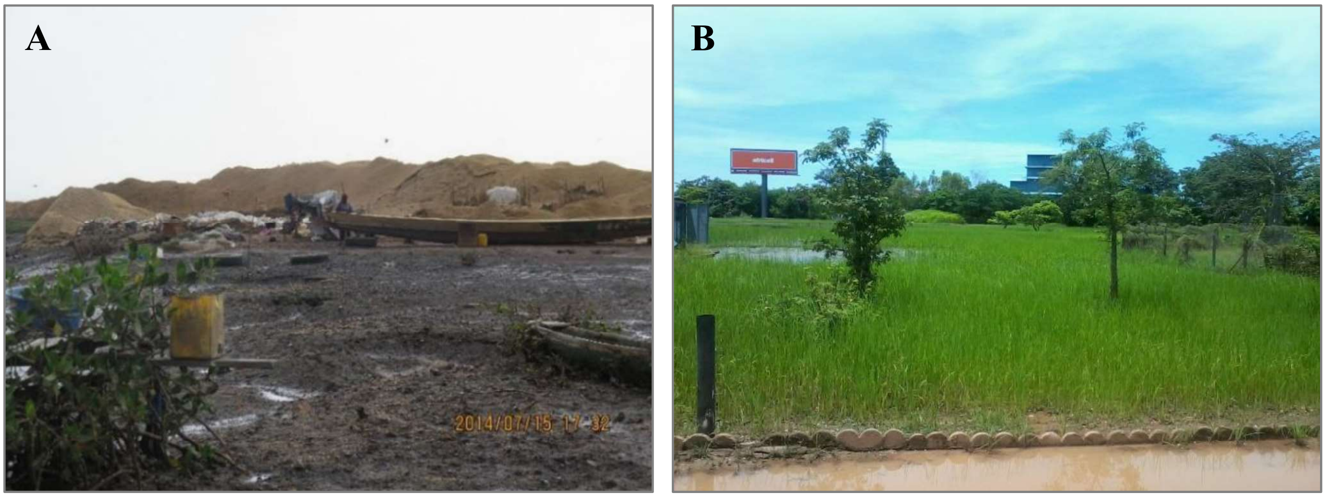

Figure 17. A view of prominent land use/land cover features at Kamalo (agriculture zone).
A: heaps of peanut shells dumped in the wetland, B: rice cultivation along the shores of the wetland.

Figure 18. A view of prominent land use/land cover features at Bund Road (partially fragmented zone).
A: mini-bridge (culvert) water exchange point, B: a view of the sparse vegetation from atop the culvert, with Banjul in the distant background.

Figure 19. A view of prominent land use/land cover features at Wencho (settlement zone).
A: thatch houses built by settlers along the shores, B: pig rearing pens built along the shores of the wetland.

Additional data were collected to facilitate easy exploitation of the images and for familiarization with the work environment. These include historical data about the TWNP from literature **(The Ramsar Convention on Wetlands, 2012)** and those generated from the images. Layers of roads, localities, rivers etc. were digitized from the panchromatic images. Protected area and administrative zone layers were also gathered from literature and existing wetlands projects **(Hirani, 2005)**.

Classification of images was done using both unsupervised and supervised methods, with the former being classically generated by the analysis software and latter systematically input by the user. The supervised classification was performed with the most recent image (2012) based on the maximum likelihood algorithm. Multiple trials were performed to enhance the resultant image and then the same process was performed for the images of the previous years under study i.e. 1973, 1984, 1995 and 2002. As vegetation composition in TWNP is very simple (only four species), both unsupervised and supervised classifications were straight forward, with no overlapping between the various classes. The *Rhizophora mangle* (Linnaeus, 1753) is usually in the central zone of the park with much denser and darker canopy layer, followed by *Laguncularia racemosa* (Gaertner, 1807) (which has a lower canopy layer of ≤ 2m and brighter color) in a landward direction and then fringed by *Avicennia germinans* (Linnaeus, 1764) (very sparse and closest to dry land). The ease of discriminating mangroves from other types of vegetation resulted in high visibility of the final images. Vegetative traits of the major mangroves species in TWNP are shown in Figure 20.

2.2.4.3. Accuracy assessment and spatial dynamics

An accuracy assessment was performed in two stages namely; the thematic and statistical validations based on methods of **Kaufmann & Seto (2001)**. The thematic validation comprised of a visual comparison between the color-composite (B) and the classification results. Historical data was also used during the accuracy assessment to aid in verification of classification results. Then, the statistical validation was performed using the confusion matrix. An overall accuracy of at least 80% and a Kappa coefficient close to 1 are expected for a good classification, based on recommended assessment scale by **Blum *et al.* (1995)**. After this assessment, a filter of 3x3 pixels was applied to eliminate isolated pixels. The classified data which were in raster format were then converted to vector files and exported to ArcGIS for the estimation of the areas of the different land use/land cover types and the analysis of their corresponding spatial dynamics.

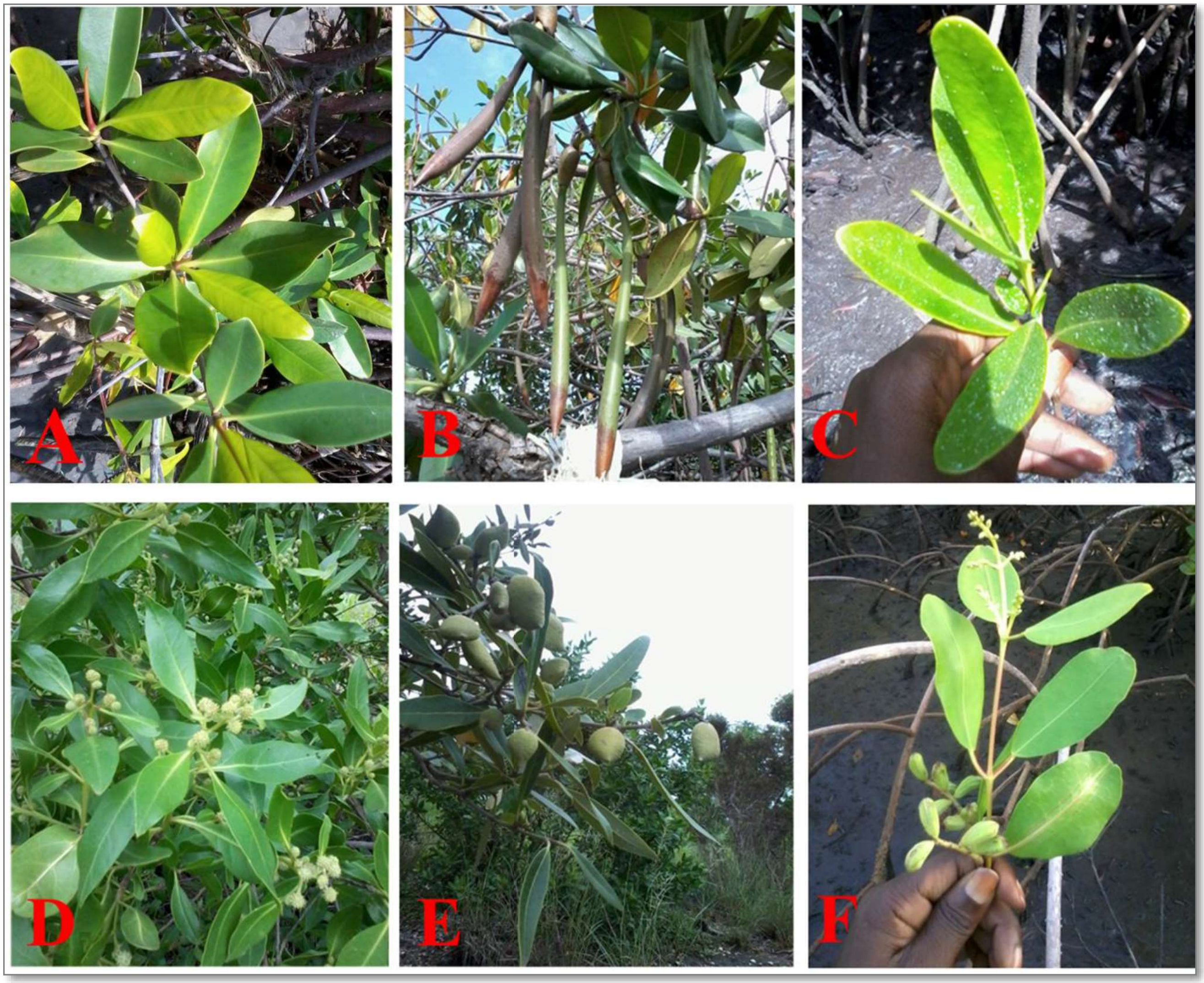

Figure 20. Dominant mangrove species in Tanbi Wetland National Park in The Gambia in 2014. *Rhizophora mangle* leaves (Linneas, 1753) (A) and propagules (B), *Laguncularia racemosa* (Gaertner, 1807) leaves (C) with "fruits" and flowers (F), and *Avicennia germinans* (Linnaeus, 1764) leaves with flowers (D) and "fruits" (E).

2.2.5. Fish assemblage

To assess seasonal variations in fish assemblage/community structure, fish sampling was done in the open waters adjacent to transects during the morning ebb tides. With the help of the same fisherman and using the same boat at all sampling stations. Fish sample collection was conducted by making three throws at each sampling station during each of the study seasons. Since the study site is a nursery ground dominated by juvenile fishes, net selection was based on recommendations for West African estuaries **(Albaret, 1994; Albaret *et al.,* 2004; Ecoutin *et al.,* 2010)**. Netting for each throw lasted about thirty minutes, during which the seine net is deployed from a small boat in a semi-circular mode, gently hauling the catches to the shore, as recommended by **Hahn *et al.* (2007)** (Figure 21).

Fish caught were measured, weighed and pictures of each fish species caught taken for verification purposes. Fish specimens were identified to species level based on morphological characteristics according to **Lévêque *et al.* (1990)**. The identified fish species were then verified using Fishbase (http://www.fishbase.org) and IRD's digital fish species identification keys for fresh and brackish waters of West Africa **(Paugy *et al.,* 2003)**. Fish sampling was done during the peak discharge period and repeated during the peak dry season to capture seasonal variations in hydrological status of the TWNP.

Fish sampling efficiency was tested for by making a species accumulation curve according to **Colwell *et al.* (2012)**. For this, the mean species similarities between the six land use types were recorded. Using the Windows EstimateS software version 7.5.0 (http://purl.oclc.org/estimates) and the species observed (Sobs), the asymptote values were analyzed for based on the Chao2 index. To do this, a sample randomization (500 times) was done in order to ensure proper statistical representation of the target assemblage **(Chao *et al*., 2005)**. Following methods of **Colwell *et al*. (2012)** for incidence data, the second order and non-parametric estimator (Chao2) was set as estimator of the species richness. Using the field incidence data and the number of samples for this study (plotted on y and x-axis respectively), the asymptote richness and real time species curves were compared. The sampling efficiency (SE) was calculated as follows:

$$SE = \frac{Sobs}{Chao2} x\ 100$$

Where: SE = sampling efficiency; Sobs = species observed

Chao2 = asymptote value at that same sampling effort

Using the same program (Windows EstimateS software version 7.5.0) and randomizing the incidence data and the sample order 500 times to ensure statistical representation, a species similarity matrix was generated in order to identify the percentage of shared species between the various sampling stations, as well as within individual sampling stations during the two seasons. The assessment of Jaccard's similarity index allowed for the description of the similarity between various land use types in terms of species composition, while Sørensen index served to measure the diversity of the fish assemblage based on ***Dosso et al.* (2013)**. The amalgamation of the two indices (Jaccard-Sørenson) provides the auto-similarity between the replicates of the same habitat and by extension, sampling stations in the same study site. Thus, the average of these two indices serve as a representative value for the percentage shared species, according to **Colwell *et al*. (2012)**.

Due to the low species richness of the River Gambia estuary, bio-ecological categorization of fish assemblage has been recommended by most researchers and gave a better picture of diversity for waters with low species richness **(Vidy *et al.,* 2004; Simier *et al.,* 2006)**. Categorization of the fish assemblage in TWNP was done according to the 8 bio-ecological fish categories reported for West African waters, according to recommendations of **Albaret (1999)**. **Albaret (1999)** proposed a grouping method based on the origin and dwelling preferences of West African fishes. The eight bio-ecological categories proposed include the following:

1. Ce: freshwater species with estuarine affinities.
2. Co: freshwater species occasional in estuaries.
3. Ec: estuarine species of continental/freshwater origin.
4. Em: estuarine species of marine origin.
5. Es: strictly estuarine species.
6. Ma: marine species accessory in estuaries.
7. ME: marine-estuarine species.
8. Mo: marine species occasional in estuaries.

It is noteworthy that Bakau (completely fragmented zone) is only accessible on foot because it gets completely dry during the dry season and is only about ≤ 32 cm deep during the rainy season (Figure 22), thus eliminating the possibility of successfully deploying any fishing gears. In addition, there were no visible sighting of any fishes and no local fishing activities at this sampling site. Nonetheless, several fishing trials were done here during the rainy season with the same fisherman and fishing gear for confirmation of the aforesaid observation, no fish could be seen or caught. For these reasons, it was excluded from the fish assemblage studies. Thus, fish study results in this research are for all sampling sites, except the completely fragmented zone (Bakau).

Figure 21. Seine net set in place for capture of fishes at dense mangrove (reference zone).

Figure 22. A view of Bakau (completely fragmented zone) during the rainy season (A, with permission from the Department of Water Resources) and dry season (B).

2.2.6. Social studies

The social studies component of this research was based on a series of semi-structured interviews according to methods of **Satyanarayana *et al.* (2012)**. A group of 138 people belonging to four occupational groups were interviewed. These include: Farming, Fisheries, Tourism and Oyster collection. A subgroup of people residing within the wetland (in Wencho, locally known as Ndangane) was also interviewed. As this study was aimed at the local people's understanding of long-term changes in the ecosystem, the age group target was set at adults of 18 years and above. For proportionate representation of the socioeconomic groups, 15 tourist workers, 19 residents, 20 oyster collectors, 40 farmers and 44 fisher folks were interviewed.

Interviewers' group was comprised of five people (two from the National Environment Agency, one from the Water Resources Department, one from the University of The Gambia and the actual researcher). This team was put together based on their background in environmental monitoring, conservation and community development work. In addition, each of the team members was fluent in at least two local languages for translation purposes. All together the team was fluent in the four major local languages in The Gambia (Mandinka, Fulla, Wollof and Jola). To prevent any biases in the way questions were administered, the team prepared by "practice-asking" each other all the questions in the questionnaire and adopting a uniform introduction of the purpose and scope of the research in the four major local languages to ensure a uniform understanding of the questions.

Interviews were conducted under an informal roundtable chat with each socioeconomic group at their place of work in TWNP. In some cases, local languages were used to administer the questionnaire for better understanding. Interviews for each respondent lasted about thirty minutes. Questionnaire details are in appendix I.

2.2.7. Data analysis

Environmental data were sorted in basic Excel format by sampling station/land use type. Individual environmental variables for all sites were subjected to a one-way Analysis of Variance (ANOVA) (P value <0.05) to detect significant differences per season and then subjected to a two-way ANOVA to determine significant differences at all land use types between the rainy and dry seasons. Pairwise student's t-test was used to establish seasonal differences in mean values of the water variables at individual sampling stations for intra-site differences during the rainy and dry seasons according to methods of **(Hayé *et al.,* 2009)**. This was followed with a Principal Component Analysis (PCA) which was performed on the five main water quality variables i.e. salinity, dissolved oxygen, pH, temperature and turbidity, together with nitrate and phosphate in order to test for their correlations with the significance level set to $P<0.05$ according to methods of **Sandbrink & Meijeren (2010)** using R version 3.1.2 statistical package for windows.

For establishing the relationship between long-term changes in mangrove vegetation and long-term rainfall anomalies for Banjul, annual rainfall index (S_{sy}) was calculated starting from 1964 to 2014 according to methods of **L'Hôte *et al.* (2002)**, based on the formula below:

$$S_{sy} = (R_{sy} - R_s) / \sigma_s$$

Where: R_{sy} = the annual rainfall of Banjul for the year y,

R_s = the mean annual rainfall for the reference period (1964 – 2014),

σ_s = the standard deviation for Banjul rainfall for the reference period (1964 – 2014).

To determine similarities in fish communities under the different land use types, all biological data were subjected to a cluster analysis, where fish species abundance for the different land use types were grouped into a similarity matrix (Bray Curtis Similarity). This yielded groups/clusters of land use types with similar species composition. Together with normalized environmental data a comparison was made with various water quality/environmental variables. Results of this were further subjected to a multivariate analysis (Multi-dimensional scaling, MDS) in order to determine the water quality variables that had the strongest influence on fish species abundance based on protocols of **Clarke & Gorley (2015)**. This identified and grouped the fish species under the various land use types based on similarities in species composition, as well as the water quality variables that had the most influence on the fish species composition. These were done using the multivariate analysis tool PRIMER version 6.

For the statistical analysis during social studies, responses from the interviews were pooled in a similarity matrix and subjected to Principal Component Analyses (PCA) using Statistical analysis software R version 2.15.2 (2012). Using occupation and experience as the independent variable and the respondents' knowledge on ecosystem changes as a dependent variable, descriptive statistical analyses were conducted using STATA 12 for windows. The methodology of this part was based on those of **Satyanarayana *et al*. (2012)**. The same protocol was followed for their understanding of their local adaptation strategies.

CHAPTER III – RESULTS AND DISCUSSION

3.1. RESULTS

3.1.1. Environment / Water quality

3.1.1.1. Salinity

During the rainy season, the highest salinity (31.2 ppt) was recorded at Wencho (settlement zone). This was followed by Kamalo (agriculture zone) with a salinity of 28.5 ppt and Mandinary (tourism zone) with a salinity of 25.2 ppt. Salinity level was 21.6 at Abuko (oyster processing zone) and 21.0 ppt at the dense mangrove (reference zone). The lowest salinity (19.2 ppt) during the rainy season was recorded at Bund Road (partially fragmented zone). During the dry season, mean salinity level was highest (37.3 ppt) at Mandinary (tourism zone). This was followed by Abuko (oyster processing zone) with 36.0 ppt, albeit not significantly different from the dense mangrove (reference zone) (*p* value, 0.9). These were followed by Bund Road (fragmented zone) with a salinity level of 35.2ppt. Salinity was also not significantly different (*P* value, 0.3) between Wencho and Kamalo during the dry season i.e. 35.0 ppt at both sites (Figure 23).

Based on the results of the pairwise student's t-test ($p<0.05$), significant seasonal intra-site differences were noted in mean salinity levels of all the sampling stations. Seasonal salinity values were most erratic at Bakau (completely fragmented zone), increasing from 12.4 ppt during the rainy season to 124.1 ppt during the dry season (Figure 24). Overall salinity values during this research seem to have been influenced by sea water intrusion as the sampling stations closest to the open coast (Bakau) had the highest salinity value (124.1 ppt) during the dry season and understandably the lowest (12.4 ppt) during the peak discharge period (Figure 25).

Based on the results of the ANOVA, significant differences were recorded in mean salinity levels during the two seasons studied in TWNP (*P* value <0.0001). With the exclusion of Bakau (completely fragmented zone) which is cut off from the main wetland, the mean salinity in TWNP was 24.5 ppt during the peak discharge period of the River Gambia (peak rainy season). This increased to 35.8 ppt during the peak dry season. Salinity also differed significantly between the various sampling stations, as well as within individual stations during the two seasons.

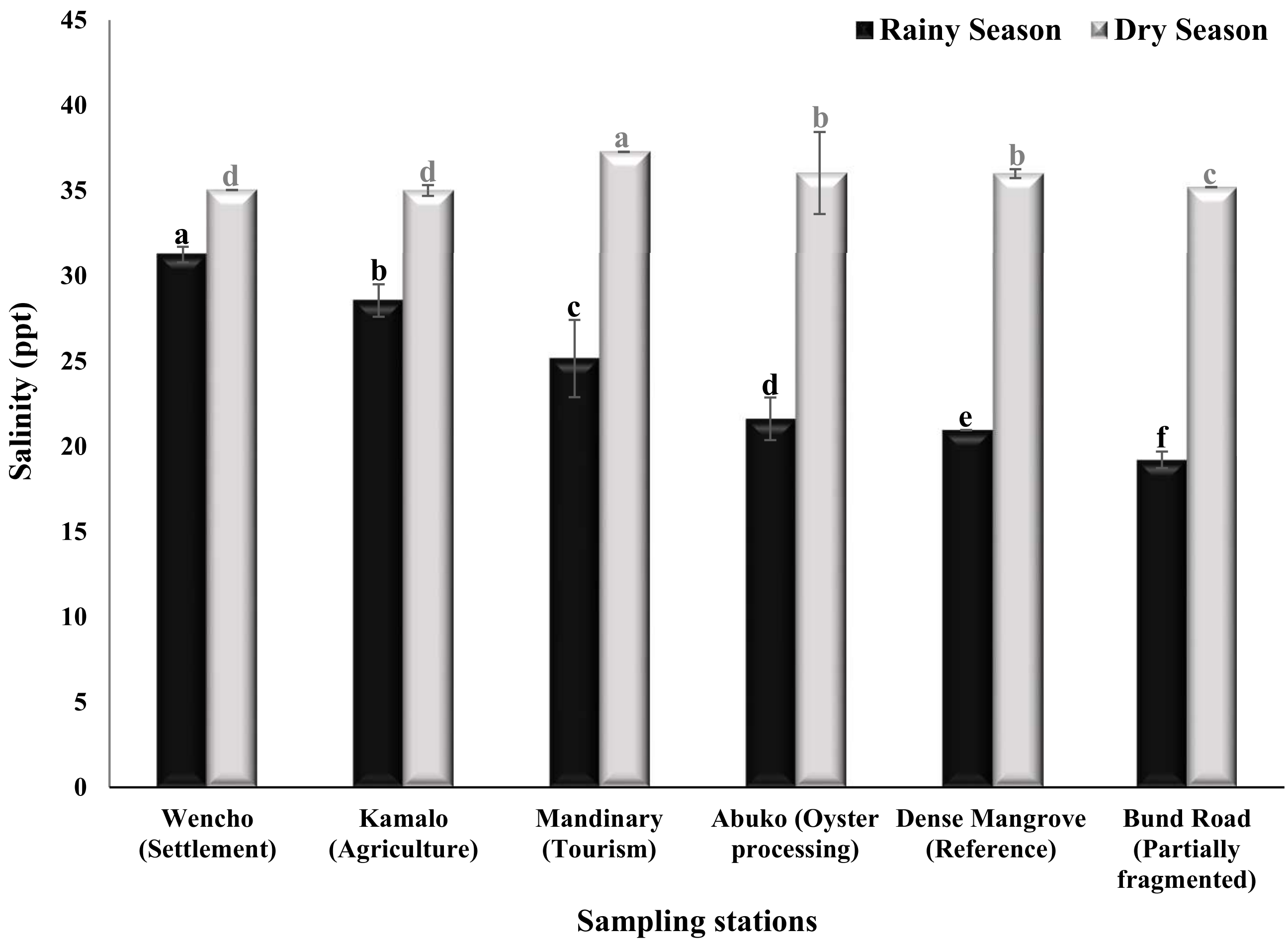

Figure 23. Seasonal variations in mean salinity level at different land use types in Tanbi Wetland National Park in The Gambia in 2014.
Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at $P<0.05$.

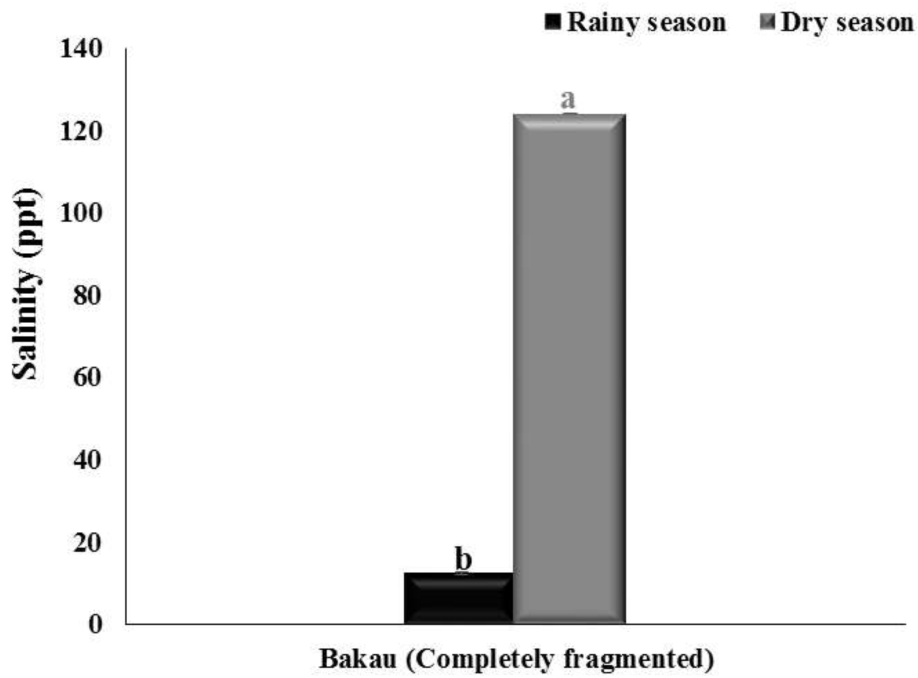

Figure 24. Seasonal variations in mean salinity level at Bakau (completely fragmented zone).

Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at P<0.05.

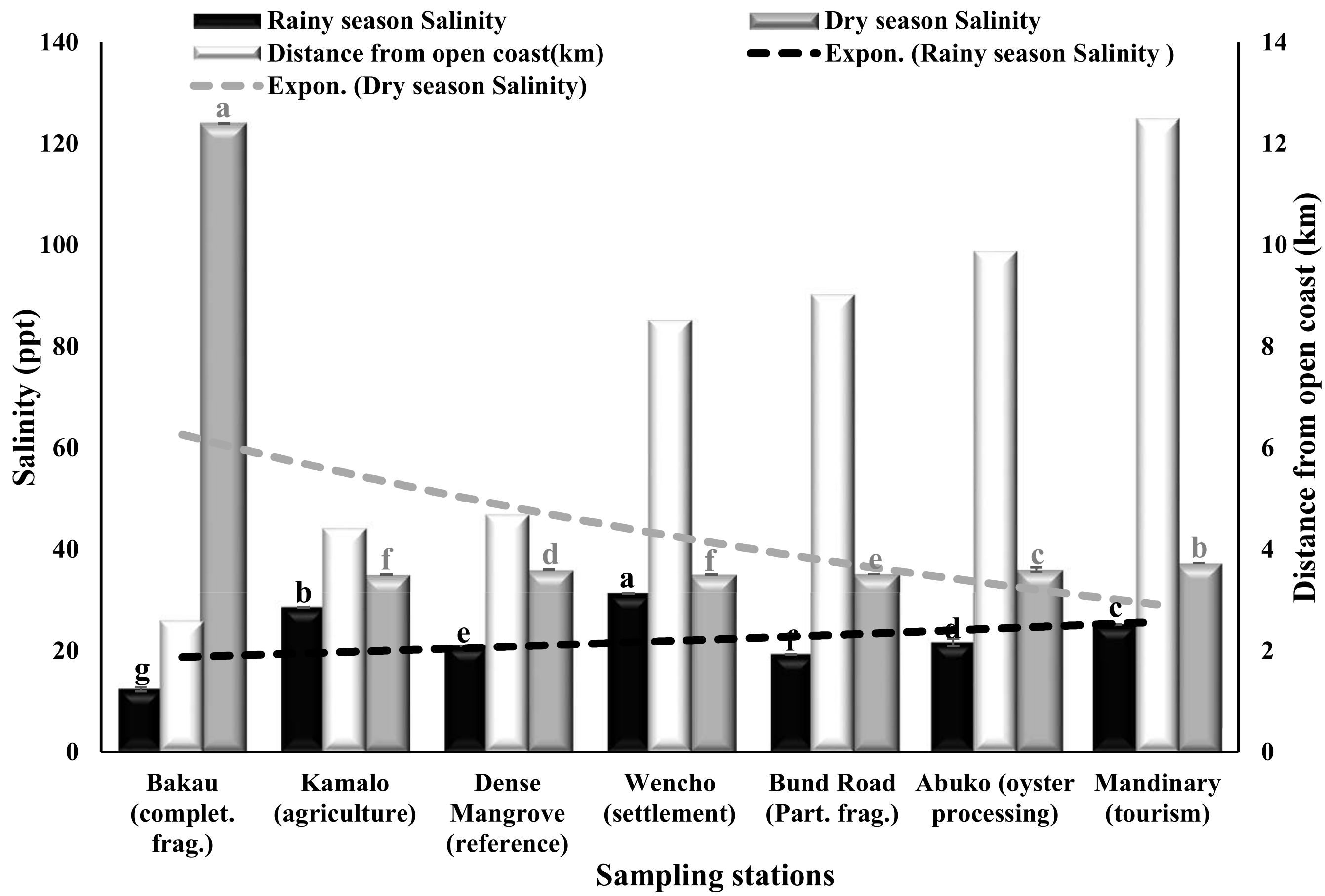

Figure 25. Salinity-distance relations between sampling stations in Tanbi Wetland National Park and the open coast during the rainy and dry seasons in 2014.
Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at P<0.05.

3.1.1.2. Dissolved oxygen (DO)

At a *P* value of 0.05, mean dissolved oxygen saturations in TWNP did not differ significantly during the two seasons studied i.e. 5.5 and 5.4 mgl^{-1} for the rainy and dry seasons respectively, based on the results of the ANOVA. However, there were significant differences in DO between the different sampling stations studied during the rainy and dry seasons.

During the rainy season, the highest (6.3 mgl^{-1}) DO saturation was recorded at dense mangrove (reference zone). This was however not significantly different from the mean DO level (6.1 mgl^{-1}) at Wencho (settlement zone) (*P* value, 0.07). This was followed by Abuko (oyster processing zone), Bund Road (partially fragmented zone) and Bakau (completely fragmented zone) whose DO levels also did not differ significantly i.e. 5.6, 5.5 and 5.4 mgl^{-1} respectively (*P* value, 0.6). Kamalo (agriculture zone) and Mandinary (tourism zone) displayed the lowest DO levels and with no significant differences during the rainy season i.e. 4.8 and 4.7 mgl^{-1} respectively.

During the dry season, the highest DO was recorded at Kamalo (agriculture zone) (7.0 mgl^{-1}), although not significantly different from the DO level at the dense mangrove (reference zone) (6.8 mgl^{-1}). DO levels showed no significant differences between Mandinary (tourism zone) and Bund Road (partially fragmented zone) i.e. 5.0 and 4.9 mgl^{-1} respectively. DO level was 4.8 mgl^{-1} at Wencho (settlement zone), Abuko (oyster processing zone), as well as at Bakau (completely fragmented zone). The results of the pairwise student's t-test indicated significant differences ($P<0.05$) in mean DO level for all the sampling stations in TWNP during the rainy and dry seasons.

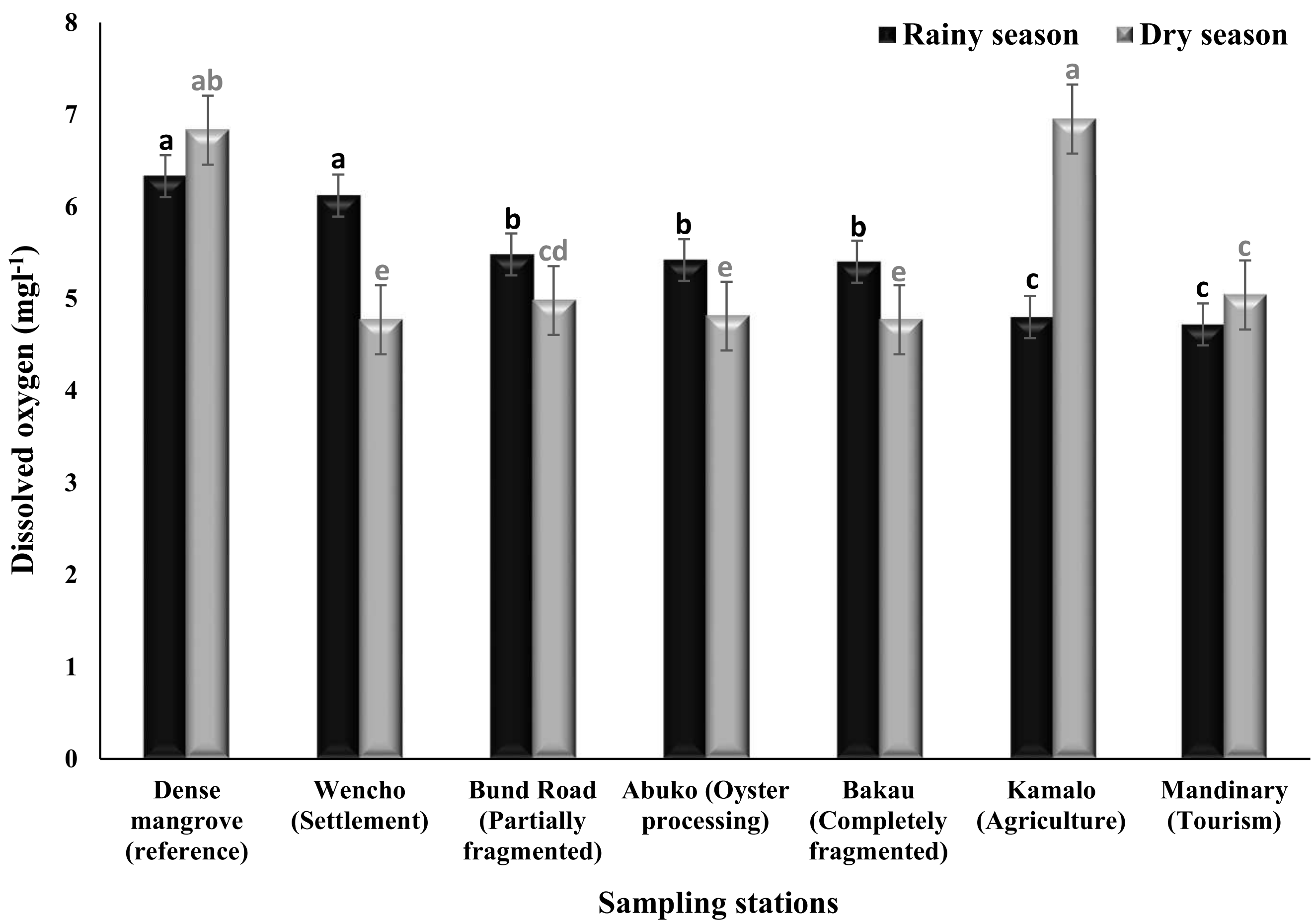

Figure 26. Variations in mean dissolved oxygen (DO) levels for the sampling stations at different land use types during the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014. Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at $P<0.05$.

3.1.1.3. Water temperatures

Water temperature in TWNP increased significantly from 27.6ºC during the rainy season to 30.2ºC during the dry season ($P<0.05$). The highest mean water temperature (29.4ºC) during the rainy season was recorded at Abuko (oyster processing zone), followed by Bakau (completely fragmented zone) and Bund Road (partially fragmented zone) with no significant differences i.e. 28.3ºC at both sites (Figure 27). At Mandinary (tourism zone) and Kamalo (agriculture zone), water temperatures did not vary significantly i.e. 27.9 and 27.6ºC respectively. Water temperatures for dense mangrove (reference zone) and Wencho (settlement zone) also show a similar situation i.e. 26.0ºC and 25.7ºC respectively.

During the dry season, the highest mean water temperature (35.7ºC) was recorded at Bakau (completely fragmented zone), followed by Abuko (oyster processing zone) with a temperature of 31.4ºC. Water temperature (29.8ºC) at the dense mangrove (reference zone) did not differ significantly from that of Wencho (settlement zone) (29.8ºC). The lowest water temperature (27.4ºC) during the dry season was at Bund Road (partially fragmented zone). The results of the pairwise student's t-test indicated significant differences ($P<0.05$) in mean water temperature levels for all the sampling stations in TWNP during the rainy and dry seasons.

3.1.1.4. ***pH***

Average pH levels did not differ significantly between the two seasons at $P<0.05$ i.e. 7.60 during the rainy season and 7.55 during the dry season. However, there were significant differences in mean pH levels between the individual use types studied during the two seasons, for instance at the agriculture, settlement and oyster processing zones. During the rainy season, the highest pH level was recorded at Bakau (completely fragmented zone) with 7.93, followed by Wencho with a pH of 7.86. pH levels at dense mangrove (reference zone), Bund Road (partially fragmented zone), Mandinary (tourism zone) and Kamalo (agriculture zone) registered no significant differences (*P* value, 0.1) during the rainy season i.e. 7.6. Abuko (oyster processing zone) displayed the lowest pH value (7.1) during the rainy season.

During the dry season, the highest pH level (7.9) was were recorded at Bakau (completely fragmented zone), followed by Bund Road (partially fragmented zone) with 7.8 and Kamalo (agriculture zone) with 7.7 with no significant difference between the latter two (*P* value, 0.06). These were followed by dense mangrove (reference zone) and Abuko (oyster processing zone), having significant differences i.e. with 7.5 and 7.3 respectively. The rest of the sites Wencho (settlement zone) and Mandinary (tourism zone) all had the same pH level (7.3) (Figure 28).

In terms of intra-site seasonal differences for the individual sampling stations, pairwise student's t-test revealed significant differences ($P<0.05$) in mean pH values during the rainy and dry seasons. However, mean pH levels at Bakau (completely fragmented zone) were not significantly different between the rainy and dry seasons i.e. 7.9 for both seasons. The rest of the sampling stations, displayed significant differences in their pH levels for the rainy and dry seasons.

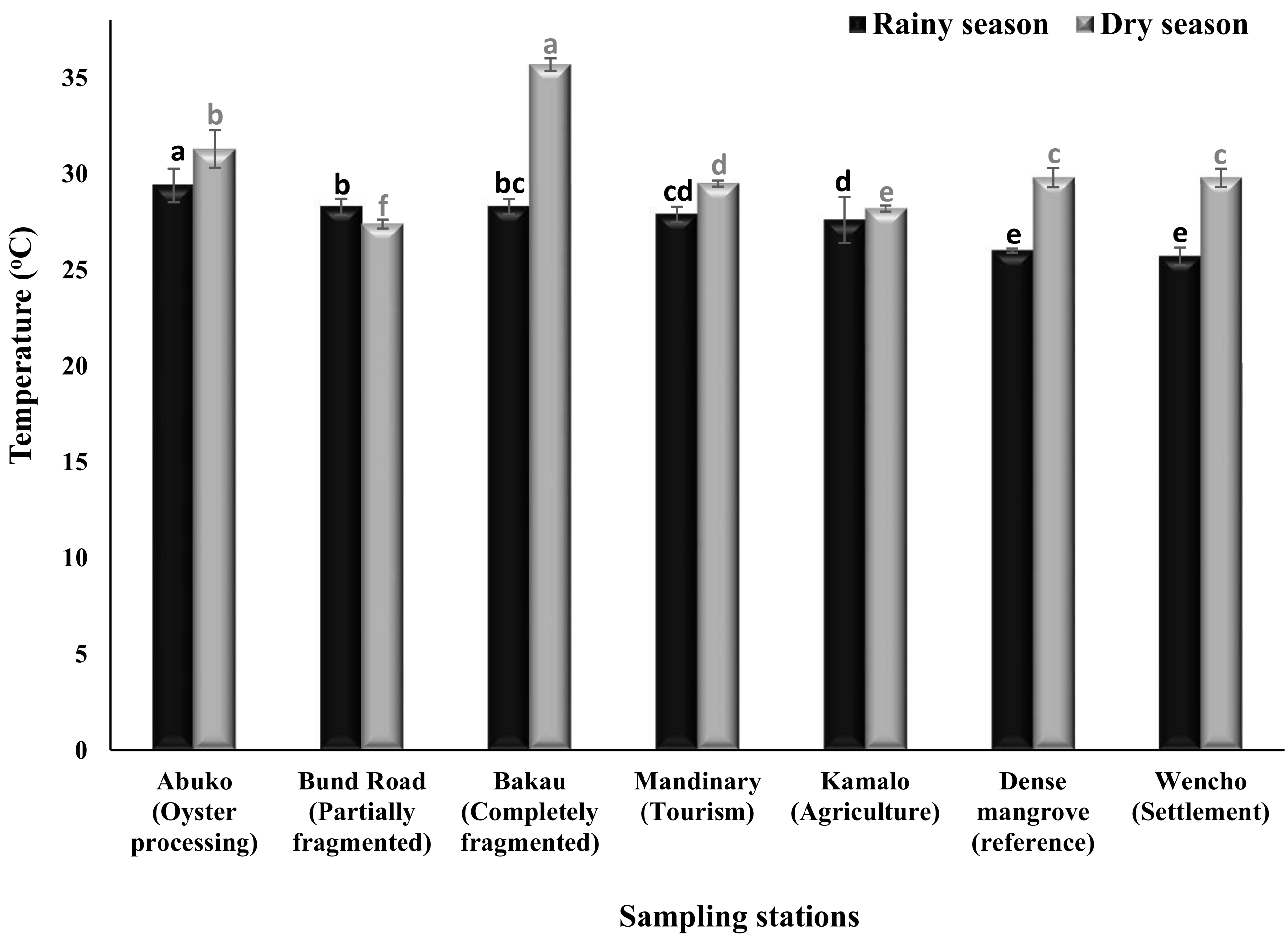

Figure 27. Variations in mean temperature for the sampling stations at different land use/land cover types during the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014.
Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at $P<0.05$.

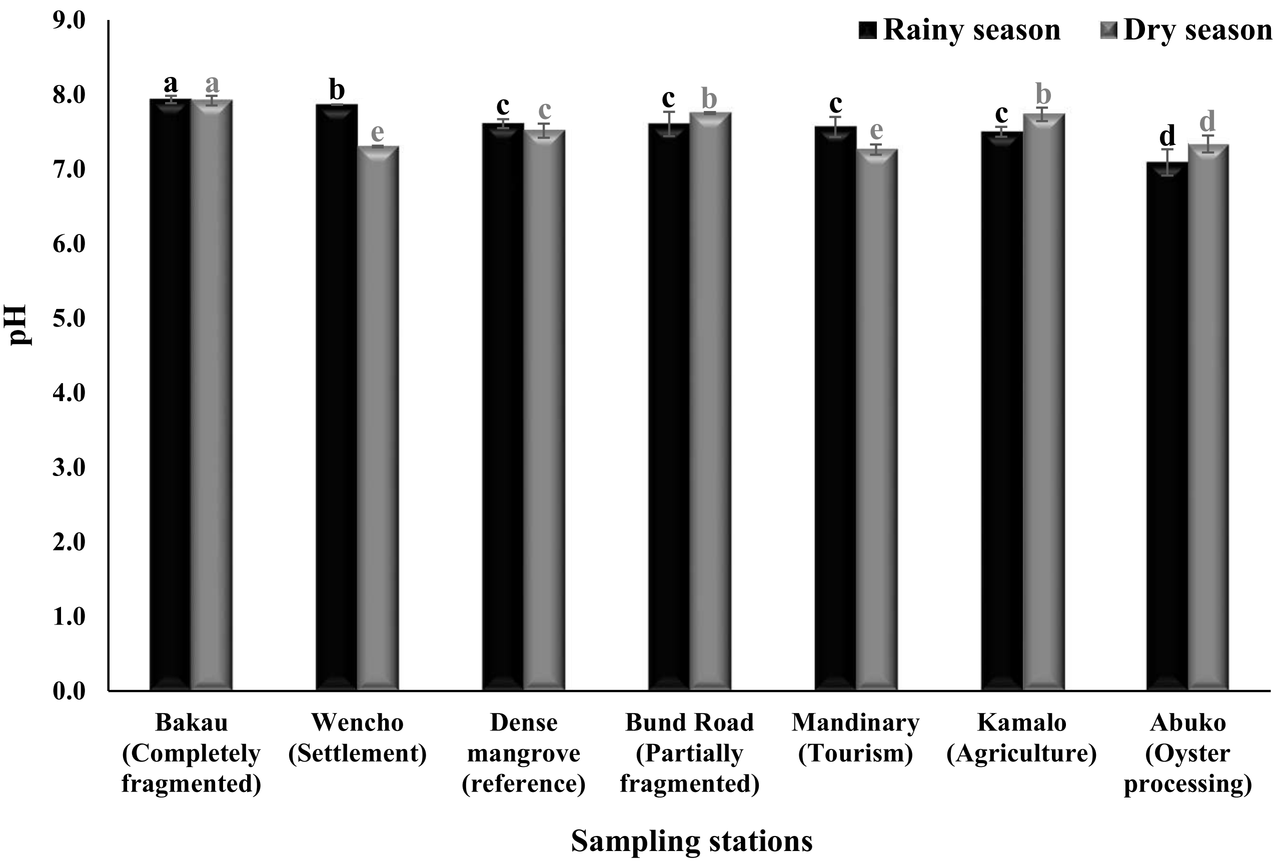

Figure 28. Variations in mean pH for the sampling stations at different land use/land cover types during the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014.
Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at $P<0.05$.

3.1.1.5. Nutrients

Nutrient analysis showed significant differences in nitrate and phosphate levels between the two seasons ($P<0.05$). There was a general decline in average nitrate and phosphate levels as the seasons changed from rainy to dry (i.e. from 2.7 to 0.8 mgl^{-1} and from 2.0 to 0.6 mgl^{-1}) respectively. During the rainy season, the highest mean level of nitrate (4.3 mgl^{-1}) was recorded at Mandinary (tourism zone) and then Wencho (settlement zone) with a nitrate level of 4.0 mgl^{-1} (Figure 29). These were followed by Abuko (oyster processing zone) with 3.8 mgl^{-1} and then Kamalo (agriculture zone) and Bakau (completely fragmented zone), whose nitrate levels did not exhibit any significant differences i.e. 2.1 mgl^{-1} at both sites during the rainy season. Bund Road (partially fragmented zone) had a mean nitrate level of 1.8 mgl^{-1}. The sampling station with the lowest nitrate level during the rainy season was the dense mangrove (reference zone) (0.6 mgl^{-1}).

During the dry season, mean nitrate levels were significantly different between the sampling sites ($P<0.05$). Mandinary (tourism zone) and Bakau (completely fragmented zone) showed the highest mean nitrate levels (1.1 mgl^{-1} at both sites) (Figure 29). These were followed by Bund Road (partially fragmented zone) where the mean nitrate level declined to 0.9 mgl^{-1} and then Abuko (oyster processing zone), having 0.8 mgl^{-1}. There were no significant differences (*P* value, 7.1) between mean nitrate levels for Wencho (settlement zone) and Kamalo (agriculture zone) (0.6 and 0.5 mgl^{-1}) respectively. Like in the rainy season, dense mangrove (reference zone) displayed the lowest nitrate level (0.4 mgl^{-1}) during the dry season.

Likewise, mean phosphate levels differed significantly ($P<0.05$) between the various land use types in TWNP during the rainy season. The highest mean phosphate level (4.6 mgl^{-1}) during the rainy season was recorded at Bund Road (partially fragmented zone) (Figure 30). This was followed by Bakau (completely fragmented zone) with a mean phosphate level of 2.2 mgl^{-1} and Kamalo (agriculture zone) with 1.5 mgl^{-1}. These were followed by Abuko (oyster processing zone) and Mandinary (tourism zone), both having 1.5 mgl^{-1} of phosphate. The dense mangrove (reference zone) showed the lowest phosphate level (0.5 mgl^{-1}) during the rainy season.

During the dry season, significant differences ($P<0.05$) were noted in phosphate levels between the various land use types in TWNP (Figure 30). The highest phosphate level (0.9 mgl^{-1}) was recorded at Bakau (completely fragmented zone) during the dry season. This was followed by dense mangrove (reference zone) with 0.03 mgl^{-1} phosphate. Although this was not significantly different from phosphate levels in Bund Road (partially fragmented zone) and Kamalo (agricultural zone), each having 0.02 mgl^{-1} of phosphate. Following this was Wencho (settlement zone) where mean phosphate level was 0.01 mgl^{-}

^{1}. Mean phosphate levels also did not differ significantly between Abuko (oyster processing) and Mandinary (tourism zone) i.e. 0.002 and 0.003 mgl^{-1} respectively. For intra-site seasonal differences in mean nutrient levels, significant differences (P<0.05) were noted in both nitrate and phosphate levels for all the individual sampling stations during the two seasons studied.

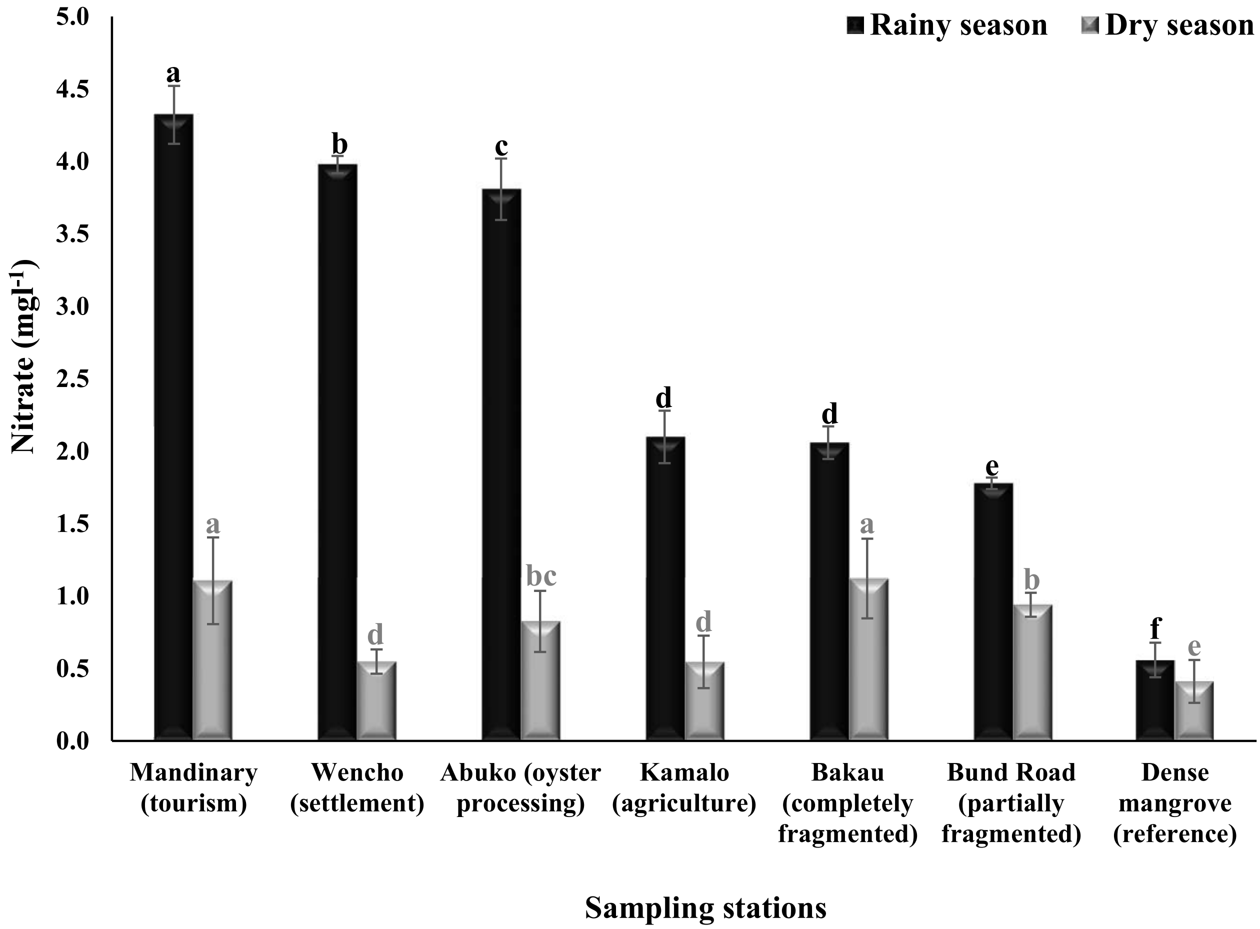

Figure 29. Variations in mean nitrate levels for the sampling stations at different land use/land cover types during the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014.

Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at $P<0.05$.

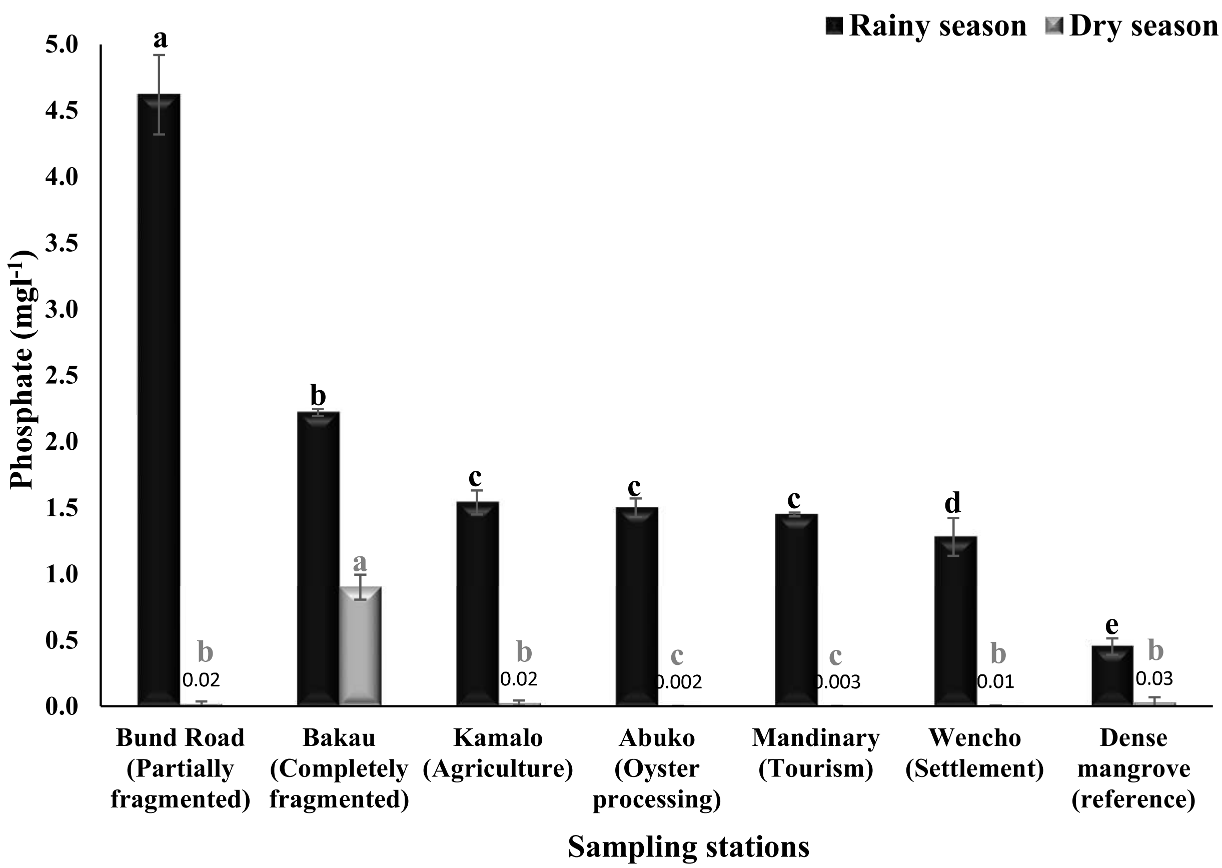

Figure 30. Variations in mean phosphate levels for the sampling stations at different land use/land cover types during the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014.

Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at $P<0.05$.

3.1.1.6. Chlorophyll a and turbidity

Results of chlorophyll a (chl-a) analysis indicated a generally low content in TWNP. Average chl-a level in TWNP declined slightly (not significantly, *P* value of 0.2) from 3.9µgl^{-1} during the rainy season to 3.6µgl^{-1} during the dry season. At a *P* value of 0.05, mean chl-a levels also differed significantly among most of the sampling stations during the same period. During the rainy season (Figure 31), Bakau (completely fragmented zone) exhibited the highest chl-a level (13.6µgl^{-1}), followed by Wencho (settlement zone) with 3.4µgl^{-1} and Bund Road (partially fragmented zone) with 2.7µgl^{-1} and then Abuko (oyster processing zone) with 2.3µgl^{-1} of chl-a. Chl-a levels did not differ significantly between Mandinary (tourism zone) and Kamalo (settlement zone) i.e. 1.3 and 1.1µgl^{-1} respectively. The lowest chl-a level 0.8µl^{-1} during the rainy season was recorded at dense mangrove (reference zone).

During the dry season, chl-a levels were significantly different between all the sampling stations. The highest chl-a (10.2µgl^{-1}) during the dry season was noted at Bakau (completely fragmented zone). This was steeply followed by Kamalo (agriculture) (3.7µgl^{-1}), Bund Road (partially fragmented) (3.2µgl^{-1}), Mandinary (tourism) (3.1µgl^{-1}), Wencho (settlement zone) (2.1µgl^{-1}), Abuko (oyster processing zone) (1.9µgl^{-1}) and the lowest value at dense mangrove (reference zone) (0.9µgl^{-1}). Significant intra-site differences were also noted in chl-a values during the two seasons, except for the dense mangrove (reference zone) where chl-a levels increased slightly (not significantly) during the dry season (from 0.8 to 0.9µgl^{-1}). Mandinary, Kamalo and Bund Road all registered significant increases, while Bakau, Wencho and Abuko showed significant decreases in chl-a during the peak dry season (Figure 31).

Average turbidity in TWNP significantly declined from 11.6 NTU during the rainy season to 8.2 NTU during the dry season. Significant differences were noted between the various sampling stations during the two seasons. During the rainy season, turbidity was highest at Bakau (completely fragmented zone) (18.9 NTU) (Figure 32), followed by Bund Road (partially fragmented) with 15.6 NTU and then Wencho (settlement zone) with 13.9 NTU. Next were Abuko (oyster processing zone) (12.0 NTU) and Mandinary (tourism zone) with a turbidity of 8.9 NTU. A lower turbidity level (6.6 NTU) was recorded at Kamalo (agriculture zone) and the lowest turbidity for the rainy season wat recorded at dense mangrove (reference zone) (5.6 NTU).

During the dry season, Bund Road (partially fragmented zone) displayed the highest turbidity level (20.7 NTU). This was followed by Bakau (completely fragmented zone) with 15.1 NTU and then Wencho (settlement zone) with 10.1 NTU. Turbidity for Mandinary (tourism zone) and Abuko (oyster processing zone) did not differ significantly i.e. 6.4 and 6.3 NTU respectively. This was followed by dense mangrove (reference zone) (3.3 NTU) and the lowest values were at Kamalo (agriculture zone) (3.0

NTU). There were significant intra-site differences in turbidity during the two seasons (Figure 32). Except for Bund Road (partially fragmented zone) where turbidity increased significantly during the dry season (*P* value, 0.01) pairwise student's t-test indicated significant intra-site declines in mean turbidity values of all other sampling stations as seasons changed from rainy to dry season. A summary of the mean values of all the environmental variables for the rainy and dry seasons in TWNP and their significance levels at $P<0.05$ is shown in Table IV; while the summary of the significance levels at $P<0.05$ for individual sampling stations during the rainy and dry seasons is shown in Table V.

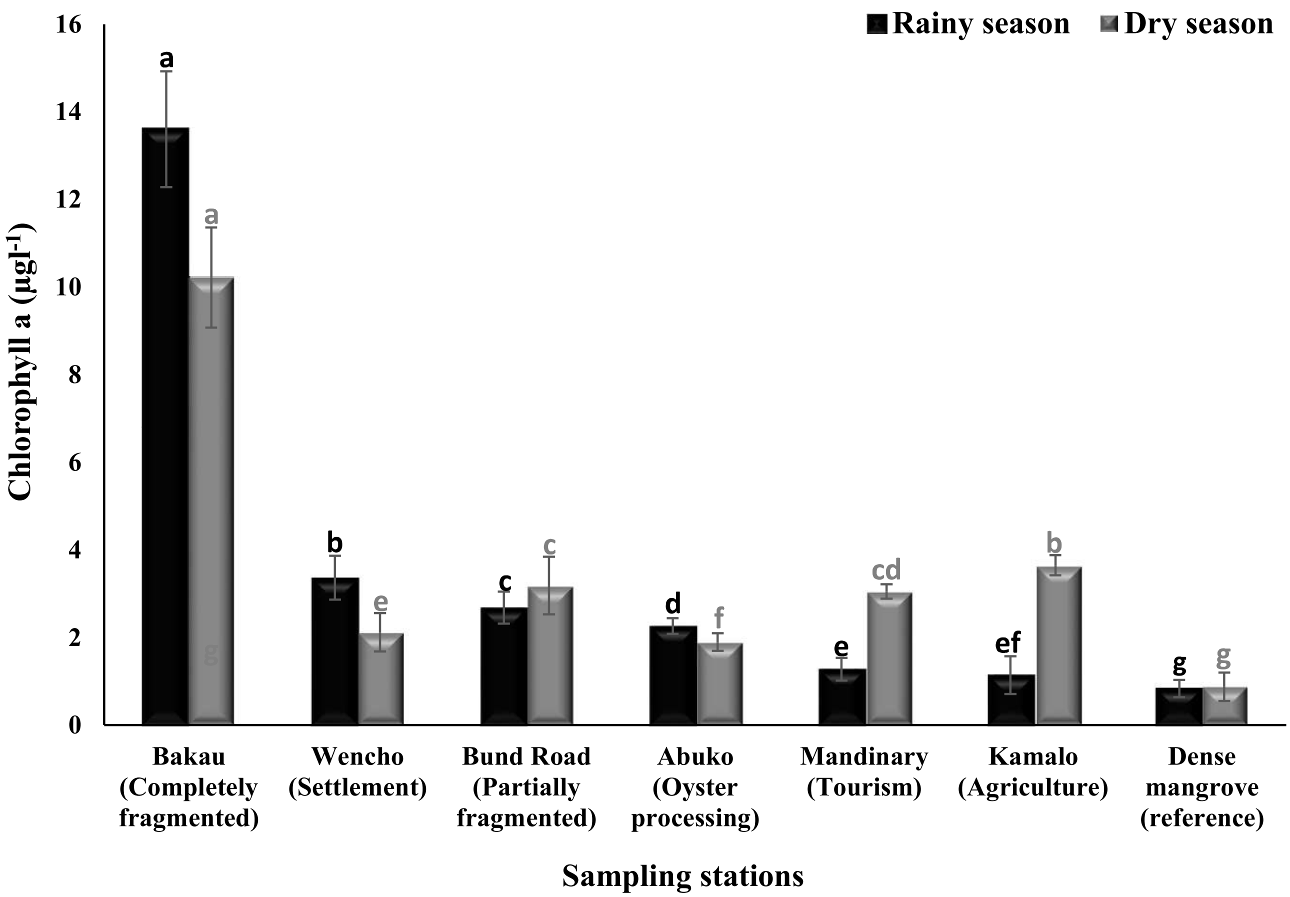

Figure 31. Seasonal variations in mean Chlorophyll-a levels at various sampling stations in Tanbi Wetland National Park in The Gambia in 2014.

Error bars are based on standard deviation of samples analyzed (n=12). Bars with the same superscripts are not significantly different at $P<0.05$.

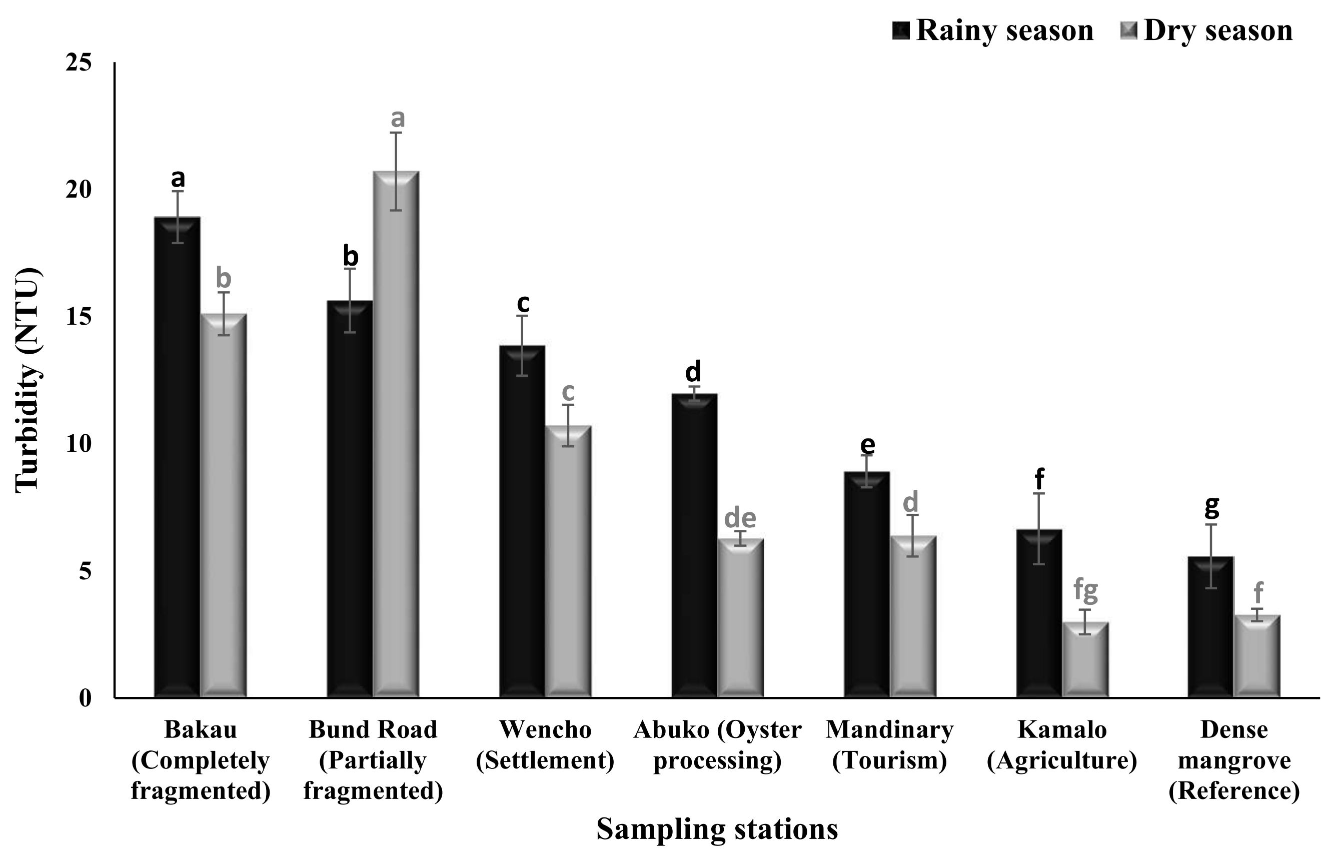

Figure 32. Seasonal variations in mean turbidity levels at various sampling stations in Tanbi Wetland National Park in The Gambia in 2014.

Error bars are based on standard deviation of samples analyzed (n=36). Bars with the same superscripts are not significantly different at $P<0.05$.

Table IV. Summary of mean values of environmental variables and their levels of significance during the rainy and dry seasons in Tanbi wetland National Park in The Gambia in 2014.

Environmental Variable	Rainy season [A]	Dry season [B]	Rainy vs. dry season [C]
Salinity (ppt)	24.5****	35.8*	****
Dissolved Oxygen (mgl^{-1})	5.5**	5.4****	ns
Temperature (°C)	27.7**	30.2****	*
pH	7.6*	7.5***	ns
Chlorophyll a (μgl^{-1})	3.9**	3.6**	ns
Turbidity (NTU)	11.6**	8.2**	**
Nitrate (mgl^{-1})	2.7***	0.8*	***
Phosphate (mgl^{-1})	1.7***	0.1****	**

Based on the results of the pairwise student's t-test comparing the mean value of each variable for all sampling sites in Tanbi Wetland National Park, during the rainy and dry seasons.

Degree of significance at p<0.05 indicated by the number of stars, *: significant at <0.05, **: significant at <0.01, ***: significant at <0.001, ****: significant at <0.0001, ns: not significant. **A**: Mean values for the whole wetland during the rainy season and the significance levels between the various sampling stations; **B**: Mean values for the whole wetland during the dry season and the significance levels between the various sampling stations; **C**: Significance level when the mean values for rainy and dry seasons are compared.

Table V. Significance levels between mean values of environmental variables at the individual sampling stations during the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014.

Environmental variable	Dense mangrove	Abuko	Mandinary	Kamalo	Wencho	Bund Road	Bakau
Salinity (ppt)	*	**	***	**	**	*	****
Temperature (°C)	****	***	****	*	*****	**	****
Dissolved oxygen (mgl^{-1})	*	***	***	****	****	**	**
pH	ns	*	***	***	****	**	ns
Turbidity (NTU)	*	****	**	****	****	ns	***
Nitrate (mgl^{-1})	*	****	***	***	****	**	**
Phosphate (mgl^{-1})	**	***	****	***	*	***	****
Chlorophyll a (μgl^{-1})	ns	ns	***	****	*	ns	**

Based on the pairwise student's t-test results. Degree of significance at P<0.05 indicated by the number of stars, *: significant at <0.05, **: significant at <0.01, ***: significant at <0.001, ****: significant at <0.0001, *****: significant at <0.00001, ns: not significant. Dense mangrove: reference zone; Abuko: oyster processing zone; Mandinary: tourism zone; Kamalo: agriculture zone; Wencho: settlement zone; Bund Road: partially fragment zone: Bakau: completely fragmented zone.

3.1.1.7. Correlation of main water quality/environmental variables

Subjection of the main water/environmental variables to a Principal Components Analysis (PCA) showed significant differences ($P<0.05$) in environmental scenarios of the land use types studied in TWNP. The principal components axes 1 and 2 respectively accounted for 26.04 and 38.8% of variation in environmental variables of the TWNP during the rainy season (Figure 33). Together, these two axes explain 64.9% of the variation in environmental parameters of the land use types in TNWP during the rainy season (Table VI). During the rainy season, nitrate was the main factor distinguishing Mandinary (tourism zone) and Kamalo (agricultural zone) from the other sampling sites. For Wencho (settlement zone), salinity was the main distinguishing variable; temperature and turbidity were the main distinguishing variables at Abuko (oyster processing zone); dissolved oxygen for dense mangrove (reference zone) and phosphate for Bund Road (partially fragmented zone).

The principal component axes 1 and 2 respectively accounted for 31.5 and 49.9% of variation in environmental variables of the TWNP during the dry season (Figure 34). Together, these two axes explain 81.4% of the variation in environmental parameters of the land use types in TNWP during the dry season (Table VII). During the dry season, temperature was the main environmental variable distinguishing Abuko (oyster processing zone) and Wencho (settlement zone) from the other sampling sites. For dense mangrove (reference zone), dissolved oxygen was the main distinguishing variable and to a lesser extent Kamalo (agriculture zone). Salinity and nitrate were the main distinguishing variables at Mandinary (tourism zone), while for Bund Road (partially fragmented zone) turbidity was the strongest environmental variable distinguishing it from the other sampling sites.

For the interaction between the specific environmental variables, a weak correlation was noted during the rainy season; except for temperature and pH which had a negatively significant correlation ($P<0.01$). During the dry season, interaction between the specific environmental variables was significant between pH and phosphate ($p<0.02$) and between temperature and phosphate ($P<0.03$) (Table VIII). The interaction between the other environmental variables did not display any significant correlation.

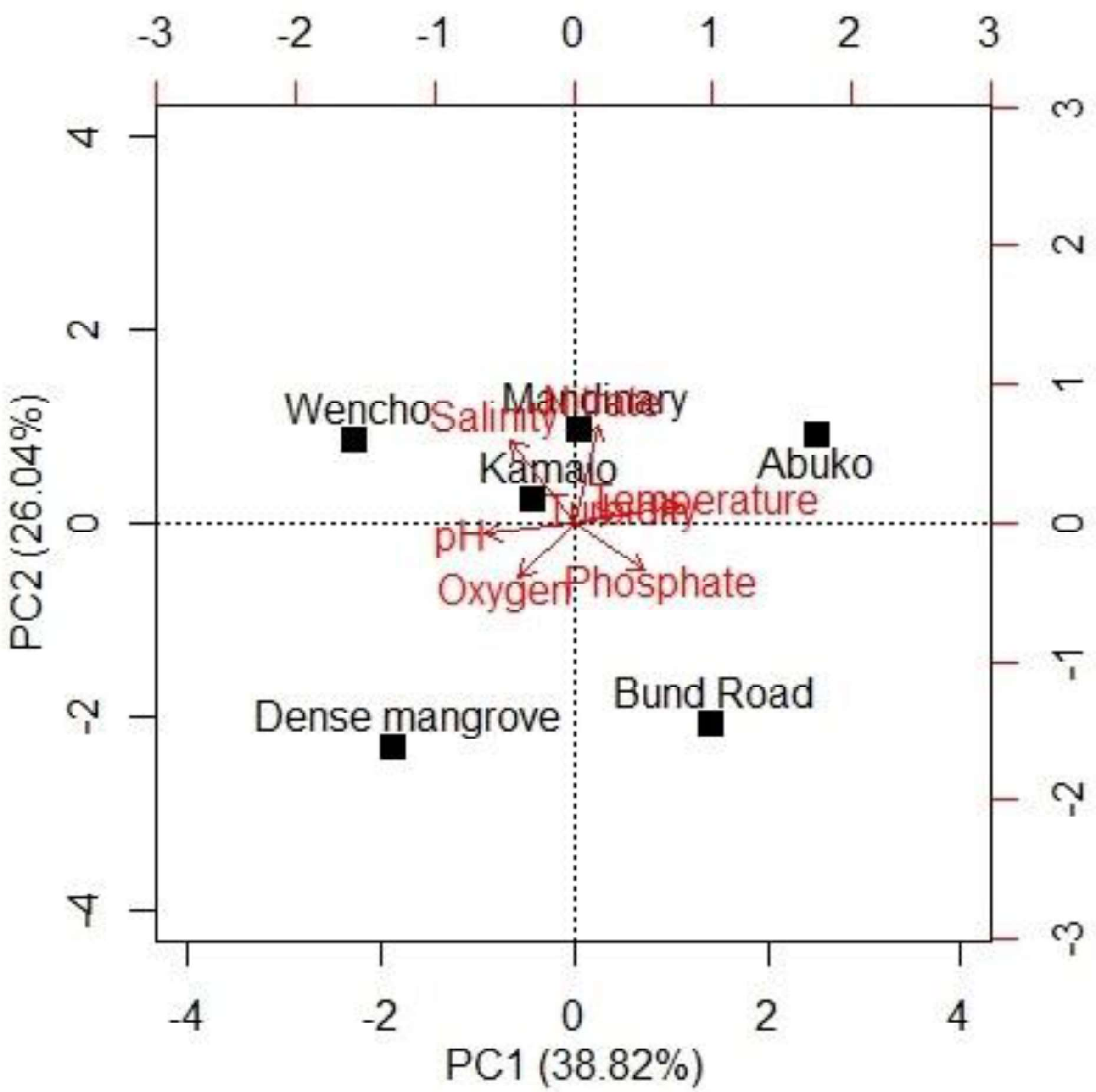

Figure 33. Correlation between the environmental variables at the various land use/land cover types during the rainy season in Tanbi Wetland National Park in The Gambia in 2014.

Based on the Principal Component Analysis of environmental variables and sampling sites during the rainy season.

Table VI. Sources of variance from correlation of environmental variables for the various land use/land cover types in Tanbi Wetland National Park during the rainy season in The Gambia in 2014.

PC	Eigenvalue	Percentage of variance	Cumulative percentage of variance
PC1	2.72	38.82	38.82
PC2	1.82	26.04	64.86
PC3	1.36	19.41	84.27
PC4	0.88	12.51	96.78
PC5	0.23	3.22	100

PC: Principal component.

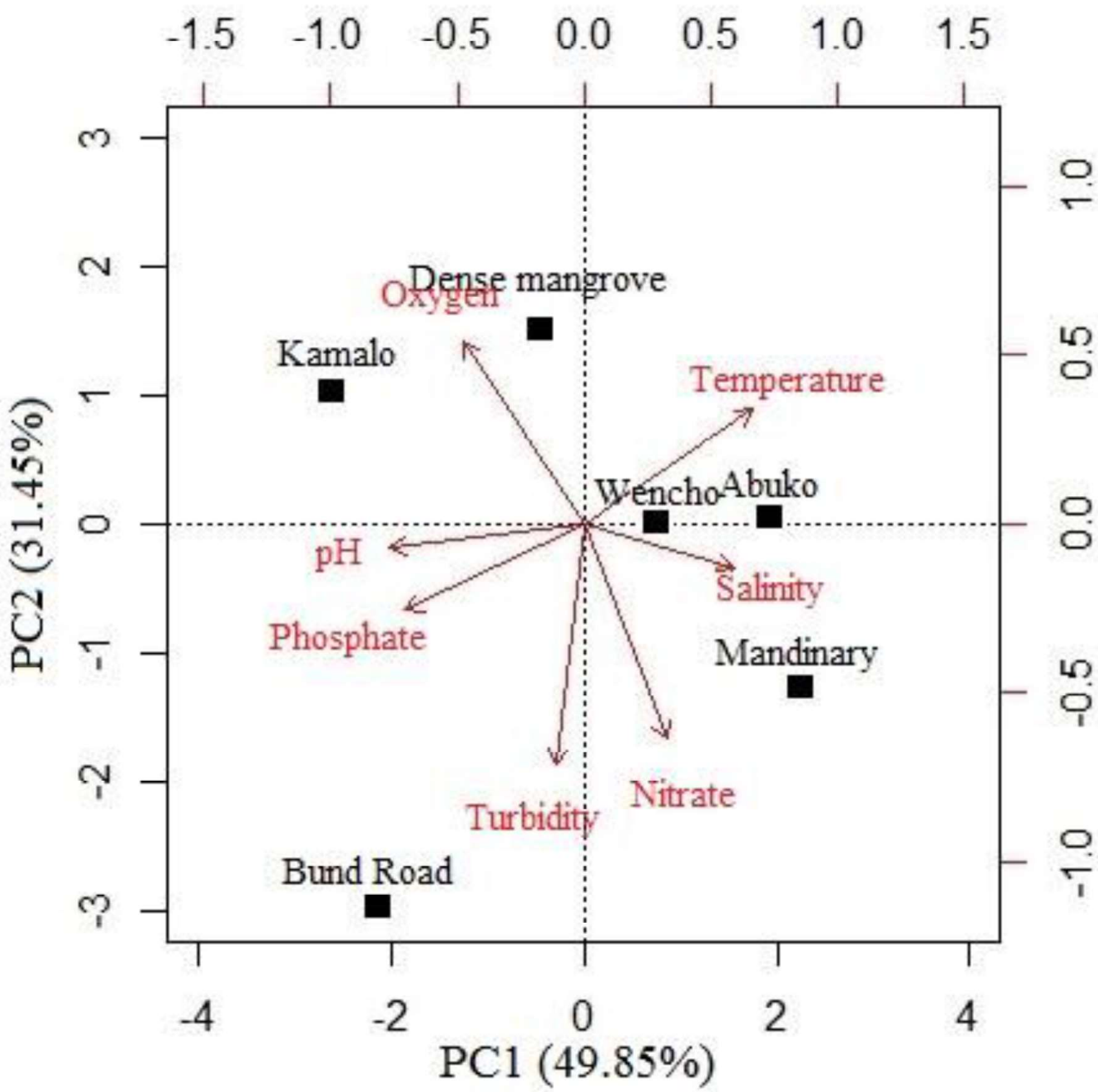

Figure 34. Correlation between the environmental variables at the various land use/land cover types during the dry season in Tanbi Wetland National Park in The Gambia in 2014.

Based on the Principal Component Analysis of environmental variables and sampling sites during the dry season.

Table VII. Sources of variance from correlation of environmental variables for the various land use/land cover types in Tanbi Wetland National Park during the dry season in 2014.

PC	Eigenvalue	Percentage of variance	Cumulative percentage of variance
PC1	3.49	49.85	49.85
PC2	2.20	31.45	81.31
PC3	0.92	13.16	94.47
PC4	0.29	4.20	98.67
PC5	0.09	1.33	100

PC: Principal Component

Table VIII. Correlation between mean values of water quality/environmental variables for the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014.

Rainy \ Dry	Oxygen	Salinity	pH	Temperature	Turbidity	Nitrate	Phosphate
Oxygen		0.61	0.24	0.53	0.20	0.17	0.53
Salinity	0.82		0.20	0.43	0.81	0.15	0.26
pH	0.54	0.40		0.05	0.74	0.62	0.02**
Temperature	0.37	0.39	0.01***		0.34	0.96	0.03*
Turbidity	0.85	0.99	0.99	0.58		0.34	0.6
Nitrate	0.45	0.34	0.77	0.53	0.50		0.98
Phosphate	0.55	0.22	0.83	0.46	0.28	0.70	

Level of significance at $p<0.05$ indicated by the number of stars (*).

3.1.2. Mangrove vegetation dynamics and its relationship with climate variables

During the vegetation study of this research, the accuracy assessment of the images analyzed was above 80% for all the images used. Kappa coefficients for the images of 1973, 1984 and 2002 scored regular, while those of 1995 and 2012 scored excellent. Kappa coefficients for images analyzed were as follows: 0.85 for 1973, 0.88 for 1984, 0.92 for 1995, 0.86 for 2002 and 0.96 for 2012. Notwithstanding, the confusion matrix highlighted a few overlaps between some of the non-mangrove land use/land cover classes i.e. the swamp, grassland / low growth, forest and planting/cultivation (ranging from 12 to 26%) (Table IX). Based on aforementioned accuracy scale, the assessment of the remotely sensed data yielded seven types of land use/land cover in TWNP. These include: Mangrove, Swamp, Forest, Water, Cultivation, Woods, and Grassland (Figure 35).

Mangrove vegetation cover in TWNP remained quiet stable between the years 1973-1984 and 1984-1995, accruing an increase of 1.9% and 1.2% coverage respectively. This trend however began to reverse between 1995-2002 and 2002-2012, declining by 7.3% and 6.6% respectively. Overall loss of mangrove vegetation in TWNP was 6% between 1973 and 2012. This was visible along the fringes of the wetland where massive number of *Avicennia germinans* stumps could be seen. This situation is even more pronounced in Bakau (fragmented zone) located in the Northwestern part of the park, where the mangrove vegetation is mostly comprised of *Avicennia germinans* (Figure 36). In relation, swamp coverage increased proportionally by 44.4% as mangrove decline and seemingly replacing the degraded mangrove areas during the period under study (Figure 37).

Significant conversion was also recorded between the other vegetation types within the wetland. For instance, within the four-decade period, the forest areas surrounding the park declined by 311.1% to be replaced by either low growth/grassland or cultivation/plantation, especially along the Southwestern part of the park (Abuko end, oyster processing zone). A similar trend was observed for the woody areas with a decline of 112.0% (Figure 38 and Figure 39). Area coverage of the various land use types and the corresponding decadal percentage changes are shown in Table X and Table XI respectively.

Table IX. Confusion matrix, accuracy assessment and Kappa coefficients of satellite images analyzed for Tanbi Wetland National Park (1973, 1984, 1995, 2002 and 2012) in The Gambia.

Year		Land use / Land cover							Accuracy	Kappa
		Ma	Sw	Fo	Wa	Cul	Wo	Gr		
	Ma	**86.9**	0	0	0	0	1.7	0		
	Sw	0.1	**65.8**	0	0.4	0	13.9	5.8		
	Fo	0	1.6	**94.5**	0	0	1.3	0		
1973	Wa	0	2.9	0	**96.5**	0.6	0.1	1.5		
	Cul	0	1.5	0	0	**96.9**	6.0	18.7		
	Wo	13	1.7	5.5	0.7	0	**76.4**	0		
	Gr	0	26.4	0	2.4	2.5	0.7	**74**	84.43	0.85
	Ma	**96**	4.4	0	0	0	0	0		
	Sw	2.8	**65.6**	0	0.8	0	0	1.6		
	Fo	0.2	0.2	**99.6**	0	0	4.2	0		
1984	Wa	0	0.6	0	**98.9**	0	0	0		
	Cul	0	0	0	0	**87.2**	5.2	0.1		
	Wo	1	14.2	0.4	0.3	5.5	**84.5**	5.8		
	Gr	0	15	0	0	7.3	6.2	**92.5**	89.19	0.88
	Ma	**96.7**	1.5	0	0.3	0	0	0		
	Sw	3	**92.5**	0	0.9	0	1.4	9.2		
	Fo	0	0.1	**98.3**	0	0.3	12.7	0		
1995	Wa	0.3	0.2	0	**98.8**	0	0	0		
	Cul	0	0.2	0	0	**96.7**	1.7	0.3		
	Wo	0	0	1.7	0	0.3	**78**	0		
	Gr	0	5.5	0	0	2.7	6.2	**90.5**	93.04	0.92
	Ma	**93.9**	0	0	0.2	0	0	0.6		
	Sw	1.8	**99.7**	0	0	0	0	4.9		
	Fo	0	0	**100**	0	0	7.1	0		
2002	Wa	0.7	0	0	**99.7**	0	0	0.4		
	Cul	0	0	0	0	98.2	9.7	0.7		
	Wo	0	0	0	0	1.8	**82.6**	0.9		
	Gr	3.6	0.3	0	0.1	0	0.8	**92.5**	95.23	0.86
	Ma	**99.2**	1.3	0	0	0	0	0.5		
	Sw	0.6	**95.8**	0	1.1	0.1	0	1		
	Fo	0	0	**98.2**	0	0	2.5	0		
2012	Wa	0.1	1.6	0	**98.8**	0	0	0.1		
	Cul	0	0	0	0	**99.5**	8.6	0.5		
	Wo	0	0	1.8	0	0.3	**86.5**	0		
	Gr	0.1	1.4	0	0.1	0.1	2.4	**97.8**	96.54	0.96

Ma: Mangrove, Sw: Swamp, Fo: Forest, Wa: Water, Cul: Cultivation/Plantation, Wo: Woods, Gr: Grassland/low growth

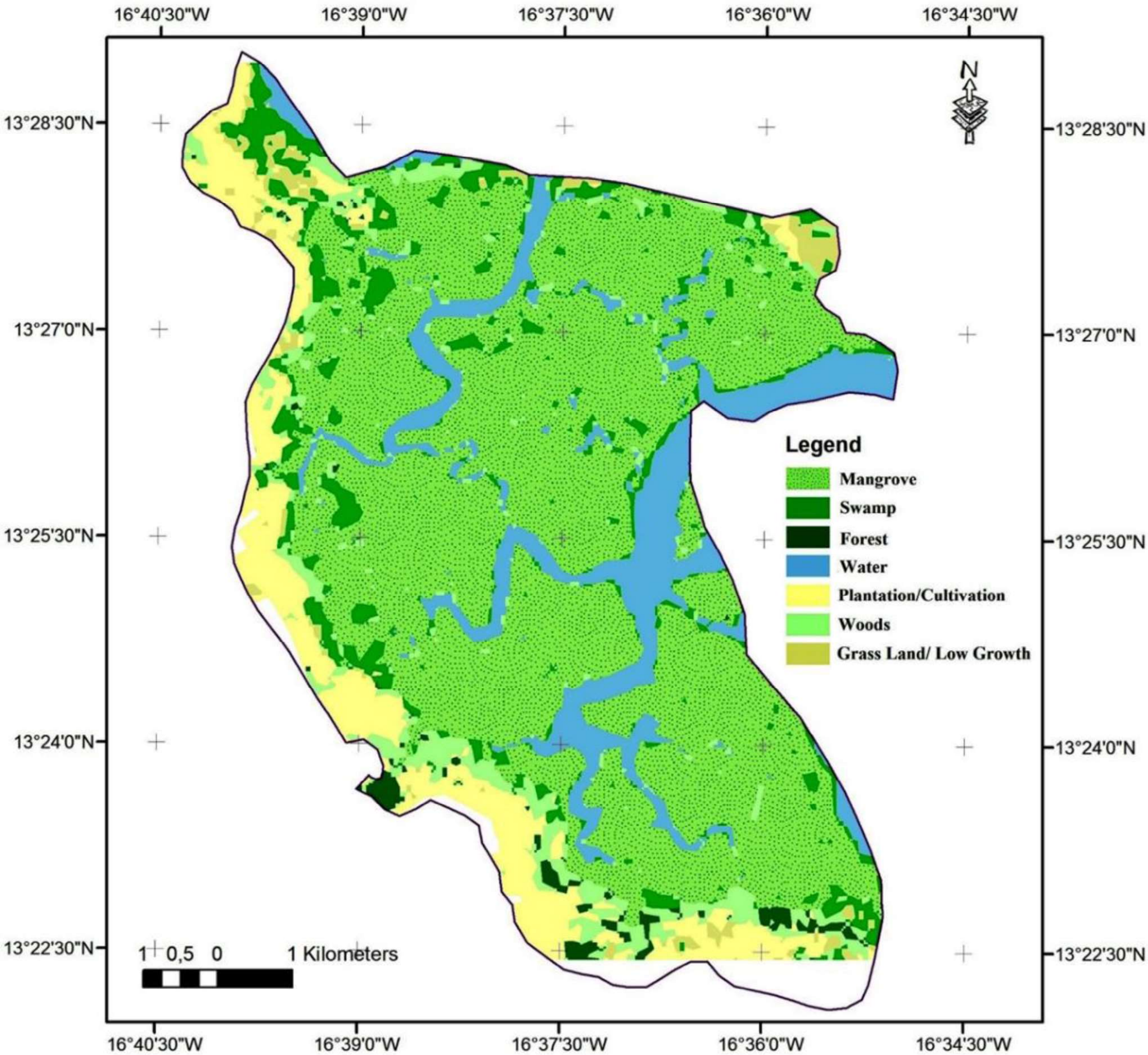

Figure 35. Land use / land cover map of Tanbi Wetland National Park in The Gambia, for 1973.

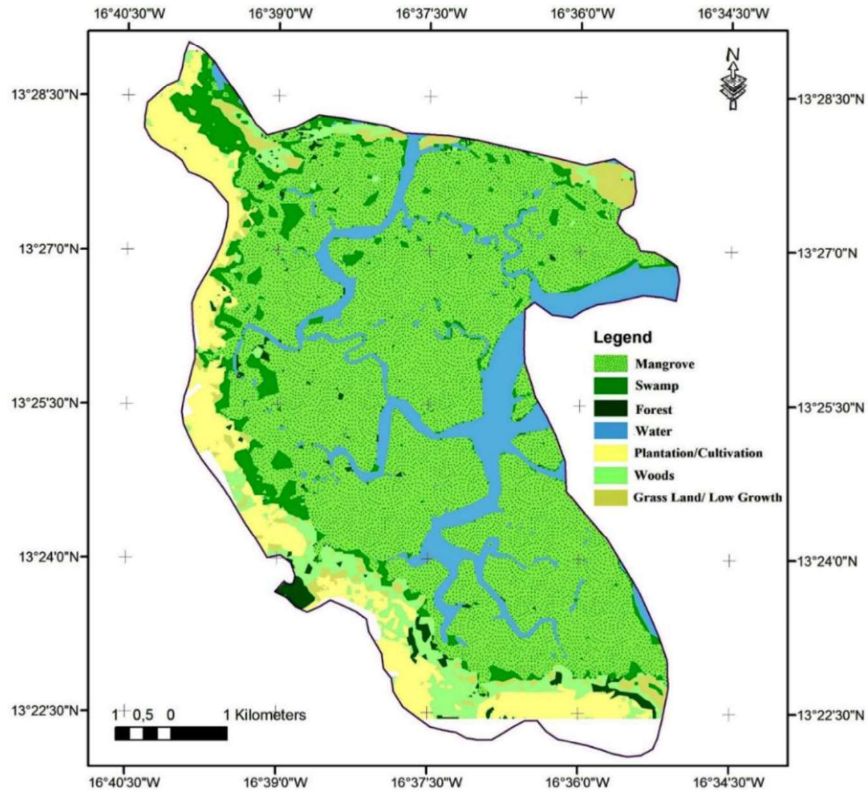

Figure 36. Land use / land cover map of Tanbi Wetland National Park in The Gambia, for 1984.

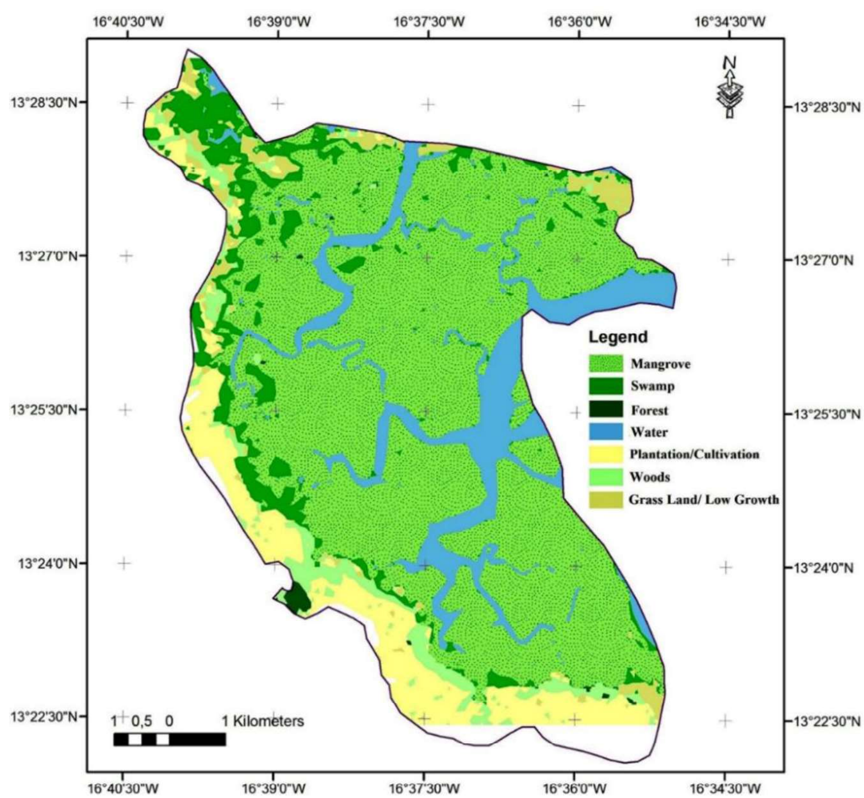

Figure 37. Land use / land cover map of Tanbi Wetland National Park in The Gambia, for 1995.

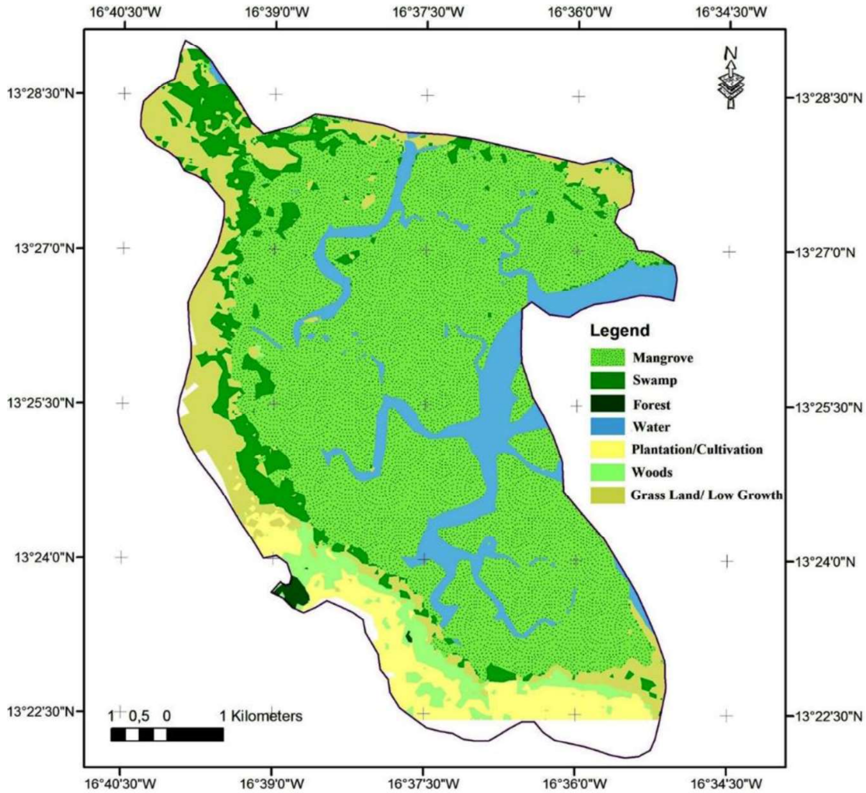

Figure 38. Land use / land cover map of Tanbi Wetland National Park in The Gambia, for 2002.

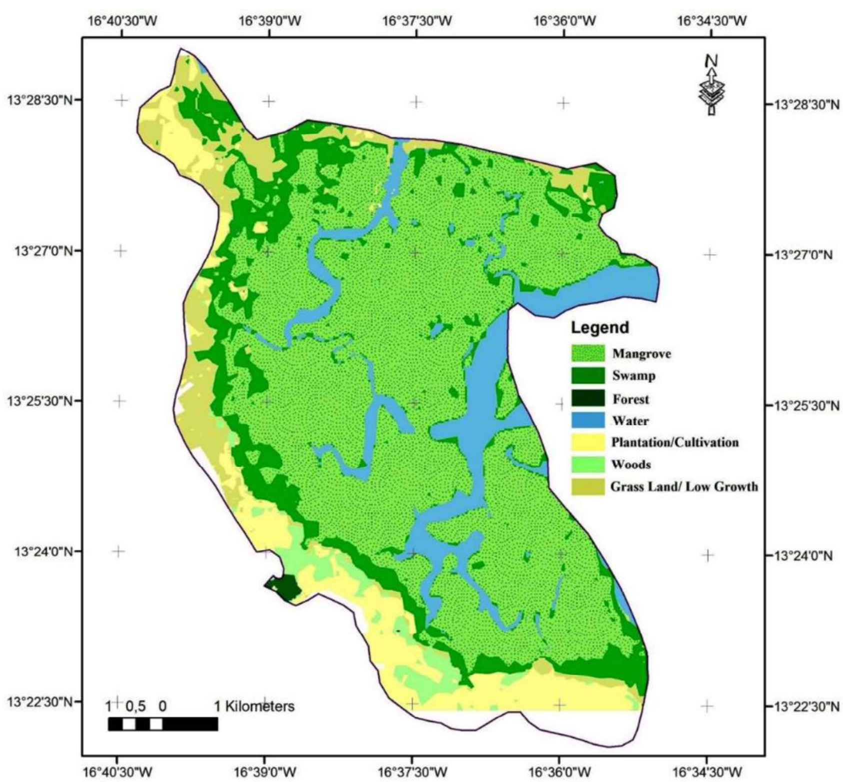

Figure 39. Land use / land cover map of Tanbi Wetland National Park in The Gambia, for 2012.

Table X. Percentage area cover of land use / land cover classes in Tanbi Wetland National Park in The Gambia, covering decades of 1973 to 2012.

Land cover	Area coverage (%)				
	1973	1984	1995	2002	2012
Mangrove	59.2	60.4	61.1	59.7	55.6
Swamp	7.7	7.1	8.5	8.0	14.1
Forest	1.3	1.5	0.4	0.3	0.3
Water	12.1	11.9	12.2	10.9	10.7
Cultivation/plantation	11.0	10.2	10.3	6.1	9.3
Woods	6.6	5.7	4.0	3.2	2.5
Grass Land/low growth	2.0	3.2	3.4	11.8	7.5

Table XI. Summary of land use / land cover changes in Tanbi Wetland National Park in The Gambia, covering decades of 1973 to 2012.

Land cover	**Decadal land use land cover changes in TWNP (%)**				**Total (%)**
	1973 - 1984	**1984 - 1995**	**1995 - 2002**	**2002 - 2012**	
Mangrove	+1.9	+1.3	-2.4	-7.3	-6.6
Swamp	-8.8	+17.0	-7.2	+43.4	+44.4
Forest	+14.6	-292.2	-17.1	-16.4	-311.1
Water	-1.7	+2.7	-12.7	-1.4	-13.3
Cultivation/plantation	-7.2	+0.4	-68.1	+34.3	-40.6
Woods	-16.0	-42.1	-24.5	-29.3	-112.0
Grass Land/low growth	+35.7	+6.5	+71.2	-57.0	+56.4

In relation to historical data of climate variables (herein rainfall and atmospheric temperatures) of Banjul, mangrove vegetation cover in TWNP declined proportionally as rainfall declined and atmospheric temperatures increased. Historical climate data showed that rainfall index for Banjul was quite positive before 1968 (Figure 40). During this period, the rainfall index for Banjul was always above 1.4. Hence the focus here is on the rainfall data during and after the Sahelian drought (1972 – 2014). The mean rainfall index for the decade leading to 1973 was -0.4; further declining to -0.2 during the decade of 1984, as well as for the decade of 1994. There was a further decline in rainfall index to -0.1 during the decade leading to 2004 and then making a slight recovery to 0.01 during the decade leading to 2012 (Figure 40).

Mean annual temperature index for Banjul followed a similar trend to rainfall, with indices staying below zero before the Sahelian drought in early 1970s (Figure 41). However, temperature indices spiked to a mean of 0.6 in 1972 and stayed above zero for that entire decade. Temperature index dropped to -0.5 in 1984, but this lasted only until 1987 and the temperature indices spike occurred again to a mean of 0.2. This lasted the rest of the decade (1987-1996). After this, the temperature index declined to -0.51 and remained cooler until 2002. This was followed by a steady increase in temperature index, staying at a mean of 0.6 until 2010 and then cooling down a bit to a mean of -0.3 until 2014 (Figure 41).

In relation to the above, the area coverage for mangrove vegetation was stable during the first couple of decades studied (Figure 42), with a slight increase of 77.8ha between the years 1973 – 1984 and then by 52.8ha from 1984 – 1995. This trend however, changed course with significant declines during the next two decades studied. Between the years 1995 – 2002, mangrove vegetation in TWNP declined by 99.9ha and then by 280.2ha between the years 2002 – 2012. Forests around the park followed a similar trend, only increasing by 14.9ha during the first decade, then declining by 75.8, 3.8 and 3.1ha during the following three decades. The grassland and swamps were the only land use types that registered a significant increase in area coverage as environmental conditions became harsher i.e. 579.2ha and 420.0ha in 1995-2002 and 2002-2012 respectively (Figure 42).

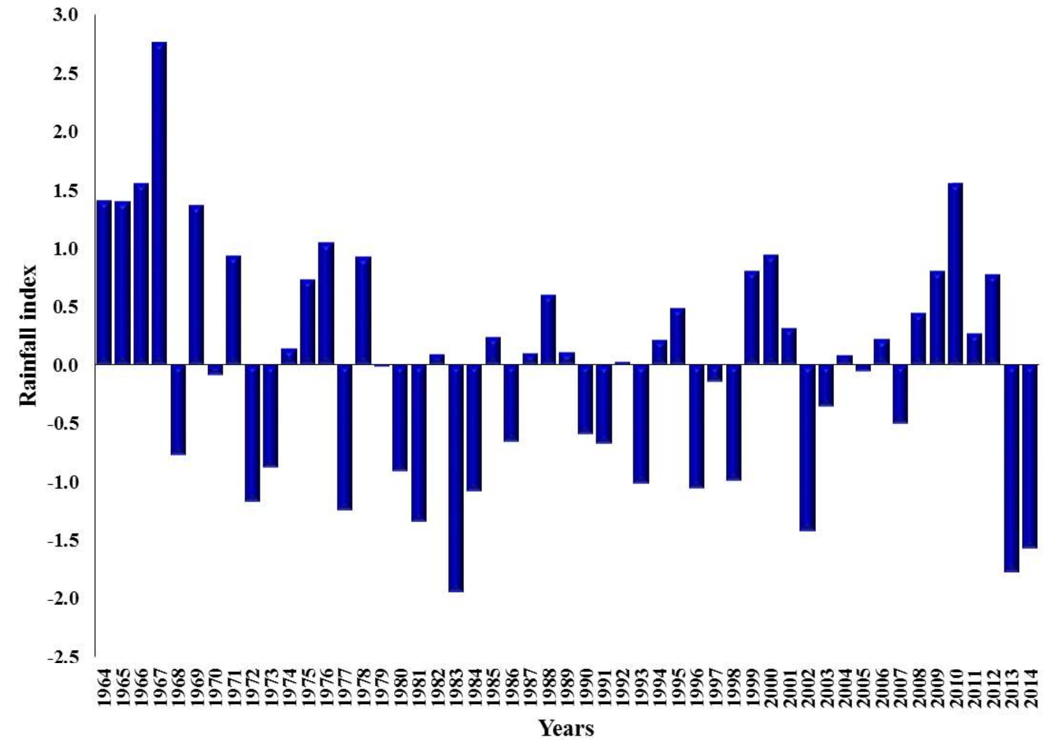

Figure 40. Rainfall anomalies in Banjul in The Gambia, from 1964-2014 (Source: **The Gambia meteorological Bureau, 2015**).

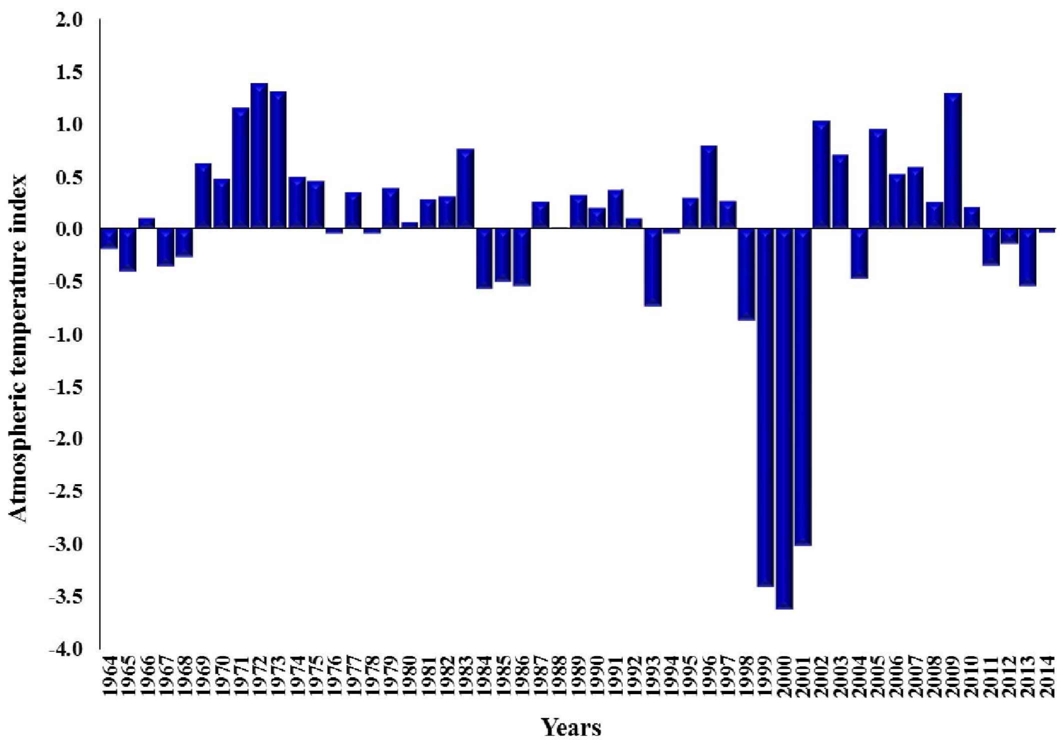

Figure 41. Atmospheric temperature anomalies in Banjul in The Gambia, from 1964-2014 (Source: **The Gambia meteorological Bureau, 2015**).

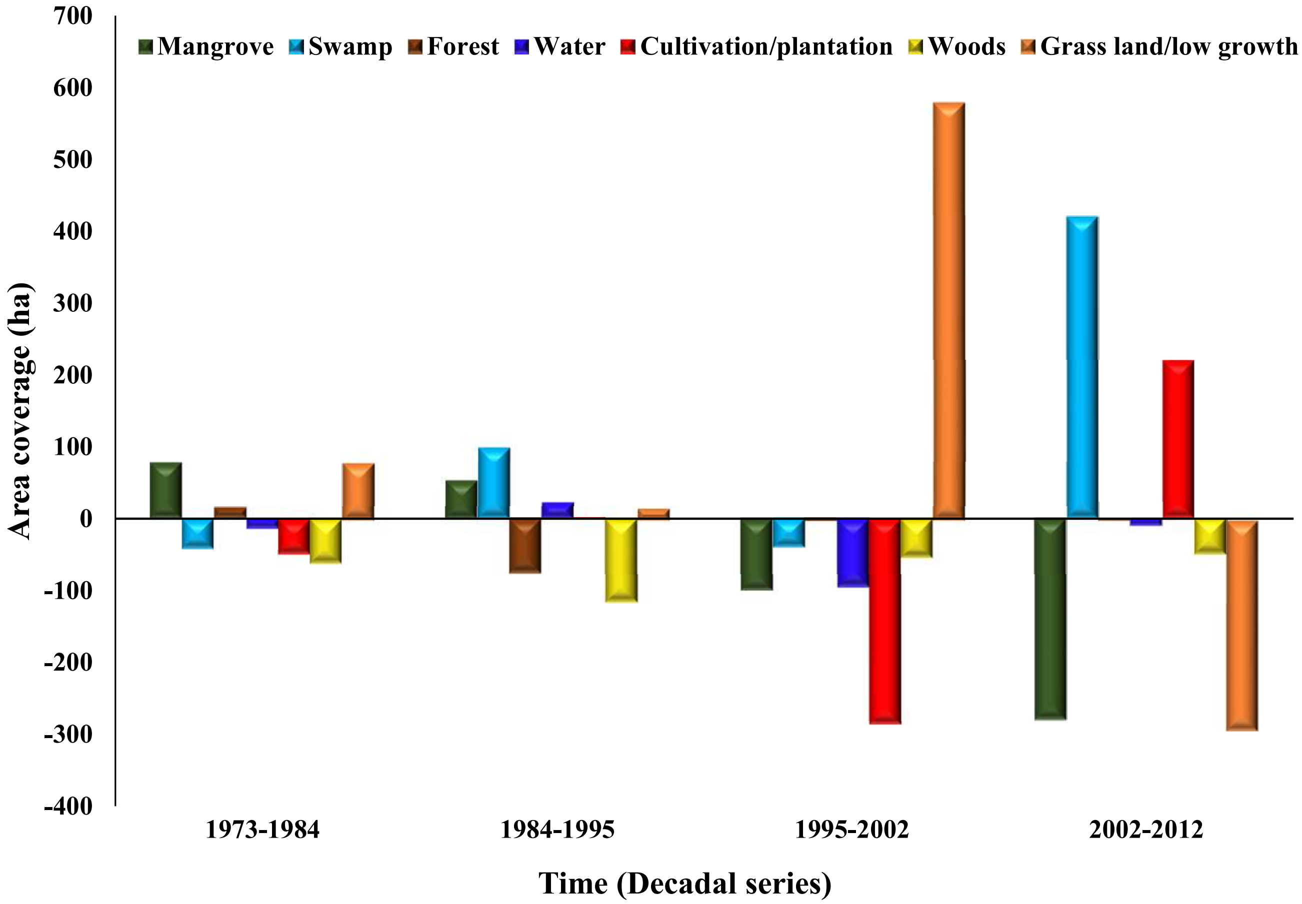

Figure 42. Land use/land cover changes in Tanbi Wetland National Park in The Gambia, covering decades from 1973 to 2012.

3.1.3. Fish assemblage

3.1.3.1. Fish diversity

Fish community in TWNP is comprised of 43 species from 25 families (Table XI). The average number of fish species caught during the two seasons were as follows: 37 species from 21 families during the peak discharge period and 31 species from 19 families during the peak dry season. The overall species richness is as follows: Mandinary (tourism zone), 27 (62.8% of total species caught); dense mangrove (reference zone), 23 (53.5%); Abuko (oyster processing zone), 22 (51.2%); Wencho (settlement zone), 19 (44.2%); Kamalo (agriculture zone), 18 (41.9%) and Bund Road (partially fragmented zone), 17 (39.5%). At family level, fish assemblage in TWNP was dominated by euryhaline fishes, with 13 fish families forming up to 90% of the overall abundance. Among these is the Mugilidae which was the most speciose family in TWNP, having 6 species; Haemulidae (5 species); Cichlidae (4 species); Clupeidae and Gerreidae (3 species each) and Cynoglossidae, Polynemidae and Sciaenidae (2 species each). The rest of the fish families were singletons (represented by only 1 species each). The least represented fish families were Carangidae and Torpedinidae, each having been caught only once and during the rainy season (Table XII).

During the rainy season, significant differences were noted in species richness between the various sampling stations (Figure 43A, B and C), except between Kamalo (agriculture zone) and Bund Road (partially fragmented zone) with 10 (27% of total species each). Abuko (oyster processing) had the highest species richness (20) (54.1%), followed by dense mangrove (reference zone) (16) (43.2%), Mandinary (tourism zone) (15) (40.5%) and Wencho (settlement zone) (13) (35.1%).

During the dry season, Mandinary (tourism zone) showed the highest number of species (20) (64.5% of total species). This was followed by Abuko (oyster processing) and Bund Road (partially fragmented zone), with 14 fish species (45.2%) at both sites. Thirteen fish species (41.9% of total species) were caught at Wencho (settlement zone), 12 (38.7%) at Kamalo (agriculture zone), and 10 at dense mangrove (reference zone) (32.3%) which exhibited the lowest species richness during the dry season. Concerning seasonal intra-site changes in species richness, significant differences were noted at all the sampling stations, except at Wencho (settlement zone).

Table XII. Complete list and occurrence of all fish species caught in Tanbi Wetland National Park in The Gambia during the rainy and dry season in 2014.

Family	Species	Abuko		Kamalo		Mandinary		Wencho		Dense mangrove		Bund Road	
		R	D	R	D	R	D	R	D	R	D	R	D
Ariidae	*Carlarius heudelotii* (Valenciennes,1840)	0	0	0	0	1	0	0	0	1	0	0	0
Belonidae	*Strongylura senegalensis* (Valenciennes,1846)	1	0	1	1	0	0	1	0	0	1	0	0
Batrachoididae	*Batrachoides liberiensis* (Steindachner, 1867)	0	0	0	1	0	0	0	0	0	0	0	1
Carangidae	*Chloroscombrus chrysurus* (Linnaeus, 1766)	0	0	0	0	0	0	1	0	0	0	0	0
Cichlidae	*Hemichromis fasciatus* (Peters, 1857)	1	1	0	1	0	1	1	1	0	0	1	1
	Sarotherodon melanotheron (Rüppell, 1852)	1	1	1	1	1	1	1	1	0	1	1	1
	Tilapia guineensis (Bleeker, 1863)	1	1	0	1	1	1	1	1	0	0	0	0
	Tylochromis jentinki (Steindachner, 1894)	0	0	0	0	0	1	0	1	1	0	0	0
Clupeidae	*Ethmalosa fimbriata* (Bowdich, 1825)	1	1	0	1	1	0	0	0	1	1	1	1
	Ilisha Africana (Bloch, 1795)	1	0	0	0	1	1	0	0	1	0	0	0
	Pellonula leonensis (Boulenger, 1916)	0	0	0	0	0	0	0	0	0	0	1	0
Cynoglossidae	*Citharichthys stampflii* (Steindachner, 1894)	0	0	0	1	0	1	1	1	0	1	0	1
	Cynoglossus senegalensis (Kaup, 1854)	1	1	0	0	1	0	0	1	0	0	0	1
Dasyatidae	*Dasyatis margarita* (Günther, 1870)	1	1	0	0	0	0	0	1	1	0	0	0
Drepaneidae	*Drepane Africana* (Osório, 1892)	1	0	0	0	0	1	0	0	0	0	0	0
Eleotridae	*Bostrychus africanus* (Steindachner, 1879)	0	0	0	0	0	0	0	0	1	0	0	0
Elopidae	*Elops senegalensis* (Regan, 1909)	0	0	0	0	0	1	0	0	0	1	1	1
Gerreidae	*Eucinostomus melanopterus* (Bleeker, 1863)	1	1	1	1	1	0	1	1	1	1	1	1
	Gerres nigri (Gunther, 1859)	0	0	0	0	0	0	0	0	1	0	0	0
Gobiidae	*Porogobius schlegelii* (Günther, 1861)	0	0	0	0	0	1	0	0	1	0	1	0
Haemulidae	*Brachydeuterus auritus* (Valenciennes, 1832)	0	0	1	0	0	0	0	0	0	0	0	0
	Plectorhincus macrolepis (Boulenger, 1899)	1	1	0	0	0	1	0	0	0	0	0	0
	Pomadasys aheneus (Mckay & Randall, 1995)	0	0	0	0	0	0	1	0	0	0	0	0
	Pomadasys jubelini (Cuvier, 1830)	1	0	1	0	1	0	0	0	0	0	0	0
	Pomadasys peroteti (Cuvier, 1830)	1	1	1	0	0	0	1	0	1	0	1	1
Lutjanidae	*Lutjanus goreensis* (Valenciennes, 1830)	0	0	1	0	0	0	0	0	0	0	0	0
Monodactylidae	*Monodactylus sebae* (Cuvier, 1829)	0	1	0	1	1	1	0	1	1	1	0	1
Moronidae	*Disentrarchus punctatus* (Bloch, 1792)	0	0	0	1	0	0	0	1	0	0	0	1
Mugilidae	*Liza aurata* (Risso, 1810)	1	1	1	1	1	1	0	1	1	0	0	0
	Liza dumerili (Steindachner, 1870)	0	0	0	0	0	1	0	0	0	0	0	0
	Liza falcipinnis (Valenciennes, 1836)	1	1	0	1	0	1	1	0	0	0	1	0
	Liza grandisquamis (Valenciennes, 1836)	0	1	0	0	0	0	1	0	0	1	0	1
	Mugil bananensis (Pellegrin, 1927)	1	0	1	0	1	1	1	1	1	0	1	1
	Mugil cephalus (Linnaeus, 1758)	0	0	1	0	1	0	0	0	0	0	0	0
Polynemidae	*Galeoides decadactylus* (Bloch, 1795)	1	0	0	0	0	1	0	0	0	1	0	0
	Polydactylus quadrifilis (Cuvier, 1829)	0	0	0	0	1	1	0	0	0	0	0	1
Sciaenidae	*Pseudolithus elongates* (Bowdich, 1825)	0	0	0	0	0	1	0	0	0	0	0	0
	Pseudolithus senegalensis (Valenciennes, 1833)	1	0	0	0	1	1	1	1	0	0	0	0
Serranidae	*Epinephelus aeneus* (Saint-Hilaire, 1817)	0	0	0	0	0	0	0	0	0	1	0	0
Sparidae	*Dentex maroccanus* (Valenciennes, 1830)	0	0	0	0	0	1	0	0	0	0	0	0
Sphyraenidae	*Sphyraena afra* (Peters, 1844)	1	0	0	0	1	0	0	0	1	0	0	0
Tetraodontidae	*Ephippion guttifer* (Bennett, 1831)	1	1	0	0	0	0	0	0	1	0	0	0
Torpedinidae	*Torpedo torpedo* (Linnaeus, 1758)	0	0	0	0	0	0	0	0	1	0	0	0
Total 25	**43**	**20**	**14**	**10**	**12**	**15**	**20**	**13**	**13**	**16**	**10**	**10**	**14**

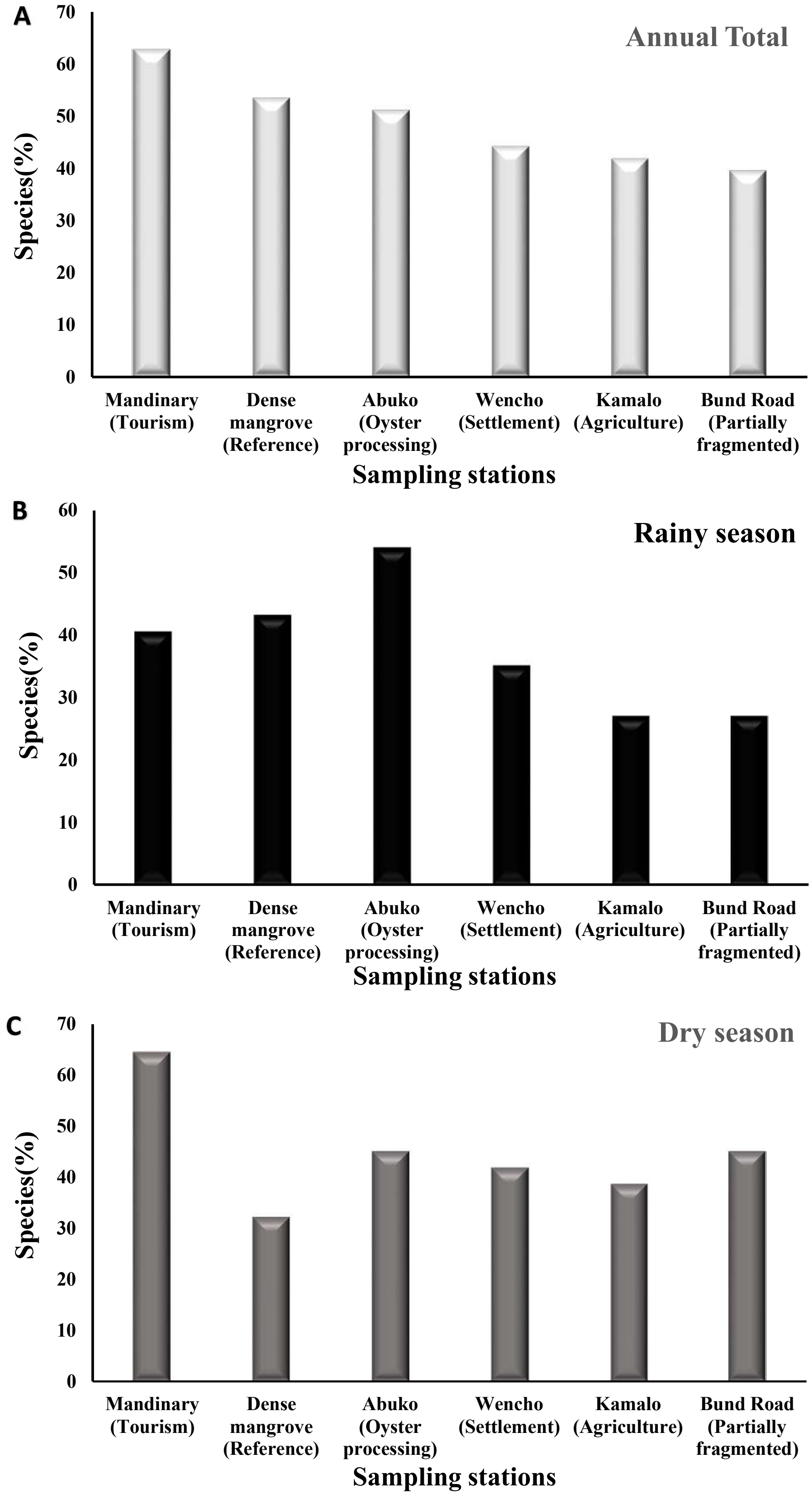

Figure 43. Percentage of the fish species present at the different land use types in Tanbi Wetland National Park in The Gambia in 2014. A: Annual total, B: Rainy season, C: Dry season.

Species composition at the sampling stations in TWNP was significantly different during the two seasons. Based on the average Jaccard-Sørensen similarity indices, the overall percentage of shared species indicated very low similarity in fish species composition of the TWNP. The similarity is 35.7% and 43.1% during the rainy and dry seasons respectively. Shared species also differed within the individual sampling stations for the two seasons. During the rainy season, the highest percentage (54.3%) of shared species was observed between Abuko (oyster processing) and Mandinary (tourism zone), while the lowest (16.7%) was observed between Wencho (settlement zone) and Dense mangrove. During the dry season, Wencho (settlement zone) and Kamalo exhibited the highest shared species i.e. 55.5%, while dense mangrove (reference zone) and Mandinary (tourism zone) shared the lowest number of species 26.7% (Table XII). Shared fish species also differed significantly at individual sites during the two seasons, with Abuko having the highest (89.8%) shared species and dense mangrove the lowest (24.5%) (Table XIII).

The accumulation trend/curve for the fish species during this research were considered satisfactory. Sampling efficiency was deemed sufficient (79.5%) as indicated by the Chao2 estimator in the species rarefaction curve (Figure 44). Examples of the largest strict estuarine fish species and the most common euryhaline fish species in TWNP are shown in Figure 45 and Figure 46.

In terms of abundance (Figure 47), a total of 3903 individuals were caught during the peak discharge period, but this declined to 2530 individuals during the peak dry season. Significant differences were also noted in fish abundance between the various sampling sites, as well as within individual sampling stations during the two seasons. During the rainy season, the highest number of individuals (1245) (31.9% of total abundance) caught was at dense mangrove (reference zone). This was followed by Abuko (oyster processing zone) with 887 (22.7%), Wencho (settlement zone) with 571 (14.6%), Bund Road (partially fragmented zone) with 475 (12.2%), Kamalo (agriculture zone) with 381 (9.8%) and the lowest being Mandinary (tourism zone) with 344 individuals (8.8% of total abundance). During the dry season, however, Wencho (settlement zone) had the highest abundance (975) (38.5% of total abundance). This was followed by Abuko (oyster processing zone), with 482 individuals (19.1%), and then Mandinary (tourism zone) with 347 individuals (13.7%), Kamalo (agriculture zone) with 274 individuals (10.8%) and Bund Road (partially fragmented zone) with 250 individuals (9.9%). The dense mangrove (reference zone) had the lowest number of individuals (202) (8.0%) caught during the dry season.

Table XIII. Shared fish species in Tanbi Wetland National Park, based on average values of Jaccard-Sørensen similarity indices during the rainy and dry seasons, 2014.

Dry (%) / Rainy (%)	Wencho (Settlement)	Kamalo (Agriculture)	Abuko (Oyster Processing)	Mandinary (Tourism)	Dense mangrove (Reference)	Bund Road (partially frag.)
Wencho (Settlement)		55.5	50.7	46.0	27.9	50.7
Kamalo (Agriculture)	37.4		53.0	35.9	46.0	53.0
Abuko (Oyster Processing)	41.7	38.5		33.5	34.0	48.6
Mandinary (Tourism)	23.5	39.8	54.3		26.7	33.5
Dense mangrove (Reference)	16.7	24.4	41.7	43.2		49.7
Bund Road (partially frag.)	46.0	32.5	38.5	25.5	31.1	

Table XIV. Shared fish species at intra-site level in Tanbi Wetland National Park, based on average values of Jaccard-Sørensen similarity indices during the rainy and dry seasons, 2014.

Sampling station	**Wencho (Settlement)**	**Kamalo (Agriculture)**	**Abuko (Oyster processing)**	**Mandinary (Tourism)**	**Dense mangrove (Reference)**	**Bund Road (Partially frag.)**
Shared species (%)	53.1	40.4	89.8	52.5	24.5	70.3

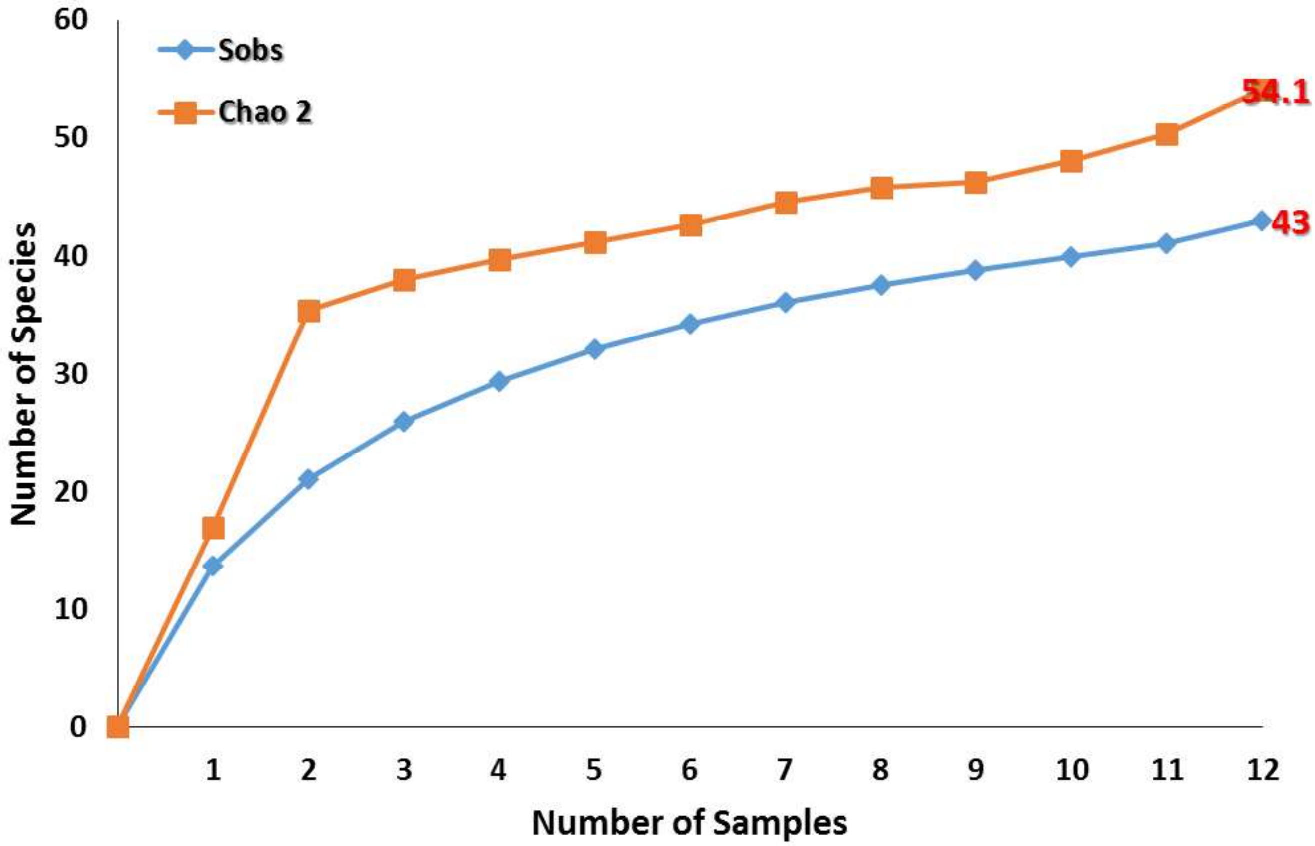

Figure 44. Species accumulation curve for Tanbi Wetland National Park in The Gambia in 2014. Based on species observed data (Sobs) versus asymptote curve (Chao 2), sampling efficiency = 79.49%.

Figure 45. *Polydactylus quadrifilis* (Cuvier, 1829) (giant African threadfin), the largest marine estuarine fish species caught from Mandinary (tourism zone) in Tanbi Wetland National Park in The Gambia in 2014.
Dark line as scale for 25cm in fish fork length.

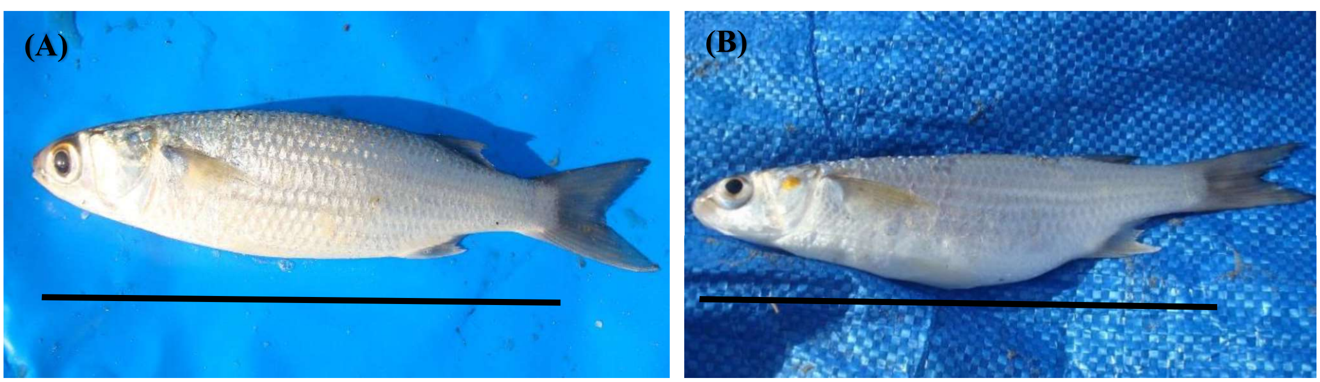

Figure 46. *Mugil cephalus* (Linnaeus,1758) (flathead mullet) (A.) and *Liza aurata* (Risso, 1810) (golden-grey mullet) (B.), two euryhaline fish species from the most dominant fish family (Mugilidae) caught from Kamalo (agriculture zone) in Tanbi Wetland National Park in The Gambia in 2014.
Dark lines as scale for 15 and 13.9 cm in fish fork length respectively.

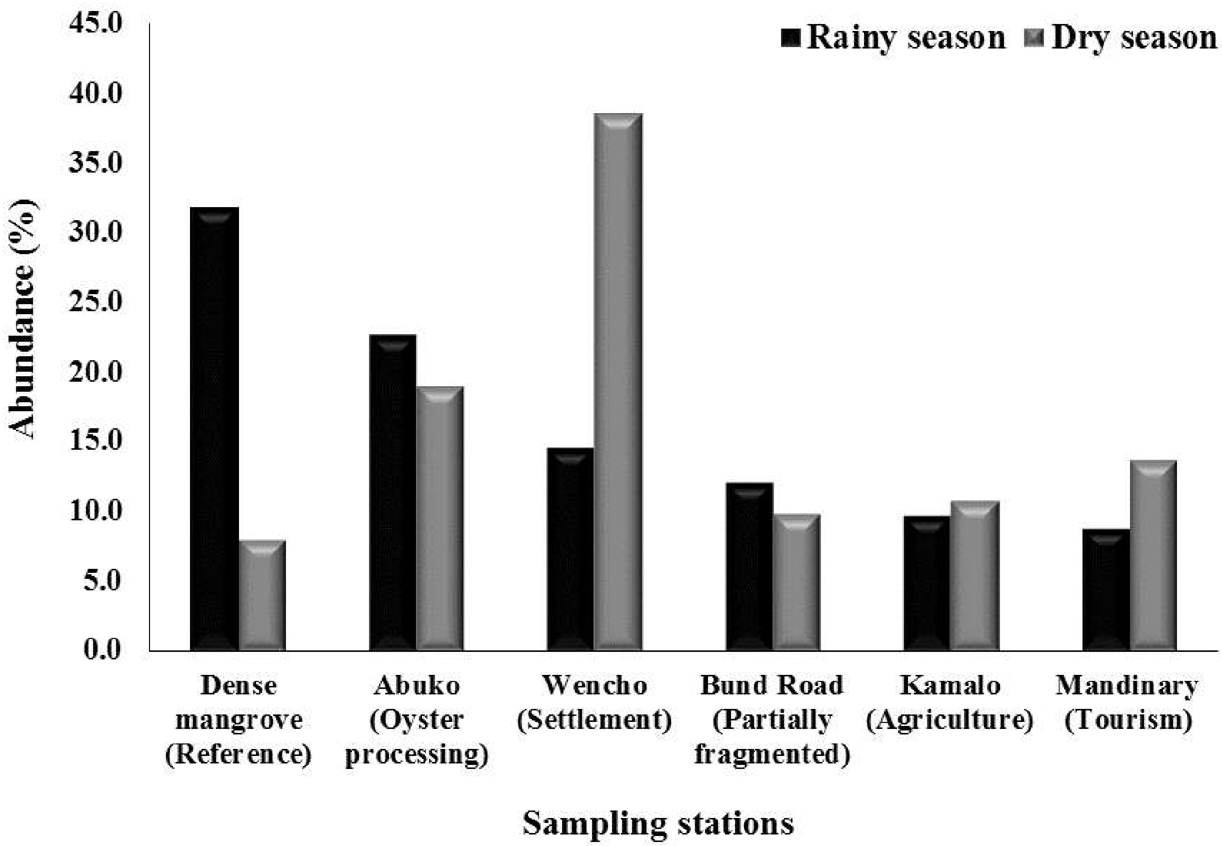

Figure 47. Percentage abundance of fish captured from sampling stations at different land use types during the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014.

3.1.3.2. Fish biomass

Total biomass of fish catches in TWNP was 110.6kg during the rainy season and 86.7kg during the dry season. Significant inter and intra-site differences were noted during the two seasons. During the rainy season, the highest fish biomass was at Abuko (oyster processing zone) (33.5kg) (30.3% of total biomass). This was followed by Wencho (settlement zone) where fish biomass was 23.2kg (21.0%), then Mandinary (tourism zone) with 21.8kg (19.7%), dense mangrove (reference zone) with 13.9kg (12.6%), Kamalo (agriculture zone) with 9.4kg (8.5%) and the lowest biomass was recorded at Bund Road (partially fragmented zone) (8.6kg) (7.8). During the dry season, fish biomass declined significantly in Mandinary, dense mangrove and Abuko, i.e. 15.5, 9.2 and 8.6kg respectively (17.9, 10.6 and 9.9% respectively). Contrary to this, Wencho, Kamalo and Bund Road all registered significant increases in fish biomass during the dry season i.e. 33.6, 11.0, and 8.8kg respectively (38.7, 12.7 and 10.2% respectively) (Figure 48). Pictorial views of fish landings typical of one throw of 30 minutes each in TWNP are shown in Figure 49 and Figure 50.

Notwithstanding the above, the relationship between fish family abundance and biomass during this study was a disproportionate one, as some of the most abundant fish families had very low corresponding biomass. During the rainy season (Figure 51), Mugilidae, Clupeidae and Cichlidae contributed 42.0, 34.2 and 8.8% of the total abundance, while contributing 57.6, 10.8 and 13% of the total biomass respectively. During the dry season (Figure 52), contribution by the Mugilidae family significantly declined to 31.3% of the abundance and 31.2% of the total biomass; Clupeidae abundance decreased significantly to 19.4% of total abundance and 7.2% of the biomass; and Cichlidae increased significantly to 32.5% of the total abundance and 47.9% of the total biomass.

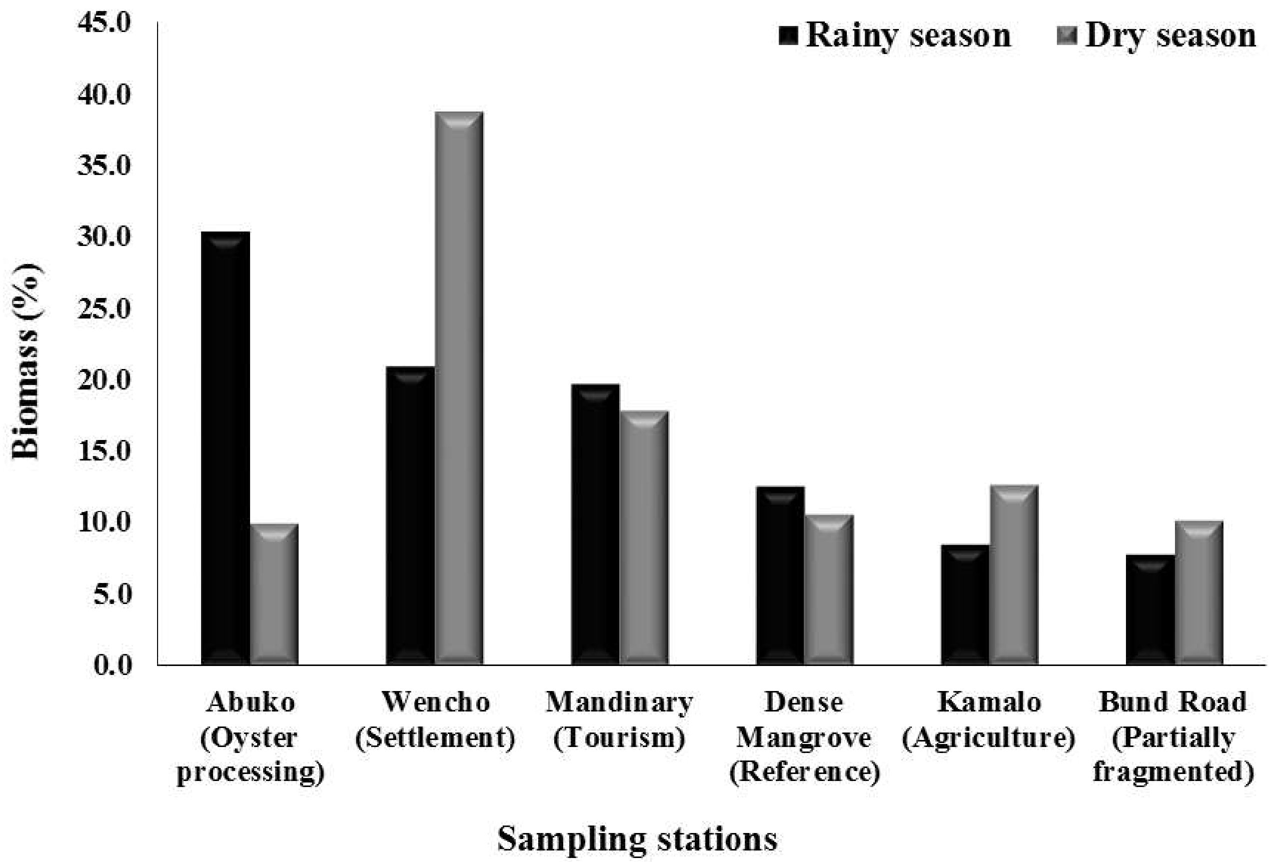

Figure 48. Percentage biomass of fish captured from sampling stations at different land use types during the rainy and dry seasons in Tanbi Wetland National Park in The Gambia in 2014.

Figure 49. Fish landings for one throw of 30 minutes in Abuko (Oyster processing zone); where *Ethmalosa fimbriata* (Bowdich, 1825) is the dominant fish species during the rainy season in Tanbi Wetland National Park in 2014. Black line as scale for 100cm.

Figure 50. Fish landings for one throw of 30 minutes in Wencho (settlement zone); where *Liza falcipinnis* (Valenciennes, 1836) is the dominant fish species during the rainy season in Tanbi Wetland National Park in 2014. Black line as scale for 100cm.

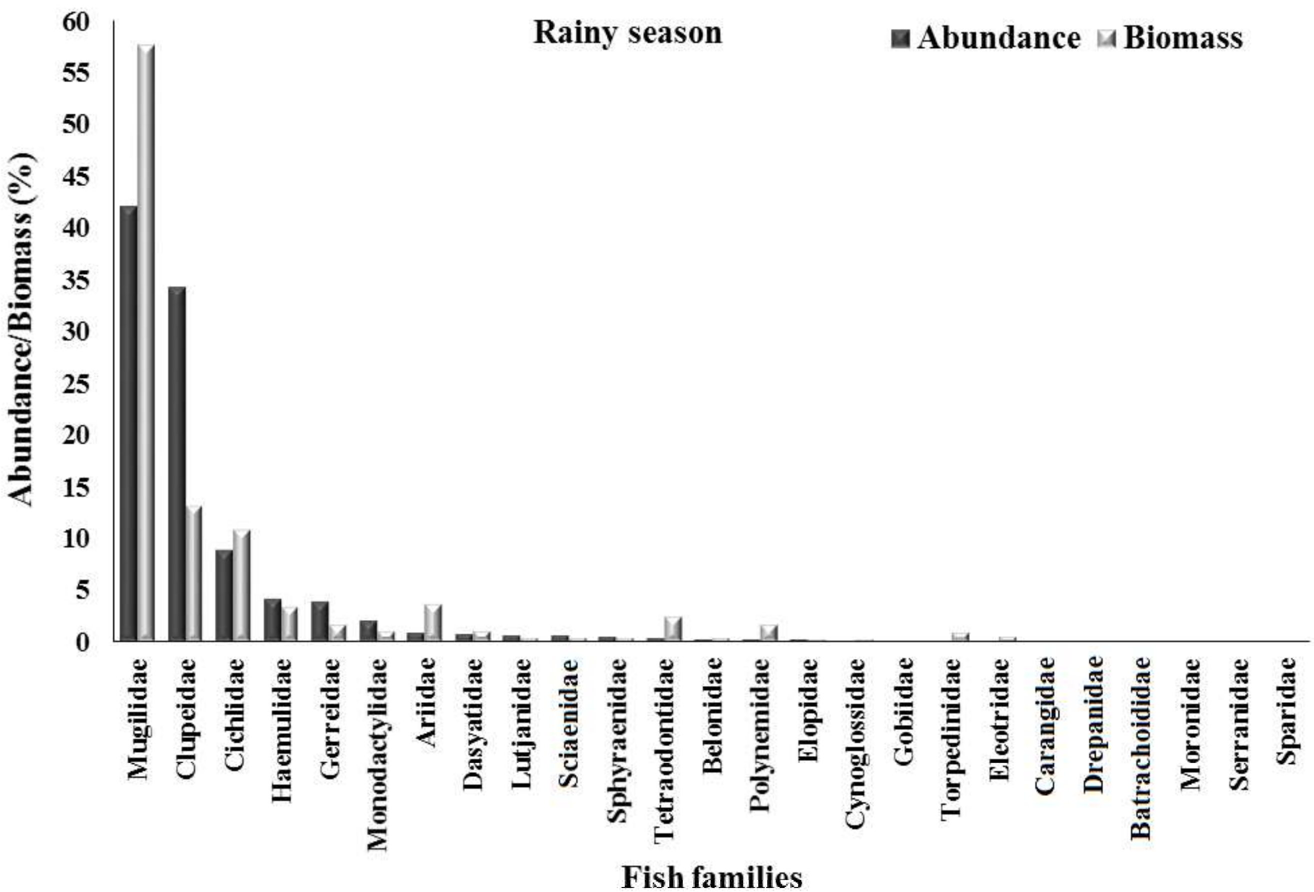

Figure 51. Relative abundance and biomass contribution of fish families during the rainy season in Tanbi Wetland National Park in The Gambia in 2014.

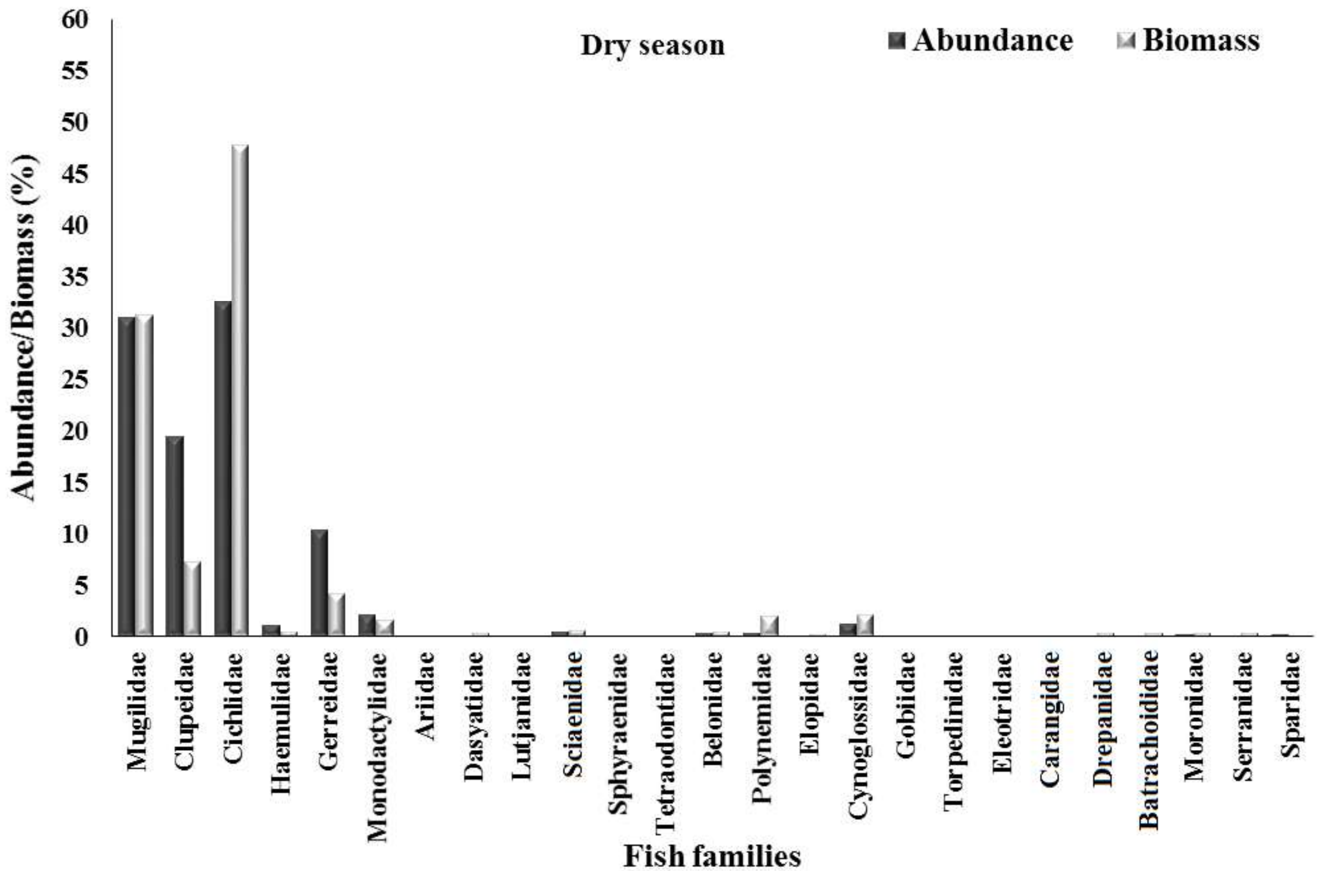

Figure 52. Relative abundance and biomass contribution of fish families during the dry season in Tanbi Wetland National Park in The Gambia in 2014.

3.1.3.3. Bio-ecological categories of the fish assemblage in Tanbi Wetland National Park

Significant differences were recorded in spatial and temporal distribution of bio-ecological categories of fish caught in TWNP. The estuarine species of marine origin (Em) was the most abundant category, contributing 43% of all catches during the rainy season and 48% during the dry season. During the rainy season, Em category contributed 50.0% of all species recorded in Abuko (oyster processing zone) and Kamalo (agriculture zone), 46.2% at Wencho (settlement zone), 40% at Bund Road (partially fragmented zone), 38.0% at dense mangrove (reference zone) and 37.5% at Mandinary (tourism zone) (Figure 53). Even though there was a decline in fish catches during the dry season, the contribution by the Em group towards the fish assemblage increased. During the dry season, the Em group contributed 60% of all catches at Abuko (oyster processing zone), 50% at Kamalo (agriculture zone), dense mangrove (reference zone) and Bund Road (partially fragmented zone), 45% at Mandinary (tourism zone) and 38% at Wencho (settlement zone).

In contrast, the strictly estuarine species (Es) group contributed 16% of the fish assemblage during the rainy season and 22.5% during the dry season. This group contributed 41.6% of the fish assemblage at dense mangrove (reference zone), 20% at Bund Road (partially fragmented zone), 15.4% at Wencho (settlement zone), 10% at Kamalo (agriculture zone) and Abuko (oyster processing zone), and its lowest contribution (3%) was at Mandinary (agriculture zone). During the dry season the Es group increased to 30.8% at Wencho (settlement zone), 25% at Mandinary (tourism zone) and Kamalo (agriculture zone) and 20% at Abuko (oyster processing zone). This bio-ecological group's contribution the fish assemblage declined however to 20% at dense mangrove (reference zone) and 14.3% at Bund Road (partially fragmented zone). The estuarine species of continental origin (Ec) group (when it appeared) contributed less than 5% at all the sites and all seasons (Figure 53).

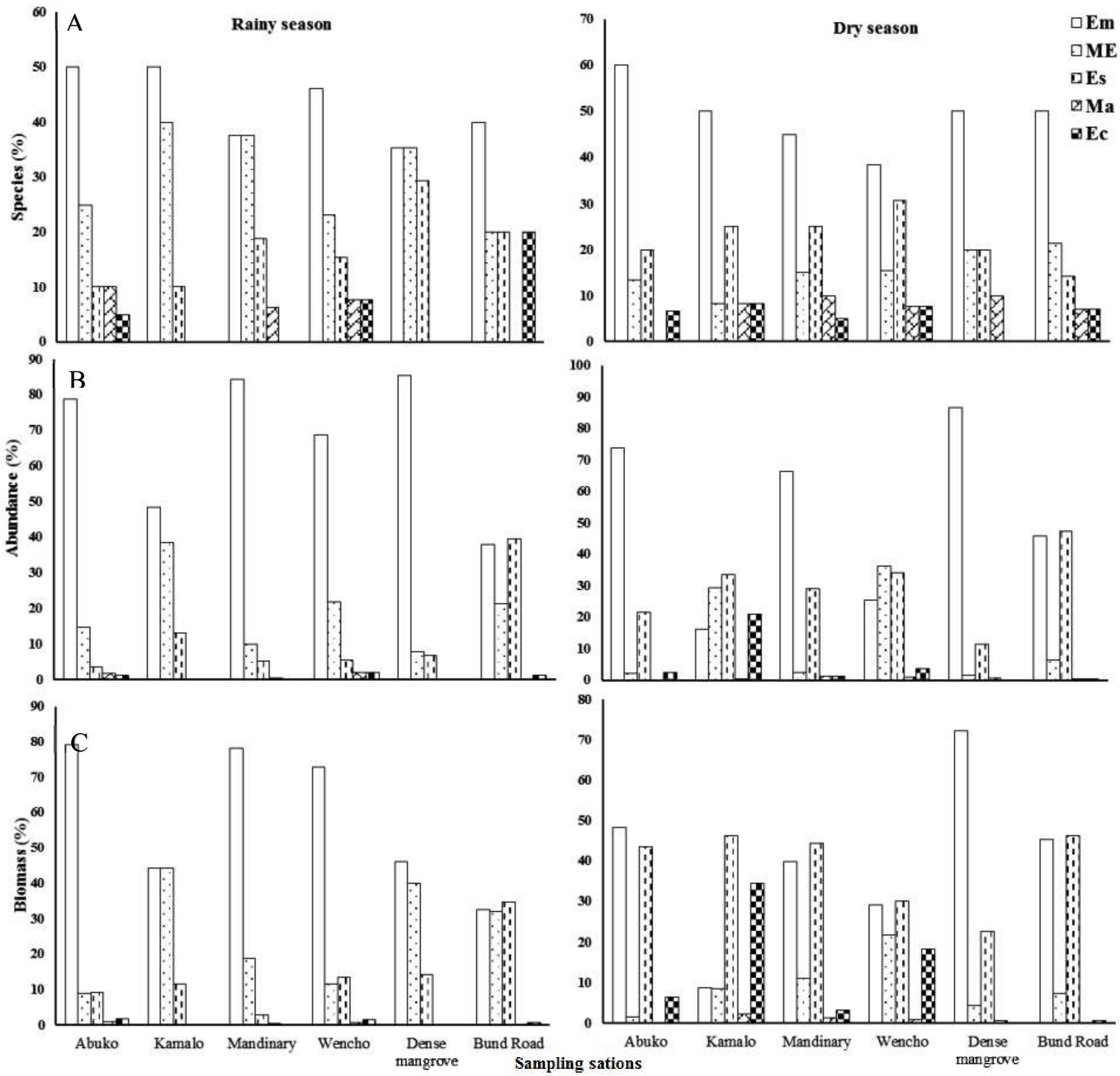

Figure 53. Seasonal variations in distribution of the bio-ecological categories in Tanbi Wetland National Park in The Gambia in 2014.

A: number of species; B: abundance; C: biomass (kg). Ec: estuarine species from continental origin; Em: estuarine species from marine origin; Es: strictly estuarine species; Ma: marine species accessory in estuaries; and ME: marine-estuarine species. Abuko: Oyster processing; Kamalo: Agriculture; Mandinary: Tourism; Wencho: settlement; Dense mangrove: Reference; Bund Road: partially fragmented.

3.1.3.4. Environmental variables' impact on fish assemblage in Tanbi Wetland National Park

Clustering of fish species abundance data for the various land use types led to the discrimination of land use types into clusters according to similarity (Figure 55). Further subjection of the environmental/water quality and fish species abundance data to a multidimensional scaling (MDS) determined which variables had the greatest influence on fish species abundance for the two seasons and six land use types in TWNP (Figure 55). For the rainy season, phosphate and nitrate were the most influential variables on the species abundance at Kamalo (agriculture zone) and to a lesser extent Abuko (oyster processing zone). During the dry season, increase in salinity had a strong correlation with the decline in species at all sampling stations except at Mandinary (tourism zone). Environmental variables pH, dissolved oxygen, temperature and chlorophyll a had no detectable effect on species abundance in TWNP.

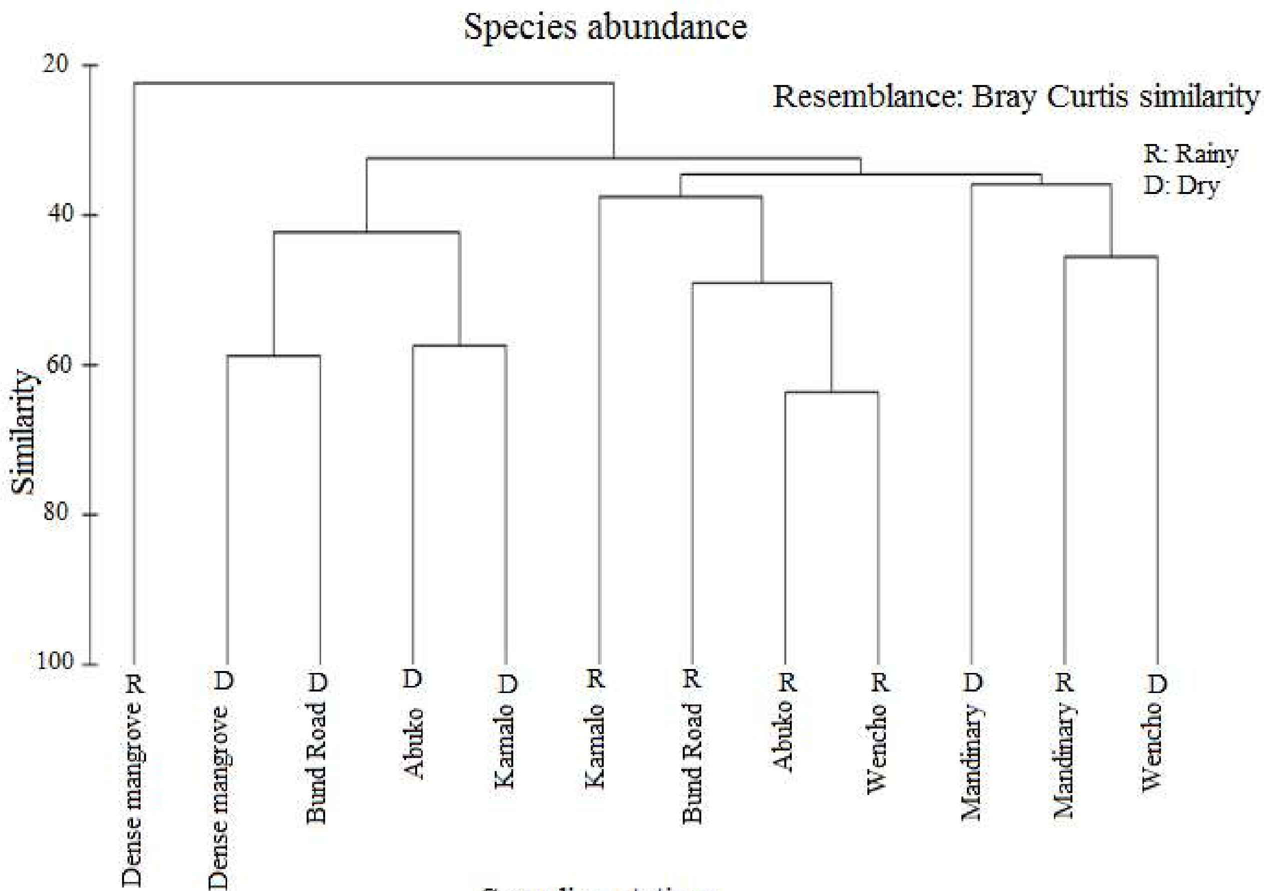

Figure 54. Hierarchical Cluster of similarity in species abundance for the 6 land use types over 2 seasons in Tanbi Wetland National Park in The Gambia in 2014.

Abuko: Oyster Processing; Kamalo: Agriculture; Wencho: Settlement; Mandinary: Tourism; Dense mangrove: Reference zone; Bund Road: Partially fragmented.

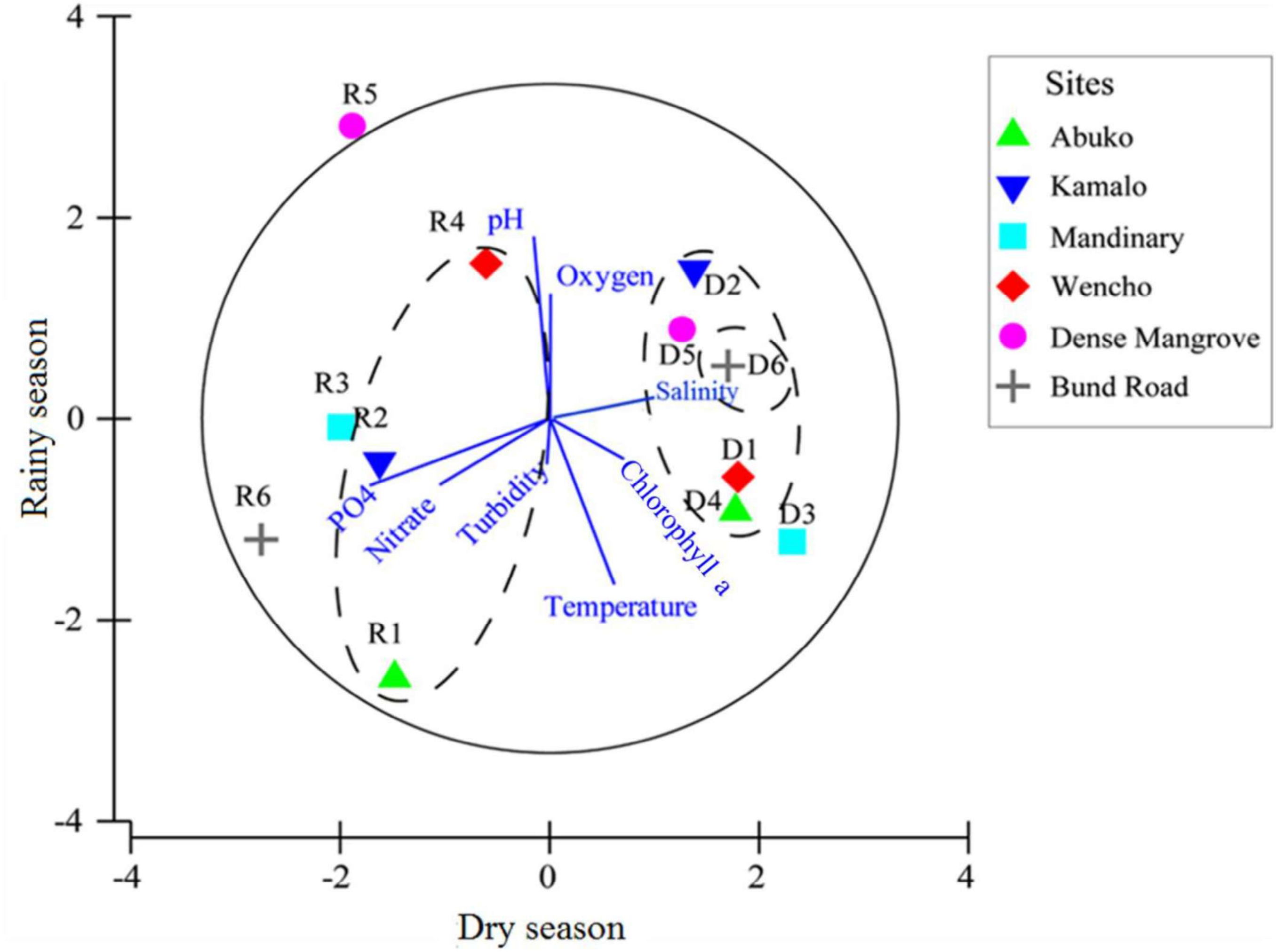

Figure 55. Influence of environmental variables on species abundance in Tanbi Wetland National Park in The Gambia in 2014.

R: Rainy and D: Dry. Abuko: Oyster Processing, Kamalo: Agriculture, Wencho: Settlement, Mandinary: Tourism, Dense mangrove: Reference zone, Bund Road: Partially fragmented.

3.1.4. Social studies

3.1.4.1. Local understanding of ecosystem changes in Tanbi Wetland National Park

Based on the responses garnered during this study, 132 (95.7%) out of the 138 respondents believe that the ecosystem of TWNP has changed over the past three decades, while the other 6 (4.3%) disagreed/were undecided. When asked about the specific changes within the TWNP, 58.33% of the respondents mentioned a decline in fish stocks along with the disappearance of key species such as the giant African threadfin (*Polydactylus quadrifilis (Cuvier, 1829)*), which is highly marketable when compared to some other native fish species. Mangrove degradation was mentioned by 55.3%; soil erosion by 21.2%, while 18.2% mentioned a decline in oyster stock.

3.1.4.2. Local understanding of climate change in Tanbi Wetland National Park

The local people's understanding of climate change is high despite the low literacy rates in The Gambia. Out of the 138 people interviewed, 103 (74.6%) said they have heard of climate change before, while 35 (25.4%) said they have never heard of the concept before. When asked about the manifestations of climate change 77.7% of the respondents associated it with changes in rainfall pattern, 45.6% associated it with changes in atmospheric temperatures, and 11.7% to droughts.

Only one respondent was encountered (within the fisher folks group) who did not believe in the concept of climate change. Among those that have heard about the concept of climate change, 46.6% claimed to have heard about it through the media, 26.2% through workshops, 8.7% from schools, 6.8% from agricultural extension workers and 5.8% from visiting tourists.

Local understanding of climate-induced ecosystem changes such as seasonal variability and hyper-salinity was very high among the socioeconomic groups in TWNP. On a scale of 0 to 10 (0 being poorest and 10 being excellent), the oyster collectors' group presented the highest level of awareness (8.3) (Figure 56), followed by the fisher folks (7.5), residents (6.8), tourism group (6.5) and the least score was recorded with the farmers (6.2). In terms of awareness on seasonal hyper-salinity, responses followed a similar trend with the oyster collectors scoring 9.1, fisher folks 8.2, farmers 7.3, residents 6.6 and the lowest scoring group being the tourism group (5.8) (Figure 56).

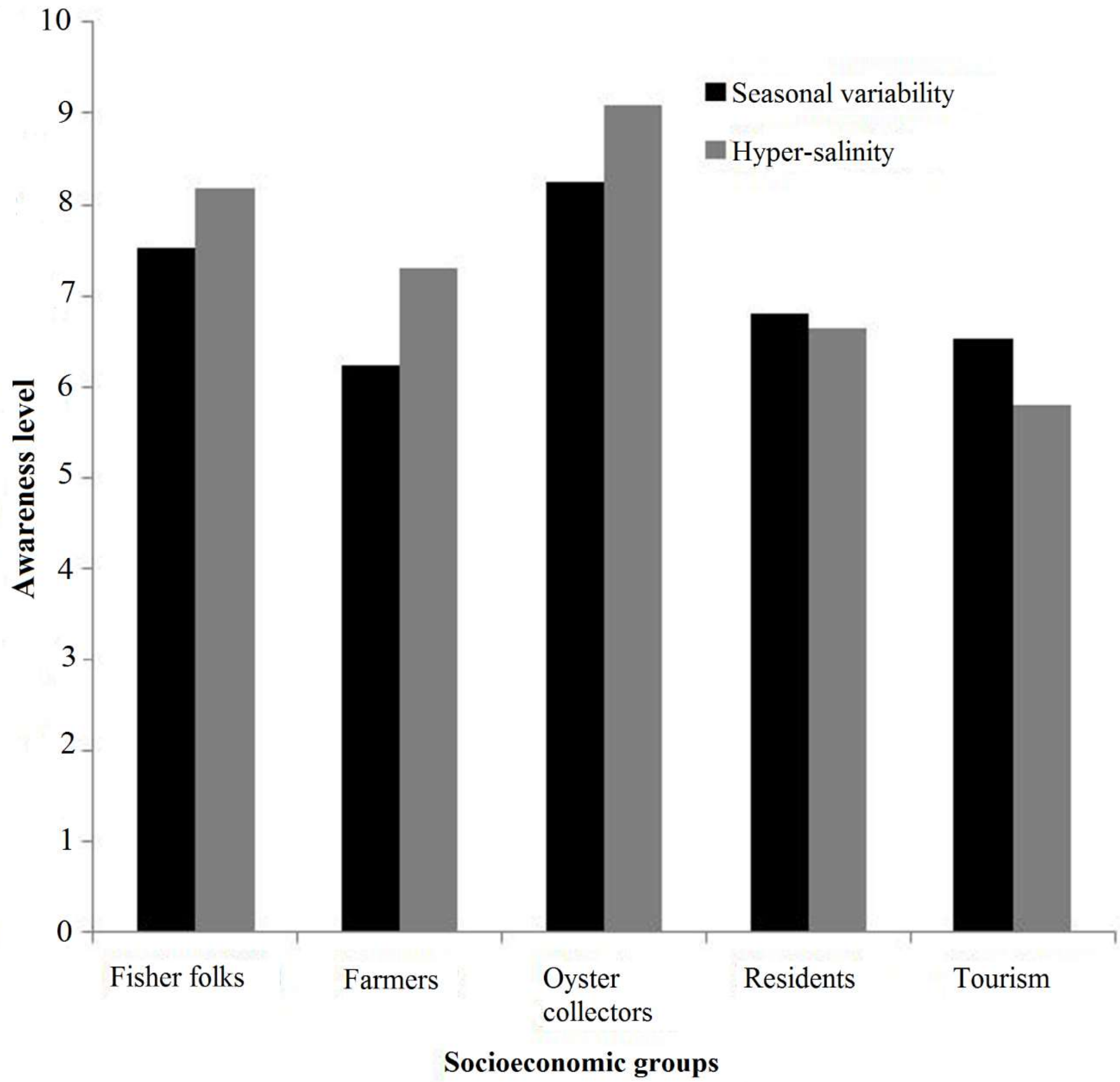

Figure 56. Local understanding of seasonal variability by socioeconomic groups in Tanbi Wetland National Park (score 0-10).

3.1.4.3. Local adaptation strategies to ecosystem changes in Tanbi Wetland National Park

In terms of the local adaptation measures/response strategies employed as coping mechanisms to the ecosystem changes in TWNP, a total of 32 different responses were given by the respondents. Most common among these was "nothing", 70 (50.7%) out of the 138 respondents have no knowledge of what measures they could take to maximize their daily output and prevent unnecessary economic losses in their place of work. Out of the remaining 68 respondents, 15 people (22.1%) seasonally shift their attention to the exploitation of alternative resources and allowing their main species of interest to "fallow". For example, the oyster collectors who shift to crabbing and lobster fishing during the rainy season, when water quality in TWNP becomes unsuitable for their primary activity; 7 (10.3%) practice crop rotation based on observed changes in soil quality due to salt intrusion; while 9 (13.2%) change their usual sowing period in anticipation of late and insufficient rains (i.e. farmers' group). The "less fortunate" groups here 5 (7.4%) deal with these changes by buying bigger boats (tourism group), while 4 (5.9%) of all respondents deal with the ecosystem changes by expanding their fishing zones (this is the case of the fisher folks).

3.1.4.4. Socio-economic changes in Tanbi Wetland National Park

In terms of economic growth, most of the respondents expressed a decline in income. About 65% of the respondents from the oyster collectors expressed a decline in income over the past three decades, this was followed by the farmers group (61% of the respondents), the residents (58% of the respondents) and the Fisher folks (42% of the respondents). About 57% of the respondents from the tourism group expressed an increase in income (Figure 57).

On average, the socioeconomic groups considered here have registered a decline of 46% in their earnings within the TWNP for the past three decades. The greatest average decline (72.7%) was recorded among the fisher folks, followed by the oyster collectors (50%) and the lowest (33.9%) among the farmers' groups (Figure 58).

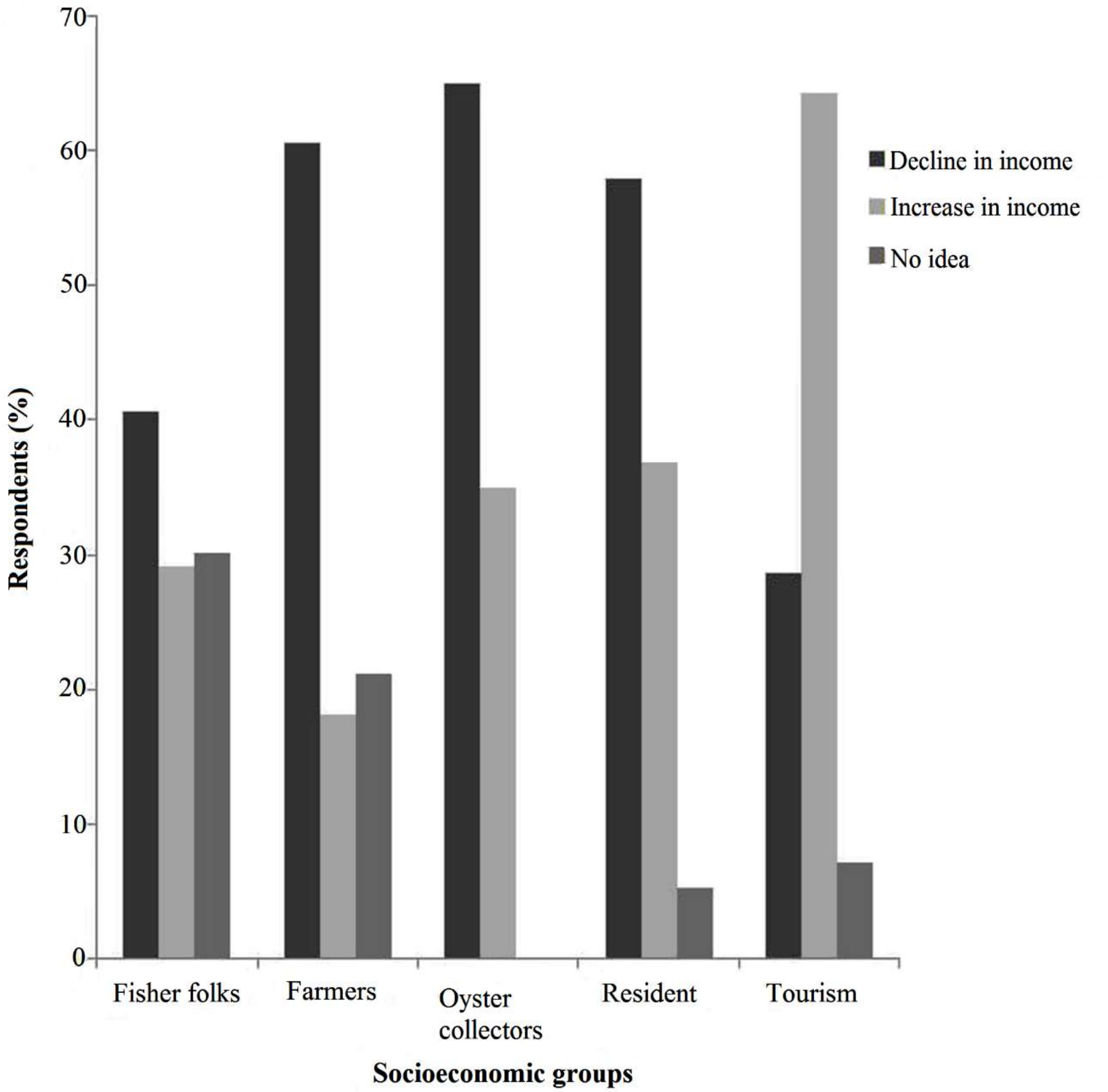

Figure 57. Changes in economic situation of the socioeconomic groups in Tanbi Wetland National Park in The Gambia in 2014.

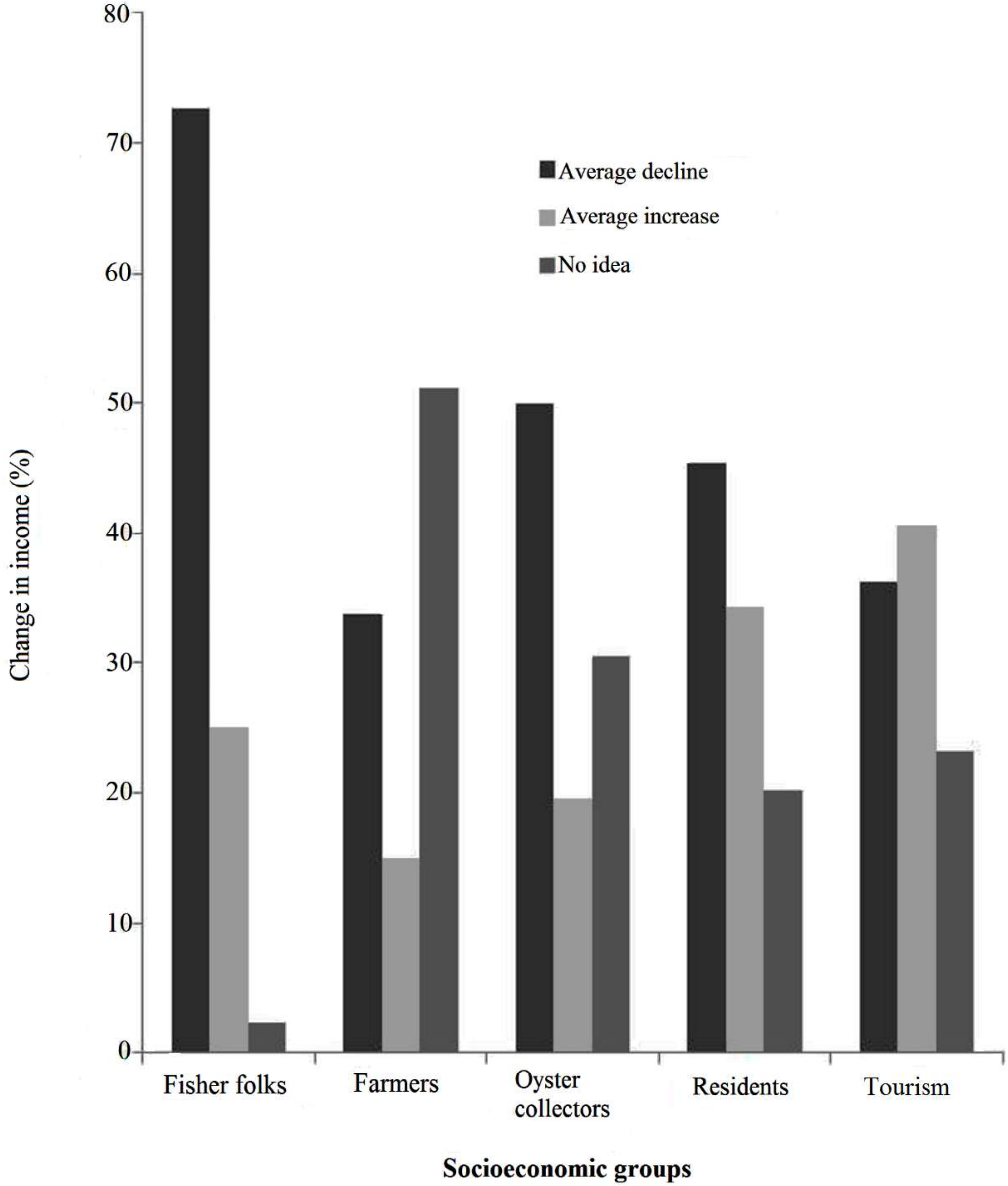

Figure 58. Average changes in the daily earnings of the socioeconomic groups in Tanbi Wetland National Park in The Gambia in 2014.

4.1. DISCUSSION

4.1.1. Environment / Water quality

For ambient water quality regime in any given estuary, there is a need for a balanced water budget i.e. one where rainfall equilibrates evaporation on a yearly basis, so that key variables such as salinity would remain stable between successive years **(Pagés & Citeau, 1990)**. A lot of research has been done on seasonal variations in estuaries of the Sahel **(Pagés & Citeau, 1990; Savenije & Pagés 1992; Ecoutin *et al*., 2014)** and of West Africa as a whole **(Anthony, 2004; White *et al*., 2012)**. The general consensus being that the seasonal variations are much more pronounced within the River Gambia estuary **(Blaber *et al*., 2000; Ecoutin *et al*., 2010; Guillard *et al*., 2012)**, especially towards the mouth of the river which is closer to the open coast **(Darboe, 2002; Albaret *et al*., 2004)**. The brackish water zone in the River Gambia extends from about 80 km in length in September to more than 220 km inland in June, while in the rainy/flood season, at least two-thirds of the estuary becomes totally fresh, oligohaline or mesohaline **(Louca *et al.,* 2008)**. Thus, the high seasonal variations recorded in salinity during this study and the inverse relation to distance from the open coast (Atlantic) are not surprising, since a negative runoff enables seawater to intrude the estuary and become concentrated by evaporation **(Pagés & Citeau, 1990)**.

The aforementioned salt intrusion was observed in the high salinity level during the dry season in Bakau (completely fragmented zone), which is nearest to the open coast. The residual effect of saltwater intrusion and concentration by evaporation during the dry season was also observed in Mandinary (tourism zone) which is farthest from the coast, but still had the highest salinity level during the rainy season. Due to insufficient rains during the rainy season, river runoff is not strong enough to dilute the resultant hypersaline water from the dry season to ambient estuarine salinity level during the rainy season, just as previously reported by **Savenije & Pagés (1992)** and **Savenije (2012)**. This also supports the deduction that land use / land cover type has little or no influence on salinity, except for the synergistic effects caused by fragmentation. This deduction is further strengthened by the fact that salinity levels did not differ significantly between Abuko (oyster processing) and dense mangrove (reference zone) during the rainy season, because they are both located within the intermediary position of TWNP where river flow is strongest during the peak discharge period of the River Gambia.

In the same vein, **Pagés & Citeau (1990)** determined that for Sahelian estuaries such as the Kaolack inverse estuary in Southwest of the River Gambia to return to the "normalcy" it had before the Sahelian drought, an annual rainfall of $\geq$2000 mm is needed. This amount of rainfall can only be dreamed of in the Sahel, considering the recent climate scenarios. Rainfall was 1067 mm before 1960 but went down to an annual of 680 between 1968 and 1977 **(Marius, 1982)**. Drastic changes in salinity, such as those due to droughts or storms that result from erratic rainfall and high atmospheric temperatures can greatly alter the numbers and types of animals and plants in the estuary **(US EPA, 2006)**.

About a decade ago, average water temperatures for the rainy and dry seasons in TWNP were 23.8 and 30ºC **(Maniatis, 2005)**. But these values have greatly increased to 27.9 and 30.2ºC during the current research, suggesting higher overall temperatures and lesser cooling effect from river flow as the region's water budget has become very low **(Schlenk & Lavado, 2011)**. These findings are concurrent with predictions of **Pagés & Citeau (1990)** that about 80% of the increase in estuarine salinity within the Sahel is explained by long-term variabilities in rainfall and excessive evaporation due to the ever increasing atmospheric temperatures. In relation, **(US EPA, 2006)** suggested that suitable water temperature in a mangrove estuary depends on the presence and health state of the vegetation, and also the cooling effect of runoff water **(Louca *et al*., 2008)**. The former was manifest in the current research by the fact that the sampling station with the least amount of vegetation cover i.e. Abuko (oyster processing zone) displayed the highest water temperature during the rainy season, notwithstanding the human activities and its location in the middle part of TWNP with active runoff. Furthermore, water temperature did not differ significantly between Bund Road (partially fragmented), Kamalo (agriculture), Mandinary (tourism) and Bakau (completely fragmented) during the rainy season; this nullifies land use type as a factor influencing water temperature and proves that the similarity in vegetation cover is the cause. A similar observation was made between dense mangrove (reference) and Wencho (settlement) where vegetation was densest (personal observation).

The latter case was observed during the dry season when runoff was at its lowest, leading to Bakau (completely fragmented) displacing Abuko (oyster processing) from having the highest to the second-highest water temperature. Mandinary (tourism), Wencho (settlement), dense mangrove (reference) and Kamalo (agriculture) followed suit; and this can be related to their closer proximity to the Gambia than the open coast. The lowest temperature was at Bund Road (partly fragmented) during the dry season and is explicable by direct human interference through the pumping of water during reconstruction of the culvert connecting the site to the Banjul city drainage system. This is also the reason for the high turbidity level at Bund Road (partially fragmented zone) during the dry season, as organic matter and sediments are dispersed into the main water column by physical mixing.

Throughout this research, dissolved oxygen (DO) values were never environmentally critical (<3 mgl^{-1}) **(US EPA, 2006)**. Agreeably, dense mangrove (reference zone) registered the highest overall dissolved oxygen during this research, oxygen values didn't seem to be affected by any specific land use type; but instead by season. As seasons changed from rainy to dry, 5 out of the 7 sampling stations registered a significant decline; the exceptions being dense mangrove and Kamalo (reference and agriculture zones respectively). This is clearly a case of reduced biological oxygen demand (BOD) during the dry season. As explained by **(Darboe, 2002)**, areas with low transparency are likely to be anoxic during the peak discharge period due to a high concentration of suspended organic matter/mud particles that can impede photosynthetic processes and increase oxygen uptake for decomposition of organic matter. Hence, this situation gets reversed during the dry season resulting in an increase in dissolved oxygen.

Meanwhile, pollution and excessive nutrient loading have been reported to cause eutrophication and anoxic conditions unsuitable for supporting marine life in estuaries surrounded by human activities such as agriculture and industry **(Hayé *et al*., 2009)**. In principle, this is true for TWNP to the extent of nitrate levels which were highest in Mandinary (tourism), Wencho (settlement) and Abuko (oyster processing) respectively during the rainy season, albeit not excessively. As the river Gambia is reported to be oligohaline **(Albaret *et al*., 2004)**, tourist aquaculture ponds, fish feeding for leisure, household wastes and fertilizers from agricultural land are possible sources of the nutrients influxes, washed in by river runoff during the rainy season. This is confirmed by the fact that nutrient levels declined by at least 50% at all the sampling stations during the dry season, except at dense mangrove (reference zone) which is not connected to the shores or any notable human activities.

Although, nutrient concentrations in estuaries vary according to surrounding land use, season, and geology **(US EPA, 2006)**, nutrient levels recorded during this research were way below the critical point, ruling out pollution as an ecosystem destabilizer in TWNP. Nitrogen and phosphorus in particular are of great importance as they are essential in the growth of aquatic plants **(US EPA, 2006)**. While the findings of this research rule out excess nutrients being released from land uses such as agriculture and settlement, it also points to a possible situation of nutrient deficiency at some sampling stations such as Kamalo (agriculture) and Bakau (completely fragmented), while indicating that nutrient levels at Wencho (settlement zone) were enough to support horizontal growth (vegetative parts) of mangroves even though vertical growth seems to have been stalled by irregularities in other variables like salinity.

Based on all the above, it is evident that water quality in TWNP is negatively impacted by seasonal variability. The main water variable i.e. salinity is unaffected by land use, but highly influenced by season in TWNP; contrary to pH which was not affected by season, but by land use; while temperature was affected by season and exacerbated by land use. In addition, land uses such as settlement and agriculture have shown some synergistic effects on other important water variables such as nitrate and phosphate and these can have significant implications for the health and survival of mangrove vegetation, as well as migratory fish species.

4.1.2. Mangrove vegetation dynamics

Based on the image accuracy scale of 0 – 1 as suggested by **Blum *et al.* (1995)**, image characterization in this research satisfactorily distinguished the land use/land cover changes in TWNP from 1973-2012. Nonetheless, mangrove rejuvenation is an integral part of the overall health of a mangrove ecosystem. Unlike most mangroves along the West African Coast, the TWNP mangroves were predicted to be undergoing a short-term lack of rejuvenation **(Dahdouh-Guebas & Koedam, 2002)**. From field observations during this research and the seemingly intact nature of the mangrove vegetation, this phenomenon appears to have persisted over the years as most of the vegetation was of uniform height (≤3 meters). Such occurrences signify a response to swift changes in hydrology, in this case excess salinity **(Austin *et al*., 2010)**. Drastic changes in hydrology were reported to induce stunting of *Avicennia marina* stands and denaturing of terminal buds in *Rhizophora mangle* (Linnaeus, 1753) seedlings in the USA **(Kathiresan, 2002)**.

Likewise, the mangrove estuaries within the Sahelian zone have suffered some of the most drastic ecosystems changes since the Sahelian drought in the early 1970s **(Pagés & Citeau, 1990)**. The increase in atmospheric temperatures, erratic rains and prolonged droughts have led to reduced habitat integrity and lowered ecosystem services/functions in many Sahelian mangrove estuaries **(Panfili *et al.,* 2004)** and in many cases, the formation of inverse estuaries **(Pagés & Citeau, 1990)**. Exponential increase in salinity for instance, was reported in the Casamance estuary in Senegal where *Rhizophora mangle* (Linnaeus, 1753) stands have been completely eradicated due to hyper-salinity, while the few *Avicennia germinans* (Linnaeus, 1764) stands that survived got severely stunted **(Savenije & Pagés, 1992)**.

In relation to the above, the simplicity of the mangrove species composition in TWNP points to long-term instability of salinity condition. **Maniatis (2005)** reported that the mangrove vegetation in TWNP is comprised of only four species, even though about nine true mangrove species were identified for the Sahelian region **(Corcoran *et al.,* 2007)**. Most mangroves in West Africa have undergone serious degradation due to deforestation, as humans cut the vegetation for fuel use and clearing for agricultural land **(Dimobe *et al*., 2015)**. Evidences of these are usually noticed in the sparseness of the mangrove vegetation in question and the presence of dead tree stumps **(Hirani, 2005; Satyanarayana *et al.,* 2012)**. Except at Bakau (completely fragmented zone), these were absent in TWNP, indicating negligible use of the wetland for the aforesaid purposes.

Maniatis (2005) also reported dwarfism in the two major mangrove species and a negative correlation between canopy height and salinity in TWNP. All of these combine to show mangrove species' response to long-term seasonal hyper-salinity, in the form of reduced growth (dwarfism) and decreased success in seedling/sapling survival **(Feller, 1995; Dahdouh-Guebas *et al.,* 2004; De Ryck *et al.,* 2012)**. In a recent study of mangrove degradation in Pichavaram (India), natural causes of mangrove degradation were attributed to high salinity, low levels of available nutrients and low microbial counts **(Kathiresan, 2002)**. The large amounts of brackish water accumulated during the summer turns hyper-saline, ultimately killing/retarding mangrove growth **(Kathiresan, 2002)**. In relation, the River Gambia estuary has one of the most drastic seasonal variations in the world; from extensive floods during the peak rainy season to overwhelming salt intrusions during the peak dry season **(Louca *et al.,* 2008)**, leading to insufficient time for adaptation/succession by any given species **(Albaret *et al*., 2004)**.

Even though climate effects on human systems are often difficult to discern from other adaptation processes **(Mertz *et al*., 2009)**, the low percentage (6%) in depleted mangrove cover, indicates nill/negligible human impacts on mangroves of the TWNP. In addition, over the past couple of decades, conservation efforts have been intensified in and around the coastal zones of The Gambia **(Lauer & Eguavoen, 2016)**. Apart from the ratification of almost all climate change and biodiversity accords, The Gambia has followed up at national level by acts such as formulation and implementation of the Coastal Zone Management Plan **(Njie, 2004),** designating the Tanbi Wetland a national park in 2007 **(The Ramsar Convention on Wetlands, 2012)**, instituting local awareness creation programs for vulnerable coastal communities and being the first West African country to award exclusive user rights and co-management status to women groups involved in oyster collection **(USAID-BaNafaa Project, 2014)**. These activities seem to have paid off in reduced human interference in the TWNP.

From all indications, mangroves of the TWNP are not as productive as expected because of their old age. In a study comparing the nursery role of young (3 – 12 years) versus old (>60 years) mangroves, **Manson *et al. (*2005)** reported a high compaction in sediments and excess deposit of leave litter/organic matter in the latter. This can affect nutrient recycling and lower the rate of nutrient export into the open coast **(Slomp, 2011)**. These are in line with recent findings, indicating that vegetation cover in TWNP is seemingly intact and basically looks the same as it did since pre-independence days (1965) **(Maniatis, 2005)**. This is a uniquely bizarre ecological situation that has not been reported elsewhere and is explicable by the long-term lack of rejuvenation stemming from low seedlings/sampling survival in estuaries with unstable hydrological regimes **(De Ryck *et al*., 2012)**.

The impacts of long-term changes in climate variables in West African estuaries have been reported by many **(Blaber, 2013)**. Rainfall anomalies following the Sahelian drought could for instance be the cause for the current degraded state of mangroves in TWNP. Since the period from 1971 – 2000 were the driest three decades ever of the 20th century **(L'Hôte *et al.,* 2002)**, the slight recovery in rainfall/wet years realized after the year 2000 are actually dry when compared to the long-term rainfall averages **(L'Hôte *et al.,* 2002)**. Thus, the current findings indicate that mangrove vegetation in TWNP is suffering the long-term effects of climate-induced hydrological changes.

4.1.3. Fish assemblage

In relation to the fish studies in this research, the number of fish species recorded in TWNP during this research was lower than that previously reported from other studies in the River Gambia estuary. Many scientists agree that The River Gambia estuary should have a more diverse fish community **(Albaret *et al*., 2004)**, given the presence of diverse hydrological situations **(Albaret, 1999)** and the existence of extensive mangrove vegetation lining the river and its creeks **(Vidy *et al*., 2004)**. These are considered favorable grounds for nursery purposes of many diadromous fish species as well as a refuge from predators **(Baran, 2000)**. However, this expectation is countered by the extreme seasonal variability as the conducive physico-chemical conditions do not last long enough for successful colonization of the estuary by any given group of fish; be it of marine or continental origin **(Albaret, 1999; Albaret *et al*., 2004)**. Despite the supposedly "normal" seasonal marine-freshwater inflow dynamics, the River Gambia estuary has always had the lowest annual fish yields compared to adjacent West African brackish waters **(Villanueva, 2015).**

Fish species diversity in the mangrove estuaries has been shown to progressively decline at sites with high seasonal variability, human population, as well as areas with relatively old vegetation **(Manson *et al*., 2005; Ecoutin *et al*., 2010)**; individual situations which hardly ever exist exclusively in a natural setup. Thus, findings in this research make past scientific predictions, which did not account for spatio-temporal variability of fish diversity, seemingly insufficient. For instance, using a drag seine **Albaret (1999)** reported a total of 89 fish species for the River Gambia estuary, and 70 species in another study **(Albaret *et al*., 2004)**, while **Simier *et al*. (2006)** reported 67 species. However, most of the research mentioned above was done in the open channel of the River Gambia estuary, thus leaving out most of the mangrove "bolongs"/creeks which are areas of large salinity gradients and strong human impacts; thereby excluding anthropogenic impacts in the estuary and as a result overestimating the overall species richness and abundance for the River Gambia estuary.

The total number of fish species caught during this research resemble findings of **Vidy *et al.* (2004)** who reported a total of 47 species from 26 families within the creeks of the River Gambia estuary, compared to the 43 species and 25 families caught during this research in TWNP. This is remarkable given the small size of the current study site and its location within a highly populated area. Similarly, **White *et al.* (2012)** reported 49 fish species for the middle part of the River Gambia, where multiple habitats were found. The overwhelmingly higher abundance of the fish families such as the Mugilidae in this research might have been as a result of a bias from the choice of fishing gear (seine net) which tends to under-sample the fast swimmers **(Portt *et al.*, 2006)**, but might as well have been due to the fact that the Mugilidae family is euryhaline and able to withstand the strong seasonal changes in salinity when compared to other fish families **(Albaret, 1994)**.

Considering the steep salinity gradient in TWNP (24.2 - 35.8 ppt) from rainy to dry season, the observed decline in fish species abundance and biomass is an indication of fish species' natural response of migrating to fresher waters when salinity stress becomes intolerable **(Baran, 2000)**. This may be the reason why dense mangrove (reference zone), which is relatively free of human activities had 6 species less in the dry season than it had during the rainy season. This is also the reason Abuko (oyster processing zone) has nearly the same number of fish species as dense mangrove (reference zone) because the two stations have similar salinity levels. Likewise, the use of growth suppression as a coping mechanism to hyper-salinity by the cichlid *Sarotherodon melanotheron (Rüppell, 1852)* **(Panfili *et al.*, 2004)** was why the Mandinary (tourism zone) showed a significant decline in fish biomass during the dry season, even though it had 5 more fish species than it did during the rainy season; bearing in mind that the Cichlidae family became the second-most abundant family during the peak dry season.

Fish assemblage in TWNP is clearly dominated by the estuarine species of marine origin (Em), with a species abundance of up to 47% while the smallest bio-ecological category was the species of continental origin (Ec) representing only 5% of species abundance. It is safe to say that seasonal changes in environmental variables are the main drivers for the decline in species diversity in TWNP; in this case salinity appears as the strongest driver instead of the strongly held notion of human activities. Of course human activities such as the use of pesticides in the agricultural zone and dumping of household waste at the settlement zone serve as strong stressors that exacerbate the effects of seasonal variability on aquatic ecosystems, just as stipulated by **Rudnick *et al.* (2005)** in the Florida Bay. However, nutrient and chl-a levels were not high enough to be suggestive of pollution, while DO levels were not low enough to suggest eutrophication. In addition, flow rate of the River Gambia is said to be as fast as 1500 m^3 s^{-1} during the rainy season and as low as $4.5 m^3 s^{-1}$ during the peak dry season **(Simier *et al.*, 2006)**.

This explains the high variation in salinities during the two seasons and the corresponding decline in fish species abundance and biomass at all the land use types, some less than others. Due to the lack of river freshwater input, the freshwater affinity component was almost absent from this ecosystem and the strictly estuarine species (Es) were few.

Consequently, such a combination of changes in environmental factors are enough to cause huge declines in estuarine fisheries output, as important life processes such as migration, reproduction timing and spawning success of various fish species get interrupted **(Panfili *et al.*, 2004; Simier *et al.,* 2006)**. Environmental conditions are said to be highly related to species richness in marine biomes, as species respond to ocean warming by shifting their latitudinal range and depth range **(Mueter & Litzow, 2008).** Such occurrences can lead to local extinctions (when a species ceases to exist in an area but still exists in another) and invasions (the expansion of a species into an area not previously occupied by it), thereby disrupting marine biodiversity and ecosystems and impacting commercial fisheries **(Cheung *et al.*, 2009)**. Based on the seasonal changes in the fish assemblages, the above seems to be an apt description of the state of fisheries in the TWNP. The size and abundance of highly marketable estuarine fish species such as the giant African threadfin (*Polydactylus quadrifilis (Cuvier, 1829)*) caught during this research are declining and moving inland in response to seasonal hyper-salinity. To top it up, changes in mangrove habitats can affect their associated faunal communities. The presence of a younger vegetation cover could have aided the ecological stability in TWNP, as dwelling fauna have been reported to be more robust in the young (3 – 12 years) than in the old mangroves (>60years) **(Manson *et al.*, 2005)**. Thus, with an old and non-rejuvenating vegetation cover, there is no "natural cushion" against the effects of climate-induced water quality stress on fish species in TWNP.

4.1.4. Social Studies

Mertz *et al.* (2009) advised for a careful formulation of policies and adaptation strategies to climate change for societies that are poor and vulnerable for a wide range of reasons. Both physical and institutional assets need to be included when formulating adaptation strategies. In TWNP the former has been made available to the groups involved in shellfisheries through the provision of canoes, sanitation facilities, oyster smoking pens and alternative livelihoods (setting up an oyster culture program), while the latter is available for groups involved in agriculture through awareness creation by agricultural extension programs, credit schemes and subsidies for improved seed variety **(National Environment Agency, 2010)**.

The latter is also in part available for the fisher folks, through the coastal zone management plan, enforcement of Fisheries Regulations and Acts, as well as guidelines on appropriate net usage within the wetland **(Government of The Gambia, 1995; Government of The Gambia, 2007)**. While the aforementioned incentives are provided alongside numerous awareness creation campaigns for the socio-economic groups such as the farmers and oyster collectors, awareness level is still low for the fisher folks, as evidenced by their poor responses to adaptation mechanisms.

Kelly & Adger (2000) suggested that in cases concerning state-run adaptation programs, it might be necessary to ''adapt to the adaptation'' as some measures might solve one problem while creating another. As an example, **Barnett & Mahul (2007)** suggested that credit schemes and new crops, accompanied by ''weather insurance,'' have been tried experimentally in some developing countries. This approach was applied to a large extent in the agricultural sector, with provision of soft loan credit schemes with flexible payment plans that took account of the possibility of crop failure due to rainfall shortages, as well as provision of drought resistant seed varieties **(National Environment Agency, 2010)**. A similar approach was also applied for the shell fisheries sector, with the provision of alternative livelihoods through value-adding (packaging) of pre-processed oyster meat as well as setting up an oyster culture program **(USAID-BaNafaa Project, 2012; Crow & Carney, 2013)**.

However, for the fisher folks the only institutional assets they have are in the form of the enactment of The Gambia's Fisheries Regulations in 1995 **(Government of The Gambia, 1995)** and Act in 2007, as well as stricter netting regulations for sustainable fisheries **(Government of The Gambia, 2007)**. This has no doubt helped reduce overfishing, especially within the nursery grounds of the TWNP, but it still did not solve the problem of declining fish catches or the low economic returns as the physical assets needed by the fisher folks are not in place. This move might have also promoted the colonization of the estuary by hardy, yet smaller sized fish species such as the native African tilapia (*Sarotherodon melanotheron* (Rüppell, 1852)), which is known to respond to environmental stress by reducing its growth rate **(Panfili *et al.*, 2004)**.

In the words of **Munang *et al.* (2010)**, it is necessary for policy makers to recognize the fundamental role of ecosystems as life-supporting systems first for successful implementation of adaptation strategies. In the absence of a go-to activity for the fisher folks during times of low catches (as shown in this study), restricting fishing activity only lowers their earning potential without necessarily solving the problem of ecosystem changes. This also does little or nothing to alleviate the declining fish catches, because fish species migrate in response to natural deterioration in their environment **(Panfili *et al.*, 2004)**. Hence, The Gambia may be letting migratory fish species grow/fallow, just so they could be harvested elsewhere.

Portner & Peck (2010) suggested that the implications of climate change for marine fish species are at four levels: organismal, individual, population and ecosystem level; individual level being the most relevant one when referring to the state of fisheries in TWNP. The strict estuarine fish species for instance have been reported to seasonally migrate inland as a response to hyper-salinity during the peak dry season and then to the creeks during the flood season **(Vidy *et al.,* 2004)**. This is now believed to be the reason behind the drastic reduction in daily catches/earnings of the fisher folks interviewed during this research.

Similar findings were reported by **Panfili *et al.* (2004)** in a study of the impacts of salinity on the life traits of the native African tilapias (*Sarotherodon melanotheron (Rüppell, 1852)*) in the estuaries of Senegal and The Gambia, where the authors reported interruptions in fish migration patterns, reproduction timing and spawning success as well as stunting, leading to smaller market sized fish and thus earning lower prices. Such phenomenon was also reported to be the cause for the complete colonization of the inverse estuary of Sine-Saloum delta in Senegal by marine fish species; thus replacing the native estuarine species and causing a decline in fisheries output for over a decade **(Dia, 2012)**. The upside of this situation for Senegal is actually the downside for The Gambia, because marine fish command a higher price than both estuarine and freshwater fish.

The aforementioned condition is worsened by the synergistic effects of human activities such as overfishing on climate-induced ecosystem changes, as evident in the responses from the fisher folks. In addition, the commonness of the phrase "in God's hands" among the fisher folks as a response to how they locally adapt to climate-induced ecosystem changes indicates their low levels of awareness. Thus leading to the deduction that the fisher folks are the most vulnerable socio-economic group when it comes to climate change adaptation in TWNP. This group has been relatively overlooked and uninvolved when it comes to awareness creation campaigns by conservationists as well as in the provision of alternative livelihoods.

The case is different for the farmers' group which apart from having its members frequently trained on alternative farming methods and provided with improved seed variety in order to adapt to climate-induced ecosystem changes; also has the luxury of having an agricultural extension worker on site to guide them by responding to their common farming problems. In comparison, the oyster collectors' group having been provided with suitable alternative livelihood programs such as the state-led oyster culture program. In addition, they were recently given management rights to the TWNP. Meanwhile, the tourism group finds it much easier to cope with the ecosystem changes, for instance by expanding sightseeing zones and proportionally increasing safari prices, which may not be a realistic approach for the other groups as one is catering to a local market, while the other targets an international market.

Of course, it is noteworthy that this current study also has its own set of limitations. For instance, difficulties in locally translating basic climate concepts to the mostly uneducated respondents might have downplayed their ability to accurately respond to questions about climate-induced ecosystem changes. The general mistrust between local resource users/end users and state-employed conservationists also played a dampening role in people's willingness to answer the questionnaires. Nonetheless, sufficient information was garnered to portray overall understanding and response mechanisms employed by the locals in order to deal with climate-induced ecosystem changes in the mangrove estuary under study (TWNP), as well as the socio-economic implications of these changes.

CONCLUSIONS AND PERSPECTIVES

The findings from this research indicate that TWNP has been very well conserved and human activities are minimal. This has been shown by the low percentage of degradation in mangrove vegetation i.e. 6.6%, which is remarkable for a natural resources-dependent country such as The Gambia. It is thus concluded that climate change is taking its toll on the habitat integrity through excessive seasonal hyper-salinity, which has been a major cause for the loss of mangrove vegetation in the Sahelian and Sahelo-Sudanian estuaries.

The main drivers of vegetation change in TWNP are the erratic seasonal changes in water quality (seasonal hyper-salinity and water temperature) caused by the long-term deficit in the region's water budget and the increase in atmospheric temperatures. Climate-induced mangrove dwarfism is evident in TWNP and natural species rejuvenation is now close to impossible. This is further confirmed by the uniformity in mangrove canopy height i.e. ≤3m in contrast to the non-sparse vegetation cover during this research period. Land uses such as dumping of household and agricultural wastes at the settlement and agriculture zones further stress the vegetation by causing spikes in phosphate and nitrogen load during the rainy season. This is a cause for concern and needs to be ameliorated soon in order to maintain habitat integrity at this important wetland. There is a need to assign new dumping grounds for the city of Banjul as well as provide environment-friendly sanitation facilities for the community of Wencho.

This research encourages the continuation of mangrove replanting exercises in TWN and also proposes that a more successful way of rejuvenating the mangrove vegetation is by direct human intervention through specialized mangrove replanting exercises, as seedlings have a near-zero chance of naturally surviving the high seasonal variations on their own. The use of saplings instead of propagules holds a greater survival potential as the saplings already have a relatively well developed vascular system when compared to propagules which may end up being washed away to less conducive zones during the flood season or become rotten when the estuary becomes hyper-haline. In order to increase ecological knowledge about the welfare of mangroves in this important wetland, there is a need for further research to assess changes in mangrove species zonation in response to hydrological changes. This will serve as a reliable guide for when choosing mangrove species suitable for revegetation projects within TWNP and the River Gambia estuary as a whole, as well as prevent low survival rates as encountered in past revegetation programs in The Gambia.

Similar to what has happened to the mangrove vegetation, the TWNP is losing its function as a conducive nursery ground for various aquatic organisms. Because of the erratic rainfall pattern in the Sudano-Sahel during the past four decades, the hydrology of the River Gambia estuary has seen its fair share of the effects of seasonal variability due to prolonged dry seasons and short but intense rainy seasons and by extension, so has the TWNP. The recurrence of such extreme events within the short the annual seasonal cycle has made sure that principle estuarine water variable (salinity) is always above the conventional standard for a healthy estuary. In the absence of the required runoff accompanied by increasing atmospheric temperatures, the hydrological balance of this mangrove estuary is compromised, further increasing its vulnerability to sea level rise. This has inevitably led to the loss of important estuarine biodiversity, along with most of the previously arable agricultural lands within the wetland. The continuation of this state will have some catastrophic implications for The Gambia's major economic sectors (agriculture, tourism and fisheries). There is a need for more research into the long-term changes in hydrology of the River Gambia in order to properly inform decision making when it comes to climate change adaptation in mangrove estuaries in The Gambia.

From this research, it is confirmed that the estuarine fish assemblage has suffered significant losses in species over the years. Most migratory fish species require a longer time with ambient water quality than what is seasonally available for successful colonization of the estuary. As a result, the fish assemblage in TWNP is foreseen to undergo a complete colonization by low value euryhaline fish species in contrast to the expected mixture of fish species from both marine and fresh water origins. Thus calling for the need to review fisheries regulations in order to take into account the long-term ecological changes taking place in the wetland and prevent unnecessary losses incurred by the fisher folks. Management measures such as controlling fishing effort will possibly only lead to a reduction in fishers' incomes without really solving the problem of fisheries decline.

The current fish assemblage in TWNP is about 38.6% less species-rich than was reported for the River Gambia estuary in 2004, due to climate-induced local extinctions. The strict estuarine species (Es) contribute only 19.3% of the annual assemblage as they are "giving in" to dominion by the estuarine species of marine origin (Em) which now contribute 47% of the estuarine assemblage. In relation, the provision of alternative livelihoods needs further intensification to compensate for the losses caused by the drastic seasonal shifts in the fish assemblage, as well as other ecosystem services provided by the TWNP for the local people depending on it. There is also a need for further research into cases of supposed local extinctions of economically important fish species in TWNP during the decades following the Sahelian drought. For example, *Oreochromis niloticus* (Trewavas, 1983) and *Sardinella maderensis* (Lowe, 1838), which were reported in literature but not caught during this research.

Based on the relatively high levels of awareness in coastal communities discovered during the social studies, the enactment and enforcement of various environmental regulations have been successful. Although, environmental awareness campaigns have been more successful with the groups involved in oyster collection and farming (who are mostly female), and least so with the groups involved in fishing and tourism (all male). This research highlights the need to make gender issues a principal component when designing awareness creation programs in this highly populous area. Awareness creation needs to be made an integral part of The Gambia's national climate adaptation programs in order to prevent "conservation bottlenecks" such as the current situation in TWNP. This will foster greater community trust in the state-run adaptation programs and ensure maximum community participation in conservation activities.

All the above if combined with more research on the response mechanisms of estuarine flora and fauna to climate change, will avail The Gambia a possibility of identifying, implementing and assessing success rates of state-run interventions for local/alternative livelihoods and provide better adaptation strategies to climate change; while at the same time recognizing the role of the mangrove estuaries as a life-supporting system for the vulnerable coastal communities who are conducting their daily socio-economic activities within this delicate environment.

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APPENDICES

APPENDIX 1 - SOCIAL STUDIES QUESTIONNAIRE

Tribe: ………………… **Sex: M** ☐ **F** ☐ **Age:** ………. **Occupation:** ……………...

Location: ………………..… **Experience:** ………………

CATEGORY	QUESTION	RESPONSE	COMMENT
ECOSYSTEM CHANGES	Does the ecosystem look the same now, as it did when you were young?	YES /NO	
	What are the things that changed?		
	Did these changes increase or limit accessibility to TWNP?		
	How did you adjust to the changes?		
	According to you, what caused those changes?		
	What will the ecosystem look like within 10 to 20 years?		
CLIMATE CHANGE	Have you ever heard of climate change?		
	Where/how did you hear about climate change?		
	How does it manifest?		
	What is your understanding of seasonal variability?		
	How does it affect you/your profession?		
IMPACT ON LOCAL ECONOMY	What is your understanding of hyper-salinity?		
	Has hyper-salinity affected your work on the wetland?		
	If yes, how?		
	Besides your work, what other social activities are conducted on TWNP?		
	Have you changed your profession in last three decades? Why?		
	Have you registered an increase/decrease in your income?		
	In case of a decline - How do you supplement your earnings?		

General Observations

Was there a Need for translation? ....…………………………………………………..…

Willingness to answer questions ………………………………………………………………...…

Understanding of the subject matter ……..…………………………………………………...…

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RESUME DE THESE DE DOCTORAT

Spécialité : Changement climatique et biodiversité

Par

CEESAY Adam

Titre

Dégradation des mangroves et ses effets sur les pêcheries en milieu estuarien : cas du Parc National des zones Humides de Tanbi (Gambie)

Superviseur

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TABLE DES MATIERES

INTRODUCTION

Les écosystèmes de mangrove sont parmi les habitats les plus perturbés du monde par les facteurs naturels et anthropiques **(Blaber *et al.*, 2000)**. Les effets anthropiques ont été bien étudiés en Afrique de l'Ouest, comme par exemple, les effets de la surpêche au Sénégal (**Blamey *et al.*, 2015**) et ceux de la pollution en Côte-d'Ivoire (**Hayé *et al*., 2009)**. De même, de nombreuses études ont été faites sur les impacts du changement climatique sur les écosystèmes marins tropicaux et subtropicaux (**Cheung *et al.*, 2009 ; Doney *et al.*, 2012**). **Doney *et al*. (2012)** ont rapporté une faible productivité de la population, ainsi qu'une réduction de la résilience aux perturbations telle que le changement de l'environnement océanique par le climat ; alors que **Cheung *et al.*** (**2009**) avaient prédit des changements dans la distribution des espèces et des extinctions locales comme une réponse au changement climatique dans les écosystèmes marins.

Les changements des variables climatiques telles que l'augmentation des températures atmosphériques, la diminution des pluies et les sécheresses prolongées sont suspectés d'avoir provoqué des changements majeurs dans l'hydrologie des estuaires à mangroves tropicales et ceux-ci ont été largement étudiés. Le consensus général est que le changement climatique est la cause principale de la réduction de l'intégrité de l'habitat à l'intérieur des estuaires de mangroves tropicale et subtropicales (**Kathiresan, 2002 ; Austin *et al.*, 2010**). Par exemple, la diminution des précipitations qui a suivi la sécheresse du Sahel des années 1970, combinée avec l'augmentation de la demande de biens et de services économiques ont conduit à des changements écologiques majeurs dans les estuaires de mangroves en Afrique Occidentale (**Vidy *et al.*, 2004)**.

Cependant, les interactions entre les facteurs naturels et anthropiques (climat et utilisation des terres) et leurs effets combinés sur les estuaires sont complexes et peu étudiés **(Blamey *et al.*, 2015**). Les informations de ce genre sont encore plus rares pour les estuaires de mangrove du Sahel, où l'hyper-salinité saisonnière est devenue un facteur de stress écologique majeur (**Savenije et Pagés, 1992**). Ainsi, leur compréhension nécessite une approche intégrée de la recherche afin de combler ce manque d'information pour un pays comme la Gambie, où les estuaires de mangrove soutiennent les trois secteurs économiques majeurs (pêche, agriculture et tourisme) (**Agence Nationale de l'Environnement, 2010**). L'information est également déficitaire en termes de changements écosystémiques induits par le climat dans l'estuaire du fleuve Gambie et la façon dont ceux-ci affectent la santé de la mangrove, la structure des communautés de poissons et ainsi que les activités socio-économiques dans et autour de ces zones généralement peuplées.

Le Parc National des Zones Humides de Tanbi (TWNP) en est un exemple situé à l'embouchure de l'estuaire du fleuve Gambie et limité par les trois principales municipalités urbaines de la Gambie (**Satyanarayana *et al.*, 2012**). Entité de l'Écorégion Marine Ouest Africaine (ERMOA), cette zone humide constitue une importante zone de frayère pour les espèces de poissons migrateurs, les oiseaux et bien d'autres organismes aquatiques précieux (**Crow et Carney, 2013**). Une étude récente au TWNP a indiquée des différences saisonnières marquées dans la salinité de l'eau et une dégradation concomitante de la végétation de mangrove (retard de croissance/nanisme) (**Maniatis, 2005**). Cependant, aucune autre étude n'a été faite sur ce site afin de déterminer l'incidence des changements à long terme de l'hydrologie sur la couverture de la mangrove, les assemblages des poissons et les groupes socio-économiques qui dépendent de la zone humide pour leur subsistance. Ainsi, l'objectif de cette recherche était d'étudier les effets des changements hydrologiques induits par le climat sur la végétation de mangrove et de ses implications sur les pêcheries estuariennes, de même que de documenter les connaissances locales des groupes socio-économiques sur le TWNP.

1. METHODOLOGIE

1.1. Site d'étude et Concept écologique

Le TWNP est localisé entre 13^{o}23N - 16^{o}34W et 13^{o}26N - 16^{o}38W (**La Convention de Ramsar sur les zones humides, 2012**) (Figure 1A). Situé dans la zone climatique sahélo-soudanienne, il a une longue saison sèche (octobre - juin) et une courte saison des pluies (juin - octobre) **(Camara, 2012)**. La végétation de mangrove y est principalement composée de *Rhizophora mangle* L. (mangrove rouge), *Avicennia germinans* L. (mangrove noir), *Laguncularia racemose* L. (mangrove blanche) et *Rhizophora harrisonii* L. (**Maniatis, 2005**).

Un concept écologique a été formulé pour montrer comment les facteurs de stress écologique affecte la relation complexe entre la végétation de mangrove, la qualité de l'eau et de la structure des communautés de poissons dans un estuaire tropical (adapté selon **Rudnick *et al.*, 2005**) (Figure 1B). Pour sa mise en œuvre, sept sites d'échantillonnage ont été identifiés sur la base des principaux types d'utilisation des terres /couvertures du sol dans le TWNP. Ceux-ci comprennent: la mangrove dense (zone de référence), Kamalo (zone d'agriculture), Wencho (zone contigue à des habitations humaines), Abuko (zone d'exploitation d'huitre), Mandinary (zone touristique), Bakau (zone complètement fragmentée) et Bund Road (zone partiellement fragmentée).

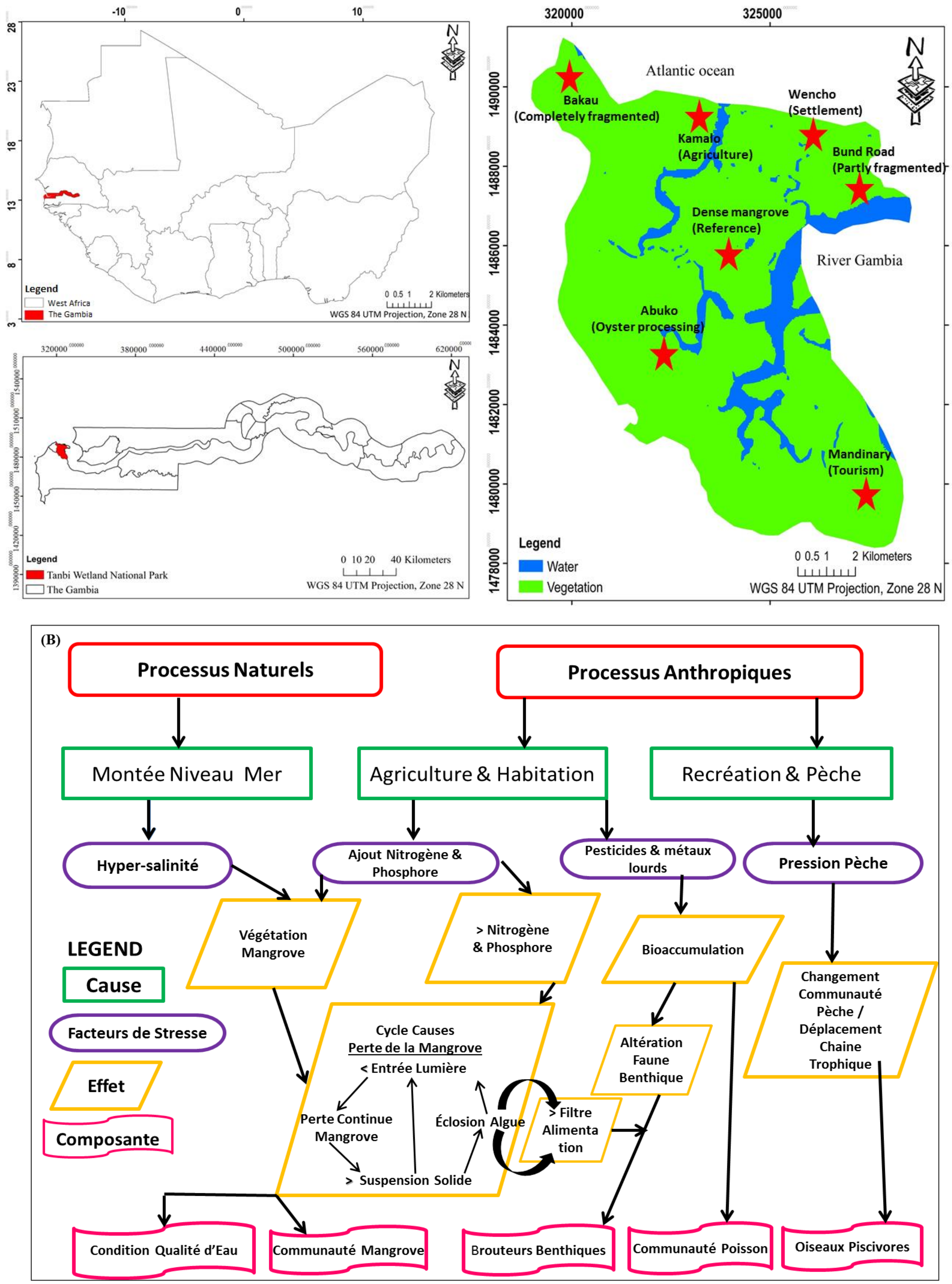

Figure 1. Localisation du site d'étude (en étoile) dans le Tanbi Wetland National Park (Gambie) (A) et le concept écologique de l'estuaire de la mangrove (B).

1.2. Echantillonnage et protocole

Un transect linéaire a été utilisé, fixé perpendiculairement à la source d'eau avec quatre parcelles répliquées trois fois pour chaque site d'échantillonnage. Le long de ces parcelles, les échantillons d'eau ont été prélevés en diagonale en trois points à partir d'une profondeur de 10-25cm (adapté selon **Maniatis, 2005**). Les paramètres physico-chimiques tels que la salinité, le pH, la température de l'eau et l'oxygène dissous ont été analysés *in situ* en utilisant un multiparamètres YSI Proplus, la turbidité avec un appareil de mesure de la turbidité (HACH 2100P) et les éléments nutritifs (nitrates et phosphates) avec un spectrophotomètre HACH (DR / 2010). Pour la présentation complète du cycle saisonnier, l'échantillonnage a été effectué pendant la période de crue du fleuve Gambie et répété pendant le pic de la saison sèche.

La dynamique de la végétation de mangrove du TWNP a été évaluée à l'aide d'une étude diachronique. En plus des données sur le terrain, les images Landsat de séries décennales chronologiques de 1973 - 2012 ont été analysées pour les changements d'occupation et d'utilisation du sol en utilisant Envi 5.2 et ArcGIS 10.3 selon les méthodes de **Scaramuzza *et al.* (2004).**

Une « seine » de dimension 100m × 4m (avec un maillage de14 mm de côté) a été utilisée pour l'échantillonnage des poissons en faisant trois poses 30 minutes chacune pour chaque site d'échantillonnage (adapté selon **Albaret *et al.*, 2004**). Les poissons capturés ont identifié été pesés, mesurés au niveau de l'espèce à l'aide des clés d'identification des poissons **(Lévêque *et al.*, 1990**).

Afin de documenter les connaissances locales et les pratiques d'adaptation face aux changements de l'écosystème induits par le climat dans TWNP, 138 personnes ont été interrogées en utilisant un questionnaire semi-structuré. Ces individus ont été choisis parmi les groupes socio-économiques suivants : les agriculteurs, les pêcheurs, les travailleurs touristiques, les collectionneurs d'huîtres et les résidents du TWNP (Adapté selon **Satyanarayana *et al.*, 2012**).

2. RESULTATS ET DISCUSSION

La salinité totale dans le TWNP était inversement corrélée à la distance de la côte pendant la saison sèche (Figure 2). La salinité moyenne a augmenté de 24.5ppt à 35.8ppt respectivement pour les saisons de crue et sèche, avec la variation saisonnière la plus élevée (12.40-124.10ppt) enregistrée à Bakau (zone complètement fragmentée) et le plus bas (31.25-35.03ppt) à Wencho (zone d'habitation humaine). L'oxygène dissous (5.5-5.4mgl-1) n'a pas été un facteur limitant. De même, les taux de nutriments (2.7-2.0 mgl-1) étaient en dessous des niveaux critiques de pollution. Les fortes variations de salinité au cours de cette recherche semblent être liées aux changements à long terme des variables climatiques, des précipitations et de la température atmosphérique. Compte tenu d'un ruissellement négatif qui permet à l'eau de mer d'envahir les estuaires et devenir concentré par évaporation (**Pagés & Citeau, 1990**), le TWNP semble être l'un des derniers estuaires du Sahel à manifester les changements hydrologiques induits par le climat en raison des déséquilibres à long terme dans son budget de l'eau ce qui peut conduire à la formation des estuaires inverses. Des occurrences similaires ont déjà été signalés dans les estuaires du Sine-Saloum et de la Casamance au Sénégal voisin (**Simier *et al.*, 2006; Ecoutin *et al.*, 2010**).

Avec une précision de la classification de plus de 80% pour toutes les images, sept types d'occupation des terres ont été identifiés dans TWNP pour l'année 2012. La végétation de mangrove a diminué de 6%, les marécages ont augmenté de 44,4% et les forêts ont diminué de 311,1% entre 1973 et 2012 (Figure 3). La perte de la mangrove entre 1973-2012 a été relativement faibles dans le PNTW, indiquant une interférence humaine minimale. Cependant, il a été rapporté que la mangrove du TWNP subit un manque de rajeunissement à court terme (**Dahdouh-Guebas & Koedam, 2002**), ce qui est une réponse naturelle de la mangrove au stress de la salinité pouvant se traduire par une croissance lente (**Austin *et al.*, 2010**). Cette situation semble avoir persisté à travers les années comme en témoigne la présence de peuplements nains de *Rhizophora mangle* avec une hauteur uniforme (inférieure ou égale à 3 mètres) et la mort massive des peuplements de *Avicennia germinans*. Ces données sont similaires aux travaux de **Maniatis (2005)** qui ont montré une forte corrélation entre la salinité et la perte de la végétation de mangrove dans le TWNP.

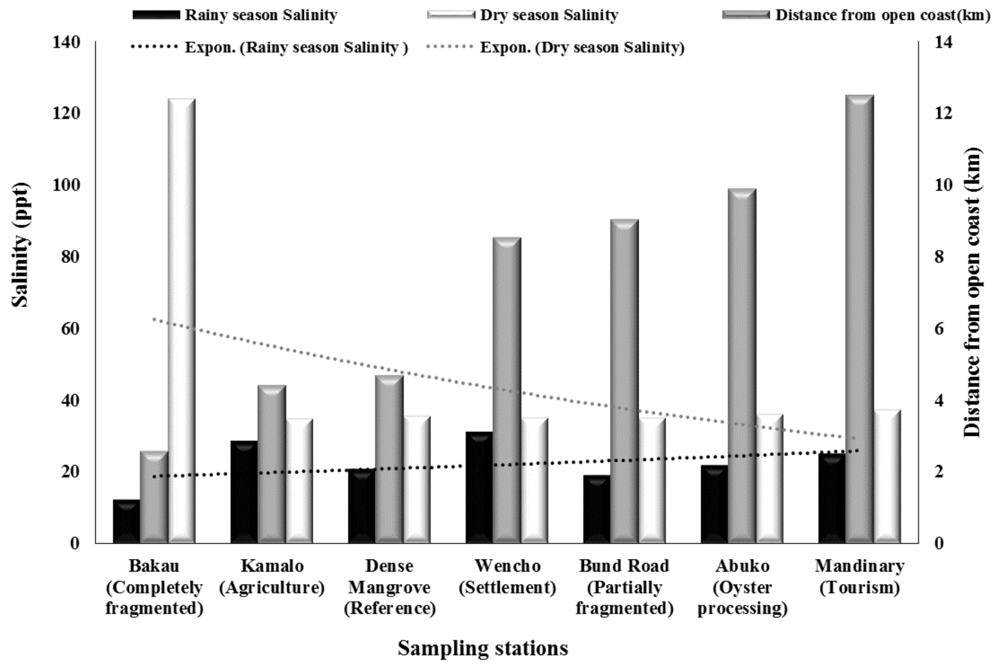

Figure 2. Evolution de la salinité en fonction de la saison et de la distance à la côte pour des sites échantillonnés dans zones humides du Parc National Tanbi (Gambie).

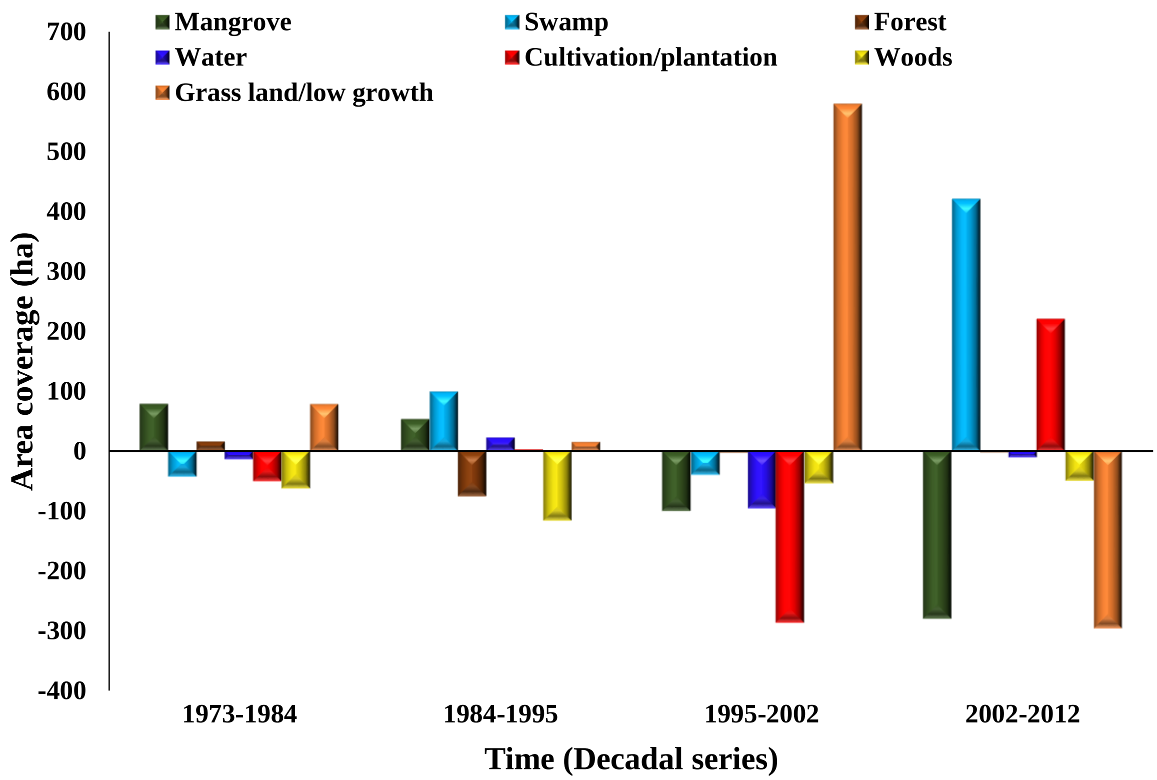

Figure 3. Evolution des types d'occupation du sol de 1973 à 2012 dans les zones humides du Parc National Tanbi (Gambie).

Au total de 43 espèces de poissons appartenant à 25 familles ont été enregistrées dans le PNTW, avec la richesse spécifique la plus élevée (n=28) notée à Mandinary (zone touristique). Cette station est suivie par la zone à mangrove dense (zone de référence) avec 23 espèces tandis que la plus faible richesse spécifique (n=18) a été observée à Wencho (zone d'habitation humaine). La communauté des poissons dans le TWNP est composée de 5 catégories bioécologiques qui est dominé par celle des espèces estuariennes d'origine marine (Em) à 47% au cours des deux saisons. En dépit de la « normalité » supposée de l'estuaire du fleuve Gambie, il a toujours eu les plus faibles rendements annuels de poissons par rapport aux eaux saumâtres d'Afrique occidentale adjacentes (**Villanueva, 2015**). Ceci est parfaitement représenté dans les rendements de pêche de cette recherche et est attribué aux fluctuations saisonnières extrêmes / dramatiques dans des conditions hydrologiques comme l'estuaire a été soumis aussi bien à des périodes prolongées sèches et qu'à de vastes inondations durant les quatre dernières décennies (**Vidy*et al.*, 2004 ; Hutchinson, 1985**). Cette situation, tout en permettant la convergence des espèces de poissons d'origines marines et continentales (**Albaret, 1999**), ne dure pas assez longtemps pour permettre la colonisation réussie de l'estuaire par un groupe donné d'espèces de poissons (**Albaret *et al.*, 2004)**

La prise de conscience locale sur le concept du changement climatique est été élevée (70%). En termes de climat induisant des changements sur l'écosystème 58,33% des répondants ont mentionné une baisse des stocks de poissons ainsi que la disparition des espèces importantes, 55.30% ont mentionné la dégradation de la mangrove, 21,21% l'érosion des sols, tandis que 18,18% ont mentionné une baisse des stocks d'huîtres. Les stratégies d'adaptation locales étaient toutefois communes à 50% des sujets, dont la plupart étaient des groupes d'agriculteurs et les collecteurs d'huîtres. Les pêcheurs avaient le moins de stratégies locales d'adaptation aux changements de l'écosystème, même s'ils ont rapporté le plus grand déclin économique (70%) au cours des quatre dernières décennies. Cette situation peut être attribuée à l'échec de la transmission des informations des autorités aux populations locales qui sont les utilisateurs. Pour les stratégies d'adaptation au changement climatique au profit des groupes socio-économiques pauvres et vulnérables, dans un premier temps des actions physiques ainsi qu'institutionnelles doivent être mis en place (**Mertz *et al.*, 2009**). Cela permettra aux habitants de « s'adapter à l'adaptation » en particulier pour les programmes d'adaptation gérés par l'État (**Kelly et Adger, 2000**), parce que certaines stratégies peuvent résoudre un problème tout en créant un autre (**Barnett et Mahul, 2007**). Les deux actions impactent les collecteurs d'huîtres a travers les droits exclusifs de gestion des utilisateurs et des moyens de subsistance alternatifs (culture d'huîtres) (**Crow et Carney, 2013**) et pour les agriculteurs par le biais de la vulgarisation agricole et la fourniture de variétés améliorées de semences (**Agence National d'Environnement, 2010**). Cependant, les pêcheurs, n'ont que des actions institutionnelles comme l'adoption du Règlement de pêche (**Gouvernement de la Gambie, 1995**) et de la loi (**Gouvernement de la Gambie, 2007**), qui contrôle les types et taille des filets "ignorant" ainsi le rôle fondamental des écosystèmes estuariens comme le premier support de la vie. Pendant ce temps, la limitation de l'activité de pêche réduit seulement le potentiel de gains des pêcheurs sans résoudre nécessairement le problème des changements des écosystèmes (**Munang *et al.*, 2010**).

CONCLUSIONS ET PERSPECTIVES

Le TWNP a été très bien conservé et les activités humaines sont minimes. Cependant, le changement climatique fait des ravages sur l'intégrité de l'habitat à travers l'hyper-salinité saisonnière excessive.

L'intervention humaine directe à travers les exercices spécialisés de replantation de la mangrove peut être le seul moyen de rajeunir le TWNP étant donné que les jeunes pousses/propagules ont une chance quasi nulle d'être de survivre face aux variations saisonnières élevées.

Au niveau de la communauté des poissons, les espèces estuariennes strictes (Es) ne contribuent qu'à 16% alors que les espèces estuariennes d'origine marine (Em), dominantes, représentent 47% des assemblages. La réglementation des pêches doive être réexaminé en prenant en compte les changements écologiques à long terme qui se déroulent dans le TWNP pour un renversement / adaptation à cette tendance.

La fourniture de plus de moyens de subsistance alternatifs est nécessaire pour compenser, d'une part, les pertes causées par les changements saisonniers drastiques et d'autre part le décalage dans les services écosystémiques fournis par le TWNP pour les populations locales qui en dépendent.

Les campagnes de sensibilisation à l'environnement ont eu plus de succès avec les groupes impliqués dans l'ostréiculture (à majorité des femmes) et moins avec ceux qui sont impliqués dans la pêche et le tourisme (surtout des hommes). Cela implique la nécessité de faire des questions du genre une composante principale lors de la conception des programmes de création de sensibilisation. Il y a une nécessité pour les chercheurs d'évaluer les changements dans la zonation d'espèces de la mangrove en réponse aux changements hydrologiques, ainsi qu'à la survie des jeunes pousses et des propagules dans le TWNP.

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Seasonal changes in water quality and fisheries of Tanbi Wetland National Park

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HIGHLIGHTS

- We studied changes in fish assemblage of TWNP during the rainy and dry seasons of The Gambia.
- Human activities influence fish assemblage in TWNP, but not as much as seasonal changes in water quality.
- Salinity is the most influential parameter on fish species richness in TWNP.
- Fish assemblage in TWNP is dominated by fish species of marine origin for both rainy and dry seasons.

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ABSTRACT

This research was aimed at studying seasonal changes in water quality of Tanbi Wetland National Park (TWNP) and how these interact with the different land use types to influence fish assemblage. Physicochemical properties were measured in situ with a portable YSI multiprobe watermeter and fish sampling was done using a seine net of 100 × 4 m. To assess nutrient (nitrogen and phosphorus) input and chlorophyll a concentration (chl-a) in TWNP, spectrophotometry (fluorescence method) was applied. Subjecting the main water variables to a Principal Components Analysis (PCA) indicated a strong correlation between water temperature and pH, phosphate and pH, as well as water temperature and phosphate. A further Multidimensional Scaling (MDS) of the environmental variables indicated salinity as the main water variable influencing fish species richness in TWNP. Except at the settlement and agricultural zones, changes in fish assemblage appear not to be influenced by the specific land use types. As judged from a three-decade time series of rainfall and atmospheric temperatures, seasonal variations in environmental conditions have intensified and are negatively influencing fish assemblage in TWNP.

1. Introduction

Mangrove estuaries are among the world's most perturbed ecosystems, both by natural and anthropogenic factors (Blaber et al., 2000). The effects of the latter on fish communities have been well studied in West African mangrove estuaries, for example the effects of overfishing in Senegal (Blamey et al., 2015) and of pollution in Ivory Coast (Hayé Claire et al., 2009). Similarly, many studies have looked at the impacts of climate change on tropical and subtropical marine ecosystems (Doney et al., 2012; Cheung et al., 2009). The former reported that poor individual performance of species can cause reduced abundance and population productivity as well as reduced resilience to disturbance as climate changes the ocean environment, while the latter predicted changes in species' distributions and productivities as well as local extinctions especially within the tropics.

Changes in climate variables such as increase in atmospheric temperature, declining rains and prolonged droughts are believed to have caused major changes in hydrology of tropical mangrove estuaries (Pagés and Citeau, 1990). As such, extensive research has been done and conclusions drawn labeling climate change as the major cause for reduced habitat integrity in both the tropics and subtropics, for example in the USA (Kathiresan, 2002), Australia

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(Austin et al., 2010) as well as in Senegal (Panfili et al., 2004). However, the interactions between climate and anthropogenic drivers and their impact on coastal ecosystem functioning are complex and largely understudied (Blamey et al., 2015; Panfili et al., 2004). Thus, their understanding requires an integrated research approach.

The decline in rainfall following the Sahelian drought in the 1970s, combined with increasing demand for economic goods and services have led to major ecological changes in West African mangrove estuaries (Vidy et al., 2004), which have not been well documented yet. Hence, there is a great need to fill this information gap for countries such as The Gambia, where mangrove estuaries support the three major economic sectors (Fisheries, Agriculture and Tourism) (National Environment Agency, 2010).

The Gambia is one of the developing countries that are most prone to the effects of climate change and variability (Camara, 2012) (e.g. sea level rise and seasonal hyper-salinity due to erratic rains and increasing atmospheric temperatures for the past three decades) (Panfili et al., 2004). Annual rainfall in this country has decreased by 30% between the years 1950 and 2000 alone, remaining at a range of 850 mm to 1200 mm, the bulk of which occurs in August causing heavy floods in one-third of the country (Lee et al., 2009).

Furthermore, due to the flat terrain of this country, sea water intrudes up to 240 km inland during the peak dry season (Leeney and Downing, 2015), when river discharge becomes as low as 4.5 m^3 s^{-1} (Belhabib et al., 2013). Such high variations in seasonal discharge of fresh and marine water influx can cause substantial change in physicochemical parameters, leading to major ecological disturbances causing shifts in fish community structure and an eventual decline in estuarine fisheries (Belhabib et al., 2013). With fish providing more than 50% of the national protein intake (FAO, 2012), estuarine research is a timely focus area for The Gambia and is in line with the search for global climate change adaptation strategies for coastal and riverine countries.

Recent studies show that the river Gambia estuary is ''normal'' when compared to other West African mangrove estuaries such as the inverse estuary of Sine Saloum in Senegal (Albaret et al., 2004; Panfili et al., 2004; Vidy et al., 2004) and the highly polluted estuary of Bietri in Ivory Coast (Hayé Claire et al., 2009). The basis for this ''normality'' was argued to be its low salinity gradient (from freshwater conditions upstream to marine conditions, 39 ppt) downstream (Simier et al., 2006). Albaret et al. (2004) described the River Gambia estuary as moderately exploited by small-scale fisheries and not receiving any severe pollution from either agriculture or industrial activities. Yet, the estuarine fisheries in The Gambia continues to progressively decline as the fish assemblage keeps changing with time, both in species number and abundance (personal communication, fisheries department).

Meanwhile, the fish assemblage of a given estuary is influenced by a multitude of factors, most of which are interdependent (Albaret, 1999). Such factors include floods (depending on force and duration) (Lee et al., 2009); a change in the balance of physicochemical parameters (Blaber et al., 2000) e.g. salinity and nutrient influx; presence, abundance and state of mangroves (Panfili et al., 2004) as well as land use/human activities occurring on it e.g. infrastructure, agriculture and industry (Albaret, 1999). Using the estuaries of Senegal, Gambia and Fatala in Guinea as case studies, Baran (2000) hypothesized that species richness in West African estuaries is principally influenced by hydrological variability between the dry and the flood seasons, as seasonal intrusion by fish species of marine and continental origin combine and adapt to form a typical estuarine community.

While many studies still refer to overfishing as the main cause of fisheries decline in estuaries (Ecoutin et al., 2014), others believe it is caused by natural habitat degradation rather than overfishing (O'Reilly et al., 2003). Either way, information is highly deficient with regard to the spatial and temporal changes occurring in the mangrove estuary of the River Gambia and how these changes affect fish community structure and fisheries productivity in this populous area. This also holds for the Tanbi Wetland National Park (TWNP), which is located at the mouth of the River Gambia estuary and flanked on three sides by the urban areas (Satyanarayana et al., 2012).

As a mangrove estuary within the West African Marine Eco Region (WAMER), this wetland serves as an important nursery ground for migratory fish species, birds and many other treasured aquatic organisms (Crow and Carney, 2013). A recent study by Maniatis (submitted for publication) in TWNP highlighted a progressive, yet significant seasonal increase in salinity levels and a concomitant degradation of mangrove vegetation (stunting/dwarfism). However, no similar studies were done at this site in terms of how these changes could affect the fish assemblage and how the supposed effects vary seasonally.

With the above in mind, this paper hypothesizes that climate-induced seasonal variations in water quality of the River Gambia estuary are culprit to the declining diversity and abundance of estuarine fishes in The Gambia. Therefore, the aim of this research was to study the seasonal changes in physicochemical parameters and their effects on fish community structure of the TWNP, as influenced by different land use types.

2. Materials and methods

2.1. Study site—Tanbi Wetland National Park (TWNP)

The Tanbi Wetland National Park (TWNP) (Fig. 1) is a lowland area with a mean altitude of 1 to 1.6 m extending between 13°23–13°26N and 16°34–16°38W (The Ramsar Convention on Wetlands, 2012). Located at the mouth of the River Gambia estuary, TWNP covers an area of about 6300 ha (Lee et al., 2009) and connects the three main urban settlements within the Greater Banjul Area (GBA). These are Banjul City (BC), Kanifing Municipality (KM) and Brikama (BA) (National Environment Agency, 2010). Due to its ecological richness, this wetland was designated a Ramsar wetland of importance in 2007 (USAID-BANAFAA Project, 2012).

The TWNP falls within the Sahelo-Sudanian climate zone (Simier et al., 2006), having a long dry season (October–June) and a short rainy season (June–October) (Camara, 2012). Mangrove vegetation in TWNP is comprised of *Rhizophora mangle* (red mangrove), *Avicennia germinans* (also known as *Avicennia africana*/black mangrove), *Laguncularia racemosa* (white mangrove) and *Rhizophora harisonni* (Maniatis, submitted for publication). This mangrove habitat serves as an important nursery ground for fish species such as shad (*Ethmalosa fimbriata)* and sardine *(Sardinella maderensis)* (Baran, 2000), African tilapias (*Sarotherodon* and *Oreochromis* species) (Albaret et al., 2004), as well as the pink shrimp (*Paneaus notialis)* and oysters (*Crassostrea gasar*) (Darboe, 2002).

Economic activities in this area are dominated by Fisheries (including shell fishery) and Tourism (Satyanarayana et al., 2012). Agricultural activities (e.g. rice cultivation and gardening) are also common (USAID-BANAFAA Project, 2012).

2.2. Sampling design

Seven sampling sites were identified to be representative of the major land use types on TWNP. Land use types were classified and include Agriculture (Kamalo), Settlement (Wencho), Oyster Processing (Abuko), Untouched (Dense mangrove), Tourism (Mandinary), Partially Fragmented (Bund Road) and Completely Fragmented (Bakau). Details of sampling sites are shown in Table 1.

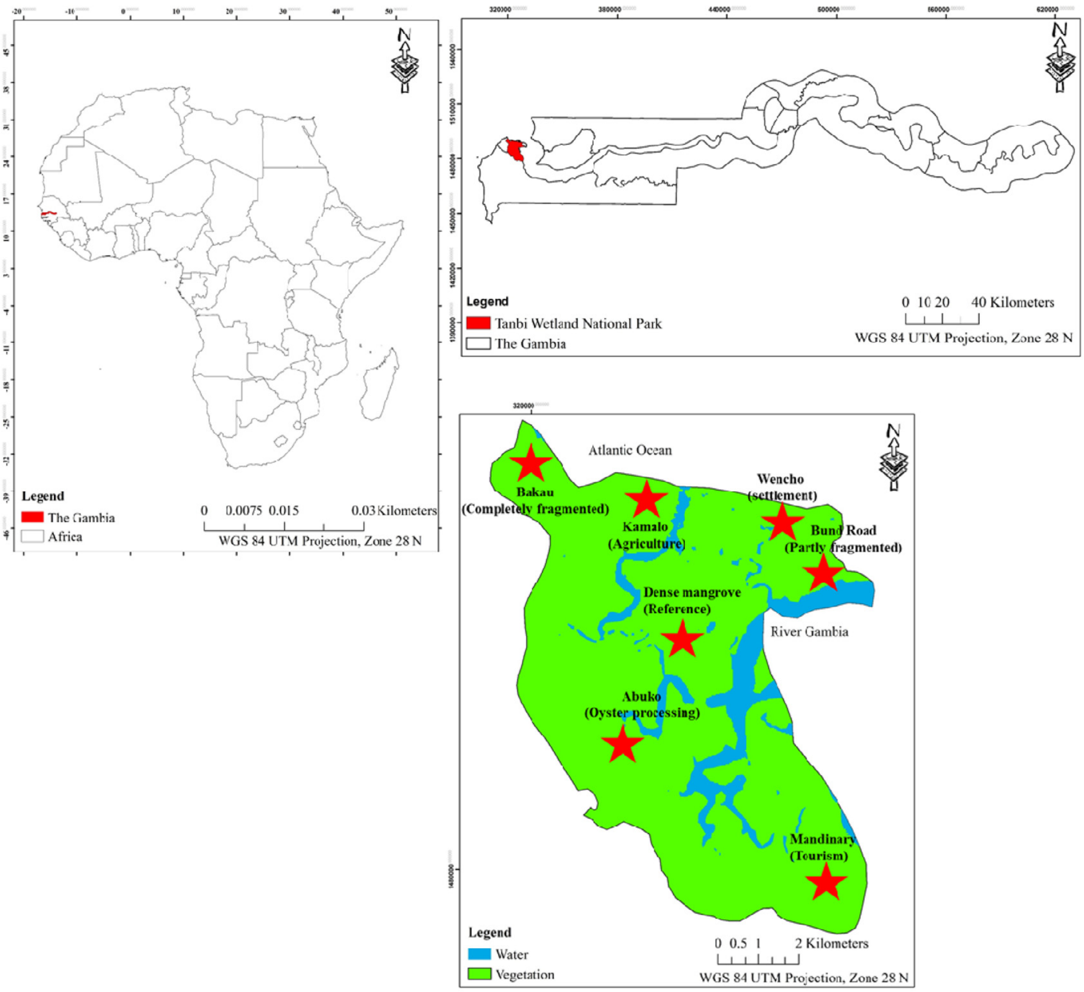

Fig. 1. Location of Tanbi Wetland National Park in The Gambia, with the sampling stations marked (red star). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Sampling sites with GPS coordinates on TWNP.

Sampling point	Land use type	GPS coordinates
Dense mangrove	Untouched (Reference zone)	13.4295N–16.6312W and 13.4306N–16.6318W
Kamalo	Agriculture zone	13.4676N–16.6338W and 13.4671N–16.6349W
Abuko	Oyster processing zone	13.4097N–16.6475W and 13.4106N–16.6481W
Mandinary	Tourism zone	13.3824N–16.0038W and13.3831N–16.0098W
Wencho	Settlement zone	13.4580N–16.5965W and 13.4592N–16.5989W
Bakau	Completely fragmented zone	13.4694N–16.6643W and 13.4693N–16.6642W
Bund road	Partially fragmented zone	13.4524N–16.5878W and 13.4531N–16.5886W

For correlation with satellite imagery on mangrove vegetation studies (not featured here) and to ensure a uniform representation of the hydrological regime of the study area, a straight-line-transect method, (adapted from Kathiresan, 1990) was used for sampling environmental/water quality parameters at each of the land use types identified. Three transects were set perpendicular to the water source at each sampling point (adapted from Louca et al., 2008). In each transect, four plots were set to give 12 plots per land use type (Fig. 2).

2.3. Sampling protocol

2.3.1. Water quality

For ensuring uniformity in water samples, three samples were collected from three points in each plot in a diagonal mode ($n = 36$). Since no significant vertical stratification has been reported for the water quality variables of the River Gambia estuary (Albaret et al., 2004; Darboe, 2002; Guillard et al., 2012) all water samples were collected at high tide from a depth of 10–25 cm for measurement of the following physicochemical parameters: salinity, dissolved oxygen, pH, water temperature and turbidity, as well as for nutrients (nitrogen and phosphate) and chlorophyll a.

In situ analysis of salinity, dissolved oxygen, pH, and water temperature were done using a Multi-probe water meter (YSI Proplus), turbidity was measured using a HACH turbidity meter (HACH 2100P). Water samples were also collected in clear polyethylene bottles, wrapped in foil and stored in ice boxes for transport to the laboratory for nutrients and turbidity analyses. Nutrient analyzes were done using a HACH spectrophotometer (DR/2010) with PhosVer® 3 reactive reagent (ascorbic acid method) and NitraVer® 5 (cadmium reduction method) for phosphate and nitrate respectively.

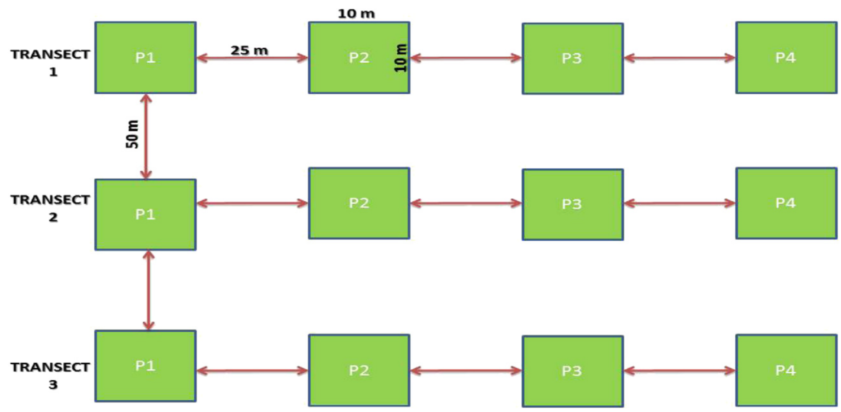

Fig. 2. Sampling design used. P: plot.
Source: Adapted from Kathiresan, 1990 and Louca et al., 2008.

To assess chlorophyll a content, twelve water samples (each of 500 ml) were collected at each sampling site using foiled polyethylene bottles, stored on ice and transported to the laboratory. Using Whatman Glass Fiber membrane filters (diameter 25 mm and porosity 0.7 μm), these samples were filtered in subdued light, wrapped in foil and stored at −20 °C until further analysis using the fluorescence method (spectrophotometry) based on the EPA protocol 445.0 (Arar and Collins, 1997).

For representation of the seasonal cycle, sampling was done during the peak discharge period of the River Gambia (September–December, 2013) and repeated during the peak dry season (April–July, 2014).

2.3.2. Fish community

To assess seasonal variation in fish community structure based on species abundance and biomass, fish sampling was done in the open waters adjacent to transects during the ebb tides. With the help of the same fisherman and boat at all sampling points, a seine net of 100 m × 4 m (with 14 mm mesh size, leaded at one side to ensure bottom contact and floaters attached to the upper end for full water depth coverage) was deployed with three throws at each site. Netting for each throw lasted about thirty minutes at all sites.

Fish caught were measured, weighed and pictures of each fish species caught were taken for verification purposes. Fish were then identified to species level based on morphological characteristics. The identification of the fish species caught was verified using Fishbase (http://www.fishbase.org) and IRD fish species identification keys for fresh and brackish waters of West Africa. Confirmation was also sought from expert researchers in West African Fisheries. Fish sampling was done during the peak discharge period and repeated during the peak dry season to capture both seasons of The Gambia.

Due to the shallowness of the water (≤30 cm), the presences of numerous dead mangrove tree trunks and the absence of any fish in the open waters at the completely fragmented zone, fish sampling could not be done here. Thus, fish study results are for all land use types, except the completely fragmented zone (Bakau).

2.3.3. Data analysis

Environmental data were sorted in basic excel format by site/land use type. Individual variables (e.g. salinity) for all sites were subjected to a one-way ANOVA (P value $<$ 0.05) to detect significant differences per season and then subjected to a pairwise student's t-test to determine significant differences at all the specific land use types between the rainy and dry seasons. This was followed with a Principal Component Analysis (PCA) performed on the five main water quality variables i.e. salinity, dissolved oxygen, pH, temperature, turbidity, as well as nitrate and phosphate in order to test level of correlation with degree of significance set to $P < 0.05$ using R version 3.1.2 statistical package for windows.

To determine abundance of fish species and similarities in fish communities under the different land use types, all biological data were subjected to a cluster analysis, where fish species abundance for the different land use types were grouped into a similarity matrix (Bray Curtis Similarity). This yielded groups/clusters of land use types with similar species composition. Environmental data were normalized to allow direct comparison between various water variables. A further MDS ordination of similarity data was carried out with environmental variables to determine most influential variables on species abundance. This identified and grouped the fish species under the various land use types based on similarities in species composition, as well as the water quality variables that had the most influence on such species composition. These analysis were done using the multivariate analysis tool PRIMER version 6.

In order to find the asymptotic richness of fish species in TWNP and also assess sampling efficiency, the Chao 2 species estimator was applied using Windows EstimateS version 9.1.0. Using the field incidence data and number of samples for this study (plotted on y and x-axis respectively), the asymptote richness and real time species curves were compared. All other graphs were plotted using SigmaPlot version 13.

3. Results

3.1. Water quality

Based on the results of the one way ANOVA, significant differences were recorded in mean salinity levels during the two seasons studied in TWNP (P value $<$ 0.0001). Average salinity was 24.5 ppt and 35.8 ppt during the rainy and dry seasons respectively. During the rainy season, the highest salinity (31.2 ppt) was recorded at the settlement zone (Wencho) and the lowest (19.2 ppt) at the partially fragmented zone (Bund Road). For the dry season, the highest salinity (37.3 ppt) was recorded at the tourism zone (Mandinary) and the lowest (35.0 ppt) at the agricultural zone (Kamalo). Salinity levels during the dry season were not significantly different (P value 0.47) between the untouched zone (dense mangrove) and the Oyster processing zone (Abuko) i.e. 36.0 ppt at both sites. Off the main wetland, the completely fragmented zone (Bakau) displayed the lowest salinity level (12.4 ppt) during the rainy season, as well as the highest salinity level (124.1 ppt) during the dry season (Fig. 3(A)).

The average pH levels did not differ significantly (P value, 0.05) between the two seasons, i.e. 7.6 during the rainy season and 7.55

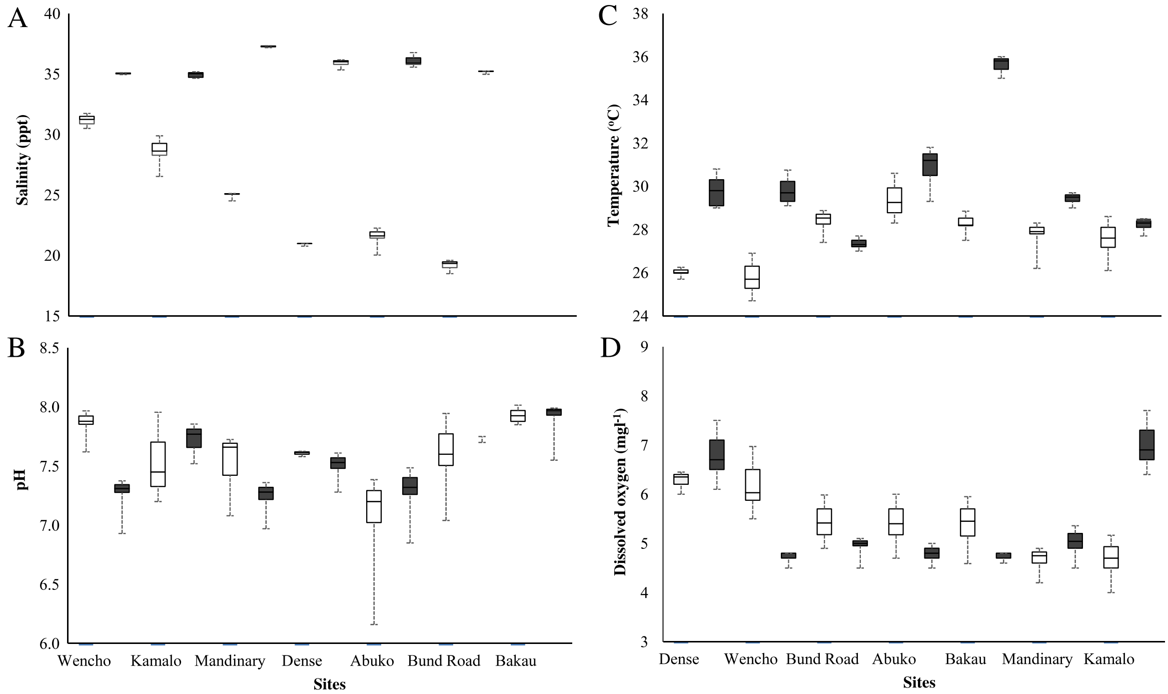

Fig. 3. Seasonal variation in salinity (A), pH (B), water temperature(C) and dissolved oxygen (D) within different land use types in TWNP. White: Rainy season, Grey: Dry season, Wencho: Settlement, Kamalo: Agriculture, Abuko: Oyster processing, Mandinary: Tourism, Dense: Untouched, Bund Road: Partially Fragmented, Bakau: Completely Fragmented.

during the dry season. However, there were significant differences in pH between the land use types studied (P value, < 0.005). The completely fragmented zone (Bakau) had the highest pH values for both seasons. pH values did not differ significantly (P value, 0.4) between the dense (untouched zone) and the Mandinary (tourism zone) during the rainy season (7.6 at both sites). The oyster processing zone (Abuko) displayed the lowest pH values for both the two seasons (Fig. 3(B)).

Mean water temperature increased significantly (P value, $<$ 0.001) from 27.6 °C during the rainy season to 30.2 °C during the dry season. The highest water temperature (29.4 °C) during the rainy season was recorded at the oyster processing zone and this increased to 31.4 °C during the dry season. During the rainy season, the lowest water temperature (25.7 °C) was recorded at the settlement zone (Wencho). This however, was not significantly different (P value of 0.06) from the water temperature at the dense mangrove (untouched zone) (26.0 °C). For the dry season, the highest water temperature (35.7 °C) was recorded at Bakau (completely fragmented zone) and the lowest (27.4 °C) at Bund Road (partially fragmented zone) (Fig. 3(C)).

Throughout the study, dissolved oxygen values were never critical ($<$3 mg l^{-1}) (US EPA, 2006). The average dissolved oxygen level was 5.5 mg l^{-1} during the rainy season and 5.4 mg l^{-1} during the dry season. However, results of the one-way ANOVA indicated significant differences between the land use types during the rainy and dry seasons (P value of $<$ 0.001). The highest (6.3 mg l^{-1}) saturation during the rainy season was recorded at the dense mangrove zone and the lowest (4.7 mg l^{-1}) at the tourism zone (Mandinary). During the dry season, the highest DO level was at the agriculture zone (Kamalo) (7.0 mg l^{-1}) and the lowest (4.8 mg l^{-1}) was recorded at the completely fragmented zone (Fig. 3(D)).

Nutrient analysis showed significant differences in nitrate levels between the two seasons (P value, $<$ 0.003). There was a general decline in nitrate as the seasons changed from rainy to dry, i.e. from 2.7 to 0.8 mg l^{-1}. The highest level of nitrate (4.3 mg l^{-1}) during the rainy season was recorded at the tourism zone, followed by the settlement zone (4.0 mg l^{-1}) and the lowest at the dense mangrove (untouched zone) (0.6 mg l^{-1}). During the dry season, nitrate levels were highest at Bakau and Mandinary (1.1 mg l^{-1} at both sites), while the dense mangrove (untouched zone) displayed the lowest nitrate level (0.4 mg l^{-1}) (Fig. 4(A)).

Mean phosphate levels in TWNP declined significantly (P value, $<$ 0.005) from 2.0 to 0.6 mg l^{-1} as seasons changed from rainy to dry. During the rainy season phosphate values were highest at the partially fragmented zone (Bund Road) (4.6 mg l^{-1}) and lowest at Wencho (settlement zone) (0.4 mg l^{-1}). During the dry season, phosphate level was highest at Bakau (completely fragmented zone) (0.9 mg l^{-1}) and lowest at Abuko (oyster processing zone) (0.002 mg l^{-1}). Phosphate level at Wencho (settlement zone) also declined significantly (P value, $<$ 0.001) during the dry season (Fig. 4(B)).

Average chlorophyll a level in TWNP was generally low during the rainy season (3.9 μgl^{-1}). This declined slightly (3.6 μgl^{-1}), but not significantly during the dry season (P value, 0.4). The results of the pairwise students t-test indicated that this decline did not occur at all sites, as the tourism and agriculture zones displayed significant increases during the dry season (P values of $<$ 0.003 and $<$ 0.01 respectively) (Fig. 4(C)).

Turbidity levels in TWNP followed a similar trend to the chl-a levels. Average turbidity level differed significantly (P value, $<$ 0.004) between the rainy (11.6NTU) and dry season (8.2NTU). The one-way ANOVA results indicated significant differences between the different land use types, with the completely fragmented zone displaying the highest turbidity level (18.9NTU) during the rainy season, while the dense mangrove (untouched zone) displayed the lowest turbidity for both seasons (Fig. 4(D)).

3.1.1. Levels of significance and correlation of water variables during the two seasons in TWNP

Results of the pairwise student's t-tests conducted for the water variables of individual land use types during the two seasons indicated significant differences in all the water variables, except

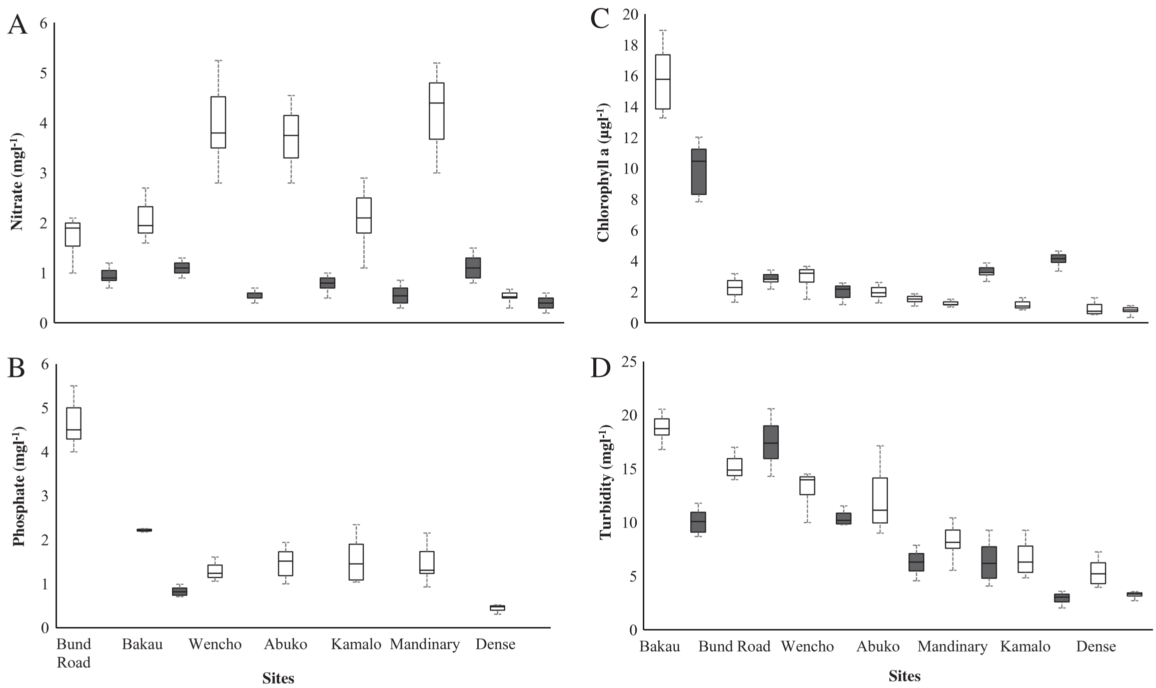

Fig. 4. Seasonal variation in nitrate (A), phosphate (B), chlorophyll a (C) and turbidity (D) within different land use types in TWNP. White: Rainy season, Grey: Dry season, Wencho: Settlement, Kamalo: Agriculture, Abuko: Oyster processing, Mandinary: Tourism, Dense: Untouched, Bund Road: Partially Fragmented, Bakau: Completely Fragmented.

Table 2
Significance levels for the differences in mean seasonal values of water variables at the individual land use types in TWNP, based on results of the pairwise student's *t*-test.

Environmental variable	Dense	Abuko	Mandinary	Kamalo	Wencho	Bund Road	Bakau
Salinity	*	**	***	**	**	*	****
Temperature	****	***	****	*	*****	**	****
Dissolved oxygen	*	***	***	****	****	**	**
pH	ns	*	***	***	****	**	ns
Turbidity	*	****	**	****	****	ns	***
Nitrate	*	****	***	***	****	**	**
Phosphate	**	***	****	***	*	***	****
Chlorophyll a	ns	ns	***	****	*	ns	**

Degree of significance at $P < 0.05$ indicated by the number of stars (*), ns: not significant. Dense: reference zone; Abuko: oyster processing zone; Mandinary: tourism zone; Kamalo: agriculture zone; Wencho: settlement zone; Bund Road: partially fragment zone: Bakau: completely fragmented zone.

Table 3
Correlation between mean values of water quality/environmental variables for the rainy and dry seasons in Tanbi wetland National Park, based on results of the PCA.

Rainy	Dry						
	Oxygen	Salinity	pH	Temperature	Turbidity	Nitrate	Phosphate
Oxygen		0.61	0.24	0.53	0.20	0.17	0.53
Salinity	0.82		0.20	0.43	0.81	0.15	0.26
pH	0.54	0.40		0.05	0.74	0.62	0.02**
Temperature	0.37	0.39	0.01***		0.34	0.96	0.03*
Turbidity	0.85	0.99	0.99	0.58		0.34	0.6
Nitrate	0.45	0.34	0.77	0.53	0.50		0.98
Phosphate	0.55	0.22	0.83	0.46	0.28	0.70	

Level of significance at $P < 0.05$ indicated by the number of stars (*).

for pH and chl-a at the dense mangrove zone, chl-a at Abuko, turbidity and chl-a at Bund Road and also pH at Bakau (Table 2).

Concerning the correlation between the specific water variables, a weak non-significant one was noted during the rainy season; with the exception of temperature and pH which had a negative, yet significant correlation ($p < 0.01$). During the dry season, correlation was significant between pH and phosphate ($p < 0.02$) and also between temperature and phosphate ($p < 0.03$) (Table 3).

3.2. Fish community

Fish community in TWNP is comprised of 43 species from 25 fish families based on the two seasons studied. Species richness was significantly different between the different land use types as well as between seasons. 37 species from 21 families were caught during the peak discharge period and 31 species from 19 families caught during the peak dry season. Fish species present/absent during the two seasons are shown in Table 4.

Table 4
Presence/absence of fish species caught during the rainy and dry seasons in TWNP.

#	Species	Rainy season	Dry season
1	*Batrachoides liberiensis*	0	1
2	*Bostrychus africanus*	1	0
3	*Brachydeuterus auritus*	1	0
4	*Carlarius heudelotii*	1	0
5	*Chloroscombrus chrysurus*	1	0
6	*Citharichthys stampflii*	1	1
7	*Cynoglossus senegalensis*	1	1
8	*Dasyatis margarita*	1	1
9	*Dentex maroccanus*	0	1
10	*Disentrarchus punctatus*	0	1
11	*Drepane africana*	1	1
12	*Elops senegaliensis*	1	1
13	*Ephippion guttifer*	1	1
14	*Epinephelus aeneus*	0	1
15	*Ethmalosa fimbriata*	1	1
16	*Eucinostomus melanopterus*	1	1
17	*Galeoides decadactylus*	1	1
18	*Gerres nigri*	1	0
19	*Hemichromis fasciatus*	1	1
20	*Ilisha africana*	1	1
21	*Liza aurata*	1	1
22	*Liza dumerili*	0	1
23	*Liza falcipinnis*	1	1
24	*Liza grandisquamis*	1	1
25	*Lutjanus goreensis*	1	0
26	*Monodactylus sebae*	1	1
27	*Mugil bananensis*	1	1
28	*Mugil cephalus*	1	0
29	*Pellonula leonensis*	1	0
30	*Plectorhincus macrolepis*	1	1
31	*Polydactylus quadrifilis*	1	1
32	*Pomadasys aheneus*	1	0
33	*Pomadasys jubilinis*	1	0
34	*Pomadasys perotaei*	1	1
35	*Porogobius schlegelii*	1	1
36	*Pseudolithus elongatus*	0	1
37	*Pseudolithus senegalensis*	1	1
38	*Sarotherodon melanotheron*	1	1
39	*Sphyraena afra*	1	0
40	*Strongylura senegalensis*	1	1
41	*Tilapia guineensis*	1	1
42	*Torpedo torpedo*	1	0
43	*Tylochromis jentinki*	1	1
	Total	**37**	31

0: Absent and 1: Present.

Overall, percentage species richness was significantly higher in the tourism zone than at all other sites (62.8% of the 43 species caught). The lowest percentages in species richness were recorded at the agriculture and partially fragmented zones (41.9 and 39.5% of the total number of species caught respectively); although not significantly different from the settlement zone (44.2%). There was no significant difference in the percentage species richness at the untouched and oyster processing zones (53.5 and 51.2% respectively) (Fig. 5).

In terms of abundance, a total of 3903 individuals were caught during the peak discharge period, but this declined to 2530 individuals during the peak dry season. Thirteen families accounted for more than 90% abundance of all fish catches throughout the study period. The major fish families were Mugilidae, Clupeidae and Cichlidae, contributing 37.7%, 28.4% and 18.1% of the total abundance respectively and 46.0%, 10.6% and 27.1% of the total biomass respectively (Fig. 6(A) and (B)).

During the rainy season Mugilidae contributed up to 42.0% of the total abundance, closely followed by Clupeidae (34.2%) and Cichlidae (8.8%). During the dry season, overall abundance declined and the Cichlidae formed the major family accounting for 32.5%, followed by Mugilidae (31.1%) and Clupeidae (19.4%). This however, did not downplay the contribution of the other fish families (others) which were represented by only 1 species each

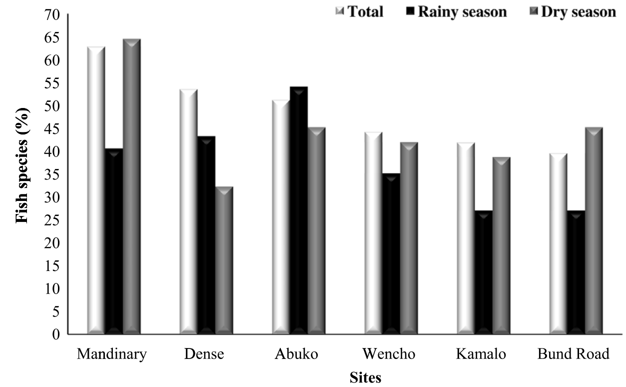

Fig. 5. Percentage species richness for rainy and dry seasons at different land use types in TWNP. Wencho: Settlement, Kamalo: Agriculture, Abuko: Oyster processing, Mandinary: Tourism, Dense: Untouched, Bund Road: Partially Fragmented.

and when combined accounted for about 2.0% abundance during the rainy season and 1.6% during the dry season (Fig. 7(A)).

Fish biomass of the aforementioned families also differed significantly between the two seasons and the sites corresponding to the six land use types. Total biomass declined from 110.6 kg during the rainy season to 86.7 kg during the dry season. Most of this decline was from the settlement (Wencho) and agricultural (Kamalo) zones at −18% and −7% respectively. For percentage biomass contribution of fish families, the Mugilidae contributed 57.7% during the rainy season, but this declined to 31.2% during the dry season. This was closely followed by Clupeidae at 13.2% and Cichlidae at 10.8% during the rainy season. This trend however, was reversed during the dry season when Cichlidae accounted for 47.8% of total biomass, while Mugilidae and Clupeidae contributed 31.2% and 7.2% of total biomass respectively (Fig. 7(B)).

The most speciose families were Mugilidae (6 species), Haemulidae (5 species), Cichlidae (4 species) and Clupeidae (3 species). Other families of importance include Cynoglossidae, Gerreidae, polynemidae and Sciaenidae, all of which were represented by 2 species each. The rest of the other families were represented by only 1 species each. Categorizing these species based on methods of Albaret et al. (2004), yielded 5 out of the 8 bio-ecological categories reported for the River Gambia estuary. These include Ec: Estuarine species from continental origin, Em: Estuarine species of marine origin; Es: strictly estuarine species; Ma: Marine species accessories in estuaries; and ME: Marine estuarine species. Significant changes in spatial (herein, land use types) and temporal (herein, seasons) distribution of these groups were recorded. The Em category was the most abundant category for both seasons.

Overall, the strict estuarine species (Es) formed only 16% of the total fish catches, thus "giving in" to dominion by the estuarine species of marine origin (Em) and marine estuarine species (ME) which formed 47% and 26% of total catches respectively. During the rainy season, Em category formed 50% of all species at the oyster processing zone and 38% at the dense mangrove zone. This shifted to the tourism zone forming 45% of all the species found there during the dry season (Fig. 8). Percentage species abundance of the bio-ecological categories at the various land use types and their trophic categories are shown in Table 5.

Clustering of fish species abundance data for the various land use types led to the discrimination of three clusters for the rainy season and two for the dry season. During the rainy season cluster one was comprised of only the dense mangrove zone which had <20% species similarity with all other sites. The second cluster was comprised of Abuko and Mandinary and they had about 65% similarity in species and also Kamalo and Bund road

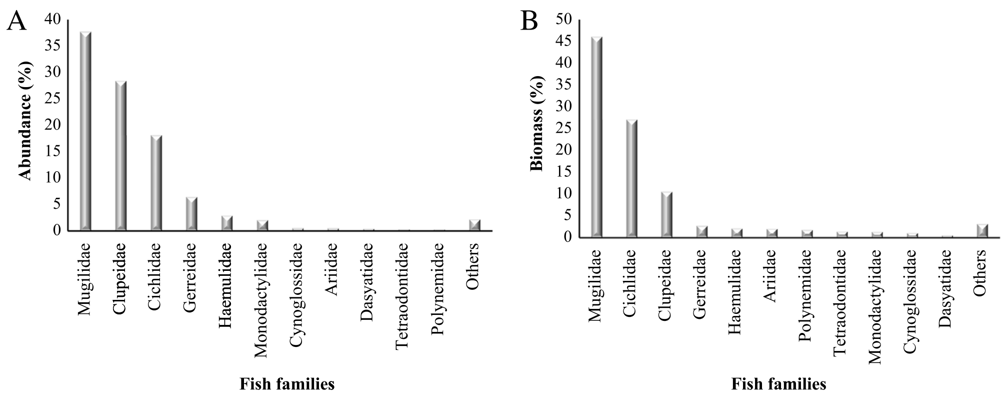

Fig. 6. Percentage abundance and biomass contributions of the fish families to total catch in TWNP.

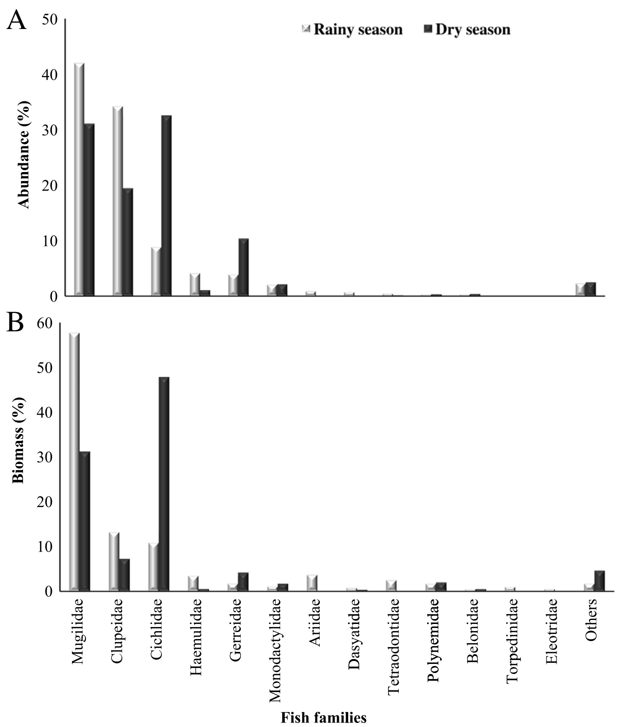

Fig. 7. Seasonal variation in percentage abundance (A) and biomass (B) of the fish families caught in TWNP.

which had about 50% similarity. The third cluster for the rainy season was comprised of Wencho, which had 45% similarity with those recorded at Mandinary during the dry season. For the dry season, similarity in species abundance was by two clusters. Cluster one was comprised of dense mangrove (untouched zone), partially fragmented (Bund road), oyster processing (Abuko) and agricultural (Kamalo), all with a similarity of 60%; while cluster two was comprised of the settlement (Wencho) and tourism (Mandinary) zones (Fig. 9(A)).

Further MDS ordination of these clusters with environmental variables determined which variables had the greatest influence on fish species abundance for the two seasons and six land use types in TWNP. For the rainy seasons, phosphate and turbidity were the most influential variables on the species abundance at Kamalo and Wencho where the least number of species were recorded and to a lesser extent, at Bund Road. During the dry season, salinity had the strongest influence on the decline in species abundance at dense mangrove zone when compared to the other land use types; while the increase in Chl-a and decline in nutrient content were responsible for the increase in species abundance at Mandinary and Wencho (Fig. 9(B)).

In terms of sampling efficiency, the area sampled/sampling effort could have been the reason for the slightly lower number of species than those reported in the literature for the creeks of the River Gambia estuary. For instance, increasing sampling points to 7 or 8 land use types might have led to the capture of a couple of more species. Nonetheless, sampling efficiency was sufficient (79.5%) as indicated by the Chao2 estimator in the species rarefaction curve (Fig. 10).

4. Discussion

Seasonal variation in water quality of the River Gambia estuary has been reported by many scientists (Darboe, 2002; Guillard et al., 2012). However, variations are much higher in TWNP probably due to its proximity to the coast. Spatial variation in salinity for instance, declined as one moved away from the coast and toward the riverine end during the rainy season and vice versa; similar to findings of Albaret et al. (2004). This indicates a deficit in water budget caused by long-term imbalances in rainfall and atmospheric temperature, leading to a negative runoff and enabling seawater to intrude the estuary and become concentrated by evaporation. Such an occurrence has been reported previously for the estuaries of Sine-Saloum and Casamance in Senegal Pagés and Citeau (1990). It also indicates negligible influence by land use type, except at the completely and partially fragmented zones (Bakau and Bund Road).

Similarly, average water temperatures for the rainy and dry seasons a decade ago in TWNP were 23.8 and 30 °C respectively (Maniatis, submitted for publication). These have increased to 27.9 and 30.2 °C respectively during the current research, suggesting considerable increase and lesser cooling effect from river flow (Schlenk and Lavado, 2011). Such combination of changes in environmental factors are enough to cause huge declines in estuarine fisheries, as important life processes such as migration, reproduction timing and spawning success of various fish species get interrupted (Panfili et al., 2004).

Pollution and excessive nutrient loading have also been reported to cause eutrophication and anoxic conditions unsuitable for supporting marine life in many estuaries surrounded by human activities such as agriculture and industry (Hayé Claire et al., 2009). Although, nutrient concentrations in estuaries vary according to surrounding land use, season, and geology, nutrient levels recorded in TWNP were way below the critical point (>1 mg l^{-1}) (US EPA, 2006), ruling out pollution as an ecosystem destabilizer for TWNP. While this rules out excess nutrients being released from land use, it also points to a possible nutrient deficiency, which would have great implications for vegetation and in turn fish species that depend on the ecosystems services such as DO regulation.

With regards the fish studies done during the two seasons in TWNP, the number of fish species recorded in TWNP during this

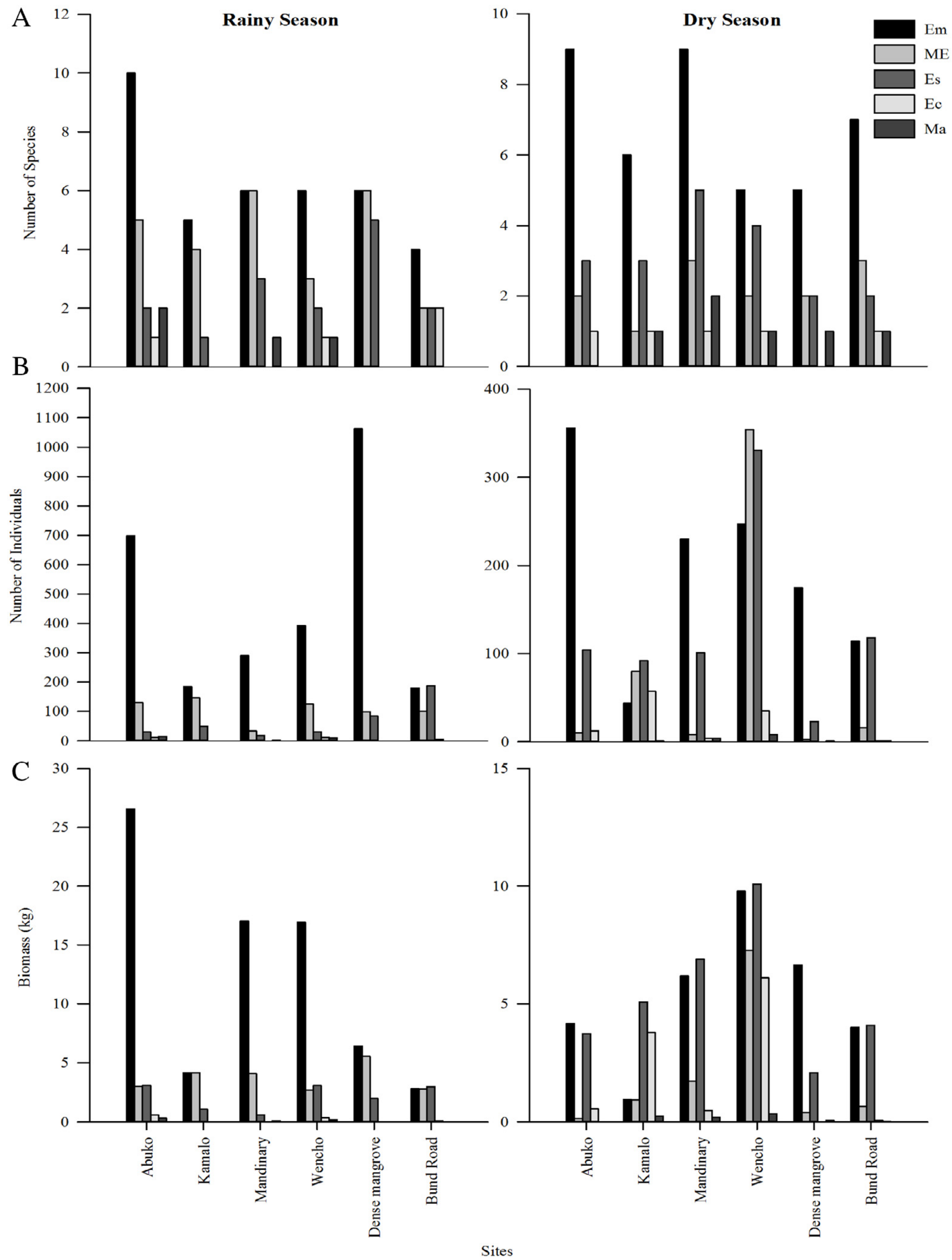

Fig. 8. Seasonal variations in spatial and temporal distribution of fish assemblages based on bio-ecological categories at the different land use types in TWNP. A: species number; B: abundance; C: biomass (kg). Ec: estuarine species from continental origin; Es: strictly estuarine species; Em: estuarine species from marine origin; ME: marine-estuarine species and Ma: marine species accessory in estuaries.

research was lower than that reported from other studies in the River Gambia estuary. Many scientists agree that The River Gambia estuary should have more diverse fish communities (Albaret et al., 2004), given the presence of diverse hydrological situations and the existence of extensive mangrove vegetation lining the river and its creeks (Albaret, 1999). These are considered favorable grounds for nursery purposes of many diadromous fish species and a refuge from predators (Baran, 2000). This expectation is however countered by the extreme seasonal variability as the suitable physicochemical conditions do not last long enough for the successful colonization of the estuary by any given group of fish; be it of marine or continental origin (Albaret, 1999; Albaret et al., 2004).

Fish species diversity in the estuaries of the Gambia as shown in this research progressively declines towards those sites where seasonal variability increases. These findings thus make past scientific predictions, which did not account for spatio-temporal variability of fish diversity, seemingly insufficient. For instance, Albaret (1999) reported a total of 89 fish species for the River Gambia estuary, and 70 species in 2004 (Albaret et al., 2004), while Simier et al. (2006) reported 67 species. However, most of the research mentioned above was done in the open channel of the River Gambia estuary, thus leaving out most of the mangrove creeks which are areas of large salinity gradients and intensive human activities; thereby excluding anthropogenic impacts in the estuary and as a result overestimating the overall species richness and abundance for the River Gambia estuary.

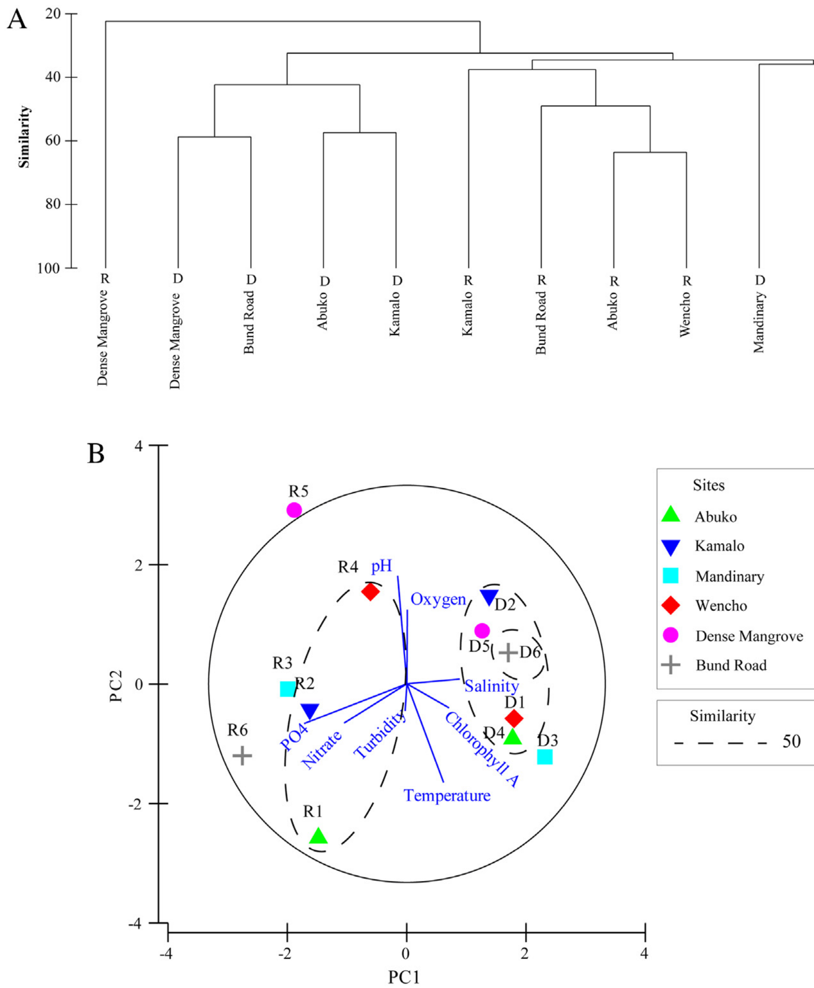

Fig. 9. Cluster dendrogram (A) and MDS ordination (B) of percentage species abundance for the 6 land use types over 2 seasons in TWNP. R: Rainy, D: Dry. 1: Abuko (Oyster Processing Zone), 2: Kamalo (Agricultural zone), 3: Wencho (Settlement Zone), 4: Mandinary (Tourism Zone), 5: Untouched (Dense mangrove zone), 6: Bund Road (Partially fragmented zone).

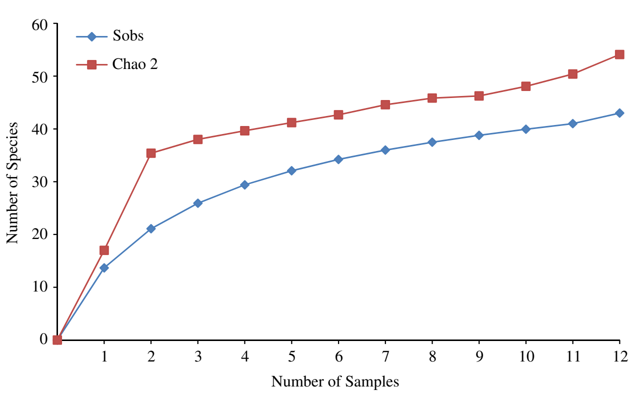

Fig. 10. Species accumulation curve for TWNP based on species observed data (S_{obs}) versus asymptote curve (Chao 2).

The total number of fish species (43) caught during this research resemble findings of Vidy et al. (2004) who reported a total of 47 fish species from 26 families within the creeks of the River Gambia estuary, similar to the 43 species and 25 families caught during this research in TWNP. This is considerable, given the small size of the current study site and its location within a highly populated area. Similarly, White et al. (2012) reported 49 fish species for the middle part of the River Gambia, where multiple habitats were found. The overwhelmingly higher species abundance of the fish families such as the Mugilidae in this research might have been as a result of a bias from the choice of fishing gear (seine net) which tends to under-sample the fast swimmers (Portt et al., 2006), but could have as well have been due to the fact that the Mugilidae family is euryhaline and able to withstand the strong seasonal changes in salinity when compared to other fish families (Albaret, 1994).

Considering the steep salinity gradient in TWNP from rainy to dry season, the observed decline in fish species abundance and biomass may be an indication of fish species' natural response of migrating to fresher waters when salinity stress becomes intolerable (Baran, 2000). This may be the reason why the dense mangrove zone, which is relatively free of human activities, had 6 species less in the dry season than it had during the rainy season. Likewise, the use of growth suppression as a coping mechanism to hyper-salinity by the cichlid *Sarotherodon melanotheron* (Panfili et al., 2004) is why the tourism zone (Mandinary) showed a significant decline in fish biomass during the dry season, even though it had 5 more fish species than it did during the rainy season; bearing in mind that the Cichlidae family became the second-most abundant family during the peak dry season.

Fish assemblage in TWNP is clearly dominated by the estuarine species of marine origin (Em), with a species abundance of up to 47% while the smallest bio-ecological category was the species of continental origin (Ce) representing only 5%. It is safe to say

Table 5
Percentage abundance and trophic categories of fish species at the various land use types in TWNP. Ec: estuarine species from continental origin; Es: strictly estuarine species; Em: estuarine species from marine origin; ME: marine-estuarine species and Ma: marine species accessory in estuaries.

Families	Bio-ecological categories	Species	Abuko	Kamalo	Mandinary	Wencho	Dense mangrove	Bund road
Ariidae	ME	*Carlarius heudelotii*[C]	–	–	1.0	–	1.9	–
Belonidae	Em	*Strongylura senegalensis*[C]	0.1	1.5	–	0.1	0.6	–
Batrachoididae	Ma	*Batrachoides liberiensis*[C]	–	0.2	–	–	–	0.1
Carangidae	ME	*Chloroscombrus chrysurus*[O*]	–	–	–	0.1	–	–
Cichlidae	Ec	*Hemichromis fasciatus*[C]	1.8	8.7	0.6	3.0	–	0.7
	Es	*Sarotherodon melanotheron*[O]	8.5	19.2	11.6	4.1	1.2	41.8
	Es	*Tilapia guineensis*[O]	0.7	0.5	1.7	18.9	–	–
	Es	*Tylochromis jentinki*[O]	–	–	0.1	0.3	0.1	–
Clupeidae	Em	*Ethmalosa fimbriata*[O]	21.9	4.3	2.2	–	11.5	5.1
	Em	*Ilisha africana*[O]	21.8	–	20.5	–	57.8	–
	Ec	*Pellonula leonensis*[C*]	–	–	–	–	–	0.3
Cynoglossidae	Em	*Citharichthys stampflii*[C]	–	0.2	1.0	0.3	0.6	0.8
	Em	*Cynoglossus senegalensis*[C]	0.2	–	0.1	0.1	–	0.3
Dasyatidae	Em	*Dasyatis margarita*[C]	0.1	–	–	0.1	1.9	–
Drepanidae	ME	*Drepane africana*[O]	0.1	–	0.1	–	–	–
Eleotridae	Es	*Bostrychus africanus*[C]	–	–	–	–	0.1	–
Elopidae	Em	*Elops senegaliensis*[C]	–	–	0.1	–	0.1	1.2
Gerreidae	ME	*Eucinostomus melanopterus*[O]	4.5	16.6	0.3	14.0	0.3	2.3
	Es	*Gerres nigri*[C*]	–	–	–	–	0.1	–
Gobiidae	Es	*Porogobius schlegelii*[O]	–	–	0.1	–	0.1	0.1
Haemulidae	ME	*Brachydeuterus auritus*[O]	–	1.1	–	–	–	–
	Em	*Plectorhincus macrolepis*[C]	0.4	–	0.3	–	–	–
	Em	*Pomadasys aheneus*[NA]	–	–	–	0.1	–	–
	Em	*Pomadasys jubilini*[C*]	0.6	11.0	0.1	–	–	–
	Em	*Pomadasys perotaei*[C*]	0.4	2.4	–	0.5	2.8	2.9
Lutjanidae	Em	*Lutjanus goreensis*[C]	–	4.1	–	–	–	–
Monodactylidae	Es	*Monodactylus sebae*[C]	0.7	2.0	3.6	0.1	5.7	0.3
Moronidae	Em	*Disentrarchus punctatus*[C]	–	0.3	–	0.1	–	0.1
Mugilidae	Em	*Liza aurata*[O]	14.0	10.8	46.2	15.5	0.3	–
	Em	*Liza dumerili*[H]	–	–	2.6	–	–	–
	Em	*Liza falcipinnis*[O]	16.6	0.3	0.9	14.4	–	20.0
	Em	*Liza grandisquamis*[O]	0.9	–	–	10.2	9.5	10.1
	ME	*Mugil bananensis*[H]	5.1	9.9	2.0	16.9	2.8	13.7
	ME	*Mugil cephalus*[O]	–	6.9	0.4	–	–	–
Polynemidae	Ma	*Galeoides decadactylus*[C*]	0.3	–	0.1	–	0.1	–
	ME	*Polydactylus quadrifilis*[C]	–	–	1.7	–	–	0.1
Sciaenidae	Em	*Pseudolithus elongatus*[C]	–	–	0.3	–	–	–
	Ma	*Pseudolithus senegalensis*[C]	0.8	–	0.7	1.2	–	–
Serranidae	ME	*Epinephelus aeneus*[C]	–	–	–	–	0.1	–
Sparidae	Em	*Dentex maroccanus*[C]	–	–	0.9	–	–	–
Sphyraenidae	ME	*Sphyraena afra*[C]	0.2	–	0.4	–	1.0	–
Tetraodontidae	ME	*Ephippion guttifer*[C]	0.4	–	–	–	1.0	–
Torpedinidae	Em	*Torpedo torpedo*[C]	–	–	–	–	0.2	–
Total			**100**	**100**	**100**	**100**	**100**	**100**

H: Herbivorous, C: Carnivorous, O: Omnivorous, *: Also feeds on detritus, NA: Not available. Categorization based on that of Diouf (1996).

that seasonal changes in environmental variables are the main drivers for the decline in species diversity in TWNP; in this case salinity emerged the strongest driver instead of the commonly held notion of human activities. Of course human activities such as the use of pesticides in the agricultural zone and dumping of household waste at the settlement zone serve as strong stressors that exacerbate the effects of seasonal variability on aquatic ecosystems, just as stipulated by Rudnick et al. (2005) in the Florida bay. However, nutrient and chl-a levels were not high enough to be suggestive of eutrophication. In addition, flow rate of the river Gambia is said to be as high as 1500 $m^3\ s^{-1}$ during the rainy season and as low as 4.5 $m^3\ s^{-1}$ during the peak dry season (Simier et al., 2006). This explains the high variation in salinity during the two seasons and the corresponding decline in fish species abundance and biomass at all the land use types, some less than others. Thus the current fish assemblage in TWNP is about 38.6% less species-rich than what was reported for the River Gambia estuary about a decade ago, due to hyper-salinity stress and climate-induced local extinctions.

5. Conclusion

With the enactment and enforcement of various environmental regulations and the new fisheries act within the past decade, exploitative fishing methods have gone down. Coastal communities have also become increasingly aware of the impacts of their activities in the TWNP. However, fisheries continue to decline leading to the assumption that there is a bigger culprit to the deteriorating environmental state and the accompanying decline in fisheries of the TWNP.

The findings in this research indicate that direct human impacts have little to do with the major environmental variables (e.g. salinity and water temperature) affecting fish assemblage in TWNP. Nonetheless, proactive efforts such as mangrove replanting could go a long way in cushioning the effects of these naturally occurring changes, for example the high water temperatures at the less vegetated zones (Abuko and Bakau).

The species abundance reported in this study is lower than that was reported for the estuary of the River Gambia. Being a nursery ground closest to the Atlantic coast of The Gambia, it is noteworthy that the current fish assemblage of this area is less than in past predictions for the River Gambia estuary both in abundance and biomass (see Albaret et al., 2004; Vidy et al., 2004; Simier et al., 2006; White et al., 2012). The implications of these changes on the daily catches/CPUE of the local fisherman are important, since they are used to fishing for estuarine species.

Considering that TWNP is an important socioeconomic hub for the active urban population involved in agriculture, tourism and fishing (sectors which contribute 19%, 12% and 8% of GDP respectively) (National Environment Agency, 2010; CIA World Fact Book, 2014), it is important to raise awareness about the ecological changes occurring in the area for proper adaptation to seasonal variability and climate change on a broader scale. Management measures such as controlling fishing effort will possibly, only lead to a reduction in fishers' incomes without really solving the problem of fisheries decline.

Further research is needed on the effects of the changes in fish assemblage in TWNP on fishers' incomes, as well as the levels of preparedness/adaptation of the three socioeconomic groups that are actively employed in TWNP. For a complete representation of changes at an ecosystem level, more research is needed to investigate the long-term changes in environmental variables, how they affect mangrove vegetation in the wetland and what the combined impacts are for the fisheries sector.

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Chapter 16
Adapting to the Inevitable: The Case of Tanbi Wetland National Park, The Gambia

Adam Ceesay, Mathias Wolff, Ebrima Njie, Matty Kah, and Tidiani Koné

Abstract The role of human activities in degradation of estuarine resources has been well documented. Besides the effects of climate change, activities such as clearing of mangroves for tourism, use of inappropriate fishing gear and excessive use of pesticides for agricultural productivity are the most powerful ecological stressors. In the Sahelian climate zone, hydrological regimes are changing due to reduced river flow and increase in atmospheric temperatures leading to the formation of inverse estuaries. The evaluation and documentation of local adaptation practices is one way to prevent "conservation bottlenecks" and encourage sustainable use of estuarine resources. This study used a questionnaire-based approach to evaluate local adaptation strategies to climate-induced ecological changes in the Tanbi Wetland National Park (TWNP) over the past three decades, targeting the communities that are engaged in the four major socio-economic sectors in the wetland i.e. Fishing, Agriculture, Oyster collection and Tourism. The agricultural zone presented the best local adaptation techniques employed as a response to ecosystem changes in the TWNP (23.53 %), followed by tourism zones (7.35 %) and fishing (5.88 %). With the disappearance of many fish species within the same timeframe, this leaves much to be desired. Bearing in mind that fisheries and tourism are the second and third largest contributors to the Gambia's GDP, this paper provides useful recommendations for management of this important wetland.

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Introduction

The effects of climate change on human systems have been reported by many, although the responses to recent changes are hard to identify due to adaptation and the presence of many non-climatic driving forces (IPCC 2007). In its fourth assessment report, the IPCC highlighted that Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. The report goes further to predict a decline of up to 50 % in yields from rain-fed agriculture by 2020 due to a reduction in arable land and changes in length of growing season in the arid and semi-arid areas. Fisheries resources, it states, will also decline due to rising water temperatures, exacerbated by continued overfishing; meanwhile, up to 30 % of global coastal wetlands are already lost due to continued mangrove ecosystems degradation and sea level rise (Church and White 2006).

Adaptation strategies to the aforementioned climate-induced ecosystem changes are gaining momentum as confidence in climate projections is getting higher. As the achievement of the Millennium Development Goals (MDGs) and successful implementation of the Poverty Reduction Strategy Papers (PRSPs) in developing countries are being achieved, adaptation strategies are now viewed as important goals (Mertz et al. 2009). In the earlier years, and to the contrary, the focus was mostly on climate mitigation (IPCC 2007). Mertz et al. (2009) pointed out that most climate data studies are done in developed countries and as such more information is needed in developing countries with tropical and subtropical climates for more knowledge in vulnerability and adaptive responses.

Over the years, research into the drivers of climate change, the magnitude of its impacts on livelihoods and the adaptations strategies have also increased, especially for the tropics where the physical impacts are predicted to be more severe. Africa for instance is expected to be warmer than the global mean, with a general decline in annual rainfall (Mertz et al. 2009). This will have great consequences for countries in arid and semi-arid zones that depend on the exploitation of natural resources from fragile ecosystems such as mangrove estuaries/wetlands, for sustenance of their socio-economic sectors. Due to the decline in agricultural productivity in countries such as The Gambia, dependency on estuarine resources has risen tremendously over the past couple of decades and now the biggest contributors to The Gambia's GDP are Agriculture, Fisheries and Tourism i.e. 27 %, 12 % and 8 % respectively (Government of The Gambia 2010).

The ecosystem services provided by mangroves are valued at US$ 900,000 per year (Corcoran et al. 2007), one can safely assume that mangrove estuaries, while serving as favorable nursery grounds for diadromous fish species (Baran 2000) and as a hub for socio-economic activities in the tropics and sub-tropics, are thus at an ecologically precarious state; especially in arid zones where they grow slowly because of climate-induced hypersaline conditions, low humidity, high temperatures, and extreme light conditions (Alongi 2008). Hence, the superimposition of climate-induced changes such as prolonged tidal inundation on other impacts resulting from human activities such as over fishing, pollution and habitat loss put these coastal areas under great stress (Chen 2008).

Mangroves occupy sensitive intertidal zones that are more prone to the immediate effects of climate change. Drastic changes in hydrology for instance was reported to induce stunting of *Avicennia marina* stands and denaturing of terminal buds in *Rhizophora mangle* seedlings in the USA (Kathiresan 2002). Austin et al. (2010) also suggested that modest changes in rainfall and temperature caused significant reductions in mean annual run off and increased stream salt concentrations in Murray-Darlin Basin (Australia), resulting in loss of mangrove vegetation. The frequent fluctuations between climate events such as extreme floods and prolonged droughts have also been reported to cause massive mangrove diebacks in Sub-Saharan countries such as Senegal and The Gambia (Dia 2012).

With an 80 km long coastline and a continental shelf area of about 4000 km^2 (IUCN 2010), The Gambia boasts of 68,000 ha mangrove estuary that accounts for 2 % of the total coverage for Africa (Spalding et al. 1997). This important part of the Western Africa Marine Eco-Region (WAMER) shelters about 600 species of fish, 26 species of cetaceans, 6 species of Turtles and more than 200 species of birds (Lee et al. 2009). But like many ecosystems in Sahelian countries, climate change has taken a serious toll on the stability of coastal and estuarine services due to erratic rainfall, increase in atmospheric temperatures and persistent droughts for the past three decades following the great Sahel drought in the 1970s (Dai et al. 2004). Annual rainfall in The Gambia has decreased by 30 % between the year 1950 and 2000 alone (Fig. 16.1), now remaining at a range of 850–1200 mm, the bulk of

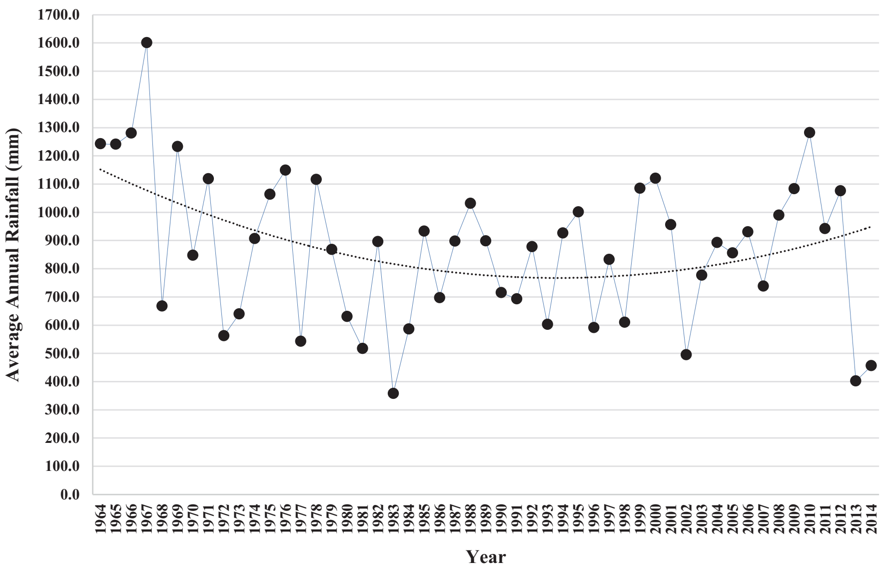

Fig. 16.1 Long-term rainfall pattern for Banjul, 1964–2014 (*Source*: The Gambia Meteorological Unit, 2015)

which occurs in August causing heavy floods in one-third of the country (Lee et al. 2009).

The progressive increase in atmospheric temperatures over the past five decades are not helping matters either. Long-term atmospheric temperatures for Banjul are shown in Fig. 16.2 below.

The Gambia's economy is heavily dependent on rain-fed agriculture, and as such the sector suffered the most decline (30 %) since the early 1970s (Government of The Gambia 2007). Like most countries in the Sahel, The Gambia responded by adapting and ratifying most (if not all) international climate-related accords including the UNFCC, Kyoto Protocol, Rio + 10 etc. (Lauer and Eguavoen 2016). In order to implement these accords at national level, The Gambia recently initiated programs such as the Program for Accelerated Growth and Employment (PAGE), the Gambia-Senegal Sustainable Fisheries Project, the Adaptation to Climate induced Coastal Changes Project etc., with the help of international bodies such as the UNDP, USAID and GEF (Lauer and Eguavoen 2016). In addition, positive changes were also effected in policies guiding the judicious use of natural resources. These include the formulation and enforcement of the Anti-littering Regulations to prevent indiscriminate waste dumping, and the Fisheries Regulations for safe-guarding the ecological integrity of fragile ecosystems such as the coast, which is already heavily influenced by the effects of Climate change (Government of The Gambia 2010).

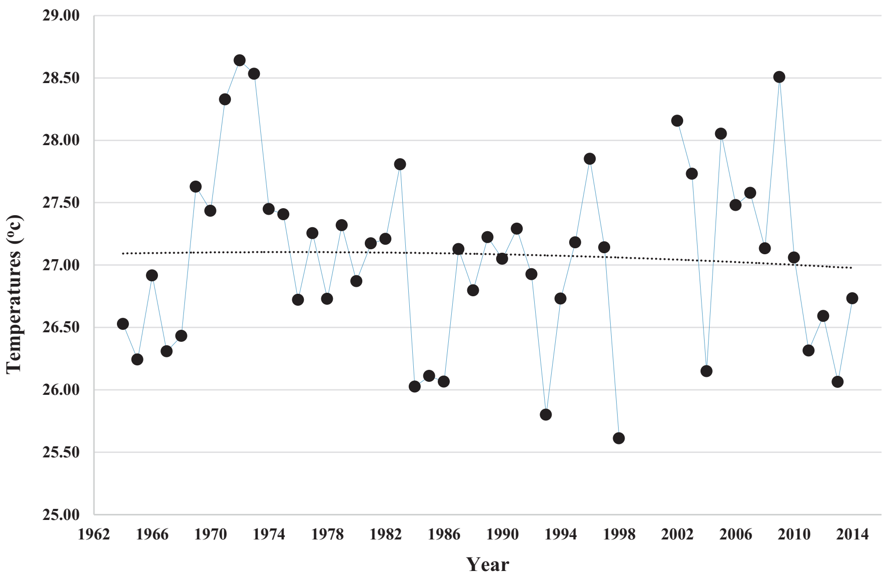

Fig. 16.2 Long-term atmospheric temperatures for Banjul, 1964–2014 (*Source*: The Gambia Meteorological Unit, 2015)

Making sure that the benefits of the aforementioned accords are felt by the local communities, farmer incentives such as provision of the drought resistant rice (NERICA) was introduced, to improve livelihoods of the poor communities involved in subsistence agriculture, as well as to create continued awareness of the farmers through agricultural extension workers and state-organized workshops (personal communication, Gambia Department of Agriculture). Successful implementation of projects such as the Gambia-Senegal Sustainable Fisheries project also gave birth to a bottom-top management approach to the fragile coastal resources such as the Tanbi Wetland National Park (TWNP), leading to the formulation of a co-management plan, which gave management rights to user groups such as the women oyster collectors. This, of course, is all based on the fact that there is an existent multi-sectoral team (comprised of all the relevant government institutions, CBOs and NGOs involved in conservation of natural resources, environmental sustainability and community development) (USAID-BANAFAA Project 2012).

Notwithstanding all the above, the socio-economic standing of vulnerable coastal communities in The Gambia leaves much to be desired. Socio-economic groups such as the fisher folks and tourism workers are not benefitting much from the institutional frameworks set up to reduce vulnerability of coastal communities within The Gambia. While abiding by all the rules set in conservation accords, these groups have little or no knowledge of the appropriate response strategies to apply/adopt at an individual level when faced with drastic ecosystem changes in their work environment. This leaves an information gap for the coastal communities, which needs to be urgently addressed for successful implementation of The Gambia's Climate Change adaptation strategies.

This paper aims to assess the socio-economic implications of climate-induced ecosystem changes in the mangrove estuaries of the River Gambia, where such information is almost non-existent. Using a questionnaire-based approach, this paper focused on evaluating relative vulnerability and adaptive capacity of the major socio-economic groups, an area that has not been well investigated in Sub-Saharan Africa. Filling this information gap will contribute toward successful implementation of National Adaptation Plans for mangrove-dependent countries such as The Gambia. Therefore, the main aim of this research was to gather and document local knowledge on climate-induced ecosystem changes, local adaptation practices adopted by the various socio-economic groups involved in Agriculture, Fisheries, Tourism, and Oyster collection, as well as the perceived changes in their economic gains in the TWNP.

Materials and Methods

Study Site: Tanbi Wetland National Park (TWNP)

The Tanbi Wetland National Park (TWNP) (Fig. 16.3) is a lowland area with a mean altitude of 1–1.6 m extending between 13°23–13°26 N and 16°34–16°38 W (The Ramsar Convention on Wetlands 2012). Located at the mouth of the River Gambia estuary, TWNP covers an area of about 6300 ha (Lee et al. 2009) and connects the three main urban settlements within the Greater Banjul Area (GBA). These are Banjul City (BC), Kanifing Municipality (KM) and Brikama (BA) (Government of The Gambia 2010). Due to its ecological richness, this wetland was designated a Ramsar wetland of importance in 2007 (Project 2012).

The TWNP falls within the Sahelo-Sudanian climate zone (Simier et al. 2006), having a long dry season (October–June) and a short rainy season (June–October) (Camara 2012). Mangrove vegetation in TWNP is comprised of *Rhizophora mangle* (red mangrove), *Avicennia germinans* (also known as *Avicennia africana*/black mangrove), *Laguncularia racemosa* (white mangrove) and *Rhizophora harisonni* (Maniatis 2005).

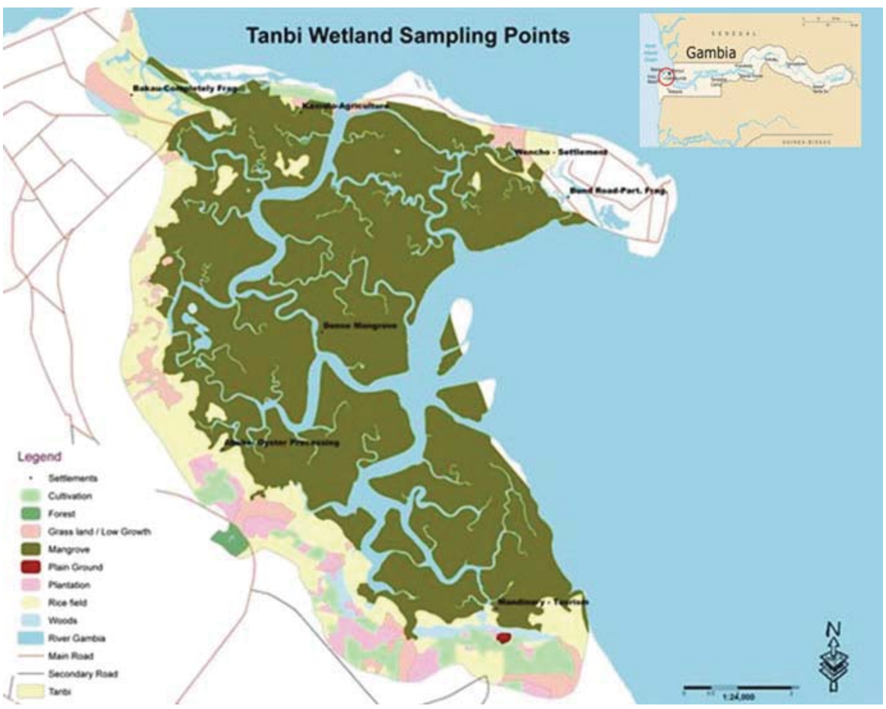

Fig. 16.3 Location of and socio-economic focus areas in Tanbi Wetland National Park on the Map of The Gambia

This mangrove habitat serves as an important nursery ground for fish species such as shad (*Ethmalosa fimbriata)* and sardine *(Sardinella maderensis)* (Baran 2000), African tilapias (*Sarotherodon* and *Oreochromis* species) (Albaret et al. 2004), as well as the pink shrimp (*Paneaus notialis)* and oysters (*Crassostrea gasar)* (Darboe 2002).

Economic activities in this area are dominated by Fisheries (including shell fishery) and Tourism (Satyanarayana et al. 2012). Agricultural activities (e.g. rice cultivation and gardening) are also common (USAID-BANAFAA Project 2012).

Methodology

Questionnaires

Questionnaires for this study were formulated to feature sustainability issues such as long-term (herein, three decades) ecosystem changes in TWNP. In addition, climate change matters were also included and their relationship with socio-economic setup based on the four categories below:

1. Ecosystem changes in TWNP (physical changes in terms of water quality, soil, vegetation and fisheries).
2. Climate change (as understood by the socio-economic groups in TWNP).
3. Economic status (as recorded in increase/decrease in daily earnings of the socio-economic groups in TWNP.
4. General observations (focusing on general understanding of the subject matter by the local people that are gainfully employed in TWNP).

Subject Groups (Interviewees) and Interviews

A group of 138 people belonging to four occupational groups were interviewed. These include: Farming, Fisheries, Tourism and Oyster collection. A subgroup of people residing within the wetland (in Wencho, locally known as Ndangane) were also interviewed. As this study was aimed at the local people's understanding of long-term changes in the ecosystem, the age group target was set at 18 years and above. For proportionate representation of the socio-economic groups, 15 tourist workers, 19 residents, 20 oyster collectors, 40 farmers and 44 fisher folks were interviewed.

Interviewers' group was comprised of five people (two from the National Environment Agency, one from the Water Resources Department, one from the University of The Gambia and the actual researcher). This team was put together based on their background in environmental monitoring, conservation and community development work. In addition, each of the team members is fluent in at least two local languages for translation purposes. All together the team is fluent in the four major local languages in The Gambia (Mandinka, Fulla, Wollof and Jola). To prevent any biases in the way questions were administered, the team prepared by "practice-asking" each other all the questions in the questionnaire and adopting a uniform introduction of the purpose and scope of the research in the four major local languages to ensure a uniform understanding of the questions.

Interviews were conducted under an informal roundtable chat with each socio-economic group at their place of work in TWNP. Where possible questionnaires were translated into the respondents' native language for better understanding. Interviews for each respondent lasted about 30 min. Questionnaire details are in appendix I.

Data Analysis

For statistical analysis, responses from the interviews were pooled in a similarity matrix and subjected to Principal Component Analyses (PCA) using Statistical analysis software R version 2.15.2 (2012). Descriptive statistical analyses were done using STATA 12 for windows. The methodology of this research was adapted from Satyanarayana et al. (2012).

Results

Based on the responses garnered during this study, 132 (95.65 %) out of the 138 respondents believe that the ecosystem of TWNP has changed over the past three decades, while the other 6 (4.35 %) disagreed/were undecided (Fig. 16.4).

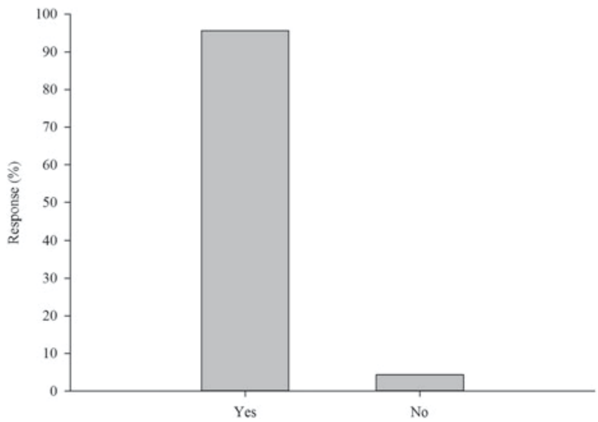

Fig. 16.4 Responses to the occurrence of ecosystem changes in TWNP

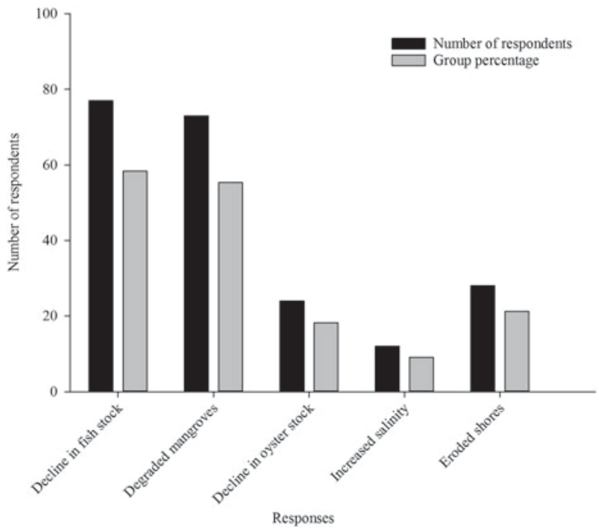

Fig. 16.5 Local perspective on specific ecosystem changes in TWNP

When asked about the specific changes within the TWNP, 58.33 % of the respondents mentioned a decline in fish stocks along with the disappearance of key species such as the giant African threadfin, which commands an attractive price compared to other native fish species. 55.30 % mentioned mangrove degradation, and 21.21 % of them mentioned soil erosion, while 18.18 % mentioned a decline in oyster stock (Fig. 16.5).

The local people's understanding of climate change is high despite the low literacy rates in The Gambia. 103 out of the 138 people (74.64 %) interviewed said they have heard of climate change before while 35 (25.36 %) said they have never heard of the concept before. When asked about the manifestations of climate change, 77.67 % of the respondents associated it with changes in rainfall pattern, 45.63 % associated it with changes in atmospheric temperatures, and 11.65 % to droughts (Fig. 16.6a and b).

Only one respondent was encountered (within the fisher folks group) who did not believe in the concept of climate change. Among those who have heard of the concept of climate change, 46.60 % claimed to have heard about it through the media, 26.21 % through workshops, 8.74 % from schools, 6.80 % from agricultural extension workers and 5.83 % from visiting tourists (Fig. 16.7).

Local understanding of climate-induced ecosystem changes such as seasonal variability and hyper-salinity was very high among the socio-economic groups in TWNP. On a scale of 0–10 (0 being poorest and 10 being excellent), the oyster collectors' group presented the highest level of awareness (8.25), followed by the fisher folks (7.52), residents (6.79), tourism group (6.53) and the least score was recorded with the farmers' group (6.23). In terms of awareness on seasonal hyper-salinity, responses followed a similar trend with the oyster collectors scoring 9.10,

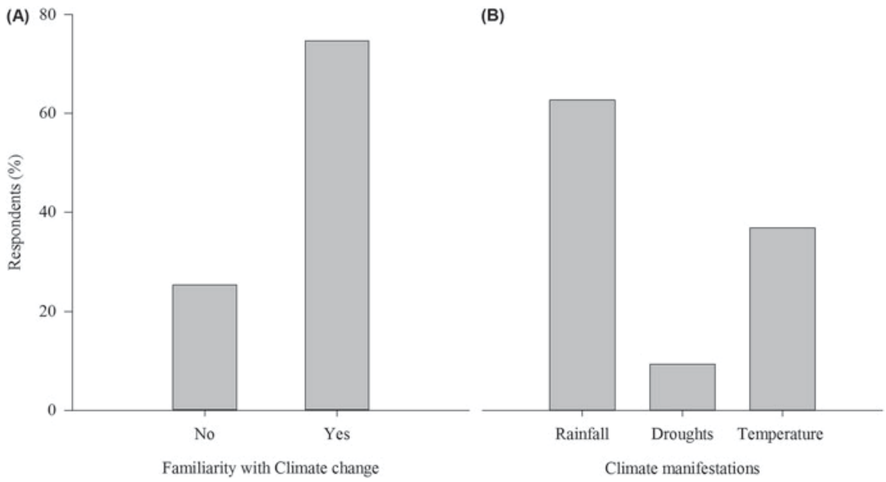

Fig. 16.6 Familiarity of the socio-economic groups with climate change concept (**a**) and local perception on manifestations of climate change (**b**)

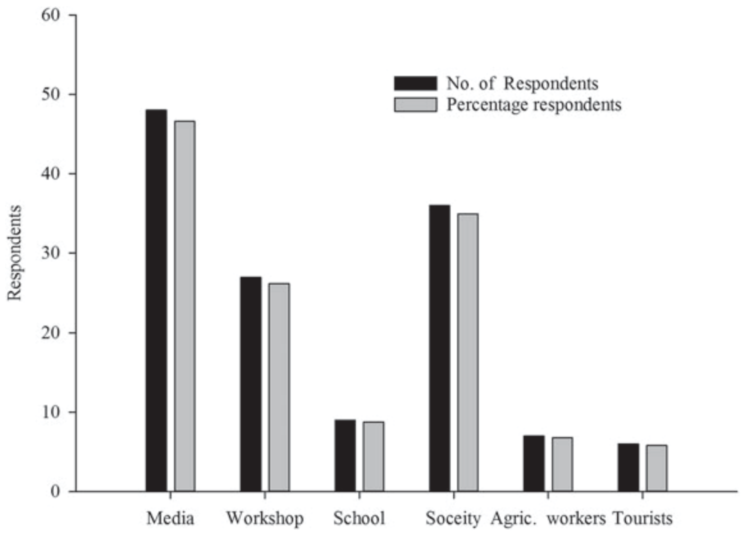

Fig. 16.7 Sources of Climate change information for the socio-economic groups in TWNP

fisher folks 8.18, farmers 7.30, residents 6.63 and the lowest scoring group being the tourism group (5.80) (Fig. 16.8).

In terms of the local adaptation measures/response strategies employed by the socio-economic as coping mechanism to the ecosystem changes in TWNP, a total of 32 different responses were given by the respondents. Most common among these was "nothing", 70 (50.72 %) out of the 138 respondents have no knowledge of

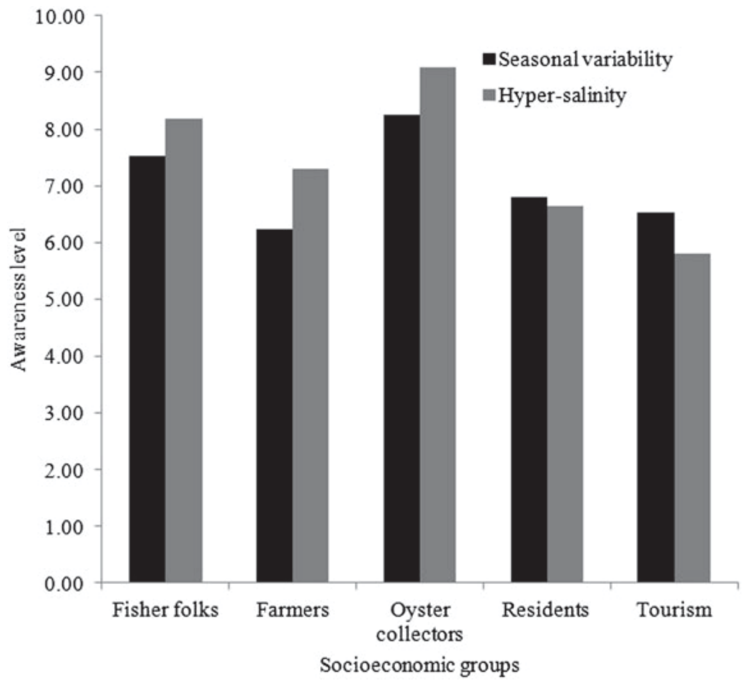

Fig. 16.8 Local understanding of climate-induced ecosystem changes by socio-economic groups in TWNP (score 0–10)

what measures they could take to maximize their daily output and prevent unnecessary economic losses in their place of work. 15 out of the remaining 68 respondents (22.06 %) seasonally shift their attention to exploitation of alternative resources allowing their main species of interest to "fallow" (case in point, oyster collectors who shift to crabbing and lobster fishing during the rainy season, when water quality is very poor in TWNP); 7(10.29 %) practice crop rotation based on observed changes in soil quality due to salt intrusion; while 9(13.24 %) change their usual sowing period in anticipation of late and insufficient rains (i.e. farmers' group). The "less fortunate" groups here 5 (7.35 %) deal with these changes by buying bigger boats (tourism group), while 4 (5.88 %) of all respondents deal with the ecosystem changes by expanding their fishing zones (this is the case of the fisher folks) (Fig. 16.9). Both of these measures in addition to being unsustainable are neither "pocket-friendly" nor "time-friendly", as they require huge financial inputs and longer fishing hours just for meagre catches.

In terms of economic growth, most of the respondents expressed a decline in income. About 65 % of the respondents from the oyster collectors expressed a decline in income over the past three decades, this was followed by the farmers group (61 % of the respondents), the residents (58 % of the respondents) and the

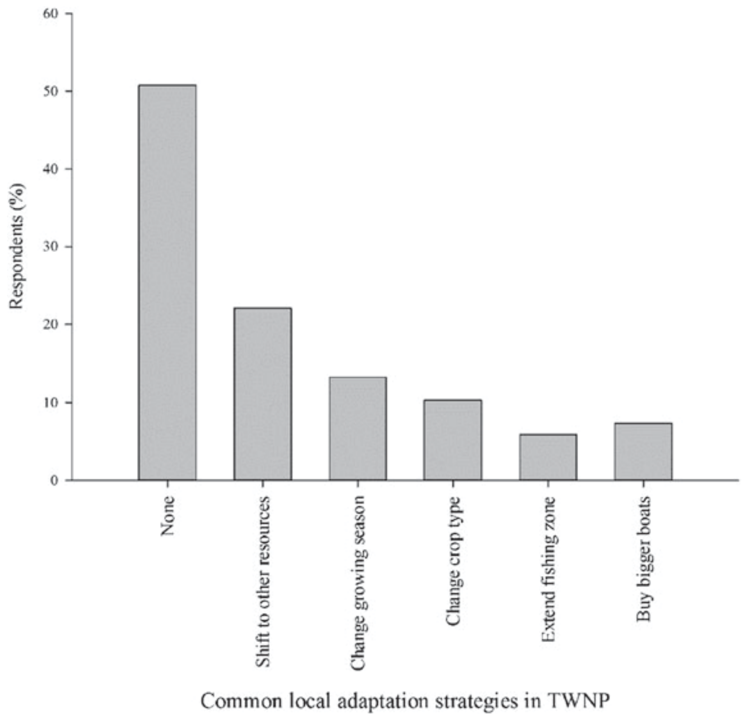

Fig. 16.9 Common local adaptation practices to climate-induced ecosystem changes in TWNP

Fisher folks (42 % of the respondents). About 57 % of the respondents from the tourism group expressed an increase in income (Fig. 16.10).

On average, the socio-economic groups considered here have registered a decline of 46 % in their earnings within the TWNP for the past three decades. The greatest average decline (72.73 %) was recorded among the fisher folks, followed by the oyster collectors (50 %) and the lowest (33.85 %) among the farmers groups' (Fig. 16.11).

Discussion

Mertz et al. (2009) advised for a careful formulation of policies and adaptation strategies to climate change for societies that are poor and vulnerable for a wide range of reasons. Hence, both physical and institutional assets need to be included when formulating adaptation strategies. In TWNP the former has been made available for the groups involved in shellfisheries through provision of canoes, sanitation facilities, oyster smoking pens and alternative livelihoods (setting up an oyster culture program), while the latter is available for groups involved in

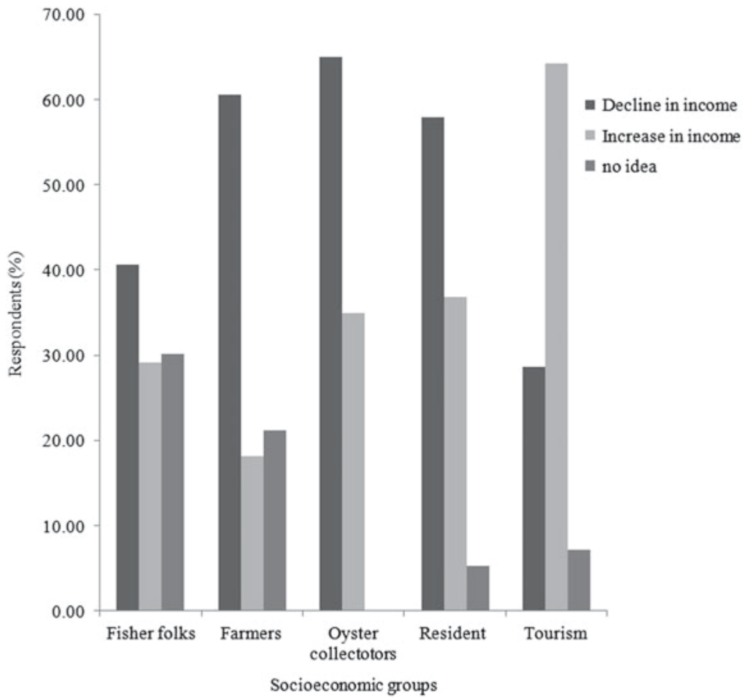

Fig. 16.10 Economic situation of the socio-economic groups in TWNP

agriculture through awareness creation by agricultural extension programs, credit schemes and subsidies for improved seed variety (National Environment Agency 2010).

The latter is also in part available for the fisher folks, through the coastal zone management plan, enforcement of fishing regulations, and guidelines on appropriate net usage within the wetland. While the aforementioned incentives are provided alongside numerous awareness creation campaigns for the socio-economic groups such as the farmers and oyster collectors, awareness levels are is still low for the fisher folks, as evidenced by their poor responses to adaptation mechanisms.

Kelly and Adger (2000) suggested that in cases concerning state-run adaptation programs, it might be necessary to "adapt to the adaptation," as some measures might solve one problem while creating another. As an example, (Barnett and Mahul 2007) suggested that credit schemes and new crops, accompanied by "weather insurance," have been tried experimentally in some developing countries. This approach was applied to a large extent in the agricultural sector, with provision of soft loan credit schemes with flexible payment plans that took account of the possibility of crop failure due to rainfall shortages (Government of The Gambia 2010). A similar approach was also applied for the shell fisheries sector, with the provision of alternative livelihoods through value-adding (packaging) of

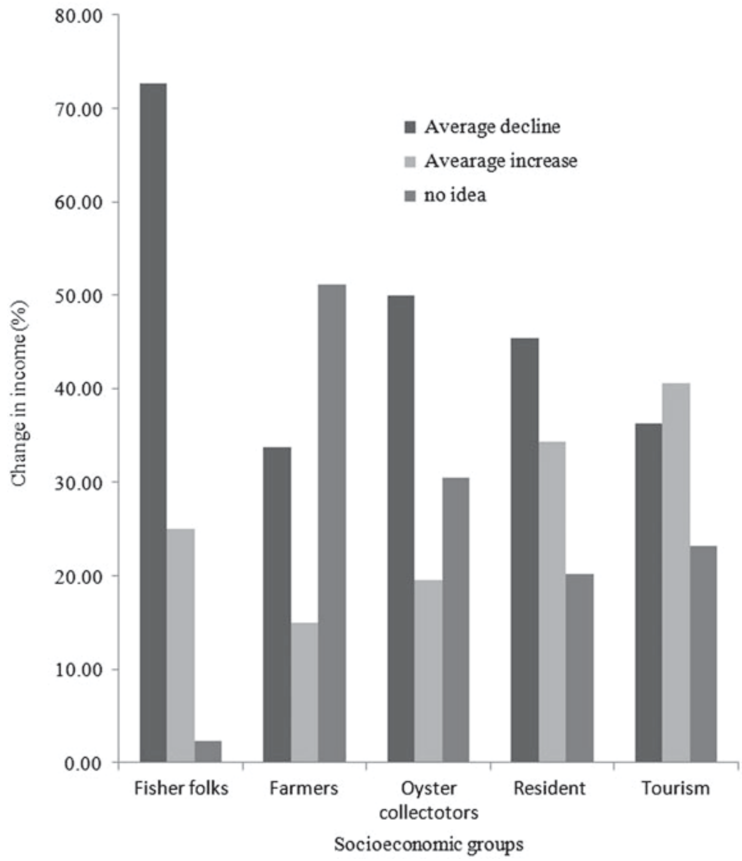

Fig. 16.11 Changes in average income of the socio-economic groups in TWNP

pre-processed oyster meat as well as setting up an oyster culture program (Crow and Carney 2013; USAID-BANAFAA Project 2012).

However, for the fisher folks only institutional assets are available in the form of the enactment of The Gambia's Fisheries Regulations (1995) and Act (2007) (Government of The Gambia 2007), as well as stricter netting regulations for sustainable fisheries in The Gambia allowing for no less than 20 mm mesh sized nets within the estuary of the River Gambia (personal communication, The Gambia Department of Fisheries). This has no doubt helped reduce overfishing, especially within the nursery grounds of the TWNP, but it still did not solve the problem of declining fish catches or the low economic returns as the physical assets needed by the fisher folks are not in place. This move might have also promoted complete colonization of estuary by hardy, but smaller sized fish species such as the native African tilapias (*Sarotherodon melanotheron*), which is known to respond to environmental stress by reducing its growth rate (Panfili et al. 2004).

In the words of Munang et al. (2010) it is necessary for policy makers to recognize the fundamental role of ecosystems as life-supporting systems first for successful implementation of adaptation strategies. In absence of a go-to activity for the fisher folks during times of low catches (as shown in this study), restricting fishing activity only lowers their earning potential without necessarily solving the problem of ecosystem change. This also does little or nothing to alleviate the declining fish catches, because fish species migrate in response to natural deterioration in their environment (Panfili et al. 2004).

Portner and Peck (2010) suggested that the implications of climate change for marine fish species are at four levels: organismal, individual, population and ecosystem level; individual level being the most relevant one when referring to the state of fisheries in TWNP. Over 23 % of the strict estuarine fish species for instance have been reported to seasonally migrate inland as a response to hypersalinity during the peak dry season and then to the creeks during the flood season (Ceesay et al. 2016—article in press). This is now believed to be the reason behind the drastic reduction in daily catches/earnings of the fisher folks interviewed during this research.

Similar findings were reported by Panfili et al. (2004) in a study of the impacts of salinity on the life traits of the native African tilapia (*Sarotheron melanotheron*) in the estuaries of Senegal and The Gambia, where he reported interruptions in fish migration patterns, reproduction timing and spawning success as well as stunting, leading to smaller market sized fish and thus earning lower prices. Such phenomenon was also reported to be the cause for the complete colonization of the inverse estuary of Sine-Saloum delta in Senegal by marine fish species; thus replacing the native estuarine species and causing a decline in fisheries output for over a decade (Dia 2012).

The aforementioned condition is worsened by the synergistic effects of human activities such as overfishing on climate-induced ecosystem changes, as evident in the responses from the fisher folks. In addition, the commonness of the phrase “in God’s hands” among the fisher folks as a response to how they locally adapt to climate-induced ecosystem changes indicates their low levels of awareness. Thus leading to the deduction that the fisher folks are the most vulnerable socioeconomic group when it comes to climate change adaptation in TWNP. This group has been relatively overlooked and uninvolved when it comes awareness creation campaigns by conservationists as well as in the provision of alternative livelihoods by state institutions.

The case is different for the farmers’ group which apart from having its members frequently trained on alternative farming methods and provided with improved seed variety in order to adapt to climate-induced ecosystem changes in TWNP; also has the luxury of having an agricultural extension worker on site to guide them in responding to common farming problems. In comparison, the oyster collectors’ group having been provided with suitable alternative livelihood programs such as the state-led oyster culture program. In addition, they were recently given management rights to the TWNP. Meanwhile, the tourism group finds it much easier to cope with the ecosystem changes, for instance by expanding sightseeing zones and proportionally increasing safari prices, which may not be a realistic approach for the other groups as one is catering to a local market, while the other targets an international market.

Of course, it is noteworthy that this current study also has its own set of limitations. For instance, difficulties in locally translating basic climate concepts to the mostly uneducated respondents might have downplayed their ability to accurately respond to questions about climate-ecosystem changes. The general mistrust between local resource users/end users and state-employed conservationists also played a dampening role in people's willingness to answer the questionnaires. Nonetheless, sufficient information was garnered to portray overall understanding and response mechanisms employed by the locals in order to deal with climate-induced ecosystem changes in the mangrove estuary under study (TWNP), as well as the socio-economic implications of these changes.

Conclusions

Interpretations of the responses gathered from the socio-economic groups during this research work in TWNP indicate the following:

- Even though slow, there has been a progressive increase in general awareness about climate change and how it affects socio-economic activities within the fragile mangrove ecosystems in The Gambia.
- Environmental awareness campaigns have been more successful with the groups involved in oyster collection and farming (who are mostly female), and least so with the groups involved in fishing and tourism (all male); as evident in their responses to observed changes and coping mechanisms. This calls for the need to make gender issues a principal component when designing awareness creation programs.
- Based on findings of this research, the reported decline in fisheries of the TWNP is mostly climate-induced. The reduction of fishing pressure and strict enforcement of Fisheries policies, legislations and net size regulations for sustainable fisheries has been going on for the past couple of decades. Yet, the positive effect of these measures are at best negligible; thus calling for the need to review the guiding fisheries policies, as well as provision of alternative livelihoods for the fisher folks.
- There is also a growing need for more research into the response mechanisms of aquatic species to environmental change and how this affects the lives of the common fisher folks. This will avail The Gambia a possibility of identifying the best modes of intervention needed in terms of sustainable alternative livelihoods for those gainfully employed within TWNP.

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ABSTRACT

Climate-induced ecosystem changes were studied in Tanbi Wetland National Park (TWNP) in conjunction with the major land use types i.e. agriculture, settlement, tourism, oyster processing, completely fragmented and partially fragmented zones. To study hydrological changes in TWNP in The Gambia, in-situ analyses of physico-chemical parameters and nutrient build-up were conducted during the peak discharge period of the River Gambia in 2013 and repeated during the peak dry season in 2014. Mangrove vegetation dynamics was assessed by remote sensing, using Landsat images of decadal time series covering 1973 – 2012. To assess seasonal changes in the fish assemblage in relation to the hydrological changes, fish were sampled at all the land use types using a seine net during the rainy and dry seasons. A questionnaire-based assessment of local knowledge on climate-induced ecosystem changes was also conducted. Average salinity in TWNP was 24.5 and 35.8 ppt for the rainy and dry seasons respectively. Mangrove vegetation cover declined by 6% while grassland increased by 56.4% from 1973-2012. 43 fish species from 25 families were recorded from 2013-2014. Fish species richness declined by 16% and abundance by 35% as the seasons changed from rainy to dry. Fish bio-ecological categories were dominated by estuarine species of marine origin (Em) (47%) throughout the year, 2014. Multidimensional Scaling (MDS) of the environmental variables indicated salinity as the main water variable influencing fish species richness in TWNP. Local awareness about the climate change concept was high (70%). However, local adaptation practices to climate-induced ecosystem changes were low (50%). Based on the low percentage loss in vegetation cover, this research concludes that except at the completely fragmented zone, the impacts of human activities on mangrove vegetation in TWNP are negligible. It also demonstrates that the decline in the fish assemblage is due to local extinctions caused by seasonal hyper-salinity.

Key words: TWNP, River Gambia estuary, climate change, adaptation, land use.

RESUME

Les modifications écosystémiques d'origine climatique ont été étudiées dans des zones partiellement et complètement fragmentées dans Parc National de Tanbi (PNT) (Gambie) en corrélation avec les principaux types d'utilisation des terres (agriculture, occupation, tourisme, traitements des huîtres. Pour étudier les changements hydrologiques dans le PNT, l'analyse des paramètres physico-chimiques et de l'accumulation des nutriments ont été faites pendant la crue du fleuve Gambie en 2013 et durant la saison sèche en 2014. L'étude diachronique des mangroves a été faite avec des images Landsat de 1973-2012 par intervalle de 10 ans. Les variations saisonnières de la diversité de l'ichtyofaune ont été évaluées en fonction des variations hydrologiques. Pour ce faire, les poissons ont été capturés dans toutes les catégories d'utilisation des terres à l'aide d'une senne pendant les deux saisons. De plus, une enquête des connaissances locales sur la variation des écosystèmes causée par le climat a été abordée. La salinité moyenne dans le PNT était de 24,5 et 35,8 ppt respectivement pour la saison pluvieuse et sèche. La couverture des mangroves a diminué de 6% alors que celle de la savane herbeuse a augmenté de 56,4% entre la période 1973-2012. 43 espèces de poisson appartenant à 25 familles ont été recensées pour l'année 2014. Leur diversité et abondance ont diminué de 16% et 35% respectivement lors de la saison pluvieuse et de la saison sèche. Durant l'année, les catégories bioécologiques des poissons ont été dominées à 47% par les espèces estuariennes d'origine marine. Le positionnement multidimensionnel des variables environnementales a indiqué que la salinité est la principale variable environnementale influençant la richesse spécifique de poissons dans le PNT. La connaissance locale sur le concept de changement climatique était élevée (70%). Cependant, les techniques d'adaptation était faible (50%). Sur la base du faible pourcentage de perte de couverture végétale, la présente recherche indique, qu'excepté la zone où la végétation de mangrove est fortement fragmentée, il y a un faible impact humain sur le PNT. Elle confirme aussi que le déclin de la richesse spécifique des poissons est dû à l'hyper-salinité saisonnière.

Mots clé : PNT, Estuaire Fleuve Gambie, Changement Climatique, Adaptation, Utilisation des terres.