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ECOLOGICAL ASSESSMENT OF SOME COASTAL LAGOONS AND ESTUARIES IN GHANA: ABIOTIC AND BIOTIC APPROACHES

MARGARET FAFA AWUSHIE DZAKPASU

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ECOLOGICAL ASSESSMENT OF SOME COASTAL LAGOONS AND ESTUARIES IN GHANA: ABIOTIC AND BIOTIC APPROACHES

BY

MARGARET FAFA AWUSHIE DZAKPASU

VERITAS NOBIS LUMEN

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

DECEMBER 2019

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DECLARATION

Candidate's Declaration

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

Candidate's Signature………………………………. Date……………………

Name: MARGARET FAFA AWUSHIE DZAKPASU

Supervisor's Declaration

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

Principal Supervisor's Signature……………………… Date…………………

Name: PROF. KOBINA YANKSON

Co-Supervisor's Signature…………………………… Date…………………

Name: DR. EMMANUEL LAMPTEY

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ABSTRACT

This study was aimed at assessing the ecological status of six coastal water bodies using abiotic parameters and benthic macroinvertebrates as indicators. Data were collected from June 2016 to August 2017. Physico-chemical parameters were measured in situ while nutrients, heavy metals analyses, sediment organic matter and particle sizes as well as species identification were done in the laboratory. Macroinvertebrates were categorised into five functional groups namely body form, feeding habit, mobility, sexuality and sociability. A total of 45 species were recorded in the six water bodies. The abiotic parameters showed Sakumo II and Fosu lagoons are polluted systems with high conductivity, TDS, nitrate, phosphate and heavy metals concentrations. This was supported by the Bray-Curtis analyses using both taxonomic and functional traits approaches which segregated the two lagoons from the other four water bodies. Pollution tolerant species namely *Chironomus* sp. and *Limnodrilus hoffmeisteri* dominated Sakumo II while *Melanoides tuberculata* and *Chironomus* sp. were dominant in Fosu. The remaining four water bodies namely Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon had higher taxonomic and functional richness and diversities than Sakumo II and Fosu. Important abiotic factors that significantly influenced the abundance of macroinvertebrates taxonomic and functional groups were conductivity, salinity, phosphate, nitrate, organic matter, arsenic, copper, chromium, iron, mercury, lead and zinc. The taxonomic and functional traits approaches used in assessing the ecological status of the water bodies in this study produced similar outcomes. In view of the advantages associated with the latter, under situations of limited resources and time, its use should be the preferred option.

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KEY WORDS

Benthic macroinvertebrates

Diversity

Ecological assessment

Estuaries

Functional approach

Ghana

Lagoons

Physicochemical

Richness

Taxonomic approach

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To my dear husband, Paul and children, Matthew and Ellen, who kept my sanity intact, I love you dearly. God bless your good hearts.

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DEDICATION

To the loving memory of my mother, Mrs. Lucy Ayawovi Tugli-Dzakpasu.

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LIST OF ACRONYMS

AAS: Atomic absorption spectrophotometer

ANOVA: Analysis of variance

DO: Dissolved oxygen

USEPA: United State Environmental Protection Agency

GAEC: Ghana Atomic Energy Commission

IRR: Incidence rate ratio

MPS: Mean particle sizes

OM: Organic matter content

TDS: Total dissolved solids

UCC: University of Cape Coast

UNICEF: United Nations International Children's Emergency Fund

USAID: United States Agency for International Development

WHO: World Health Organisation

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CHAPTER ONE

INTRODUCTION

Coastal lagoons and estuaries are highly productive semi-enclosed inland water bodies that act as transitional zones between land and sea (Schubert & Telesh, 2017). These ecosystems provide habitats, feeding, breeding, and nursery grounds for economically important fish species (Clark, 1992). Lagoons and estuaries in Ghana have become recipients of wastes from industrial, domestic and agricultural sources, as well as sites for mining which result in siltation, oxygen depletion, proliferation of aquatic plants and subsequent loss of biodiversity in these water bodies. Regular monitoring is therefore necessary to evaluate the impacts of anthropogenic activities on these ecosystems. In Ghana, in addition to measuring physico-chemical parameters, ecological monitoring involves the use of indicator species, as well as taxonomic diversity and richness indices of benthic macroinvertebrates (Armah, Luginaah, Essandoh, & Afrifa, 2012; Dzakpasu, 2012; Okyere, 2010). Meanwhile, recent studies in many developed countries have shifted from the taxonomic approach to the use of functional traits of benthic macroinvertebrates (Logan, 2007; Oliveira & Callisto, 2010). This current study explores the use of both approaches in assessing the ecological status of six lagoons and estuaries in Ghana, and serves as a foundation for future research in the country.

1.1 Background to the Study

Coastal areas comprise 20 % of the earth’s surface yet serve as home for over 50 % of the human population (World Ocean Network, 2013). Coastal

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populations, according to World Ocean Network (2013), are expected to account for 75 % of the total world population by the year 2025. An average human population density in coastal areas is about 80 persons per square kilometre, which is twice the global average population (World Ocean Network, 2013). In Ghana, the coastal zone represents about 7 % of the total land area of the country (Armah & Amlalo, 1998) and is home to 25 % of the country’s 24 million total population, according to the 2000 population and housing census (Ghana Statistical Service, 2010).

Clark (1992) stated that the coastal zone is essential to marine life and supports a large part of the world's living marine resources. Lagoons and estuaries in this zone maintain exceptionally high levels of biological productivity (Clark, 1992; Basset, Elliott, West & Wilson, 2013). These environments constitute a much higher percentage of the world’s coasts than is generally recognised (Day & Yáñez-Arancibia, 1982). Their critical ecosystem services such as storage of runoff, prevention of shoreline erosion, denitrification and detoxification of polluted water, as well as feeding, breeding and nursery grounds for commercially important fish species, reptiles and birds have been well documented (Clark, 1992; Kennish & Paerl, 2010; Basset et al., 2013; Thrush et al., 2013).

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In Ghana, inhabitants living close to these water bodies depend on their shell and fin fishes for food, mangroves for fuel wood and water for domestic activities, among other things. Despite their numerous ecological and socio-economic importance, lagoons and estuaries in Ghana have come under severe threats from both anthropogenic and natural causes at an alarming rate within the last decades (Biney, 1982; Karikari, Asante & Biney, 2009). This development poses a serious danger to the health and biodiversity of the coastal ecosystems. Wastewater, fertilizers and sewage containing high levels of nutrients end up in water bodies as a result of run-offs and direct discharges. Nutrients, especially nitrates and phosphates, encourage the proliferation of algae and other aquatic macrophytes (Chiras, 2004; Fried, Mackie & Nothwehr, 2003). It is not uncommon to find farmlands along water bodies on which nitrogen and phosphorus containing fertilizers are used. Refuse dumps are situated on some lagoons while others are direct recipients of wastes and sewage. These activities degrade water quality and have adverse effects on the aquatic life in the affected water bodies.

Chemical pollution also poses problems in aquatic ecosystems with metals and solvents from industries entering into water bodies. Chemicals such as weedicides, insecticides and pesticides, used on farm lands end up in water bodies. These chemicals are poisonous to many forms of aquatic life and may slow their development, make them infertile and kill them (Fried et al., 2003; McVicker, 1963).

Another common degradation practice on water bodies is illegal small-scale mining, otherwise known as "galamsey". The term "galamsey" was apparently corrupted from "gather and sell" which describes the traditional method for gold mining by the first foreign big-scale miners (British Broadcasting Coporation, 2017). This activity is a common practice on a number of water bodies, particularly rivers in Ghana. Mining affects the aesthetic value of water bodies, besides resulting in water quality issues such as siltation, chemical and heavy metal pollution and loss of biodiversity.

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According to Sciortino and Ravikumar (1999), trace quantities of many metals are important constituents of most waters. However, the presence of these metals in excessive quantities interferes with many beneficial uses of the water because of their toxicity. Forstner and Wittmann (1983) noted that heavy metals originate from multiple sources including industrial effluents, domestic wastes, agricultural fertilizers, and geological weathering. Heavy metals can either be adsorbed onto the sediment or accumulated by benthic organisms to toxic levels (Yu, Tsai, Chen & Ho, 2001) which eventually gets into the aquatic food chain causing harm to fish and subsequently humans (Reinhold, Hendriks, Slager & Ohm, 1999). They are poisonous and difficult to clean up from the environment because of their non-biodegradable nature (Wuana & Okieimen, 2011; Gautam, Gautam, Banerjee, Chattopadhyaya & Pandey, 2016).

The quality of aquatic ecosystems can be evaluated through the analysis of physical, chemical and biological parameters (Navas-Pereira & Henrique, 1996). According to Imevbore (1970), physico-chemical factors serve as a basis for the richness or otherwise biological productivity of any aquatic environment. The physical and chemical properties of water immensely influence its uses, the distribution and richness of the biota (Courtney & Clements, 1998). Also, the productivity of aquatic organisms depends on the physico-chemical properties of the water body (Rehman et al., 2015).

Physical and chemical parameters such as temperature, salinity, dissolved oxygen (DO) concentration, pH, conductivity, total dissolved solids (TDS), turbidity, nitrate, phosphate and heavy metals – influence the growth and metabolism of aquatic organisms (Aiwerioghene & Ayoade, 2016; Beasley & Kneale, 2003; Danes & Hynes, 1980; Woke & Eze, 2014; Yap & Cheng, 2009; Yap, Rahim Ismail, Azrina, Ismail & Tan, 2006). DO for instance is responsible for the survival of aquatic life. Temperature affects the solubility of chemicals and therefore influences the effects of pollutants on aquatic life (Chapman & Kimstach, 1996). Heavy metals have the potential of causing environmental and health problems for humans and animals when present beyond tolerable levels (Hassaan, El Nemr & Madkour, 2016). According to Beasley and Kneale (2003), heavy metals have harmful effects on macroinvertebrates. Measurement of these parameters are crucial for ecosystem monitoring. Apart from physical and chemical parameters, biological parameters are also used in ecosystem assessment (Navas-Pereira & Henrique, 1996). The popularly used biological parameters include pathogens, algae, benthic macroinvertebrates, etc. As opined by Navas-Pereira and Henrique (1996), these biological parameters have the advantage of providing information on the water quality over longer periods of time, especially with the use of sessile organisms, thus providing a better reflection of the general ecological conditions of the water body.

Benthic macroinvertebrates are considered a suitable group for aquatic ecosystem monitoring because they are sedentary (thereby reflecting local conditions), live in the sediment which is often a major source and reservoir of contaminants, and are important food source for many fish. Environmental impacts on these organisms will therefore have an effect on the aquatic food web and aquatic resources as a whole (Reynoldson & Metcalfe-Smith, 1992; Sallenave, 2015; Wuana & Okieimen, 2011). Some benthic macroinvertebrates are considered more or less pollution tolerant, and their presence or absence reflect good or bad environmental conditions. In addition, sampling of these macroinvertebrates is easy (compared to plankton and fish) and does not have adverse effects on other organisms (Sallenave, 2015). It is due to some of these merits that several researchers have utilized them globally for ecosystem assessment (Aheto, Okyere, Asare, Dzakpasu & Wemegah, 2014; Balogun, Ladigbolu & Ariyo, 2011; Cummins, Merritt & Andrade, 2005; Dzakpasu, Yankson & Blay, 2015; Liu, 2016; Martins, Stephan & Alves, 2008; Merritt et al., 2002, 1996; Metcalfe, 1989; Nkwoji, Igbo, Adeleye & Obienu, 2010; Okyere, 2015; Olive & Dambach, 1973; Reizopoulou et al., 2014; Reynoldson & Metcalfe-Smith, 1992; Smith, Gresens, Kenney & Sutton-Grier, 2009; Smolders, Lock, Van der Velde, Medina Hoyos & Roelofs, 2003; Wallace & Webster, 1996).

1.2 Statement of the Problem

Increasing human populations especially in coastal areas have exposed lagoons and estuaries to degradation activities such as indiscriminate waste disposal methods, dredging, filling and excavation for various agricultural and industrial uses. Prominent among these degradation activities in Ghana is the issue of waste disposal. Lack of law enforcement of local regulations on waste disposal and sewage treatment and lawlessness among citizens allows for open defaecation, littering, indiscriminate disposal of waste and sewage. These waste materials find their ways into water bodies through rain runoffs. Wastewater and sewage treatment plants in the country are few, hence most wastewater is disposed directly into water bodies. UNICEF (2016) reported low coverage for wastewater and faecal sludge treatment in Ghana.

In the midst of these degradation activities, there is inadequate information on the ecological status of most coastal water bodies in Ghana. The Kakum Estuary, Pra Estuary, Benya Lagoon, Sakumo II Lagoon, Fosu Lagoon and Muni Lagoon are among the ninety-eight (98) lagoons and ten (10) estuaries documented by Yankson and Obodai (1999) on the 550 km long coastline of Ghana. These lagoons and estuaries are at various stages of degradation. While the Kakum Estuary (Biney, 1982; Dzakpasu et al., 2015) and Muni Lagoon (Biney, 1982; Tay, Asmah & Biney, 2009) have been considered to be clean, others like the Sakumo II Lagoon (Nixon et al., 2007; Nartey, Edor, Doamekpor & Bobobee, 2012) and Fosu Lagoon (Armah, Ason, Luginaah & Essandoh, 2012; Baffour-Awuah, 2014) have been reported as polluted. The Fosu Lagoon serves as a receptacle for wastes in the Cape Coast metropolis. Akpabey and Amole (2015) reported that the massive presence of plant matter on the water surface affects the quality of water in the Fosu Lagoon since the decaying weeds decrease dissolved oxygen concentration and inadvertently affect the fauna as a result of hypoxia. Similarly, aquatic macrophytes and plastic bags floating on the surface of the Sakumo II Lagoon pose adverse effects. This lagoon is located in the industrial hub of Ghana and receives effluents and wastes from a large catchment area.

The Pra Estuary and Benya Lagoon have their peculiar issues. There have been reports of “galamsey” mining upstream the Pra Estuary resulting in high siltation. Refuse dumps and piggery have been situated in close proximity to the Benya Lagoon. Apart from the biological and ecological implications, the visual state of these water bodies are an eyesore and have negative implications for eco-tourism, aside polluting them. There is, therefore, an urgent need for the

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ecological assessment of these water bodies to determine their current status for appropriate policy decisions.

Additionally, with the exception of the Sakumo II Lagoon, the other five water bodies are located in the Central and Western regions, where “galamsey”, oil drilling and sand winning are common practices. The Sakumo II Lagoon, on the other hand, is located in Tema, in the Greater Accra region, where it is exposed to wastes from major industries in the country. These present the six water bodies with various threats of biodiversity degradation and hence the need for ecological assessment.

Benthic macroinvertebrates are preferred biological indicators for aquatic ecosystem monitoring for reasons explicated in section 1.1. The use of invertebrates is already known in Ghana. However, most readily available identification keys for brackish water systems are based on species in the temperate regions making it difficult to identify majority of such benthic macroinvertebrates to species level. Many brackish water benthic macroinvertebrates, therefore, remain both taxonomically and ecologically undescribed (Palmer et al., 1997). Also, biomonitoring studies in Ghana focus mainly on the traditional approach of describing diversity indices (Okyere, Blay, Aggrey-Fynn & Aheto, 2011; Aheto et al., 2014; Dzakpasu et al., 2015) and a few on biotic approaches (Armah, Luginaah, et al., 2012), with the view that diversity indices approach is easy to interpret and can be used to compare different habitats. Meanwhile, aquatic ecosystem monitoring in developed countries has gradually shifted from describing diversity indices to other approaches such as the study of the functional trait approach.

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According to Tillin, Hiddink, Jennings and Kaiser (2006), the functional trait approach enhances the understanding of ecosystem functioning and the necessity of accurate biological and ecological information. It is more rapid and reduces taxonomic effort because data on the family levels are usually enough (Merritt et al., 2002; Cummins et al., 2005; Smith et al., 2009). Also, the functional approach does not require a large sample size compared to the taxonomic approach. Combining the functional approach with the traditional taxonomic approach enhances the amount of ecological information available (White, Hill, Bickerton & Wood, 2017). Lamptey (2015) used this functional traits approach in the Guinea Current Large Marine Ecosystem (GCLME). The use of this approach is uncommon in coastal water bodies in the West African sub-region, apart from some isolated studies in Epe and Lagos lagoons (Uwadiae, 2010a, 2010b; Uwadiae et al., 2012) in Nigeria. According to Uwadiae (2010b), using various macroinvertebrate functional group ratios as surrogates for water quality assessment can provide critical data with much less effort. This present study is the first to explore the use of functional traits approach, in comparison to the taxonomic approach, for ecological assessment of coastal lagoons and estuaries in Ghana.

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1.3 Purpose of the Study

This study was conducted to assess the ecological status of six coastal lagoons and estuaries in Ghana, based on benthic macroinvertebrate taxonomic and functional traits approaches. In the wake of ongoing degradation activities in several important aquatic ecosystems in Ghana, there is the need for a biomonitoring approach that is reliable, even with limited resources.

1.4 Hypotheses

On the basis of the foregoing, the following hypotheses were formulated to drive this research:

Hypothesis 1

H_{01}: Abiotic parameters do not show differences in the six water bodies.

H_{A1}: Abiotic parameters show differences in the six water bodies.

Hypothesis 2

H_{02}: Benthic macroinvertebrates communities do not vary in the six water bodies.

H_{A2}: Benthic macroinvertebrates communities show variations in the six water bodies.

Hypothesis 3

H_{03}: Benthic macroinvertebrate functional groups in the six water bodies do not differ.

H_{A3}: Benthic macroinvertebrate functional groups in the six water bodies are different.

Hypothesis 4

H_{04}: Abiotic factors do not have any significant influence on benthic macroinvertebrate communities in the six water bodies.

H_{A4}: Abiotic factors influence benthic macroinvertebrate communities significantly in the six water bodies.

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Hypothesis 5

H_{05}: Abiotic factors have no significant influence on functional traits groups in the six water bodies.

H_{A5}: Abiotic factors have significant effect on functional trait groups in the six water bodies.

1.5 Research Objectives

This study aimed at determining the ecological status of six water bodies in Ghana based on abiotic and biotic parameters. The following objectives were set in order to evaluate the above hypotheses.

i. Assess abiotic factors in the six water bodies.
ii. Compare benthic macroinvertebrate species and functional richness and diversity in the six water bodies.
iii. Determine the similarity between the water bodies based on species and functional traits composition and abundance.
iv. Assess the influence of abiotic factors on benthic macroinvertebrate taxonomic and functional trait groups in the six water bodies.

1.6 Significance of the Study

This study is the first ecological assessment of coastal lagoons and estuaries Ghana based on both taxonomic and functional traits approaches. The study also focusses on the response of macroinvertebrates to changes in abiotic factors. This thesis serves as a reference baseline, providing a better understanding for students and researchers on functional traits of benthic macroinvertebrates in coastal water bodies in Ghana.

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The research also provides valuable data which will inform the protection and preservation of biodiversity in coastal water bodies. This is important for the achievement of the Sustainable Development Goal 14 (United Nations Development Programme).

This work also feeds into the USAID/UCC Fisheries and Coastal Management Capacity Building Support Project Activity 2.1.5, under the theme “Monitor the biodiversity and health of coastal ecosystems”. Monitoring of ecological health of coastal ecosystems has become necessary as a result of the many degradation activities going on in and around coastal water bodies. It is imperative to ascertain the ecological status of these water bodies for effective management. Lagoons and estuaries generally serve as breeding and nursery grounds for fishes, hence their ecological health reflect on the fisheries.

In line with Activity 2.1.3 of the USAID/UCC Fisheries and Coastal Management Capacity Building Support Project, which is to “Research on fish and shellfish of commercial value”, there is an on-going research monitoring environmental parameters and heavy metals concentrations of coastal water bodies to determine their ecological healthy status for the culture of oysters. Findings from this study will supplement the outcome of that research to indicate to stakeholders the suitability or otherwise of the water bodies studied for oyster culture.

1.7 Delimitations

Heavy metals analysis was conducted at the Ghana Atomic Energy Commission (GAEC) Chemistry Laboratory due to the unavailability of an

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operational Atomic Absorption spectrophotometer (AAS) at the Department's Laboratory causing delays in the analysis.

Composite samples at each station were used for sediment heavy metals analysis to reduce cost since the analysis was done in an external laboratory (indicated above) at a fee.

Sampling was done quarterly, specifically in the first week of the last month of each quarter. However, sampling for the 3rd quarter of 2017 was done in the last week of the second month of that quarter (i.e. last week of August 2017 instead of the first week of September) due to time constraints. Thus, for this research, sampling was done in the last weeks of June, September and December 2016 and March, June and August of 2017.

During the first quarter of data collection (i.e. the 2nd quarter of 2016), sampling was done at four (4) stations in each water body. The number of sampling stations was increased to six (6) in the subsequent quarters in order to cover a wider area of the water bodies for samples to be more representative.

1.8 Limitations

Ideally, nitrate and phosphate determinations should be done within 24 hours. Due to tight sampling schedules, samples for nitrate and phosphate were occasionally stored in a refrigerator (4 °C) and analysed within 48 hours.

In the 2nd quarter of 2017, one out of the six stations in the Sakumo II Lagoon was inaccessible due to overgrowth of aquatic plants. Similarly, in the 3rd quarter of 2017, three stations were inaccessible in the same lagoon, again due to overgrowth of aquatic plants. Two stations in the Pra Estuary were inaccessible during the same period as a result of flooding. Also, samples were collected at five stations in the Muni Lagoon in the same 3rd quarter of 2017. The sixth station was inaccessible at the time of sampling as a result of a training programme by the nearby Police Training College forbidding that area to the public.

1.9 Definition of Terms

Functional trait: Morphological, physiological, structural, or behavioural characteristics of organisms that define species in terms of ecological roles.

Functional group: Group of individuals that perform a similar role in an ecosystem.

Feeding habit: The way an organism feeds, considered in terms of what types of food are eaten.

Deposit feeder: An organism that feeds on materials at the bottom of the water body. **Detritivores** were captured under this group.

Filter feeder: An animal that feeds by straining food particles from the water column.

Omnivore: An animal that eats both plants and animals.

Deposit feeder+omnivore: An organism that is predominantly a deposit feeder but sometimes an omnivore depending on food availability.

Deposit feeder+filter feeder: An animal that is usually a deposit feeder but sometimes engages in filter feeding.

Deposit feeder+scavenger: An organism that is predominantly a deposit feeder but sometimes feeds on carcasses of other animals.

Scavenger: Any animal that feeds on carcasses of other animals.

Carnivore/predator: An animal that feeds on other live animals.

Carnivore+deposit feeder: An animal that feeds on other live animals but also feeds on materials at the bottom.

Carnivore+scavenger: A carnivore that sometimes feeds on carcasses.

Body form: The shape or physical frame of an organism.

Sociability: The tendency/skill of living together with others.

Solitary: The act of existing alone.

Commensal: Living in close association with others without causing harm.

Mobility: The ability to move or be moved freely.

Burrower: An animal that digs into the ground.

Crawler: An animal that moves by dragging its body close to the ground.

Swimmer: An animal that moves through water by using its body or parts of the body.

Burrower+swimmer: An animal that usually burrows but swims sometimes.

Burrower+crawler: An animal that usually burrows but sometimes crawls.

Crawler+swimmer: An animal that is predominantly a crawler but sometimes swims.

Sessile: An animal that is restricted in movement.

Sexuality: Natural condition regarding the possession of sex organs.

Hermaphrodite: An organism that has both male and female reproductive organs.

Gonochorist: Species that exhibits the separation of male and female sexes.

1.10 Organisation of the Study

This thesis is divided into six chapters. Chapter One is a general introduction of the subject matter, covering background information on coastal

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lagoons and estuaries, aquatic ecosystem assessment, hypothesis and the objectives of the study. Chapter Two reviews relevant literature on physicochemical parameters, heavy metals, benthic macroinvertebrates and their functional trait, as well as biomonitoring in general in Ghanaian coastal waters. Information on the study area, materials and methods for data collection and analysed are provided under Chapter Three. Secondary data and their sources are stated in this chapter. Chapter Four covers the results of the study with information on abiotic parameters, occurrence and composition of macroinvertebrates and their functional groups in the study areas. Interpretation of the findings in this study, possible explanations and comparison with other works are provided in Chapter Five. The summary of the research findings, together with conclusions and recommendations for future work are presented under Chapter Six. Data on physico-chemical parameters, sediments and heavy metals are presented in the Appendices. The taxonomic and functional trait databases are also shown under the Appendices.

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CHAPTER TWO

LITERATURE REVIEW

The previous chapter dealt with the ecological and socio-economic importance of coastal lagoons and estuaries, the threats facing them and the importance of ecosystem monitoring using benthic macroinvertebrate communities and their functional groups. This chapter reviews relevant literature on the influences of human activities on coastal lagoon and estuarine systems, physico-chemical parameters of such water bodies, occurrence of heavy metals in them, nature of sediments, roles of benthic macroinvertebrates and their functional traits and finally, ecosystem monitoring in Ghana.

2.1 Lagoon-Estuarine Ecosystems

Coastal lagoons and estuaries, characterised by shallow depths, are important ecological features of the coastal landscape, serving as a transition between the land and the sea (Biney, 1990; Basset et al., 2013; Pérez-Ruzafa, Marcos, Pérez-Ruzafa & Pérez-Marcos, 2013). These ecosystems provide many essential services to humans. Ecologically, they are highly productive, efficient in nutrient cycling, support coastal biodiversity, stabilise shorelines thereby protecting coastal areas from floods and storm surges, etc. (Clark, 1992; Yáñez-Arancibia, Day, Knoppers & Jiménez, 2001; Basset et al., 2013; Miththapala, 2013). They also have historical, recreational, aesthetic and inspirational values, boosting eco-tourism of many countries (Kennish & Paerl, 2010; Miththapala, 2013; Thrush et al., 2013).

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Coastal lagoons and estuaries are especially important for fisheries. They are utilised by many fish species as habitat as well as nursery, spawning and feeding grounds (Clark, 1992; Yanez-Arancibia, Dominguez & Pauly, 1994). According to McHugh (1967), anadromous and catadromous fishes also use the estuarine-lagoon environment as transport routes. Any form of pollution in the estuarine-lagoon environment will likely affect these fish species and by extension, human populations that feed on them.

A report from the Architecture and roadmap to manage multiple pressures on lagoons (ARCH) project highlighted that high human population density and demand for ecosystem services lead to a number of activities that exert multiple pressures on coastal lagoons and estuaries, introducing contaminants and leading to their deterioration (ARCH, 2015). These activities usually originate from agriculture, industry, transport, fishery, energy production, infrastructure, recreation and urbanization in addition to climate change. Biney (1982) believed the quality of these ecosystems is influenced by human activities inland in many cases. Human activities along water bodies can also cause a change in biological communities. Increased human activities at the Mormugao harbour for instance resulted in a shift in polychaete population from carnivores to deposit feeders encountered (Sivadas, Ingole & Nanajkar, 2010). Essentially, human activities along coastal lagoons and estuaries reflect on the physico-chemical parameters and the biological communities in these water bodies.

The water bodies under study are the Kakum Estuary, Pra Estuary, Benya Lagoon, Sakumo II Lagoon, Fosu Lagoon and Muni Lagoon. These water bodies are feeding, breeding and nursery grounds for commercially

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important fish species and serve as a fishery resource of both fin and shell fish for the nearby communities (Obodai, Yankson & Blay, 1991; Blay & Asabere-Ameyaw, 1993; Blay, 1995; Okyere, Blay, et al., 2011). Inhabitants close to the Kakum and Pra estuaries use water from these water bodies for domestic activities such as cooking, bathing, washing, etc. The Sakumo II Lagoon, for instance, serves as a source of drinking water for livestock. The Muni Lagoon and the Sakumo II Lagoon (both RAMSAR sites) are feeding grounds for migratory birds. Any form of pollution in these water bodies will, therefore, have a direct effect on livestock and humans deriving food and other resources from them, apart from the impact on biodiversity in these water bodies.

2.2 Physico-chemical Parameters

Physico-chemical parameters of water provide nutritional balance and ultimately control the biotic relationships of aquatic organisms including their ability to withstand pollution load (McCaffrey, 1997; Udoh, Ukpatu & Otoh, 2013). According to Udoh et al. (2013), industrialization, urbanization and modern agriculture practices have direct impacts on water resources quantitatively and qualitatively. Temperature ranges in aquatic ecosystems, for instance, can be influenced by man-made structures such as dams and the release of water from them (McCaffrey, 1997). Temperature affects the rates of photosynthesis, metabolism, development, timing and success of reproduction, mobility, migration patterns, life cycles of aquatic organisms, and sensitivity of organisms to toxins, parasites and diseases (McCaffrey, 1997). Decreased temperatures tend to retard the rate of reproduction of organisms that break down organic matter (Badu, 2012). Temperature is known to affect conductivity

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by increasing ionic mobility as well as the solubility of many salts and minerals. Increasing temperature also results in decreasing solubility of dissolved oxygen (Chapman & Kimstach, 1996). This was evident in the Nyan and Kakum estuaries (Dzakpasu, 2012) as well as water bodies around the University of Port Harcourt Community (Woke & Eze, 2014).

Lalli and Parsons (1997) acknowledged salinity plays a key role in the distribution and survival of aquatic organisms. Sources such as urban and rural runoff containing salt, fertilizers, organic matter, etc. contribute dissolved salts into water bodies (McCaffrey, 1997). Cyrus, Vivier, Owen and Jerling (2010) found salinity to be among the factors influencing the distribution of benthos in the Mfolozi-Msunduzi estuarine system on the south-east coast of South Africa. Lawal-Are and Kusemiju (2010) related salinity to survival rates of the blue crab (*Callinectes amnicola*). The authors recorded higher survival rate (75 %) of the blue crab in the Lagos Lagoon at 10 ppt compared to when salinity increased to 35 ppt.

Salinity and conductivity vary greatly between different water bodies. Freshwater generally has low salinity and conductivity levels (Fondriest Environmental Inc., 2014a). The ocean, on the other hand, has high conductivity and salinity due to the presence of high dissolved salts. In streams and rivers, normal conductivity levels come from the surrounding geology. According to Chapman and Kimstach (1996), conductivity is a rough indicator of mineral content and can be used to establish a pollution zone or the extent of influence of run-offs. A significant change in conductivity, whether due to natural flooding, evaporation or man-made pollution can be very detrimental to water quality (Fondriest Environmental Inc., 2014a).

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Dissolved oxygen (DO) is an important determinant of life in aquatic ecosystems. According to Chapman and Kimstach (1996), DO in water bodies varies daily and seasonally in relation to temperature and biological activity such as photosynthesis, respiration and decomposition. Davies, Ugwumba and Abolude (2008) reported a lower DO in the wet season compared to the dry season in the Woji creek of the Niger Delta as a result of reduced photoperiod and photosynthetic activities of aquatic plants in the wet season. The solubility of oxygen is influenced by salinity; with higher salinity levels resulting in a decreasing oxygen level (Fondriest Environmental Inc., 2013a).

Chapman and Kimstach (1996) mentioned that changes in pH can be used as an indicator of the presence of certain effluents, particularly when measured with conductivity. According to these authors, pH influences many biological and chemical processes in water bodies and is controlled by both natural and man-made factors. Most natural changes occur due to interactions with surrounding rock (particularly carbonate forms) and other materials. pH fluctuates with precipitation (especially acid rain), wastewater and mining discharges (Fondriest Environmental Inc., 2013b). Majority of aquatic organisms prefer a pH range of 6.5 – 9.0, though some can survive outside of this range. An increase or decrease in pH levels stresses animal systems and reduces hatching and survival rates. Mortality rates go up when pH levels exceed 10.0. High pH levels can damage gills and skin of aquatic organisms. In addition to biological effects, pH affects solubility and toxicity of chemicals and heavy metals in water bodies. Low pH levels usually increase the solubility of elements and compounds, making toxic chemicals more “mobile” and

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increasing the risk of absorption by aquatic life (Fondriest Environmental Inc., 2013b).

Sciortino and Ravikumar (1999) believed turbidity has an influence on life in water bodies. This is because high turbidity restricts light penetration and limits phytoplankton production (Lalli & Parsons, 1997). Turbidity measurements are often used as an indicator of water quality based on clarity and estimated total suspended solids in water (Fondriest Environmental Inc., 2014b). Surface water turbidity is expected to be between 1 to 50 NTU and increases can be caused by the presence of organic matter pollution, other effluents, or run-off with a high suspended matter content (Chapman and Kimstach, 1996).

All ion particles smaller than 2 microns (0.0002 cm), thus include all dissociated electrolytes that make up salinity, as well as other compounds such as dissolved organic matter constitute total dissolved solids (TDS) (Fondriest Environmental Inc., 2014b). TDS in wastewater or polluted areas includes organic solutes (such as hydrocarbons and urea) in addition to the salt ions. Apau, Appiah and Marmon-Halm (2012) attributed high TDS values in the Kpeshie Lagoon to effluents from domestic, municipal and small scale industry. Depending on the ionic properties of the water, excessive TDS can produce toxic effects on fish and fish eggs (Fondriest Environmental Inc., 2014b).

Nutrients, particularly nitrate and phosphate, are essential for the growth of aquatic plants. High concentrations of nitrate and phosphate have been recorded in the Sakumo II Lagoon (Nixon et al., 2007; Asmah, Dankwa, Biney & Amankwah, 2008; Nartey et al., 2012; Nonterah, Xu, Osae, Akiti & Dampare, 2015) with the lagoon being hyper-eutrophic at the riverine end and oligotrophic

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at the seaward end (Ansa-Asare, Mensah & Entsua-Mensah, 2008). These nutrients were suspected to come from domestic waste, agricultural run-offs, etc. Asmah et al. (2008) stated that the current rate of nutrient loading in the lagoon would likely change the structure and function of plankton, benthic and fish communities with time, thereby affecting the whole ecology of the lagoon. Higher concentrations of nutrients were observed during the dry season when there was low discharge of water from the feeder streams. Asmah et al. (2008) attributed this to mineralization of organic matter and the reduced flushing rate of the lagoon in the dry season.

Chapman and Kimstach (1996) reported nitrate occurs naturally in groundwater as a result of soil leaching, but in areas of high nitrogen fertilizer applications, concentrations increase. According to these authors, surface waters have nitrate concentrations often less than 1 mg/l NO_3-N but concentrations in excess of 5 mg/l NO_3-N usually indicate pollution by human or animal wastes, or fertilizer runoff. Nartey et al. (2012) recorded higher nitrate levels in the wet season than the dry season in the Sakumo II Lagoon indicating the influence of run-offs on nitrate levels.

Green (2017) noted that phosphate enters water bodies as a result of runoff from fertilizer on farmlands, human and pet sewage, chemical manufacturing, detergents, vegetable and fruit processing, and the pulp and paper industry. Nartey et al. (2012) attributed the proliferation of aquatic plants in the Sakumo II Lagoon to high phosphate concentrations. Phosphate causes excessive growth of algae, which creates imbalances, destroys other life forms and produces harmful toxins (Green, 2017).

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2.3 Heavy Metals

Traces of all heavy metals occur naturally in water bodies, organisms and sediments (Bryan, 1976; Sciortino & Ravikumar, 1999) and their concentrations are increasing continually as result of anthropogenic influences through industrial, agricultural and mining activities, discharge of effluent from sewage treatment plants and urban runoff (Kalay & Canli, 2000; Iwasaki, Kagaya, Miyamoto & Matsuda, 2009; Basyigit & Tekin-ozan, 2013). A study on the heavy metals concentrations of the Sakumo II Lagoon showed higher levels of iron, copper, manganese, lead, cadmium and zinc in the mid-section, where there was intense anthropogenic activities than the southern and northern sections (Tay et al., 2009). High recoverable silver content recorded in the Pra and Kakum estuaries was also as a result of anthropogenic activities such as mining (Essumang & Nortsu, 2008).

Heavy metals, when accumulated in the sediment, undergo physical, biological and chemical transformations that could have implications for living organisms (Wuana & Okieimen, 2011). For instance, metals such as zinc, iron, copper and manganese are known to play important physiological roles in coastal and other aquatic environments as they serve as co-factors of metallo-enzymes and proteins where they are involved in the general metabolic processes of phytoplankton and other marine organisms (Sunda, 1988; Hunter, Kim & Croot, 1997).

It has been reported that trace metals can also enter the aquatic food chain via the chironomid larvae (Reinhold et al., 1999). These larvae serve as an important food source for fish and aquatic birds. An assessment of the flesh of *Sarotherodon melanotheron* in the Fosu Lagoon showed lead and cadmium concentrations above the recommended levels by the EU (Akoto, Bismark Eshun, Darko & Adei, 2014). Eshun (2011) documented the contamination of Fosu Lagoon sediments by the same heavy metals.

The heavy metals of interest in this study are arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni) and zinc (Zn). According to Evanko and Dzombak (1997), these metals are most commonly found at contaminated sites. Yadav, Gaur, Srivastava and Yadav (2016) described arsenic as ubiquitous and occurs naturally in various concentrations in water, soil, air and food. Arsenic is acute to freshwater animals at concentrations as low as 850 µg/l (United States Environmental Protection Agency [USEPA], 1986). Yadav et al. (2016) indicated that apart from atmospheric concentration of arsenic being transported into water bodies by dry fallout and rain, domestic wastes, sewage, fertilizers and pesticides from farmlands, wastewater, chemicals and dyes from industrial wastes also contribute to arsenic contamination.

Cadmium and its compounds enter the environment from geological or human activities such as metal mining, smelting and fossil fuel combustion (Sciortino & Ravikumar, 1999). This metal is highly toxic to organisms and not essential in biological processes. Chronic exposure of cadmium has been reported to lead to adverse effects on growth, reproduction, immune and endocrine systems, development, and behaviour in aquatic organisms such as crustaceans and mayfly (USEPA, 1986, 2017).

Chromium, according to Sciortino and Ravikumar (1999), exists naturally in most rocks and soils in a highly insoluble form. Common soluble forms found in soils are mainly the result of contamination by industrial emissions. It becomes readily available in the environment because of its usage for chrome alloys, chrome plating, oxidising agents, corrosion inhibitors, pigments for the textile glass and ceramic industries as well as in photography. USEPA (1986) indicated concentrations from 13 to 36.74 μg/l are lethal for polychaetes and mysids.

Copper is one of the most toxic metals to aquatic organisms and ecosystems (Solomon, 2009). Meanwhile, it is required in small amounts by humans, other mammals, fish and shellfish for carbohydrate metabolism and the functioning of enzymes. According to Sciortino and Ravikumar (1999), copper is present in anti-fouling paints, wood preservatives as well as urban sewage. It is moderately soluble in water and binds easily to sediments and organic matter (Solomon, 2009). USEPA (1986) reported the sensitivity of fish and invertebrates to concentrations of 3.87 – 60.36 μg/l.

According to Andromeda (2018), high concentrations of iron sometimes result in increased acidity of water leading to the death of aquatic life. Iron occurs naturally in water at a rate of roughly 1 – 3 ppb in ocean water, about 1 ppm in river water and 100 ppm in groundwater. Contamination affects the reproduction and feeding habits of fish and other animals.

Lead has been reported among the most abundant of heavy metals occurring in nature (Sciortino & Ravikumar, 1999). These authors noted that most lead used in compound forms like paints, mercurial fungicides and petrol additives is lost to the environment, eventually ending up in the aquatic environment. Lead has no known functions in biochemical processes (Opaluwa et al., 2012).

According to Nagpal (2001), manganese is an essential trace element for aquatic and terrestrial biota and is present in almost all organisms. It is slightly to moderately toxic to aquatic organisms in excessive amounts. Concentrations in the environment may be well above the aquatic toxicity levels in effluents originating from mines, municipal sewage and landfills (Nagpal, 2001).

Mercury is ubiquitous as a result of natural geological activity and man-made pollution (Sciortino & Ravikumar, 1999). It is highly toxic, especially in the form of methyl mercury because it cannot be excreted and therefore acts as a cumulative poison. According to Sciortino and Ravikumar (1999), levels above 1 ppb in water are due to industrial effluents connected with chlorine and caustic soda production, pharmaceuticals, mirror coatings, mercury lamps and certain fungicides.

Similar to mercury, nickel is ubiquitous in the environment. According to Sciortino and Ravikumar (1999), it is a relatively non-toxic element; however, certain nickel compounds have been shown to be carcinogenic in animal experiments.

Zinc is an essential trace element for all living organisms. It is mainly used in the production of noncorrosive alloys and brass; and in galvanizing steel and iron products (Sciortino & Ravikumar, 1999). Zinc undergoes oxidation on the surface, therefore protecting the underlying metal from degradation. Galvanized products, according to Elinder (1986), are widely used in construction materials, automobile parts, and household appliances.

2.4 Sediment Characteristics

Substratum particle size, stability, organic matter contents, habitat spatial heterogeneity and sediment grain size regulate the distribution and richness of benthic macroinvertebrates (Graça, Ferreira, Firmiano, França & Callisto, 2015). According to Ruellet and Dauvin (2007), particle size composition plays an important role in the distribution of benthic macroinvertebrate populations. Polychaetes inhabit the sediment surface and are dependent upon the benthic sediment characteristics and also on the near-bottom water quality (Musale, Desai, Sawant, Venkat & Anil, 2015). Harkantra (1982) reported low benthic fauna in very coarse sand and very fine sand while medium grain sized sediment was reported to have a rich fauna.

It is also worth noting that pollutant concentrations in sediments increase with decreasing sediment particle size (Tsai, Ho & Yu, 2003). Metals have high affinities for fine-grained sediment. The concentrations of metals are therefore controlled to a large extent by processes governing sediment transport and deposition (Australian Online Coastal Information, 2015). According to Ongley (1994), sandy soil does not aid in the transport of pollutants due to its rough and large particle size which reduces its surface area. Metals tend to be highly attracted to ion exchange sites that are associated with clay particles and with the iron and manganese coatings that commonly occur on these small particles (Ongley & Food and Agriculture Organization of the United Nations, 1996). Tsai et al. (2003) observed the concentrations of heavy metals in sediment increased as the amount of organic materials increased. Cadmium, for instance, strongly adsorbs to organic matter in soils.

The decomposition of organic matter including faeces, dead organisms and leaf litter also releases phosphorus into the water column and sediment pore water (Mainstone & Parr, 2002). Badu (2012) noted that benthic organisms depend primarily on organic matter for food and the sources of organic carbon include overland runoff, primary productivity, decomposition of plant debris and shoreline erosion which eventually settle to the bottom and are incorporated into the sediments. Sediments with very low and high organic carbon content show poor fauna and medium values show rich fauna (Harkantra, 1982). Dahanayaka and Aratne (2010) observed substrates with high organic matter content were preferred by sedentary polychaetes and amphipods. Badu (2012) pointed out that, high organic matter can lead to the depletion of oxygen in the sediment and overlying water, which can have a deleterious effect on the benthic and fish communities.

2.5 Benthic Macroinvertebrates

Benthic macroinvertebrates are animals without backbones within the size range of 0.5 – 2.0 mm that can either live within the sediment (infauna) or on the sediment-water interface (epifauna). They form an important part of aquatic ecosystems. Macroinvertebrates play an important role in the trophic structure of aquatic ecosystems, linking primary producers to higher levels, feeding on living or decomposing organic matter and serving as food for other invertebrates and vertebrates (Moulton, Magalhães-Fraga, Brito & Barbosa, 2010). Additionally, bottom feeders break down waste products and dead plants and animals (Chesapeake Bay Program, 2018).

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In estuaries and coastal lagoons, muddy sediments are characteristic of environments with low water currents or with low water renewal and are colonized by detritivorous fauna (Gamito, 2006). According to Levinton (2001), suspension-feeding animals mostly dominate sandy sediments, deposit feeders dominate muddy sediments, while carnivores and other feeding types occur in both types of sediments. Small sedimentary particles are indicative of a quiet water environment where fine-grained organic matter tends to settle from the water column. Suspension feeders function poorly in muddy sediments due to the clogging effect of re-suspended particles and the destabilizing effect of deposit feeders on the sediment.

Research on ecological communities is characterized following two major approaches, the traditional taxonomic and functional approaches. The traditional approach is based on taxonomic structure, whereas the functional approach is based on the functional trait characteristics of species (Heino, 2008). Cummins et al. (2005) simply describe the taxonomic approach as 'what is it?' and the functional approach as 'what does it do?' The functional approach has been used in the study of streams in the past (Cummins, 1973; Cummins & Klug, 1979). Its recent revival is due to increased interest in the connections between ecosystem functioning, biodiversity, and environmental degradation (Kinzig, Pacala & Tilman, 2002).

Functional traits of benthic macroinvertebrates have been extensively studied in streams (Merritt et al., 1996; Wallace & Webster, 1996; Cummins et al., 2005; Heino, 2005) and marine ecosystems (Bremner, Rogers & Frid, 2003; Bremner, 2005; Törnroos et al., 2014; Lamptey, 2015). A gap in functional traits categorisation of benthic macroinvertebrates in lakes, coastal lagoons and estuaries has been recognised. In Ghana as pointed earlier, no known study in coastal and inland water bodies has used the functional traits approach for ecosystem assessment.

Merritt et al. (2002) explained that functional evaluation is based on easily observed morphological and behavioural attributes associated with feeding, modes of attachment, concealment and locomotion, together with life history patterns and drift propensity. The value of this kind of approach is that these attributes relate more directly to ecosystem ecology and integrity than the taxonomic approach. The distribution of feeding groups along a river, for instance, can determine the availability of feeding resources and the status of related environmental conditions (Goncalves & Menezes, 2011). Lamptey (2015) noted that functional traits have a strong effect on ecosystem functioning and occur in most of the benthic macrofauna. The traits considered in this study are feeding habits, body form, mobility, sociability and sexuality. These traits reflect life history (sexuality), morphology (e.g. body form) and behaviour (mobility, sociability and feeding habit) (see Bremner et al., 2003).

Among benthic invertebrate communities, it is not unusual to find organisms that feed essentially on detritus or on the bacteria benthic layer in the sediments, and others that filter water to retain the plankton and suspended particles. Based on feeding categories, benthic macroinvertebrates are generally divided into five groups: deposit feeders (detritivores), suspension (filter) feeders, carnivores, herbivores (or grazers), and omnivores (Pearson, 2001). Levinton (2001) noted that some organisms are difficult to classify into a feeding group since they use more than one feeding modes depending on food availability; a combination of feeding groups becomes necessary such that some

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organisms feed either on detritus or suspended material, while some carnivores also feed on dead tissues or detritus (Gamito & Furtado, 2009; Levinton, 2001). According to Gamito and Furtado (2009), several feeding groups are expected to coexist in different proportions in the same area, due to hydrodynamic conditions, which in turn determines the sediment characteristics.

Van Der Linden et al. (2012) however acknowledged that traits-based analysis of benthic invertebrates has been mostly limited to feeding habits while other traits have received far less attention, despite addressing important aspects of ecosystem functioning. According to Statzner (1987), while food and feeding habits reflect ecological functions, others are indirect indicators. Mobility affects the capture method of prey organisms or other food resources and defines the trophic relationships of a benthic community. It describes the capacity of organisms to move in and outside of the sediment. Semi-mobile organisms have the ability to move but only do so if necessary and usually very slowly (Lamptey, 2015). Many macroinvertebrates move by burrowing (dig down and reside in soft, fine sediments). Swimmers are adapted to moving through water. Clingers maintain a firm position on substances while climbers dwell on living plants and plant debris.

Mobility and feeding habits play a major role in bioturbation of the aquatic ecosystem. According to Nichols and Boon (1994), benthic macroinvertebrates are able to process, transport and modify sediments through their various activities. Some of these organisms bind, protect and stabilize near-surface sediment while others loosen and destabilize the sediment. Deposit-feeding and burrowing movement of polychaetes result in increased sediment oxygenation, vertical movement of sediment particles, repacking of sediments and alteration of sediment stability which ultimately results in the degradation or redistribution of organic matter (Rhoads & Young, 1970; Rhoads, 1973; Fauchald & Jumars, 1979).

2.6 Aquatic Ecosystem Monitoring in Ghana

Perusal of literature over the past decades indicates that monitoring of coastal lagoons and estuaries in Ghana is not on regular basis. Also, there is inadequate information on ecological status of many coastal water bodies in Ghana. It is also evident that ecological research on some of our water bodies were from one-time sampling (Nixon et al., 2007; Aggrey-Fynn, Galyuon, Aheto & Okyere, 2011; Okyere, Aheto & Aggrey-Fynn, 2011) making it difficult to draw reliable conclusions.

Studies on ecosystem monitoring in Ghana have dwelt mainly on indicator species, species diversity and richness. Based on benthic macroinvertebrate diversity indices, Dzakpasu, Yankson and Blay (2015) concluded that the Kakum and Nyan estuaries were ecologically healthy with 40 and 45 species respectively and Shannon-Wiener diversity indices between 1.14 – 1.61 for Kakum Estuary and 1.11 – 1.55 for Nyan Estuary. Okyere (2010) on the other hand, encountered only an unidentified oligochaete and chironomid larvae in the tidal pools at the Kakum Estuary wetland, suggesting a stressed environment. Oligochaetes and chironomid larvae are known to adapt well to low oxygen and polluted environments (Gerber & Gabriel, 2002). Okyere (2010) acknowledged that the ephemeral nature of the habitat could account for the observed poor richness of benthic fauna community of the wetland.

A number of works have been carried out in the six water bodies of interest. Some key areas studied in the Pra Estuary are sedimentation rates (Nyarko, Klubi, Laissaoui & Benmansour, 2016), breeding of oyster populations (Obodai, Yankson & Blay, 1991-96), and water quality (Biney, 1982; Essumang & Nortsu, 2008; Okyere, 2015; Okyere & Nortey, 2018). These studies showed evidence of siltation and heavy metals pollution as a result of mining activities upstream. Apart from the works by Okyere (2015) and Okyere and Nortey (2018) who looked at fish and benthic macroinvertebrates in relation to some physico-chemical parameters in the Pra Estuary, the rest were not aimed at investigating the response of biological indicators to environmental parameters.

Dzakpasu (2012) examined the ecological status of the Kakum Estuary using benthic macroinvertebrates as biological indicators over a period of one year. The estuary was found to be in an ecologically healthy state. Other studies on the Kakum Estuary were on heavy metals (Fianko, Osae, Adomako, Adotey & Serfor-Armah, 2007; Essumang & Nortsu, 2008), mangroves and fish (Aheto, Owusu & Obodai, 2011; Aheto et al., 2014).

Comparative studies on human activities and nutrients in the Muni and Sakumo II lagoons are common (Nixon et al., 2007; Ansa-Asare et al., 2008; Mensah & Biney, 2008; Tay et al., 2009; Mitchell, Boateng & Couceiro, 2017); all of them describing the Sakumo II Lagoon as polluted. Other studies on heavy metals and nutrients in the Sakumo II Lagoon all point to the pollution of this water body (Biney, 1990; Asmah et al., 2008; Mensah & Biney, 2008; Agbemehia, 2014; Nonterah et al., 2015). Regarding the Muni Lagoon, Tiakor (2015) looked at the impact of farming activities on the Muni-Pomadzi wetland.

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Other areas like land use and biodiversity conservation (in reference to water birds) have been investigated on the Muni Lagoon (Wuver & Attuquayefio, 2006; Atampugre, 2010; Lamptey & Ofori-Danson, 2014). Lamptey and Armah (2008) studied the response of macrobenthic fauna to some environmental parameters. None of these authors described the Muni Lagoon as polluted. They however noted that growing human activities around this lagoon are likely to impact on its water quality.

The Benya and Fosu lagoons have received some attention. The Fosu Lagoon has been studied for its heavy metals (Bentum, Anang, Boadu, Koranteng-Addo & Antwi, 2011; Eshun, 2011; Akoto et al., 2014), polycyclic aromatic hydrocarbons (Armah, Luginaah, et al., 2012), fish (Blay & Asabere-Ameyaw, 1993; Badu, 2012; Dankwa, Quarcoopome, Owiredu & Amedorme, 2016), and macrophytes (Akpabey & Amole, 2015). These studies described the Fosu Lagoon as polluted. Studies in the Benya Lagoon examined its nutrient concentrations (Biney, 1982; Nixon et al., 2007; Ansa-Asare et al., 2008; Mensah & Biney, 2008) and heavy metals (Vowotor et al., 2014). Assessment of the ecological health of the Benya and Fosu lagoons by Armah, Ason, et al. (2012) showed low species richness and proliferation of *Chironomus* sp. (a pollution tolerant species) in the Fosu Lagoon in comparison to the Benya Lagoon which supported high species richness and densities.

Despite the fact that some of these water bodies have been studied for their ecological status based on benthic macroinvertebrates in the past decade, it is evident that ecological studies in coastal water bodies in Ghana are completely silent on the functional (biological) traits approach. Meanwhile, the numerous advantages of this approach cannot be over-emphasized as

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demonstrated by other researchers (Bremner et al., 2003; Bremner, 2005; Törnroos et al., 2014; Lamptey, 2015).

2.7 Chapter Summary

It has been established in this chapter that ecosystem assessment involves both the physico-chemical and biological components of an environment under study. Physico-chemical parameters and sediment characteristics have been seen to define the type of benthic macroinvertebrates present in a water body. Functional traits have been proven to be very vital in determining the ecological state of water bodies but have not been utilised in Ghanaian coastal water bodies. It is also clear that there is a need to determine the ecological state of coastal water bodies in Ghana for the institution of proper management strategies.

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CHAPTER THREE

MATERIALS AND METHODS

The importance of combining biological elements (in this case, benthic macroinvertebrates) with physico-chemical parameters in aquatic ecosystem assessment have been highlighted in the previous chapter. This chapter deals with the description of the six coastal water bodies studied, techniques for collecting data on physico-chemical parameters, heavy metals, sediments and benthic macroinvertebrates and how data were analysed.

3.1 Study Area

The study was conducted in six coastal water bodies along the central coast of Ghana namely Kakum Estuary, Pra Estuary, Benya Lagoon, Sakumo II Lagoon, Fosu Lagoon and Muni Lagoon. These water bodies were selected based on proximity, accessibility and evidence of substantial human interaction. These water bodies are located in the dry Equatorial climatic region of Ghana. The region experiences double maxima rainfall, the major one occurring between April and June, with June being the wettest month (Obirikorang, 2010). The minor rainy season is between September and October. Figure 3.1 shows the map of southern Ghana indicating the study sites.

3.1.1 Kakum Estuary

The Kakum Estuary (5°5' N, 1°19' W) is located along the Cape Coast – Takoradi trunk road near Iture village in the Central Region. It is about 3.0 km west of the University of Cape Coast West Gate and about 4.0 km east of

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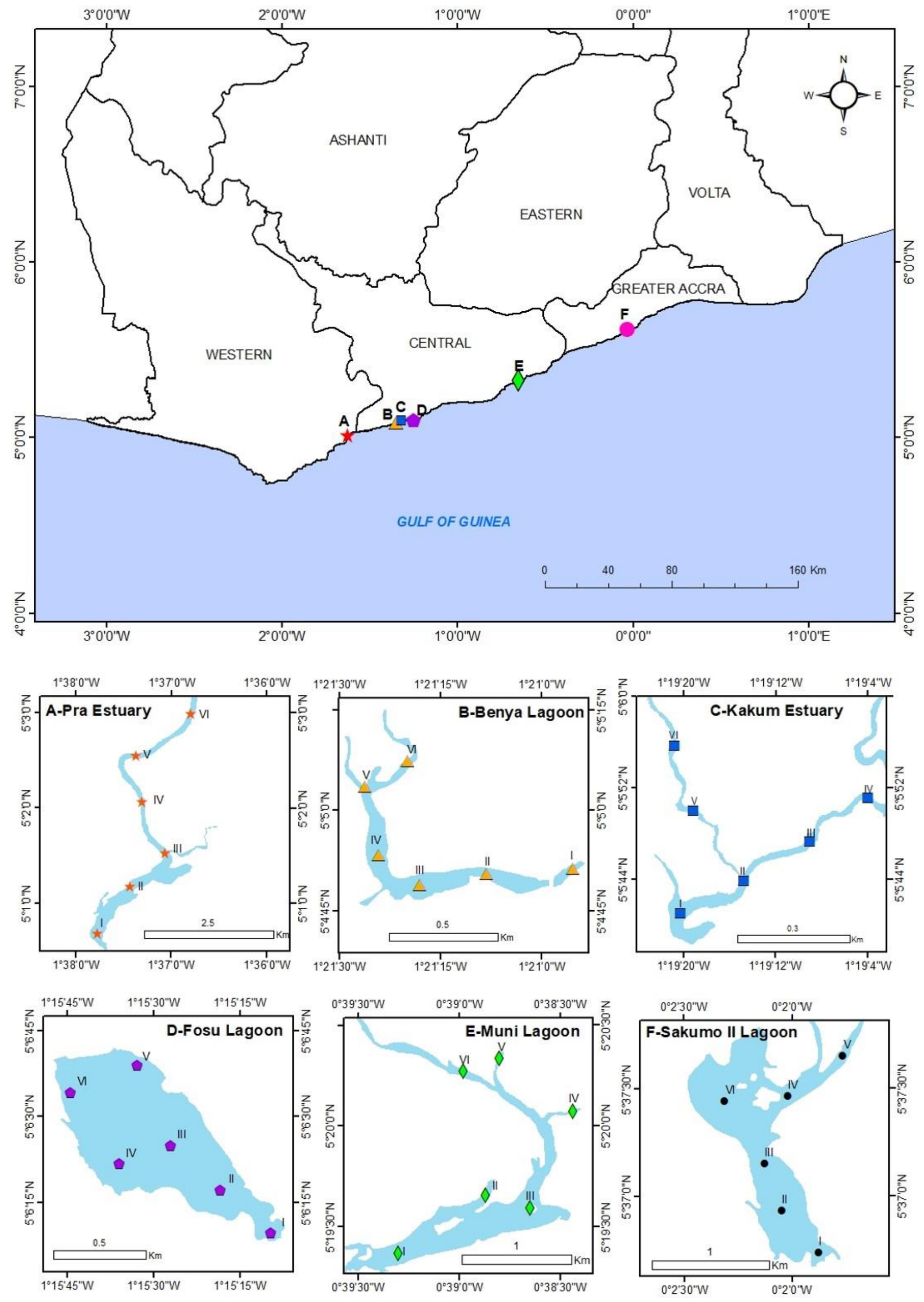

Figure 3.1: Map of southern Ghana showing the six study sites and the sampling stations

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Elmina. This estuary is formed by two rivers: the relatively bigger Kakum River and the Sorowie River, which explains the naming of the estuary after the bigger river (Dzakpasu, 2012). The length of the Kakum River is 47.86 km from its source, the Kakum Forest Reserve. Along the estuary are mangrove species interspersed with other vegetation. The depth of this estuary ranges from 0.18 m to 5 m. It is a source of fish and water for domestic use for communities living along it. Sand winning is common in this estuary as a source of livelihood for the youth. The Kakum Estuary has been described as unpolluted (Biney, 1982; Dzakpasu et al., 2015).

3.1.2 Pra Estuary

The Pra Estuary (5°0'45.01" N, 1°37'43.45" W), the second largest estuary in Ghana, is located in the Shama District of the Western Region. The estuary is formed by the Pra River, which is about 239.8 km long from its source at the highlands of Kwahu Plateau in the Eastern Region. The depth of the estuary ranges between 0.5 m and 10 m depending on the season and location. The estuary is approximately 64.0 km west of Cape Coast and 26.9 km east of Takoradi. It is fringed by mangroves, palm trees and other vegetation types. Aside from fishing, inhabitants engage in farming along the banks of the estuary. Local fishermen dock their canoes close to the mouth of the estuary, where various trading activities (such as selling of fish landings and food) take place. The estuary also serves as a transport route for people commuting between Shama and Anlo beach. Communities along this estuary depend on it for their domestic needs. The inhabitants are fishermen and fish mongers. There have been reports of illegal mining activities upstream. Okyere (2015) documented high siltation in this estuary.

3.1.3 Benya Lagoon

The Benya Lagoon (5°04'59.72" N, 1°21'15.32" W) is a man-made open lagoon located in Elmina in the Komenda-Edina-Eguafo-Abrem (KEEA) Municipality of the Central Region. This lagoon is approximately 0.12 km^2 in size and 0.2 – 3.5 m deep. It is about 7.0 km west of the University of Cape Coast (UCC) West Gate. It is located in the heart of the Elmina fishing harbour making the site a very busy place for boat docking, boat construction, net mending and other business activities such as trading of fish landings. A piggery and two major refuse dumps are situated along this lagoon. Women in the KEEA area are mainly involved in fish processing activities such as smoking, drying and salting for sales. The bank of the lagoon is fringed by mangrove vegetation, settlements and boat construction workshops. Water from this lagoon is directed into salt pans for salt production. Fishing is prohibited in this lagoon on Tuesdays. Biney (1982) reported slight pollution in this lagoon.

3.1.4 Sakumo II Lagoon

The Sakumo II Lagoon (5°37'24.27" N, 0°02'09.69" W) forms part of the Sakumo Ramsar site in the Greater Accra region of Ghana. It is located about 3 km west of Tema, the industrial hub of Ghana, and 1 km east of the Regional Maritime University. The lagoon has a surface area of 1.10 km^2 and depth ranging between 0.1 m and 1.5 m. It is a man-made open lagoon (Yankson & Obodai, 1999) fed by the Mamahuma and the Gbagbla Ankonu streams (Tay et

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al., 2009). Both streams have been dammed to provide water for crop and livestock farming but have become polluted as a result of industrial and domestic activities. Fishermen are usually seen using cast nets in this lagoon. The common vegetation found around the lagoon are *Sesuvium portulacastrum*, *Bothriochloa bladhii*, *Imperata cylindrica* and *Typha domingensis* (Ntiamoa-Baidu & Gordon, 1991). The surface of the water is covered by *Pistia stratiotes* and other vegetation for the most part of the year. There is a closed fishing season in this lagoon from October/November to end of March/early April just before the Kpledjoo festival of the people of Tema (Ntiamoa-Baidu, 1991). Nartey et al. (2012) reported nutrient pollution in this lagoon.

3.1.5 Fosu Lagoon

The Fosu Lagoon (5°06'21.85" N, 1°15'26.64" W) is a classical closed lagoon (Yankson & Obodai, 1999) located in the Cape Coast Metropolis of the Central Region. It is about 0.77 km^2 in size and 0.3 – 2.5 m deep. Within the vicinity of the lagoon are the Cape Coast Metropolitan Hospital and St. Augustine College which discharge wastes directly into the lagoon. Situated along the lagoon is an automobile garage (at Siwdu), which is a constant source of solvents, oils, fuels of various types, acids and alkalis, among others. Drains from the municipality discharge wastes directly into the lagoon. Fishes from this lagoon are reported to be stunted (Blay & Asabere-Ameyaw, 1993; Dankwa et al., 2016). They are caught by cast nets and traps. Mats of mixed vegetation, dominated by *Paspalum vaginatum* and *Typha domingensis* grow around the banks and the shallow sections of the lagoon (Akpabey & Amole, 2015). Dankwa et al. (2016) noted that fishing was done throughout the week in this lagoon even though fishing is prohibited on Tuesdays (Taboo days). This necessitated a one month ban on fishing in the lagoon (in August) just before the Fetu Afahye festival which is usually celebrated in the first week of September. Armah, Luginaah et al. (2012) described the Fosu Lagoon as highly polluted.

3.1.6 Muni Lagoon

The Muni Lagoon (5°20'19.81" N, 0°38'47.70" W) is a classical closed lagoon (Yankson & Obodai, 1999) in the Efutu Municipality of the Central Region. It is located within the Muni-Pomadze Ramsar Site, adjacent the Police Training School in Winneba. The lagoon is approximately 3 km^2 in size with a depth of 0.15 – 2.5 m. The Muni Lagoon serves as a feeding site for migratory birds, one of the reasons for its designation as a Ramsar site. It is a popular fishing ground among artisanal fisher folks from Akosua village and Winneba in the Municipality; who collect crabs and cockles (*Anadara senilis*) from the lagoon for sustenance. People are normally seen collecting oyster shells which is an indication that there used to be a thriving oyster population in the lagoon. The lagoon is closed to fishing activities on Wednesdays. According to Atampugre (2010), the lagoon is fed by two seasonal rivers namely the Aboaku and Pratu. The vegetation along this lagoon is mainly *Avicennia africana* at the eastern fringes and *Sporobolus* spp. and coconut palms (*Cocos nucifera*) on the sand dune which separates the lagoon from the sea. This Muni Lagoon has been reported to be of relatively good quality (Biney, 1982; Tay et al., 2009).

3.2 Sampling Stations

Stratified sampling technique was employed in this present study by dividing the water bodies into stations to order to get a representative sample size. Six sampling stations were demarcated across the length and breadth (where applicable) of each water body. Distances between sampling stations were dependent on the size of the water body; Station I was closest to the sea while station VI farthest from the sea (see Figure 3.1).

3.3 Sampling Period

Sampling was done quarterly from June 2016 to August 2017. Sampling coincided with specific climatic seasons. June and September represent the major and minor wet seasons respectively, December and March mark the onset and end of dry seasons respectively and August represents the coldest month of the year. Sampling was done in the first week of the last month of each quarter, except in the third quarter of 2017 when sampling was done in the last week of the second month due to time constraints. In 2016, sampling was carried out in June, September and December representing the 2nd, 3rd and 4th quarters of 2016 respectively and continued in March, June and August 2017 representing the 1st, 2nd and 3rd quarters of 2017 respectively.

3.4 Data Collection

Data on rainfall were obtained from secondary sources. Anthropogenic activities (such as farming, animal rearing, disposal of waste and sewage, etc.) close to the selected water bodies were documented. Some physico-chemical parameters were measured *in-situ* (see section 3.4.2) while water and sediment

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samples were transported to the laboratory for other analyses. Nitrate and phosphate concentrations were determined in the water samples as the procedure in section 3.4.3. Heavy metals, namely, arsenic, cadmium, chromium, copper, lead, manganese, mercury, nickel, iron and zinc were tested for both the water and sediment samples. Sediment organic matter and mean particle sizes were determined in the laboratory following a standard protocol. Sediment samples were also collected and screened on the field for benthic macroinvertebrates. Samples and measurements were taken in triplicates in order to ensure the validity and reliability of the data collected.

3.4.1 Secondary data

Rainfall data (mm) for the study vicinities were obtained from Tutiempo Network (2018). Data for the Pra Estuary were obtained from the Takoradi weather station. For Benya Lagoon, Kakum Estuary, Fosu Lagoon and Muni Lagoon, data were obtained from the Saltpond weather station while Sakumo II Lagoon rainfall data were obtained from the Tema weather station.

3.4.2 *In-situ* measurements

Temperature (°C), dissolved oxygen (DO) concentration (mg/l), pH, salinity (psu), conductivity (µS/cm) and total dissolved solids (TDS) (ppm) were measured using a multi-parametric water quality checker (HI9829) at every sampling station by lowering the probe to the near bottom and readings taken. Turbidity (NTU) was measured with a turbidimeter (Oakton T-100). All measurements were taken in triplicates at each station on every sampling occasion.

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3.4.3 Nitrate and phosphate determination

Water samples were collected into 500 ml plastic bottles. Three replicate samples were taken at each station in all six water bodies per each sampling quarter. Samples were kept on ice and transported to the laboratory where they were refrigerated at 4 °C and analysed within 3 days of sampling. Nitrate and phosphate were measured using the HACH DR 900 spectrophotometer with the aid of HACH reagents. Blanks were used to check contamination during sample preparation. Before analysis, samples were allowed to warm up to room temperature and filtered through a 110 microns filter paper.

NitraVer 5 reagent powder pillow was used for nitrate analysis. This reagent operates on the principle of cadmium reduction method. A specimen vial was filled with 10 ml of sample and the contents of one NitraVer 5 powder pillow was added. The sample was shaken vigorously for 1 minute and allowed to stand for 5 minutes (Note: an amber colour develops if nitrate-nitrogen is present) while NO_3^--N was selected on the spectrophotometer. Another specimen vial was filled with 10 ml of the same sample (which served as the blank), placed into the cell holder, covered tightly with the equipment cap and zeroed. The prepared sample was then placed in the cell holder, tightly covered with the equipment cap and the concentration read within 2 minutes. NO_3^- was calculated from NO_3^--N by multiplying the reading by 4.427.

PhosVer 3 powder pillow was used in the determination of phosphate based on the molybdovonadate method. The same procedure described for nitrate above was followed except that the reaction time was 2 minutes and PO_4^{3-} was selected on the spectrophotometer. Readings were taken within 2 minutes.

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3.4.4 Heavy metals determination

Heavy metals were determined for both water and sediments in the Chemistry Laboratory of Ghana Atomic Energy Commission (GAEC), Accra.

Water samples for heavy metals analyses were acidified on the field before transporting to the laboratory. Forty (40) ml of sample was poured into a 100 ml borosilicate beaker. Five (5) ml aqua regia was added in the ratio of 4.5 ml concentrated HCl to 0.5 ml concentrated HNO_3 in a fume chamber. The beaker was covered with a cling film, placed on a hot plate and digested at a temperature of 45 °C for 3 hours. The sample was then transferred into a 100 ml measuring cylinder and topped to the 30 ml mark with distilled water. The whole content was transferred into a test tube for analysis.

Sediment samples for heavy metals were dried and sieved prior to analysis. One gramme (1 g) of the dried and sieved sample was put into a 100 ml borosilicate beaker followed by the addition of 25 ml aqua regia in the ratio of 3 ml conc. HCl to 1 ml conc. HNO_3 in a fume chamber. The sample was placed on a hot plate and digested for 3 hours at a temperature of 45 °C. The digested sample was transferred into a 100 ml measuring cylinder and topped to the 30 ml mark with distilled water. The whole content was transferred into a test tube for analysis. This technique of exposing the sample to a strong acid and moderate temperature leads to a thermal decomposition of the sample and the solubility of heavy metals in solution.

The digestates for both water and sediment samples were then assayed for the presence of arsenic, cadmium, chromium, copper, lead, manganese, mercury, nickel, iron and zinc using VARIAN AA 240FS – Atomic Absorption Spectrometer (AAS) in an acetylene-air flame.

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Reference standards used for the elements of interest, blanks and duplicates of samples were digested under the same conditions as the samples. Reference standards used were product of Switzerland from Fluka Analytical, Sigma-Aldrich Chemie GmbH. They were to ensure efficiency of the equipment. Blanks were used to check contamination during sample preparation. Measurements were done in duplicates to guarantee reproducibility. These served as internal positive controls.The final concentration of each heavy metal in the water samples was determined as

$$Final\ concentration\ (mg/l) = \frac{Concentration\ (df) \times Nominal\ volume}{Sample\ volume}$$

where nominal volume refers to volume after digestion (final volume).

Similarly, final concentration of each heavy metal in the sediment samples was determined as

$$Final\ concentration\ \left(\frac{mg}{kg}\right) = \frac{Concentration\ (df) \times Nominal\ volume}{Sample\ weight}$$

where nominal volume refers to volume after digestion (final volume). Recommended instrument parameters and working conditions of the AAS used are shown in Table 3.1.

Results from the heavy metals analysed were compared to the permissible limits set by the World Health Organisation (WHO)/United State Environmental Protection Agency (USEPA) as shown in Table 3.2.

Table 3.1 - *Recommended Instrument Parameters and Working Conditions of the AAS*

Element	Wavelength (nm)	Lamp current (mA)	Slit width (nm)	Fuel	Support	DL
As (By Hydride)	193.7	10	0.5	Argon	Nitrous oxide	<0.001
Cd	228.8	4	0.5	Acetylene	Air	<0.002
Cr	357.9	7	0.2	Acetylene	Air	<0.003
Cu	324.7	4	0.5	Acetylene	Air	<0.003
Fe	248.3	5	0.2	Acetylene	Air	<0.006
Hg (By Hydride)	253.7	4	0.5	Acetylene	Air	<0.001
Mn	279.5	5	0.2	Acetylene	Air	<0.002
Ni	341.5	5	0.2	Acetylene	Air	<0.001
Pb	217	5	1	Acetylene	Air	<0.001
Zn	213.9	5	1	Acetylene	Air	<0.001

DL = detection limit

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Table 3.2 - *WHO/USEPA Maximum Permissible Limits of Heavy Metals in Water and Sediment*

Heavy metal	**Water (mg/l)**	**Soil/Sediment (mg/kg)**
Arsenic	0.1	20
Cadmium	0.01	6
Chromium	0.1	25
Copper	2.0	25
Iron	1.0	17000
Lead	0.05	40
Manganese	0.2	300
Mercury	0.002	0.3
Nickel	0.2	20
Zinc	5.0	90

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3.4.5 Sediment organic matter (OM) content determination

Sediment samples were dried to a constant weight at a temperature of 105 °C. Debris were handpicked from the dried sediments where necessary and the samples sieved through a 2 mm sieve. Ten grammes (10 g) of the dried and sieved sediments was placed in a furnace at 550 °C for 4 hours to burn off the organic matter. After cooling in a desiccator, the sediments were weighed and the loss in weight was recorded as “weight loss on ignition”. The percentage organic matter content was then calculated as:

$$\text{OM content (\%)} = \frac{\text{Weight loss on ignition (g)}}{\text{Weight of dry soil (g)}} \times 100$$

3.4.6 Sediment mean particle size (MPS) determination

Composite samples were taken out of the triplicate samples at each station. In the laboratory, a known weight of air-dried samples were poured into a 0.0625 mm (63 µm) mesh sieve and washed thoroughly with 10 % sodium hydroxide solution to break the bonds between the particles. Particles finer than 63 µm were washed through leaving the bigger sizes on the sieve. Samples left were washed into pre-weighed beakers and dried in an oven at 105 °C until a constant weight was attained. Dried samples were again weighed (the weight loss accounts for particles less than 63 µm) and sieved through a set of sieves of different mesh sizes (2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm and 0.0625 mm) and a collector (pan) at the base. Samples retained within each sieve were collected, weighed and recorded. Particles smaller than all the sieves were retained in the pan. The weight of each sieve fraction was calculated as a percentage of the original soil sample used as indicated in the equation:

$$\text{Composition of sieve content (\%)} = \frac{\text{Weight of sieve content}}{\text{Weight of dry sample}} \times 100$$

With the known percentage compositions of the various sieve contents, MPS were determined using the calculation method developed by Yankson (2000) as:

$$\text{MPS} = \frac{\sum(\bar{x}.Y)}{100}$$

where, $\bar{x}$ = mean size of the soil separates (mm) and Y = corresponding percentage composition.

MPS obtained were compared to the Wentworth classification of particle grades as shown in Table 3.3 to determine the corresponding particle grade size.

3.4.7 Benthic macroinvertebrates

Benthic macroinvertebrates samples were collected using a 15 cm × 15 cm Ekman grab. The samples were screened through a set of sieves (2 mm, 1 mm and 0.5 mm) with the larger meshed sizes stacked above the smaller ones, preserved in formalin and stained with eosin to aid sorting. Organisms collected were identified to the lowest possible taxonomic level using a dissecting microscope with the aid of some identification keys (Macan, 1959; Day, 1967; Edmunds, 1978; Yankson & Kendall, 2001; Gerber & Gabriel, 2002; Al-yamani et al., 2012).

Table 3.3 - *Wentworth Classification of Particle Grades and Phi Scale*

Grade name	Particle size range (mm)	Particle size range (Phi units)
Boulder	> 256	< -8.0
Cobble	64 – 256	-8.0 to -6.0
Pebble	4 – 64	-6.0 to -2.0
Granule	2 – 4	-2.0 to -1.0
Very coarse sand	1 – 2	-1.0 to 0
Coarse sand	0.5 – 1	0 to 1.0
Medium sand	0.25 – 0.5	1.0 to 2.0
Fine sand	0.125 – 0.25	2.0 to 3.0
Very fine sand	0.0625 – 0.125	3.0 to 4.0
Silt	0.0039 – 0.0625	4.0 to 8.0
Clay	< 0.0039	> 8.0

Source: Tait and Dipper (1998)

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3.4.8 Functional traits categorisation

The benthic macroinvertebrates identified were categorised into six functional traits using some available literature (Day, 1967; Afinowi, 1975; Yankson & Kendall, 2001; Gerber & Gabriel, 2002; Lamptey, 2015) and some web sources (Animal Spot, 2018; Hammond, 2009; MarLIN, 2006; Missouri Department of Conservation, n.d.; Non-Annual Killifish, 2017; Ramel, n.d.; The Columbia Encyclopedia, 2016). Traits categorisation was adopted and modified from Bremner et al. (2003) and Lamptey (2015).

The functional traits considered were body form, feeding habit, mobility, sexuality and sociability. For every species, information was assigned in each trait category. Under each trait category, organisms were assigned groups; for example, functional groups such as deposit feeder, carnivore, filter feeder, etc. were assigned under the trait feeding habit (Table 3.4).

3.6 Data Analyses

The various parameters studied in the six water bodies were analysed as indicated below.

3.6.1 Physico-chemical parameters

Means were computed quarterly for each water body, and results presented in box-and-whisker plots (readings of six sampling stations were pooled per quarter for each water body). For every parameter, one-way analysis of variance (ANOVA) was ran to test for significant differences across water bodies and sampling quarters. Tukey’s post hoc tests were performed to confirm where the differences occurred.

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Table 3.4 - *Trait Categorisation of the Macroinvertebrates*

Functional trait	**Categories**
Mobility	Burrow
	Crawl
	Swim
	Sessile
	Tube building
Body form	Cylindrical
	Laterally compressed
	Elongate
	Vermiform
	Fusiform
	Sausage-shaped
	Threadlike
	Conical
	Triangular
Feeding habit	Carnivore
	Omnivore
	Deposit feeder
	Filter feeder
	Scavenger
	Predator
Sexuality	Hermaphrodite
	Gonochorist
Sociability	Solitary
	Colonial
	Commensal

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3.6.2 Heavy metals concentrations

Means and standard errors were computed for heavy metals concentrations, both for sediment and water column and the results represented in Tables. One-way ANOVA were ran in SPSS to test for differences in mean concentrations within the water bodies and sampling quarters at 95 % confidence interval. Where significant differences occurred, Tukey's post hoc tests were performed.

3.6.3 Sediment organic matter and mean particle sizes (MPS)

For sediment organic matter, means were computed quarterly for each water body, and results presented in box-and-whisker plots. MPS was computed for each sampling quarter and results presented in a Table. One-way ANOVA and where necessary, Tukey's post hoc tests were performed to determine differences in mean organic matter and MPS within the water bodies and the sampling quarters.

3.6.4 Benthic macroinvertebrates

Data on macroinvertebrates were cleaned and all rare species which could potentially introduce 'noise' in the analyses were eliminated (Lamptey, 2015). Species considered rare were those that were encountered only once (with < 5 individuals) out of the six sampling quarters.

Percentage compositions were computed for the benthic macroinvertebrates taxonomic and functional groups in the six water bodies.

Species and functional richness were computed by counting the number of species and functional groups respectively.

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For further analysis, data on macroinvertebrates were fourth root transformed to stabilise and normalise the variance. Species diversity was computed using Shannon Wiener index (H') in PRIMER v6 package based on the formula:

$$H' = -\sum_{i=1}^{s} \mathrm{p_i} \ \mathrm{In} \ \mathrm{p_i}$$

s = number of species recorded, and pi = proportions of the i^{th} species. Functional diversity was also computed by adopting Shannon-diversity index (Heino, 2005; Bazzanti, Della Bella & Grezzi, 2009; Uwadiae et al., 2012).

The similarity between water bodies based on species composition and abundance was determined with Bray-Curtis similarity index in PRIMER v6 package. Site classification was achieved using complete linkage. Similarity Profile test (SIMPROF) was ran to identify and test for significant similarities in macroinvertebrate communities within the six water bodies. Similarities between water bodies was also determined based on functional groups with the same procedure used for taxonomic groups.

Prior to determining the impact of abiotic factors on species and functional groups, Similarity profile (SIMPER) was performed in PRIMER v6 package to select species/functional groups that contributed most to the similarities in the water bodies.

Negative binomial regression in Stata 13.0 was used to predict the relationship between abiotic factors and the abundance of species and functional groups selected in the SIMPER analysis. Negative binomial regression was found suitable for this analysis because the benthic macroinvertebrates abundance, which is the response variable, was counted and not measured. Also, negative binomial regression was chosen because of the over-dispersed nature of the data. Two multivariate models were ran:

- Model 1 was ran to determine the influence of physico-chemical parameters, sediment MPS and organic matter content on benthic macroinvertebrates abundance in the water bodies.
- Model 2 was ran to determine the influence of parameters in Model 1, in addition to heavy metals on benthic macroinvertebrates abundance in the water bodies.

Similar models were used to predict the influence of abiotic factors on functional groups.

3.7 Chapter Summary

This chapter provides information on the six water bodies studied. Sampling protocols were also described here. Samples and measurements were replicated to ensure sample sizes were representative enough and also to avoid sampling errors. Also, as indicated earlier, sampling for 3rd quarter 2017 was done in August instead of September due to time constraints. Some sampling stations were not accessible during the 2nd and 3rd quarters of 2017 due to flooding and outgrowth of aquatic weeds. Heavy metals analyses were done at GAEC. Quality assurance measures were put in place to ensure the wholesomeness of data collected. Appropriate statistical analyses utilized were described in this chapter for easy comparison of results across water bodies and also to make reliable inferences.

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CHAPTER FOUR

RESULTS

This study assesses the influence of some abiotic factors on benthic macroinvertebrate communities and their functional traits. The previous chapter described the study areas, methods for data collection and analyses. The results of this research are presented under various sections in this chapter. Sampling periods are denoted by 2nd Q. 2016, 3rd Q. 2016, 4th Q. 2016, 1st Q. 2017, 2nd Q. 2017 and 3rd Q. 2017.

4.1 Anthropogenic Activities within the Study Areas

Table 4.1 shows a record of anthropogenic activities observed within the catchment area of the water bodies during the study period. The Kakum Estuary experiences minimal human activities while illegal mining activities go on upstream of the Pra Estuary. The Benya, Sakumo II and Fosu lagoons were observed serving as direct receptacles for untreated sewage from adjoining communities. The Fosu Lagoon is also exposed to activities at the automobile shop. Animal rearing along the fringes of the water bodies was common except the Muni Lagoon.

4.2 Total Rainfall Values (mm)

Rainfall values from Tutiempo Network (2018) for the study vicinities are presented in Table 4.2. Higher rainfall values were recorded in the vicinities of the Benya Lagoon, Kakum Estuary, Fosu Lagoon and Muni Lagoon in the 3rd quarter of 2016, followed by the 2nd quarter of 2017 than the rest of the

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Table 4.1 - *Possible Impacts on the Water Bodies*

Water body	**Location**	**Direct sewage**	**Animals**	**Comments**
Kakum Estuary	Cape Coast (Cape Coast Metropolis)	-	+	Formed by two rivers, presence of piggery, minimal fishing activities
Pra Estuary	Shama/Anlo beach (Shama District)	-	+	Mining and farming activities upstream, water looks turbid
Benya Lagoon	Elmina (KEEA District)	+	+	Fishing harbour with intense human activities, presence of piggery, salt pans and refuse dumps, closed fishing day is Tuesday
Sakumo II Lagoon	Tema (Tema Metropolis)	+	+	Feeding site for cattle, invasive weeds covering surface of water, farming activities on the banks, numerous plastic bags
Fosu Lagoon	Cape Coast (Cape Coast Metropolis)	+	+	Situated close to a huge automobile shop, drainage pipe directed into the lagoon, presence of piggery, minimal fishing activities, closed fishing season in August/September
Muni Lagoon	Winneba (Effutu Municipal)	-	-	Mangrove restoration activities ongoing, minimal fishing activities

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Table 4.2 - *Total Quarterly Rainfall Values (mm) Recorded in the Vicinities of the Water Bodies during the Study Period*

Water body	**Work station**	**2nd Q. 2016**	**3rd Q. 2016**	**4th Q. 2016**	**1st Q. 2017**	**2nd Q. 2017**	**3rd Q. 2017**
Kakum Estuary	Saltpond	54.62	252.98	0.51	5.08	145.54	30.99
Pra Estuary	Takoradi	89.66	18.03	0.00	41.14	247.42	9.40
Benya Lagoon	Saltpond	54.62	252.98	0.51	5.08	145.54	30.99
Sakumo II Lagoon	Tema	53.59	44.70	6.10	25.15	222.01	12.45
Fosu Lagoon	Saltpond	54.62	252.98	0.51	5.08	145.54	30.99
Muni Lagoon	Saltpond	54.62	252.98	0.51	5.08	145.54	30.99

Source: Tutiempo Network (2018)

period. Higher rainfall was recorded in the Sakumo II Lagoon and Pra Estuary vicinities in the 2nd quarter of 2017 compared to the rest of the period. Generally, the least rainfall values were obtained in the 4th quarter of 2016.

4.3 Physico-chemical Parameters in the Six Water Bodies

Variations in temperature, salinity, conductivity, DO, pH, turbidity, TDS, nitrate and phosphate in each of the water bodies during the study period are presented in box-and-whisker plots. The minimum and maximum values for the various parameters are presented in Appendix A. ANOVA at 95 % confidence interval and Tukey's post hoc tests showing the differences in the various parameters across the water bodies and sampling quarters are presented as Appendices B and C.

4.3.1 Temperature

Generally, temporal variations in temperature occurred in all the water bodies, with the highest values recorded mostly in the 1st quarter of 2017 and the lowest values in the 3rd quarter of 2016 and 2017 (Figure 4.1). Variations were statistically significant across water bodies and sampling quarters ($p < 0.05$). Tukey's post hoc test indicated significantly high temperature values in the 1st quarter of 2017 and low values in the 3rd quarter of 2017 (Appendix C2). Significantly high values were obtained in the Muni Lagoon while low values were obtained in the Kakum Estuary (Appendix C1). Mean temperature ranges were 24.85 – 29.11 °C for Kakum Estuary, 26.70 – 29.04 °C for Pra Estuary, 23.62 – 30.93 °C for Benya Lagoon, 26.48 – 30.91°C for Sakumo II Lagoon, 28.58 – 31.71 °C for Fosu Lagoon and 26.33 – 33.36 °C for Muni Lagoon.

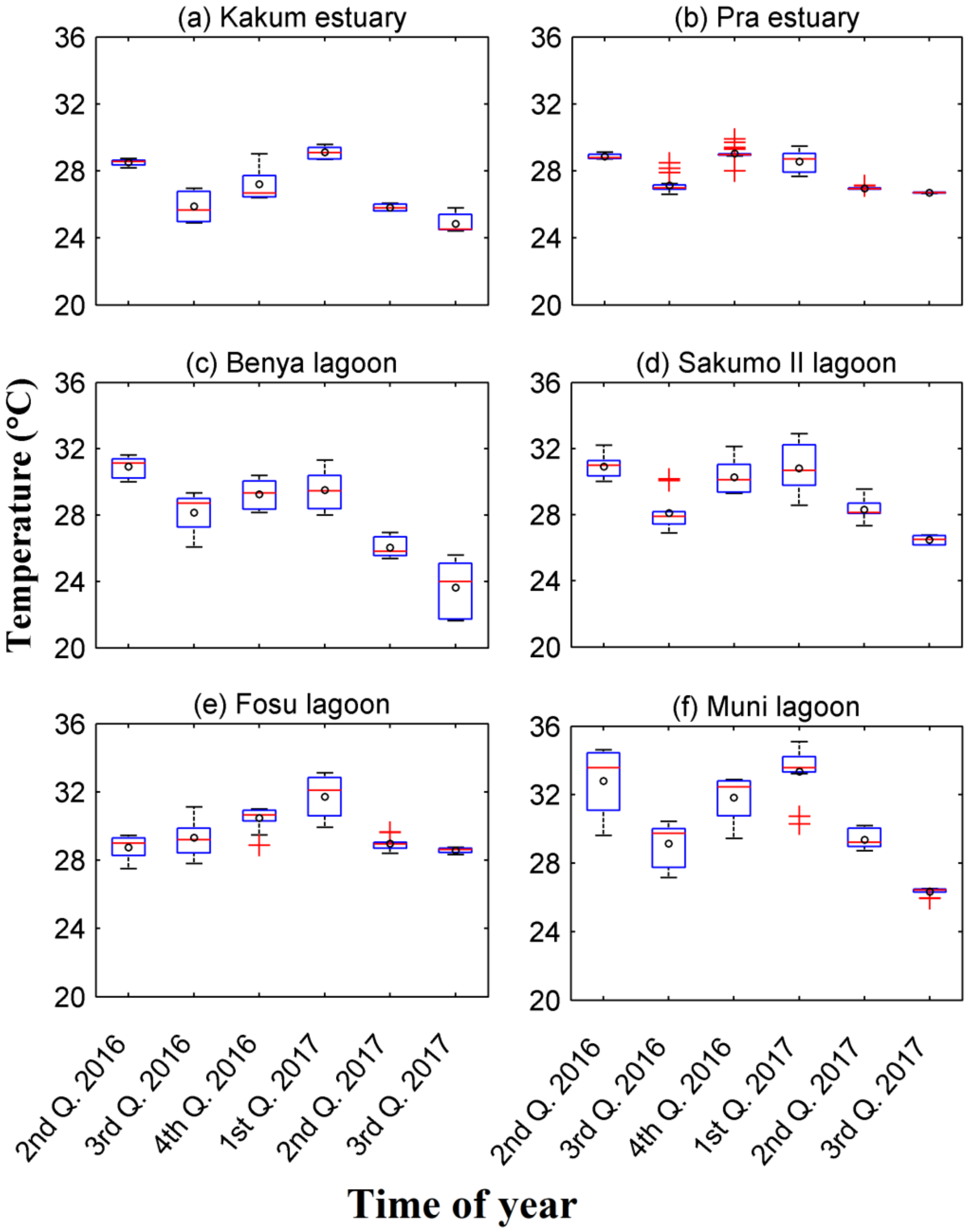

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Figure 4.1: Quarterly variations in temperature (°C) in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ° indicates means)

4.3.2 Salinity

Salinity was generally low (< 8 ppt) in the Pra Estuary, Sakumo II Lagoon and Fosu Lagoon (Figure 4.2). The highest values (mostly around 30 ppt) were recorded in Benya and Muni lagoons. Significant spatial and temporal variations were recorded at $p < 0.05$ (Appendix B). Tukey's post hoc test confirmed significantly higher values in the Benya and Muni lagoons while the lowest values were in the Pra Estuary, Sakumo II and Fosu lagoons (Appendix C1). The 1st quarter of 2017 had the highest salinity values (Appendix C2). Temporal variations were more pronounced in Kakum Estuary and Muni Lagoon. Mean salinity ranges for the six water bodies were 0.13 – 25.25 ppt for Kakum Estuary, 0.04 – 7.96 ppt for Pra Estuary, 4.23 – 30.46 ppt for Benya Lagoon, 0.43 – 5.5 ppt Sakumo II Lagoon, 2.11 – 7.50 ppt for Fosu Lagoon and 6.55 – 38.25 ppt for Muni Lagoon.

4.3.3 Conductivity

Generally, low and fairly stable conductivity (< 100 µS/cm) was recorded in Benya and Muni lagoons than the rest of the water bodies (Figure 4.3). Significant variations in conductivity were recorded temporally and spatially at $p < 0.05$ (see Appendix B). Conductivity in the Fosu Lagoon was significantly higher than the rest of the water bodies as indicated in the post hoc test (Appendix C1). The Kakum Estuary, Pra Estuary and Fosu Lagoon showed marked temporal variations. The post hoc test also indicated higher values in the 4th quarter of 2016 than the rest of the period (Appendix C2).

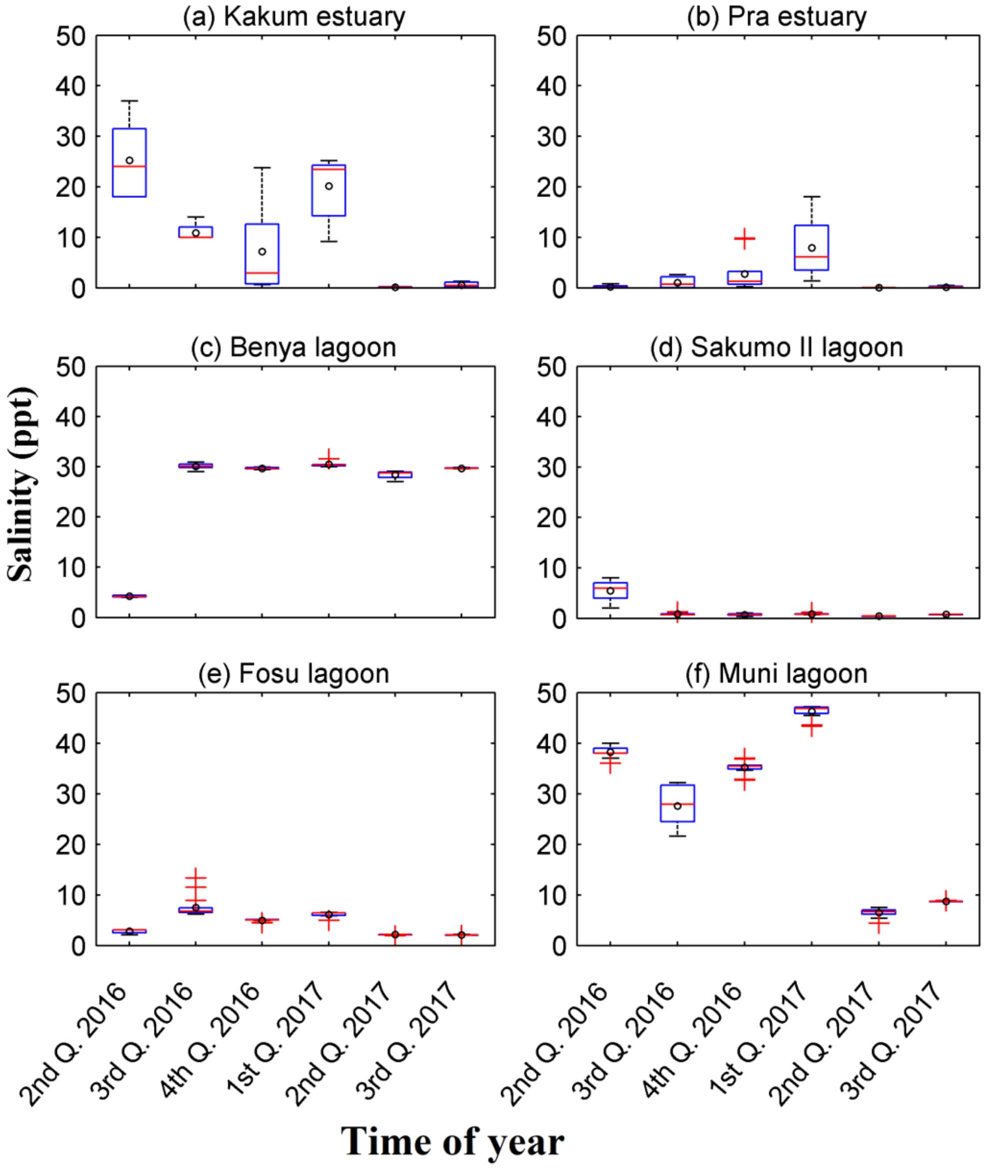

Figure 4.2: Quarterly variations in salinity in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ᵒ indicates means)

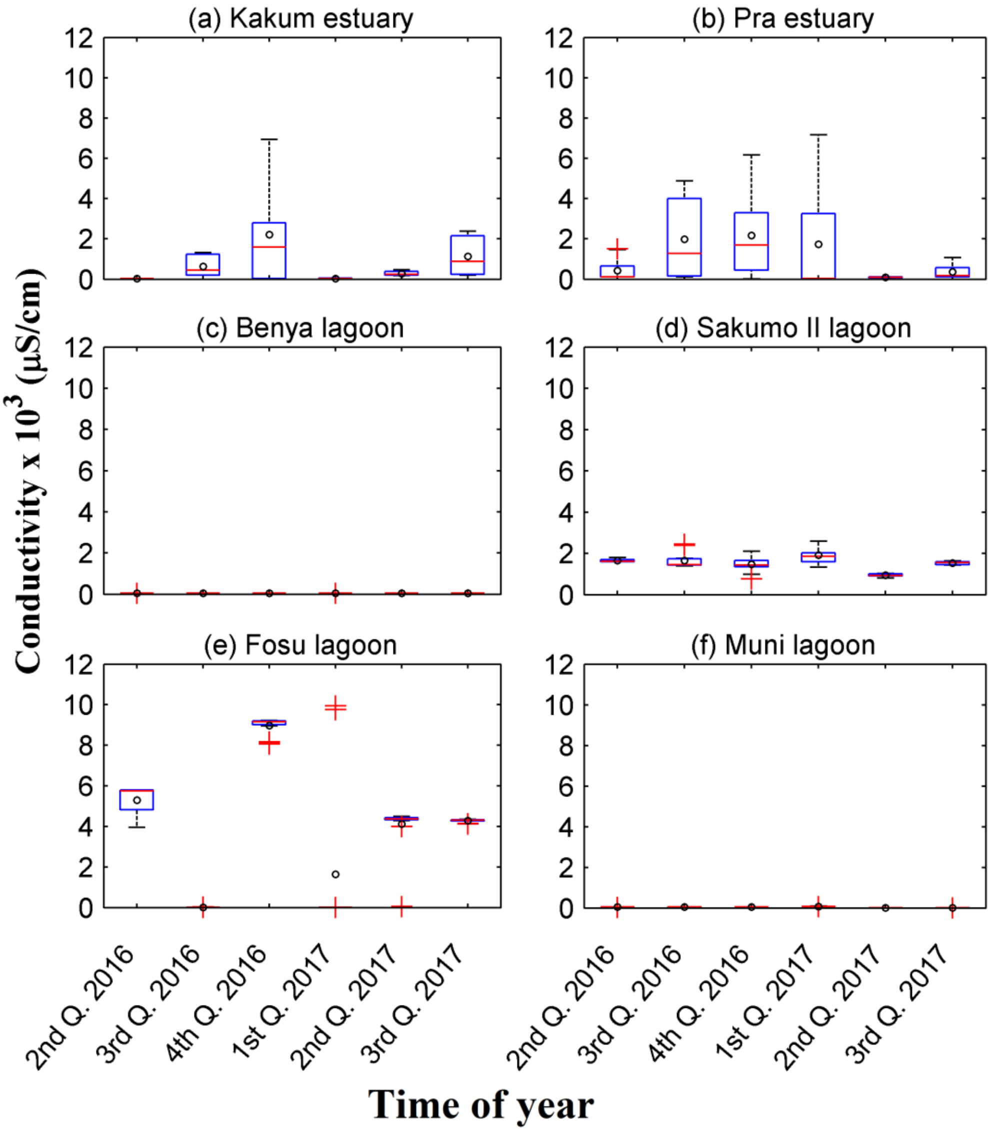

Figure 4.3: Quarterly variations in conductivity in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ° indicates means)

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4.3.4 Dissolved oxygen (DO) concentration

From figure 4.4, marked temporal variations were recorded in all the water bodies with values fluctuating among the sampling quarters. DO values were generally low in the 3rd quarter of 2016 and the 1st quarter of 2017. ANOVA showed DO variations recorded both spatially and temporally were significant at $p < 0.05$ (Appendix B). Values obtained in the 4th quarter of 2016 were significantly higher ($p < 0.05$) than the rest of the period (Appendix C2). Mean DO ranges obtained were 2.79 – 6.07 mg/l, 2.07 – 6.92 mg/l, 1.90 – 5.92 mg/l, 2.16 – 5.91 mg/l, 2.13 – 9.23 mg/l and 2.44 – 9.83 mg/l for Kakum Estuary, Pra Estuary, Benya Lagoon, Sakumo II Lagoon, Fosu Lagoon and Muni Lagoon respectively.

4.3.5 pH

There was a general increasing trend of pH from the 2nd quarter of 2016 to the 1st quarter of 2017, then a decline in the 2nd and 3rd quarters of 2017 (Figure 4.5). ANOVA in Appendix B showed pH variations were significant, both spatially and temporally ($p < 0.05$). Higher values were recorded in the 1st quarter of 2017 than the rest of the periods (Appendix C2). Temporal variations were distinct in all the water bodies except Benya Lagoon. Generally, high mean values (7.26 – 8.96 and 7.35 – 8.54 respectively) were observed in Fosu Lagoon and Muni Lagoon (see post hoc test in Appendix C1). The ranges for the rest of the water bodies were 6.40 – 7.73 for Kakum Estuary, 6.33 – 7.73 for Pra Estuary, 7.34 – 7.73 for Benya Lagoon and 6.72 – 8.09 for Sakumo II Lagoon.

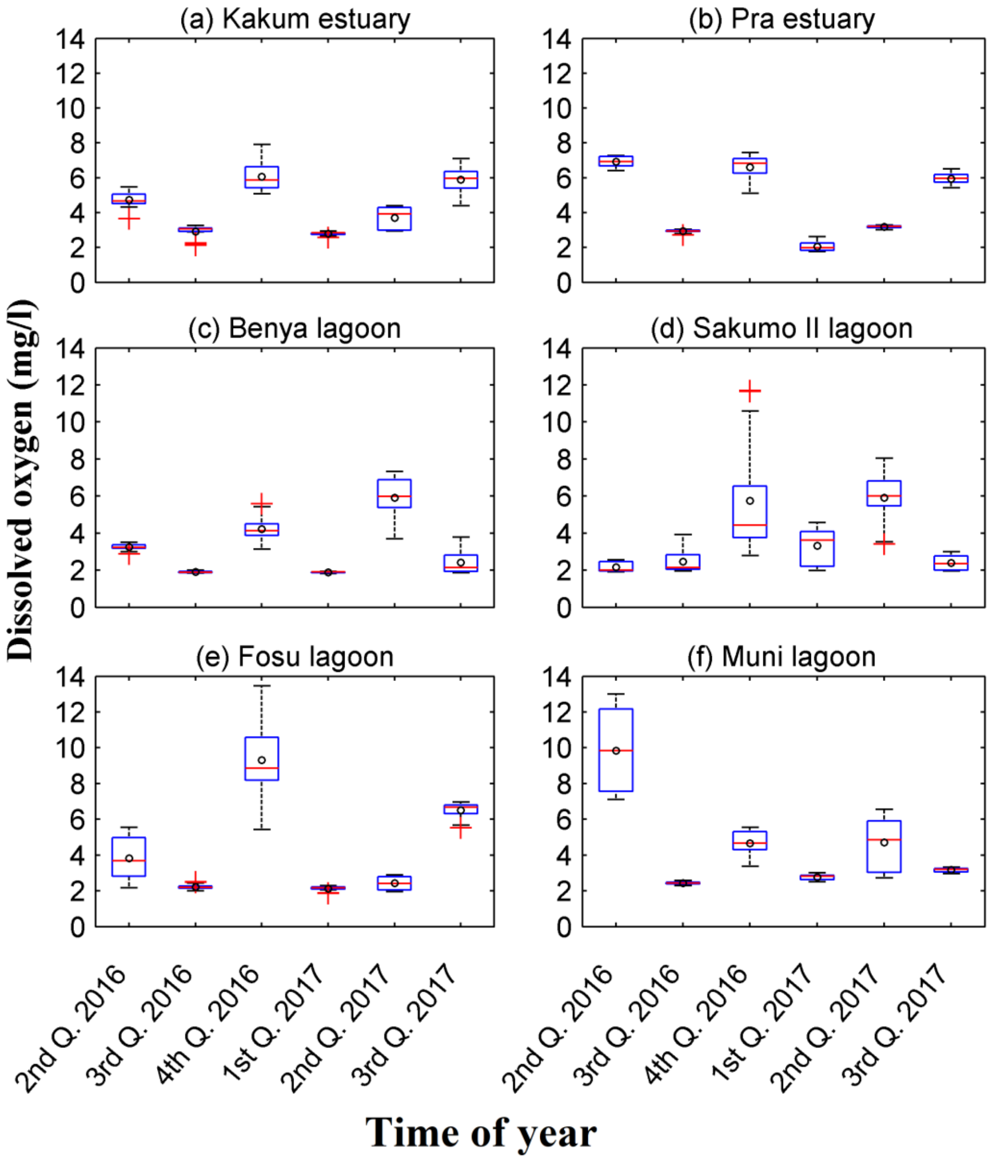

Figure 4.4: Quarterly variations in DO concentrations in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ᵒ indicates means)

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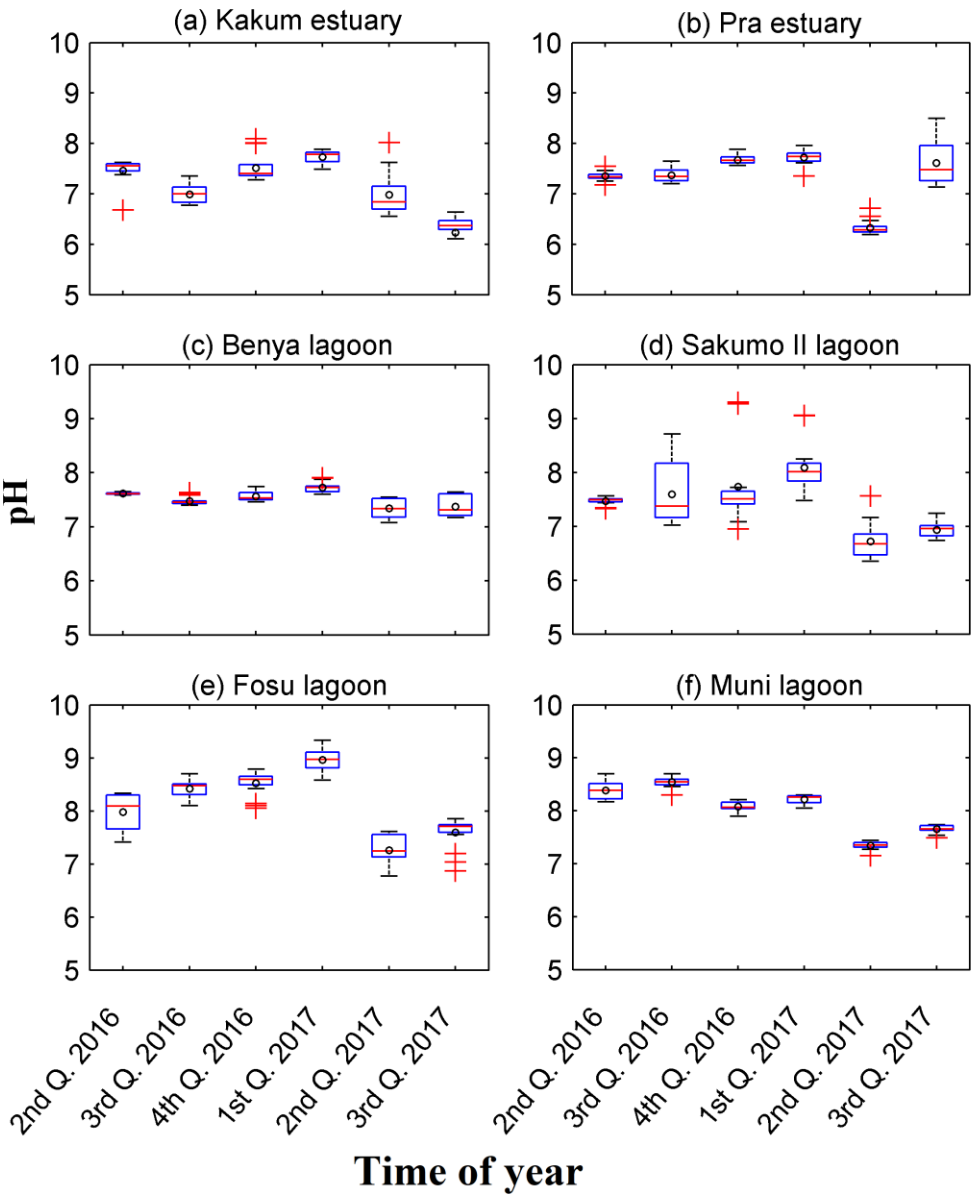

Figure 4.5: Quarterly variations in pH in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ᵒ indicates means)

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4.3.6 Turbidity

Mean values were higher (86.1 – 755.92 NTU) in Pra Estuary compared to the other five water bodies which had values < 125 NTU except in the 2nd quarter of 2016 in Sakumo II Lagoon when 349.93 NTU was recorded (Figure 4.6). Differences in turbidity across water bodies and sampling quarters were significant at $p < 0.05$ (Appendix B). Post hoc confirmed the Pra Estuary had significantly higher turbidity values than the other five water bodies (Appendix C1). Significantly higher values were obtained in the 2nd and 3rd quarters of 2016 compared to the rest of the periods in all the water bodies (Appendix C2).

4.3.7 Total dissolved solids (TDS)

Comparatively higher mean TDS values ranging from 2003.44 to 6252.67 ppm were recorded in Fosu Lagoon while the rest of the water bodies recorded values mostly below 2000 ppm (Figure 4.7). However, in Pra Estuary, mean TDS of 2687.09 ppm was recorded in the 1st quarter of 2017, while in Muni Lagoon, 5771.11 ppm and 7522.33 ppm were recorded in the 2nd and 3rd quarters of 2017, respectively. ANOVA in Appendix B showed significant differences across water bodies and sampling quarters ($p < 0.05$). The Fosu Lagoon had significantly higher values ($p < 0.05$) than the rest of the water bodies (Appendix C1). Also, significantly low values were obtained in the 2nd quarter of 2016 (Appendix C2). With the exception of Benya and Sakumo II lagoons, temporal variations were evident in many of the water bodies studied.

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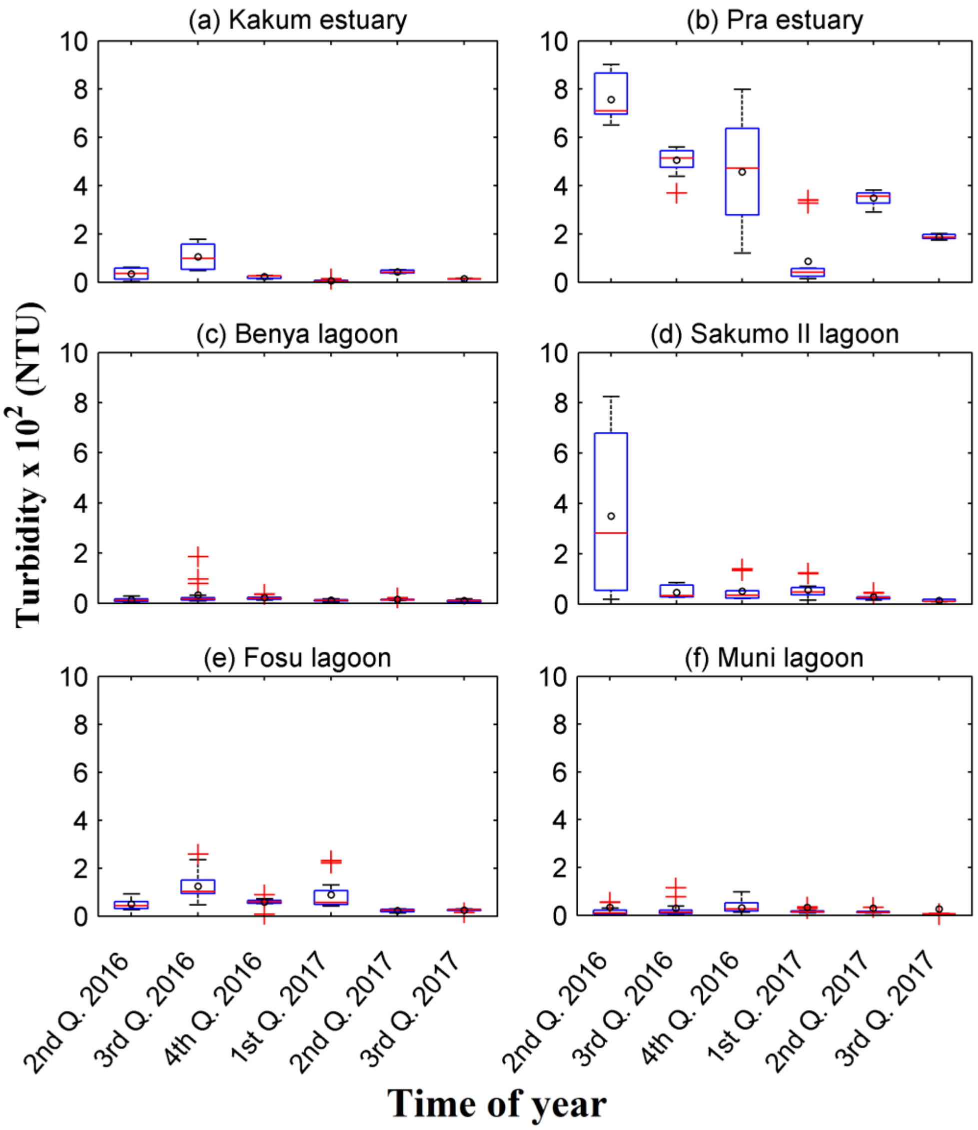

Figure 4.6: Quarterly variations in turbidity in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ᵒ indicates means)

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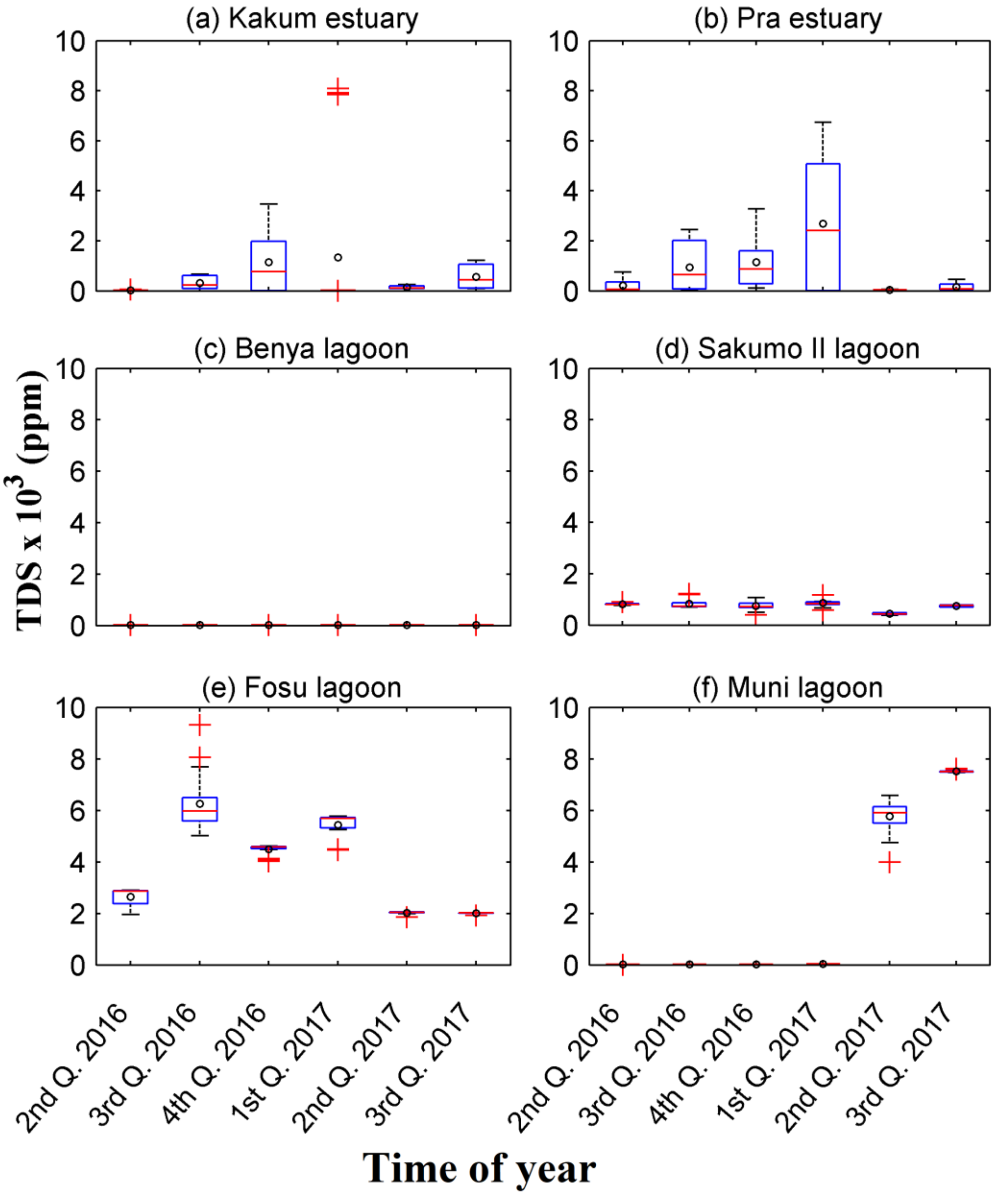

Figure 4.7: Quarterly variations in total dissolved solids (TDS) in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ° indicates means)

4.3.8 Nitrate

Mean nitrate values were generally < 10 mg/l in all the water bodies (Figure 4.8). However, 11.62 mg/l was recorded in the 3rd quarter of 2016 in the Fosu Lagoon. Also, in Sakumo II Lagoon, 12.1 mg/l, 16.56 mg/l and 19.12 mg/l were recorded in the 2nd and 3rd quarters of 2016 and the 3rd quarter of 2017 respectively. Spatial and temporal variations were significant ($p < 0.05$) (Appendix B). Tukey's post hoc test indicated higher values in the Sakumo II Lagoon than the rest of the water bodies (Appendix C1). Similarly, significantly high values were obtained in the 3rd quarters of 2016 and 2017 (Appendix C2). Temporal fluctuations were most distinct in the Sakumo II Lagoon.

4.3.9 Phosphate

Mean phosphate values were below 2.1 mg/l for all the water bodies with the exception of Sakumo II Lagoon (Figure 4.9). In this lagoon, mean values were above 3.5 mg/l except for the 2nd quarters of 2016 and 2017 when 0.08 mg/l and 1.25 mg/l respectively, were recorded. The mean phosphate value was as high as 29.57 mg/l in the 1st quarter of 2017 in Sakumo II Lagoon. Significant differences were recorded at $p < 0.05$ across water bodies and sampling quarters from the ANOVA results (Appendix B). Tukey's post hoc test indicated higher values in the 1st quarter of 2017 compared to the rest of the period (Appendix C2). Also, the values in Sakumo II Lagoon were significantly higher than the rest of the water bodies (Appendix C1).

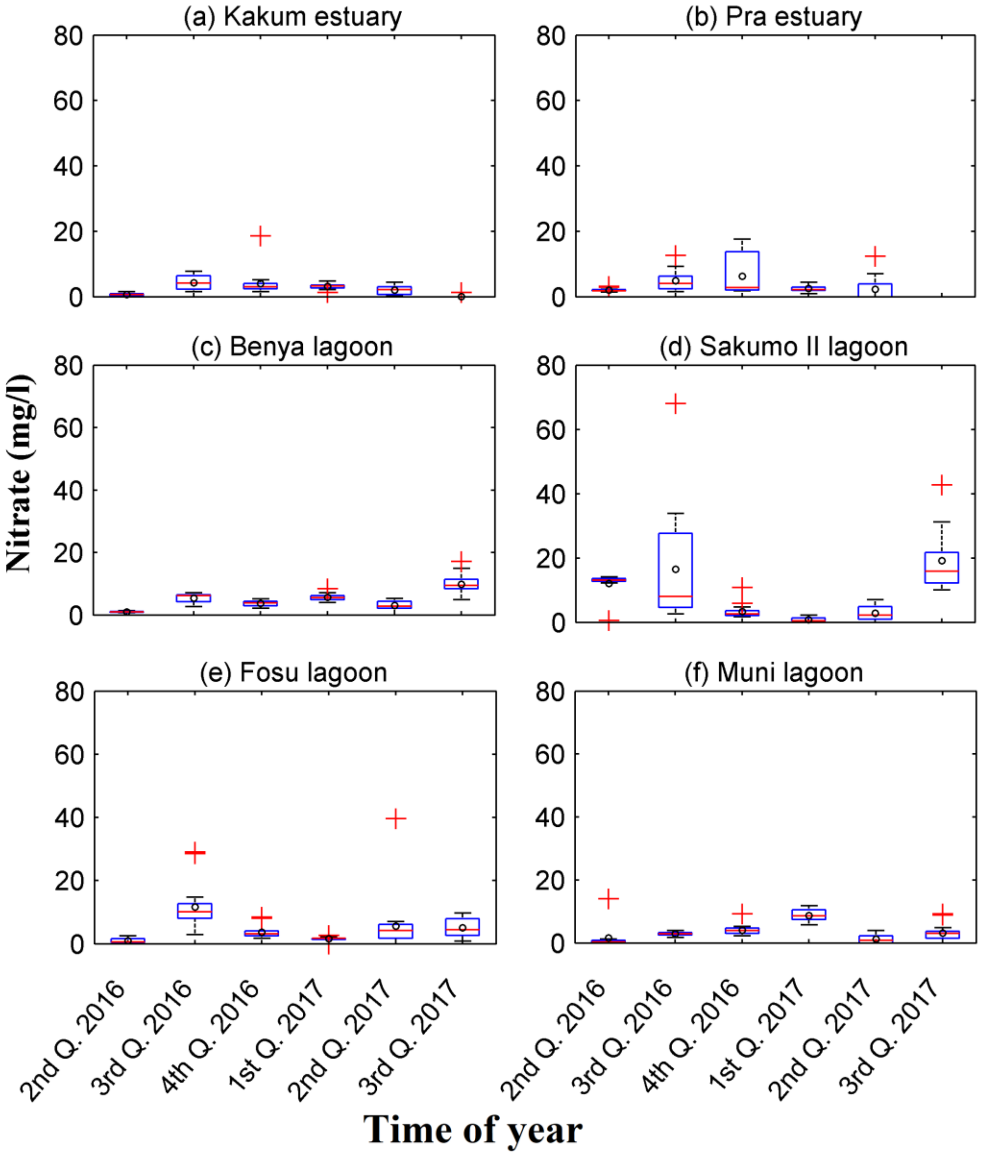

Figure 4.8: Quarterly variations in nitrate concentrations in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; º indicates means)

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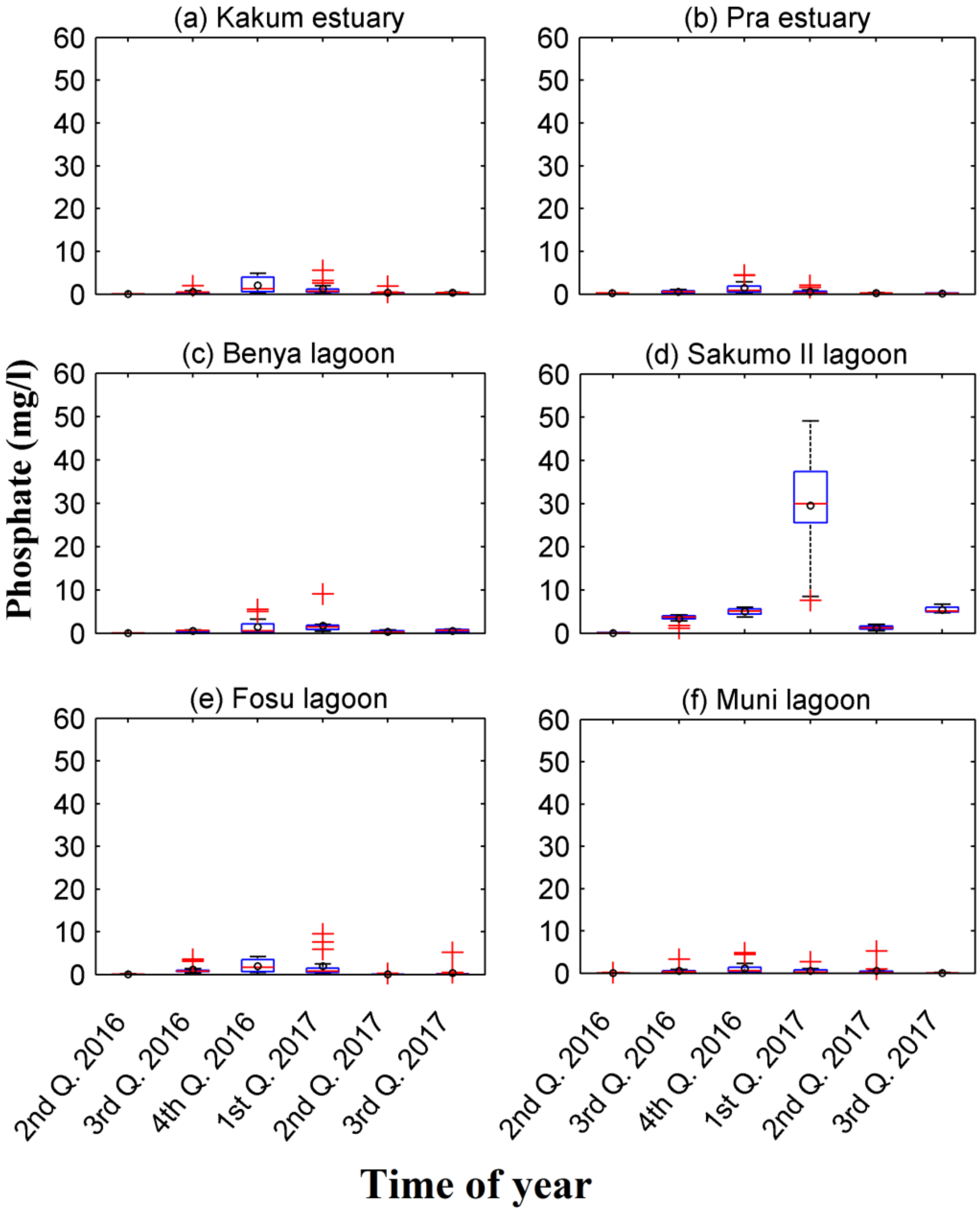

Figure 4.9: Quarterly variations in phosphate concentrations in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ° indicates means)

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4.4 Heavy Metals Concentrations

Arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni) and zinc (Zn) concentrations in the water column (mg/l) and sediments (mg/kg) in the six water bodies during the study period are presented in this section. Minimum and maximum values recorded for all ten heavy metals are presented in Appendix D. ANOVA tests (at 95 % confidence level) performed to determine the differences in heavy metal levels across water bodies and sampling quarters are presented in Appendix E. Tukey's post hoc tests are presented in Appendix F1 and G2 for water bodies and sampling quarters respectively.

4.4.1 Arsenic

Arsenic values in the water column were generally higher in the 4th quarter of 2016 compared to the rest of the periods for all water bodies (Table 4.3). Sediment concentrations did not show any regular trend. ANOVA in Appendix D indicated significant differences ($p < 0.05$) both in the water column and sediment spatially and temporally. Tukey's post hoc test showed higher concentrations in the water column in the 4th quarter of 2016 (Appendix F2) which is reflected in all the water bodies except the Sakumo II Lagoon. Sediment concentrations were significantly lower in the 2nd quarter of 2017 than the rest of the periods. On the spatial level, Fosu Lagoon recorded significantly higher concentrations ($p < 0.05$) in the sediments than the rest of the water bodies (Appendix F1).

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Table 4.3 - *Quarterly Arsenic Concentrations in the Six Water Bodies (BDL < 0.001; WHO/USEPA Permissible Limits of 0.1 mg/l for Water and 20.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	0.005 ± 0.000	0.010 ± 0.000	0.011 ± 0.000	0.015 ± 0.002	0.013 ± 0.001	0.007 ± 0.000
3rd Q. 2016	0.006 ± 0.000	0.009 ± 0.000	0.012 ± 0.000	0.030 ± 0.001	0.015 ± 0.000	0.010 ± 0.004
4th Q. 2016	0.075 ± 0.001	0.025 ± 0.008	0.068 ± 0.010	0.016 ± 0.000	0.089 ± 0.001	0.071 ± 0.001
1st Q. 2017	0.007 ± 0.000	0.011 ± 0.001	0.012 ± 0.000	0.031 ± 0.001	0.015 ± 0.000	0.007 ± 0.000
2nd Q. 2017	0.007 ± 0.000	0.010 ± 0.000	0.012 ± 0.001	0.026 ± 0.003	0.015 ± 0.001	0.007 ± 0.000
3rd Q. 2017	0.007 ± 0.000	0.009 ± 0.001	0.010 ± 0.000	0.005 ± 0.000	0.015 ± 0.000	0.006 ± 0.000
			Concentration in sediments (mg/kg)			
2nd Q. 2016	4.212 ± 0.167	4.732 ± 0.012	4.240 ± 0.281	4.668 ± 0.196	4.668 ± 0.020	3.773 ± 0.017
3rd Q. 2016	3.943 ± 0.155	4.597 ± 0.027	3.760 ± 0.282	4.820 ± 0.005	4.690 ± 0.033	3.597 ± 0.002
4th Q. 2016	3.590 ± 0.047	4.533 ± 0.020	4.523 ± 0.121	4.880 ± 0.012	4.693 ± 0.018	3.260 ± 0.036
1st Q. 2017	4.007 ± 0.156	4.627 ± 0.023	3.820 ± 0.275	4.160 ± 0.059	4.743 ± 0.036	3.713 ± 0.012
2nd Q. 2017	3.863 ± 0.164	2.829 ± 0.546	3.663 ± 0.265	0.022 ± 0.002	4.643 ± 0.032	3.360 ± 0.024
3rd Q. 2017	3.696 ± 0.131	4.480 ± 0.019	3.907 ± 0.311	3.767 ± 0.015	4.706 ± 0.095	3.448 ± 0.010

BDL denotes below detection limit

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4.4.2 Cadmium

There was some temporal patchiness in cadmium levels in the water column in all water bodies (Table 4.4). Concentrations were below detection limit for all the water bodies in the 1st and 2nd quarters of 2017. Spatially, there were no significant differences in cadmium concentration ($p > 0.05$), however, significant differences were noted for temporal variations across water bodies ($p < 0.05$).Values in the Pra Estuary and Fosu Lagoon were lower than the concentration in the Kakum Estuary; but not the rest of the water bodies (Appendix F1). Cadmium concentrations in sediments were below detection limit in all the water bodies during the study period.

4.4.3 Chromium

The concentration of chromium was mostly below detection limit in the water column (Table 4.5). In the sediments, the highest value of 4.612 ± 2.353 was recorded at Sakumo II. There was a decline in chromium in the sediments from the 2nd quarter of 2016 to the 4th quarter of 2016. In 2017, values below detectable limits were obtained in at least one quarter for all the water bodies with the exception of the Pra Estuary. ANOVA shows significant differences in concentration of chromium in sediments across water bodies and sampling quarters at $p < 0.05$ (Appendix E).

Table 4.4 - *Quarterly Cadmium Concentrations in the Six Water Bodies (BDL < 0.002; WHO/USEPA Permissible Limits of 0.01 mg/l for Water and 20.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	0.134 ± 0.008	0.024 ± 0.005	0.108 ± 0.027	0.160 ± 0.005	0.085 ± 0.011	0.046 ± 0.004
3rd Q. 2016	0.116 ± 0.003	0.127 ± 0.003	BDL	0.013 ± 0.003	0.069 ± 0.007	0.129 ± 0.003
4th Q. 2016	BDL	0.035 ± 0.014	0.107 ± 0.040	0.158 ± 0.002	BDL	BDL
1st Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL
2nd Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL
3rd Q. 2017	0.118 ± 0.003	0.135 ± 0.004	BDL	BDL	0.072 ± 0.005	0.129 ± 0.003
			Concentration in sediments (mg/kg)			
2nd Q. 2016	BDL	BDL	BDL	BDL	BDL	BDL
3rd Q. 2016	BDL	BDL	BDL	BDL	BDL	BDL
4th Q. 2016	BDL	BDL	BDL	BDL	BDL	BDL
1st Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL
2nd Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL
3rd Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL

BDL denotes below detection limit

Table 4.5 - *Quarterly Chromium Concentrations in the Six Water Bodies (BDL < 0.002; WHO/USEPA Permissible Limits of 0.1 mg/l for Water and 25.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
	Concentration in water (mg/l)					
2nd Q. 2016	BDL	BDL	BDL	BDL	BDL	0.011 ± 0.001
3rd Q. 2016	BDL	BDL	BDL	0.049 ± 0.005	BDL	BDL
4th Q. 2016	0.014 ± 0.002	BDL	0.034 ± 0.004	BDL	0.012 ± 0.005	0.006 ± 0.001
1st Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL
2nd Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL
3rd Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL
	Concentration in sediments (mg/kg)					
2nd Q. 2016	1.760 ± 1.520	3.152 ± 0.019	1.357 ± 0.075	4.612 ± 2.353	1.633 ± 0.112	2.665 ± 0.018
3rd Q. 2016	0.220 ± 0.000	3.020 ± 0.015	1.170 ± 0.082	0.717 ± 0.092	1.643 ± 0.117	2.560 ± 0.019
4th Q. 2016	0.560 ± 0.079	1.833 ± 0.258	0.713 ± 0.131	0.677 ± 0.091	0.933 ± 0.058	0.870 ± 0.091
1st Q. 2017	BDL	3.120 ± 0.054	BDL	BDL	BDL	2.440 ± 0.018
2nd Q. 2017	BDL	1.045 ± 0.462	BDL	BDL	0.080 ± 0.000	BDL
3rd Q. 2017	0.120 ± 0.000	2.955 ± 0.027	1.110 ± 0.075	1.213 ± 0.056	1.541 ± 0.113	2.550 ± 0.026

BDL denotes below detection limit

4.4.4 Copper

Similar to chromium, copper concentrations were mostly below detection limit in the water column (Table 4.6). Differences were not significant across temporally ($p > 0.05$) (Appendix E2). In the sediments, there was an apparent increase in the concentrations of copper from the 2nd quarter to the 4th quarter of 2016 in the Pra Estuary, Benya and Muni lagoons. Conversely, a reduction in the concentration of copper was noted in the Sakumo II lagoon within the same period. The highest value of 9.320 was obtained in the 3rd quarter of 2017 from sediment from the latter lagoon. ANOVA results show significant differences spatially and temporally at $p < 0.05$ (Appendix E) with higher concentrations in the Benya, Sakumo II and Fosu lagoons (Appendix F1). Higher levels were also obtained in the 3rd quarter of 2017 (Appendix F2).

4.4.5 Iron

Iron concentrations in the water fluctuated from the 2nd Quarter of 2016 to a maximum in 2nd quarter of 2017 in all water bodies except for Sakumo II lagoon which had higher values in the 3rd Quarter of 2017 (Table 4.7). In the sediments, there was a general increase in the concentration of iron from the 2nd Quarter of 2016 to a maximum in the 1st quarter of 2017 for all six water bodies. Iron concentrations were generally higher in the Pra Estuary in both the water column and sediments. ANOVA in Appendix E shows concentrations were significantly different spatially and temporally in the water and sediment ($p < 0.05$).

Table 4.6 - *Quarterly Copper Concentrations in the Six Water Bodies (BDL < 0.003; WHO/USEPA Permissible Limits of 2.0 mg/l for Water and 25.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	BDL	BDL	BDL	BDL	BDL	BDL
3rd Q. 2016	BDL	BDL	BDL	BDL	BDL	BDL
4th Q. 2016	BDL	BDL	BDL	BDL	BDL	BDL
1st Q. 2017	BDL	BDL	0.004 ± 0.001	BDL	BDL	0.032 ± 0.002
2nd Q. 2017	BDL	BDL	0.019 ± 0.004	0.005	0.028 ± 0.003	BDL
3rd Q. 2017	BDL	BDL	BDL	BDL	BDL	BDL
			Concentration in sediments (mg/kg)			
2nd Q. 2016	BDL	0.423 ± 0.038	1.136 ± 0.631	7.347 ± 0.791	2.142 ± 0.439	0.235 ± 0.026
3rd Q. 2016	BDL	0.370 ± 0.017	2.410 ± 0.697	2.320 ± 0.175	3.093 ± 0.364	0.113 ± 0.005
4th Q. 2016	0.180 ± 0.000	1.037 ± 0.359	3.060 ± 0.792	2.370 ± 0.169	2.947 ± 0.294	6.480 ± 0.000
1st Q. 2017	BDL	0.480 ± 0.000	BDL	1.940 ± 0.689	0.400 ± 0.036	0.120 ± 0.018
2nd Q. 2017	1.230 ± 0.425	0.480 ± 0.000	1.588 ± 0.454	BDL	4.503 ± 0.492	1.000 ± 0.000
3rd Q. 2017	BDL	0.880 ± 0.260	5.420 ± 0.358	9.320 ± 0.000	4.037 ± 0.899	BDL

BDL denotes below detection limit

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Table 4.7 - *Quarterly Iron Concentrations in the Six Water Bodies (BDL < 0.006; WHO/USEPA Permissible Limits of 1.0 mg/l for Water and 25.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	0.102 ± 0.017	0.425 ± 0.105	0.065 ± 0.018	0.104 ± 0.027	0.102 ± 0.031	0.168 ± 0.021
3rd Q. 2016	0.097 ± 0.011	0.112 ± 0.017	0.005 ± 0.001	0.320 ± 0.004	0.015 ± 0.005	0.120 ± 0.020
4th Q. 2016	0.269 ± 0.010	0.877 ± 0.136	0.088 ± 0.014	0.045 ± 0.014	0.109 ± 0.033	0.132 ± 0.017
1st Q. 2017	0.024 ± 0.002	0.408 ± 0.135	0.094 ± 0.010	0.120 ± 0.034	0.116 ± 0.025	0.224 ± 0.029
2nd Q. 2017	0.910 ± 0.212	1.633 ± 0.245	0.324 ± 0.109	0.440 ± 0.176	0.476 ± 0.165	0.303 ± 0.103
3rd Q. 2017	0.107 ± 0.011	0.131 ± 0.020	0.007 ± 0.001	1.137 ± 0.162	0.017 ± 0.005	0.109 ± 0.019
			Concentration in sediments (mg/kg)			
2nd Q. 2016	16.828 ± 0.653	18.981 ± 0.062	16.934 ± 0.260	18.220 ± 0.489	18.707 ± 0.043	18.805 ± 0.008
3rd Q. 2016	16.068 ± 0.653	19.022 ± 0.054	17.480 ± 0.238	117.557 ± 24.083	18.745 ± 0.037	18.821 ± 0.005
4th Q. 2016	163.937 ± 17.762	80.084 ± 21.313	143.927 ± 21.858	117.368 ± 24.049	18.195 ± 0.064	173.390 ± 16.961
1st Q. 2017	169.050 ± 16.615	200.803 ± 6.189	196.080 ± 2.616	193.740 ± 7.965	177.932 ± 17.490	207.007 ± 3.018
2nd Q. 2017	79.633 ± 20.195	121.728 ± 24.051	46.166 ± 15.126	0.120 ± 0.027	18.425 ± 0.078	66.659 ± 13.114
3rd Q. 2017	16.094 ± 0.648	18.898 ± 0.055	17.486 ± 0.241	19.176 ± 0.019	18.761 ± 0.038	18.832 ± 0.006

BDL denotes below detection limit

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4.4.6 Lead

Concentrations in the water column were mostly below detection limit in the Kakum Estuary, Fosu and Muni lagoons (Table 4.8). Spatial and temporal differences were not significant ($p > 0.05$) (Appendix E). Sediments concentrations appear higher in the Sakumo II and Fosu lagoons than the rest of the water bodies. Higher values were obtained in the 4th quarter of 2016 for most of the six water bodies with Sakumo II recording the highest value of 9.550 for the said quarter. ANOVA showed significant differences across water bodies at $p < 0.05$ (Appendix E).

4.4.7 Manganese

Manganese concentrations fluctuated in both water and sediments (Table 4.9). Significant differences ($p < 0.05$) were recorded spatially and temporally (Appendix E) in the six water bodies. Post hoc test showed values were significantly higher in the Sakumo II Lagoon and the Fosu Lagoon than the rest of the water bodies for water and sediments respectively (Appendix F1).

4.4.8 Mercury

Mercury concentrations in water were mostly below detection limit in the Kakum Estuary, Benya and Muni lagoons (Table 4.10). Concentrations in the sediments were below detection limit in the Muni Lagoon except in the 2nd quarter of 2017 when a value of 4.000 was recorded. Concentrations within the sediments appear to be higher in the Fosu Lagoon, Sakumo II Lagoon and the Pra Estuary. ANOVA in Appendix E shows concentrations were significantly different on spatial and temporal levels in all the water bodies ($p < 0.05$).

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Table 4.8 - *Quarterly Lead Concentrations in the Six Water Bodies (BDL < 0.001; WHO/USEPA Permissible Limits of 0.05 mg/l for Water and 40.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	BDL	0.006	0.021 ± 0.004	0.018 ± 0.002	0.004	0.017 ± 0.004
3rd Q. 2016	BDL	0.015 ± 0.002	BDL	0.008 ± 0.001	BDL	BDL
4th Q. 2016	BDL	0.013 ± 0.004	0.025	0.014 ± 0.001	BDL	BDL
1st Q. 2017	0.004 ± 0.000	0.010 ± 0.002	0.032 ± 0.003	0.015 ± 0.005	BDL	0.056 ± 0.028
2nd Q. 2017	0.008	0.014 ± 0.006	0.022 ± 0.005	0.010 ± 0.003	0.021 ± 0.007	BDL
3rd Q. 2017	0.004	0.011 ± 0.002	BDL	0.008	BDL	BDL
			Concentration in sediments (mg/kg)			
2nd Q. 2016	BDL	0.583 ± 0.024	0.580 ± 0.069	1.780 ± 0.523	3.505 ± 0.847	0.808 ± 0.017
3rd Q. 2016	BDL	0.483 ± 0.017	0.647 ± 0.089	5.867 ± 3.043	4.780 ± 0.802	0.720 ± 0.017
4th Q. 2016	BDL	0.633 ± 0.030	2.025 ± 0.355	9.550 ± 4.566	5.850 ± 0.990	0.820 ± 0.000
1st Q. 2017	0.633 ± 0.119	0.660 ± 0.133	0.680 ± 0.093	1.390 ± 0.550	5.113 ± 0.784	0.840 ± 0.067
2nd Q. 2017	BDL	0.445 ± 0.156	BDL	0.023 ± 0.000	6.937 ± 2.133	BDL
3rd Q. 2017	1.400 ± 0.000	0.435 ± 0.053	0.740 ± 0.188	0.813 ± 0.035	4.576 ± 0.783	0.644 ± 0.018

BDL denotes below detection limit

Table 4.9 - *Quarterly Manganese Concentrations in the Six Water Bodies (BDL < 0.002; WHO/USEPA Permissible Limits of 0.2 mg/l for Water and 300.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	0.019 ± 0.002	0.008 ± 0.002	0.061 ± 0.021	0.042 ± 0.007	0.077 ± 0.010	0.013 ± 0.002
3rd Q. 2016	0.029 ± 0.006	0.055 ± 0.005	0.008 ± 0.001	0.307 ± 0.014	0.069 ± 0.009	0.024 ± 0.001
4th Q. 2016	0.010 ± 0.001	0.013 ± 0.005	0.020 ± 0.002	0.036 ± 0.005	0.036 ± 0.002	0.024 ± 0.008
1st Q. 2017	BDL	0.003 ± 0.000	BDL	0.065 ± 0.012	0.007	0.022 ± 0.002
2nd Q. 2017	0.026	0.015 ± 0.002	0.015 ± 0.003	0.056 ± 0.006	0.018 ± 0.003	BDL
3rd Q. 2017	0.031 ± 0.006	0.066 ± 0.007	0.009 ± 0.001	BDL	0.066 ± 0.009	0.023 ± 0.001
			Concentration in sediments (mg/kg)			
2nd Q. 2016	16.518 ± 2.602	6.300 ± 2.521	19.078 ± 1.908	45.293 ± 7.032	42.336 ± 5.719	24.668 ± 0.768
3rd Q. 2016	20.673 ± 1.281	10.517 ± 2.707	12.407 ± 2.109	38.737 ± 6.419	27.657 ± 1.097	23.177 ± 0.701
4th Q. 2016	6.167 ± 0.857	35.310 ± 4.413	9.713 ± 1.801	38.727 ± 6.366	57.670 ± 7.288	12.290 ± 3.981
1st Q. 2017	11.347 ± 2.382	7.577 ± 2.239	3.493 ± 0.935	15.217 ± 3.425	36.633 ± 4.888	18.257 ± 2.663
2nd Q. 2017	7.177 ± 0.899	4.913 ± 2.037	21.190 ± 2.093	0.016 ± 0.004	34.387 ± 4.975	10.951 ± 1.608
3rd Q. 2017	20.617 ± 1.249	2.575 ± 0.038	10.787 ± 2.138	21.155 ± 0.049	30.910 ± 1.851	22.640 ± 0.775

BDL denotes below detection limit

Table 4.10 - *Quarterly Mercury Concentrations in the Six water Bodies (BDL < 0.001; WHO/USEPA Permissible Limits of 0.002 mg/l for Water and 0.3 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	0.001 ± 0.000	0.016 ± 0.000	BDL	0.005 ± 0.002	0.007 ± 0.002	BDL
3rd Q. 2016	0.001 ± 0.000	0.001 ± 0.000	BDL	0.001 ± 0.000	0.001 ± 0.000	0.001 ± 0.000
4th Q. 2016	0.026 ± 0.001	0.018 ± 0.003	0.045 ± 0.001	0.003 ± 0.001	0.036 ± 0.001	BDL
1st Q. 2017	BDL	0.015 ± 0.000	BDL	0.006 ± 0.000	0.001 ± 0.000	BDL
2nd Q. 2017	BDL	0.014 ± 0.001	BDL	0.006 ± 0.001	0.002 ± 0.000	BDL
3rd Q. 2017	BDL	0.011 ± 0.001	BDL	0.002 ± 0.000	0.001 ± 0.000	BDL
			Concentration in sediments (mg/kg)			
2nd Q. 2016	1.723 ± 0.111	2.185 ± 0.030	1.290 ± 0.366	2.075 ± 0.088	2.117 ± 0.013	BDL
3rd Q. 2016	1.463 ± 0.091	1.433 ± 0.222	1.432 ± 0.181	1.643 ± 0.022	2.363 ± 0.182	BDL
4th Q. 2016	1.750 ± 0.065	2.183 ± 0.017	1.773 ± 0.069	2.173 ± 0.010	2.127 ± 0.016	BDL
1st Q. 2017	1.477 ± 0.100	1.857 ± 0.075	1.464 ± 0.182	1.343 ± 0.051	2.113 ± 0.007	BDL
2nd Q. 2017	1.263 ± 0.102	1.131 ± 0.225	1.457 ± 0.148	0.004 ± 0.001	1.952 ± 0.017	4.000 ± 0.000
3rd Q. 2017	4.094 ± 1.575	0.970 ± 0.259	1.344 ± 0.163	0.347 ± 0.035	1.943 ± 0.021	BDL

BDL denotes below detection limit

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4.4.9 Nickel

Concentrations of nickel in the water column were below detection limit in at least one sampling quarter for all six water bodies (Table 4.11). Concentrations in the sediments were relatively higher in the Sakumo II and Fosu lagoons. Differences in nickel concentrations were statistically significant at $p < 0.05$ (Appendix E). Higher values in the Sakumo II and Fosu lagoons were corroborated by the post hoc test (Appendix F1). In the two estuaries, higher values were obtained in the 4th quarter of 2016; however, among the four lagoons, there were no clear trends.

4.4.10 Zinc

No clear trends were observed in zinc concentrations in the water column but in the sediments, concentrations were generally higher in the Fosu Lagoon (Table 4.12). Significant differences were recorded spatially and temporally ($p < 0.05$) as shown in Appendix E. Tukey's post hoc test indicated that concentrations in the water column were significantly higher in the Sakumo II Lagoon while in the sediments, Fosu Lagoon concentrations were higher (Appendix F1). In the sediments, lower concentrations were obtained in the 4th quarter of 2016, 1st and 2nd quarters of 2017 (Appendix F2).

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Table 4.11 - *Quarterly Nickel Concentrations in the Six Water Bodies (BDL < 0.001; WHO/USEPA Permissible Limits of 0.2 mg/l for Water and 20.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	BDL	0.016 ± 0.002	BDL	BDL	BDL	0.006 ± 0.001
3rd Q. 2016	BDL	BDL	0.017 ± 0.001	0.039 ± 0.003	0.009 ± 0.001	BDL
4th Q. 2016	0.005 ± 0.001	0.013 ± 0.005	0.007 ± 0.002	BDL	0.002 ± 0.000	0.001 ± 0.000
1st Q. 2017	BDL	0.013 ± 0.005	0.007 ± 0.001	0.001	BDL	0.019 ± 0.003
2nd Q. 2017	0.017 ± 0.003	0.073 ± 0.057	0.040 ± 0.009	0.017 ± 0.003	0.019 ± 0.003	0.021 ± 0.002
3rd Q. 2017	BDL	BDL	0.016 ± 0.001	0.019 ± 0.003	0.009 ± 0.001	BDL
			Concentration in sediments (mg/kg)			
2nd Q. 2016	2.318 ± 0.184	0.286 ± 0.030	0.883 ± 0.350	4.126 ± 0.545	3.155 ± 0.198	0.193 ± 0.012
3rd Q. 2016	1.543 ± 0.105	0.283 ± 0.063	1.560 ± 0.279	3.417 ± 0.075	3.290 ± 0.168	0.130 ± 0.007
4th Q. 2016	4.410 ± 0.993	1.790 ± 0.279	1.963 ± 0.128	3.520 ± 0.080	2.700 ± 0.145	2.573 ± 0.236
1st Q. 2017	1.953 ± 0.219	1.527 ± 0.255	1.137 ± 0.116	1.430 ± 0.207	1.833 ± 0.129	1.167 ± 0.269
2nd Q. 2017	1.627 ± 0.090	1.649 ± 0.320	2.216 ± 0.140	BDL	3.353 ± 0.168	0.169 ± 0.014
3rd Q. 2017	1.470 ± 0.123	0.175 ± 0.008	1.507 ± 0.263	1.520 ± 0.026	3.013 ± 0.158	0.092 ± 0.003

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Table 4.12 - *Quarterly Zinc Concentrations in the Six Water Bodies (BDL < 0.001; WHO/USEPA Permissible Limits of 5.0 mg/l for Water and 90.0 mg/kg for Sediment)*

Sampling period	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
			Concentration in water (mg/l)			
2nd Q. 2016	0.005 ± 0.001	0.005 ± 0.001	0.005 ± 0.001	0.005 ± 0.001	0.008 ± 0.001	0.004 ± 0.000
3rd Q. 2016	0.007 ± 0.001	0.006 ± 0.001	0.004 ± 0.001	0.062 ± 0.011	0.007 ± 0.001	0.005 ± 0.000
4th Q. 2016	0.014 ± 0.001	0.009 ± 0.001	0.009 ± 0.001	0.007 ± 0.001	0.029 ± 0.014	0.013 ± 0.001
1st Q. 2017	0.013 ± 0.001	0.009 ± 0.001	0.011 ± 0.002	0.010 ± 0.001	0.008 ± 0.001	0.009 ± 0.001
2nd Q. 2017	0.013 ± 0.001	0.019 ± 0.002	0.017 ± 0.003	0.015 ± 0.002	0.009 ± 0.002	0.009 ± 0.002
3rd Q. 2017	0.009 ± 0.001	0.009 ± 0.001	0.004 ± 0.000	0.006 ± 0.001	0.009 ± 0.001	0.014 ± 0.008
			Concentration in sediments (mg/kg)			
2nd Q. 2016	1.648 ± 0.339	4.627 ± 0.033	4.193 ± 0.572	7.670 ± 1.384	7.868 ± 0.685	3.913 ± 0.161
3rd Q. 2016	1.360 ± 0.287	4.523 ± 0.025	4.997 ± 0.577	3.977 ± 0.332	9.313 ± 0.548	3.470 ± 0.131
4th Q. 2016	1.073 ± 0.104	3.093 ± 0.221	2.303 ± 0.441	3.980 ± 0.335	4.937 ± 0.239	2.003 ± 0.618
1st Q. 2017	0.767 ± 0.051	3.073 ± 0.312	2.170 ± 0.097	2.943 ± 0.413	3.640 ± 0.179	2.190 ± 0.209
2nd Q. 2017	2.177 ± 0.350	1.797 ± 0.420	2.673 ± 0.391	0.010 ± 0.002	5.907 ± 0.392	1.338 ± 0.093
3rd Q. 2017	8.382 ± 1.729	2.175 ± 0.169	3.770 ± 0.772	1.093 ± 0.209	6.409 ± 0.588	0.484 ± 0.048

BDL denotes below detection limit

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4.5 Sediment Parameters

This section covers organic matter content and particle size analyses of sediments in the six water bodies during the study period. The minimum and maximum values obtained are presented in Appendix G, ANOVA (95 % confidence level) tables comparing water bodies and sampling quarters in Appendix H and Tukey's post hoc test in Appendix I.

4.5.1 Organic matter (OM) content

Mean OM content declined from the 2nd quarter of 2016 to the 4th quarter of 2016 in all water bodies except the Fosu Lagoon. This was followed by a gradual increase to the end of the 3rd quarter of 2017 (Figure 4.10). Generally, mean organic matter content was low for Muni Lagoon (0.66 – 2.62 %) while the other water bodies had relatively higher values within the range of 2.51 – 13.35 %. Spatial differences were significant ($p < 0.05$) (Appendix H). Evidently, Tukey's post hoc showed significantly lower organic matter content in the Muni Lagoon while Fosu Lagoon had the highest (Appendix I1). Temporal variations were however, not distinct (Appendix I2).

4.5.2 Mean particle sizes (MPS)

Muni Lagoon was dominated by coarse sand whilst medium sand was most prevalent in the Benya Lagoon (Table 4.13). Particles in the Pra Estuary were generally smaller and varied between medium sand and very fine sand. The other water bodies had a general change from coarse sand to medium particles during the study period. Sediment particle sizes did not show any particular trend temporally.

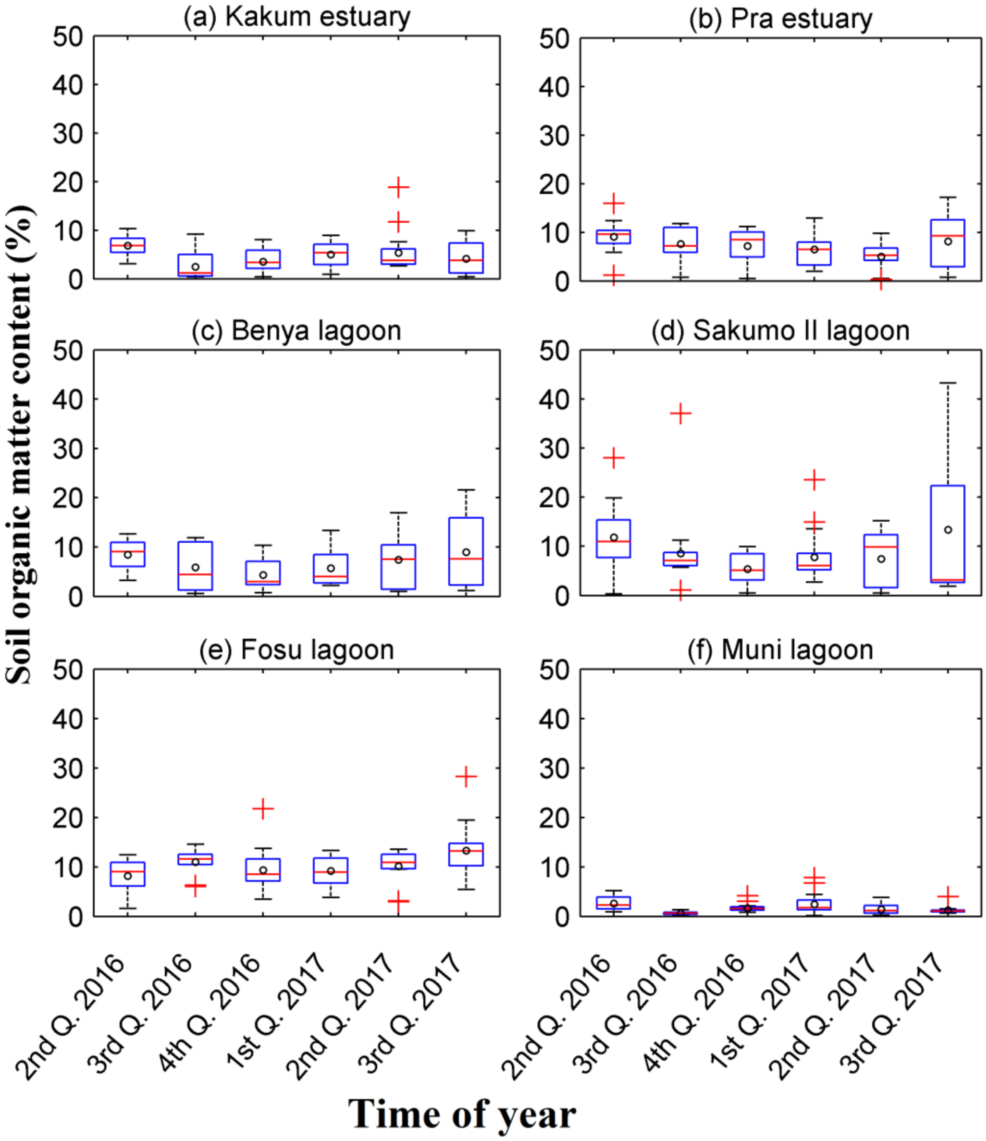

Figure 4.10: Quality variations in organic matter content in the six water bodies (lines extending vertically from the boxes indicate the lowest and highest values in the data, + indicates outliers; ᵒ indicates means)

Table 4.13 - Quarterly MPS and Corresponding Particle Grade Type in the Six Water Bodies throughout the Study Period

	Kakum Estuary		**Pra Estuary**		**Benya Lagoon**		**Sakumo II Lagoon**		**Fosu Lagoon**		**Muni Lagoon**	
Sampling period	**MPS**	**Particle grade name**	**MPS**	**Particle grade name**	**MPS**	**Particle grade name**	**MPS**	**Particle grade name**	**MPS**	**Particle grade name**	**MPS**	**Particle grade name**
2nd Q. 2016	0.833	Coarse sand	0.472	Medium sand	0.724	Coarse sand	0.903	Coarse sand	0.813	Coarse sand	0.769	Coarse sand
3rd Q. 2016	0.509	Coarse sand	0.117	Very fine sand	0.439	Medium sand	0.682	Coarse sand	0.620	Coarse sand	0.349	Medium sand
4th Q. 2016	0.591	Coarse sand	0.201	Fine sand	0.485	Medium sand	0.424	Medium sand	0.250	Medium sand	0.591	Coarse sand
1st Q. 2017	0.577	Coarse sand	0.212	Fine sand	0.408	Medium sand	0.374	Medium sand	0.701	Coarse sand	0.660	Coarse sand
2nd Q. 2017	0.340	Medium sand	0.163	Fine sand	0.286	Medium sand	0.496	Medium sand	0.401	Medium sand	0.561	Coarse sand
3rd Q. 2017	0.430	Medium sand	0.337	Medium sand	0.305	Medium sand	0.517	Coarse sand	0.297	Medium sand	0.643	Coarse sand

4.6 Benthic Macroinvertebrate Taxonomic Groups

This section covers the different macroinvertebrates identified in each water body – their abundance, frequency of occurrence, percentage compositions of the major groups, Shannon-Wiener indices and Bray-Curtis similarity. It also covers models relating benthic macroinvertebrates abundance to abiotic factors. The term "species" is used here loosely referring to the 45 different macroinvertebrate taxa encountered, some of which were not identified beyond the phylum level.

4.6.1 Richness and abundance

To compare species richness, the number of species encountered in each water body was collated. Sakumo II Lagoon consistently recorded the lowest number of species throughout the study period with a total of 4 different taxa, followed by Fosu Lagoon, Pra Estuary, Kakum Estuary, Muni Lagoon and Benya Lagoon with 8, 12, 18, 20 and 21 respectively (Table 4.14). Most water bodies apparently had their highest number of species in the 1st quarter of 2017.

The six water bodies recorded an increasing number of individual organisms in the following order: Pra Estuary < Kakum Estuary < Sakumo II Lagoon < Benya Lagoon < Fosu Lagoon < Muni Lagoon ranging from 344 to 4618. Four of the water bodies namely Pra Estuary, Benya, Sakumo II and Fosu lagoons recorded their highest numbers in the 3rd quarter of 2016 while Kakum Estuary and Muni Lagoon recorded their highest numbers in the 2nd quarter of 2017. The two estuaries, Pra and Kakum estuaries recorded their lowest numbers in the 4th quarter of 2016 but the lagoons did not show any clear patterns with respect to lowest numbers.

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Table 4.14 - *Quarterly Benthic Macroinvertebrate Abundance in the Six Water Bodies*

Sampling	**Kakum Estuary**		**Pra Estuary**		**Benya Lagoon**		**Sakumo II Lagoon**		**Fosu Lagoon**		**Muni Lagoon**	
period	**Species**	**Ind.**	**Species**	**Ind.**	**Species**	**Ind.**	**Species**	**Ind.**	**Species**	**Ind.**	**Species**	**Ind.**
2nd Q. 2016	13	208	3	20	6	590	2	5	6	500	14	639
3rd Q. 2016	10	182	5	129	13	931	3	1624	2	1080	16	706
4th Q. 2016	9	74	4	8	10	762	3	1002	6	617	12	1084
1st Q. 2017	14	172	12	73	15	632	3	1104	6	388	10	578
2nd Q. 2017	9	216	7	97	13	372	3	6	4	753	13	1183
3rd Q. 2017	8	122	4	17	6	664	0	0	5	1015	14	428
All quarters	**18**	**974**	**12**	**344**	**21**	**3951**	**4**	**3741**	**8**	**4353**	**20**	**4618**

*Ind. refers to individual organisms. Values for all quarters represent the total number of species and individuals encountered for each water body

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4.6.2 Percentage composition

The 45 'species' (taxa) encountered in the six water bodies were under seven major groups namely: Phoronida, Nemertea, Polychaeta, Oligochaeta, Crustacea, Insecta and Mollusca. Figure 4.11 shows the quarterly percentage compositions of the various groups. Polychaetes were dominant in most of the water bodies (with compositions mostly above 50 %) but the Sakumo II and Fosu lagoons. In these two lagoons, polychaetes accounted for < 20 % composition except in the 2nd quarter of 2016 when they constituted 80 % in the Sakumo II Lagoon. Molluscs and insects dominated (14 – 89 % and 20 – 82 % respectively) the Fosu Lagoon while insects and oligochaetes co-dominated (25 – 70 % and 20 – 75 %) the Sakumo II Lagoon. Crustaceans were completely absent in the Sakumo II Lagoon but quite prominent in the Muni Lagoon and Kakum Estuary within the ranges of (14 – 40 % and 30 – 38 % respectively). Insecta was absent in the Muni Lagoon. Nemerteans (ribbon worms) were either in low composition or absent in the water bodies studied except in Pra Estuary where they were quite prominent (7 – 20 % composition). Phoronids were only present in the Kakum Estuary with less than 2 % composition except in the 4th quarter of 2016 where it constituted 10 % of the composition.

Percentage compositions of species in each of the six water bodies are presented in Table 4.15. For brevity, the table shows only species with > 1 % composition. The remaining species were grouped and categorised as 'Others'. In the Kakum Estuary, *Nephtys* sp., *Chironomus* sp., *Nereis* sp. and *Ampithoe* sp. accounted for about 63 % composition with their respective compositions as 23.0 %, 20.64 %, 11.09 % and 9.24 %. The rest of the species had < 7 % each. *Pristina* sp. dominated the Pra Estuary with 59.59 %, followed by *Capitella*

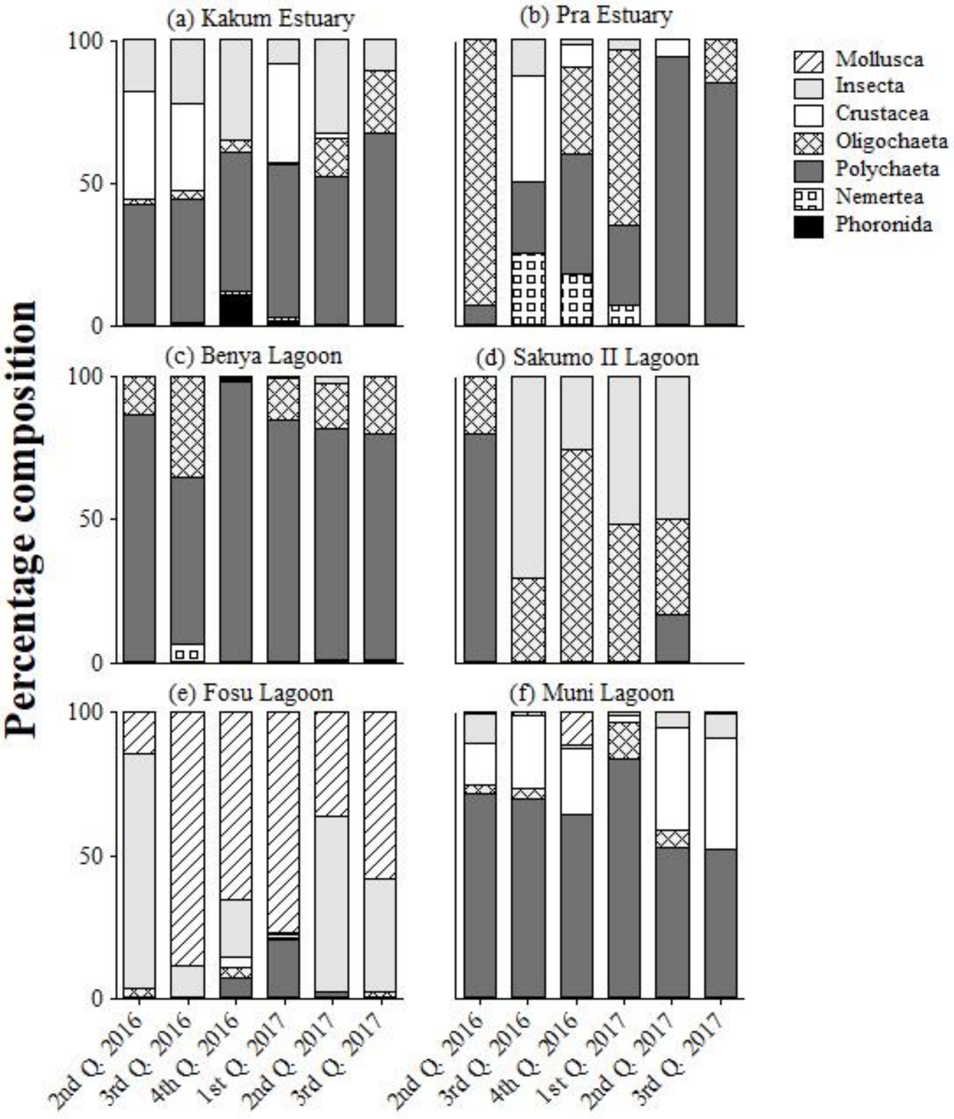

Figure 4.11: Quarterly percentage compositions of benthic macroinvertebrates major groups in the six water bodies

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Table 4.15 - *Percentage Composition of Benthic Macroinvertebrates in the Six Water Bodies (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)*

Water bodies	**Species**	**Composition (%)**
Kakum Estuary	*Nephtys* sp. (P)	23.00
	Chironomus sp. (I)	20.64
	Nereis sp. (P)	11.09
	Ampithoe sp. (C)	9.24
	Tubifex sp. (O)	6.98
	Capitella capitata (P)	6.78
	Gammarus sp. (C)	5.54
	Mysid (C)	5.34
	Nicomache sp. (P)	2.87
	Euclymene sp. (P)	2.57
	Eunice indica (P)	1.44
	Phoronida	1.33
	Marphysa sp. (P)	1.33
	Others	1.85
Pra Estuary	*Pristina* sp. (O)	59.59
	Capitella capitata (P)	9.88
	Branchiomaldane sp. (P)	8.14
	Lineus sp. (N)	6.40
	Sphaerodorum gracile (P)	4.07
	Melitidae (C)	2.91
	Nereis succinea (P)	2.91
	Scoloplos madagascariensis (P)	2.03
	Chironomus sp. (I)	1.45
	Polyophthalmus pictus (P)	1.16
	Others	1.45
Benya Lagoon	*Capitella capitata* (P)	62.47
	Pristina sp. (O)	10.88
	Parasclerocheilus capensis (P)	9.42
	Tubifex sp. (O)	6.53
	Heteromastus sp. (P)	3.21

Table 4.15, continued

Water bodies	Species	Composition (%)
	Lineus sp. (N)	1.77
	Polydora sp. (P)	1.29
	Notomastus sp. (P)	1.16
	Others	3.26
Sakumo II Lagoon	*Chironomus* sp. (I)	50.76
	Limnodrilus hoffmeisteri (O)	47.45
	Backswimmer (I)	1.66
	Capitella capitata (P)	0.13
Fosu Lagoon	*Melanoides tuberculata* (M)	59.73
	Chironomus sp. (I)	33.68
	Capitella capitata (P)	3.33
	Lumbriculus sp. (O)	1.26
	Others	2.00
Muni Lagoon	*Capitella capitata* (P)	44.02
	Ampithoe sp. (C)	16.89
	Tympanosyllis prampramensis (P)	9.18
	Rhodine gracilior (P)	6.15
	Lumbriculus sp. (O)	4.09
	Chironomus sp. (I)	4.01
	Melitidae (C)	3.88
	Tellina sp. (M)	2.73
	Gammarus sp. (C)	2.62
	Notomastus sp. (P)	1.52
	Heteromastus sp. (P)	1.34
	Nereis sp. (P)	1.21
	Others	2.36

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capitata (9.88 %) and *Branchiomaldane* sp. (8.14 %), with the rest recoding < 7 % each. The Benya Lagoon was dominated by *C. capitata* (62.47 %), followed by *Pristina* sp. (10.88 %), *Parasclerocheilus capensis* (9.47 %), *Tubifex* sp. (6.53 %) and *Heteromastus* sp. (3.21 %). In the Sakumo II Lagoon, *Chironomus* sp. (50.76 %) and *Limnodrilus hoffmeisteri* (47.45 %) exhibited co-dominance. Similarly, *Melanoides tuberculata* and *Chironomus* sp. dominated the Fosu Lagoon with 59.73 % and 33.68 % respectively. The Muni Lagoon was dominated by *C. capitata* (44.02 %), followed by *Ampithoe* sp. (16.89 %) and *Tympanosyllis prampramensis* (9.18 %). Inventory of species in each water body is shown in Appendix J.

4.6.3 Frequency of occurrence

Table 4.16 shows the frequency of occurrence of dominant species encountered in this study. For brevity, only species with a total composition ≥ 3.0 % were used for this analysis. Six species, accounting for 81.18 % of individuals in all six water bodies, fell under this category. Two species, namely *C. capitata* and *Chironomus* sp. were present in all six water bodies, thus, recording a 100 % occurrence. The *Pristina* sp. and *Ampithoe* sp. had 83.33 % and 50 % occurrence respectively. The remaining two species (*M. tuberculata* and *L. hoffmeisteri*) had 16.67 % occurrence. Details of the percentage frequency occurrence are shown in Appendix K.

Table 4.16 - *Percentage Frequency of Occurrence of Dominant Species in the Six Water Bodies (P = Polychaeta, I = Insecta, C = Crustacea, O = Oligochaeta)*

Species	**Overall composition (%)**	**Frequency of occurrence (%)**
Capitella capitata (P)	26.42	100.00
Chironomus sp. (I)	20.95	100.00
Pristina sp. (O)	4.89	83.33
Ampithoe sp. (C)	4.84	50.00
Melanoides tuberculata (M)	14.46	16.67
Limnodrilus hoffmeisteri (O)	9.87	16.67

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4.6.4 Species diversity

A comparison of taxonomic diversity in the various water bodies was done using Shannon-Wiener diversity index. Figure 4.12 shows the overall diversity indices for each of the six water bodies. Diversity indices were comparatively low in the Sakumo II and Fosu lagoons (1.01 and 1.58 respectively). The water bodies recorded an increasing order of diversity indices as follows: Sakumo II Lagoon < Fosu Lagoon < Pra Estuary < Benya Lagoon < Muni Lagoon < Kakum Estuary. Due to the low quarterly species richness (3 species or less) in the Sakumo II Lagoon, quarterly diversity indices were not computed.

4.6.5 Similarity in water bodies

A dendrogram based on Bray-Curtis similarity was used to determine the relationship between the six water bodies with respect to benthic macroinvertebrates composition and abundance. SIMPROF was used to test the significance of the relationship at 95 % confidence level. Figure 4.13 shows two significant clusters; the Sakumo II and Fosu lagoons formed one cluster at a similarity level of 44.29 % while the Muni Lagoon, Benya Lagoon, Kakum Estuary, and Pra Estuary formed another significant cluster with a similarity of 25.36 %. The Muni and Benya had the highest similarity at a level of 50.91 % whereas the two estuaries, Kakum and Pra were similar at 28.27 %.

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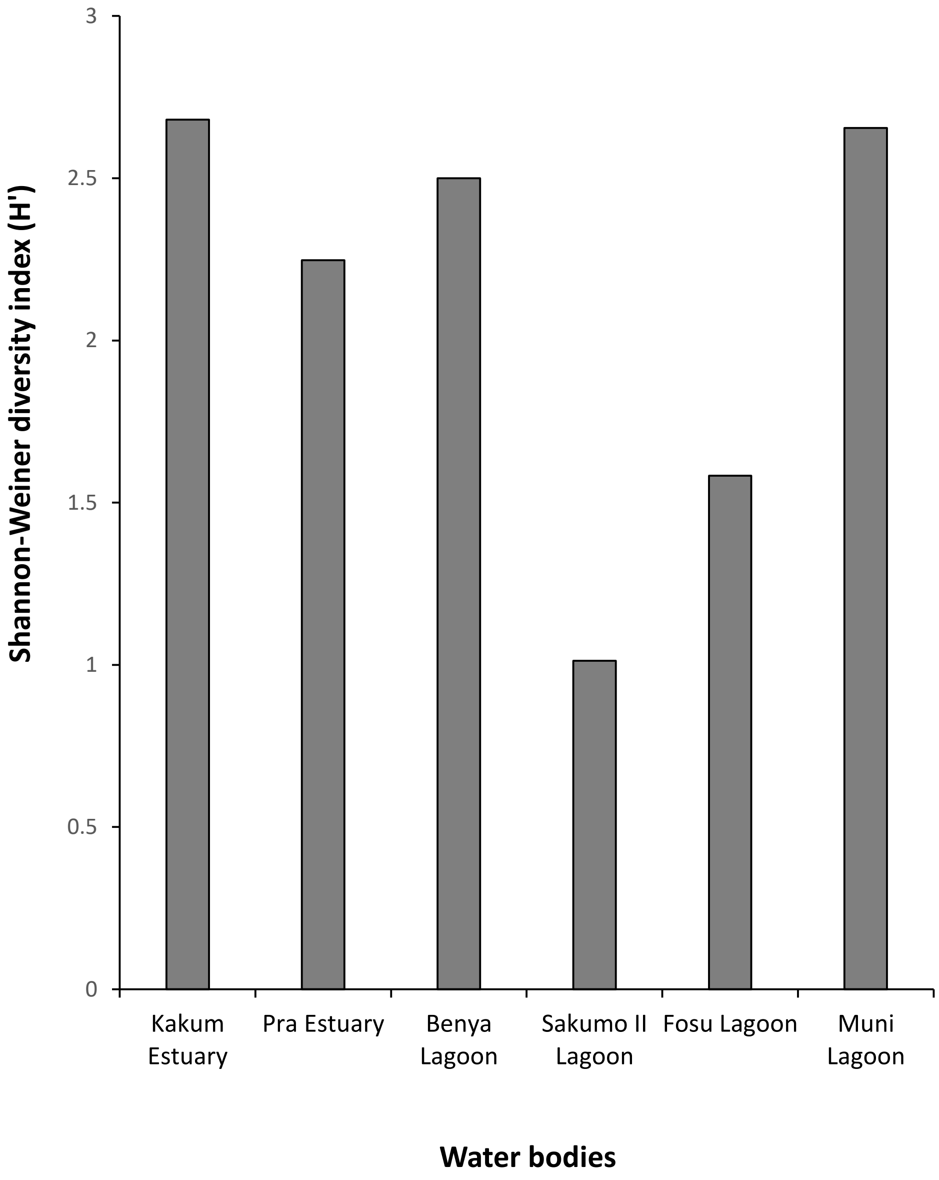

Figure 4.12: Shannon-Wiener diversity in the six water bodies

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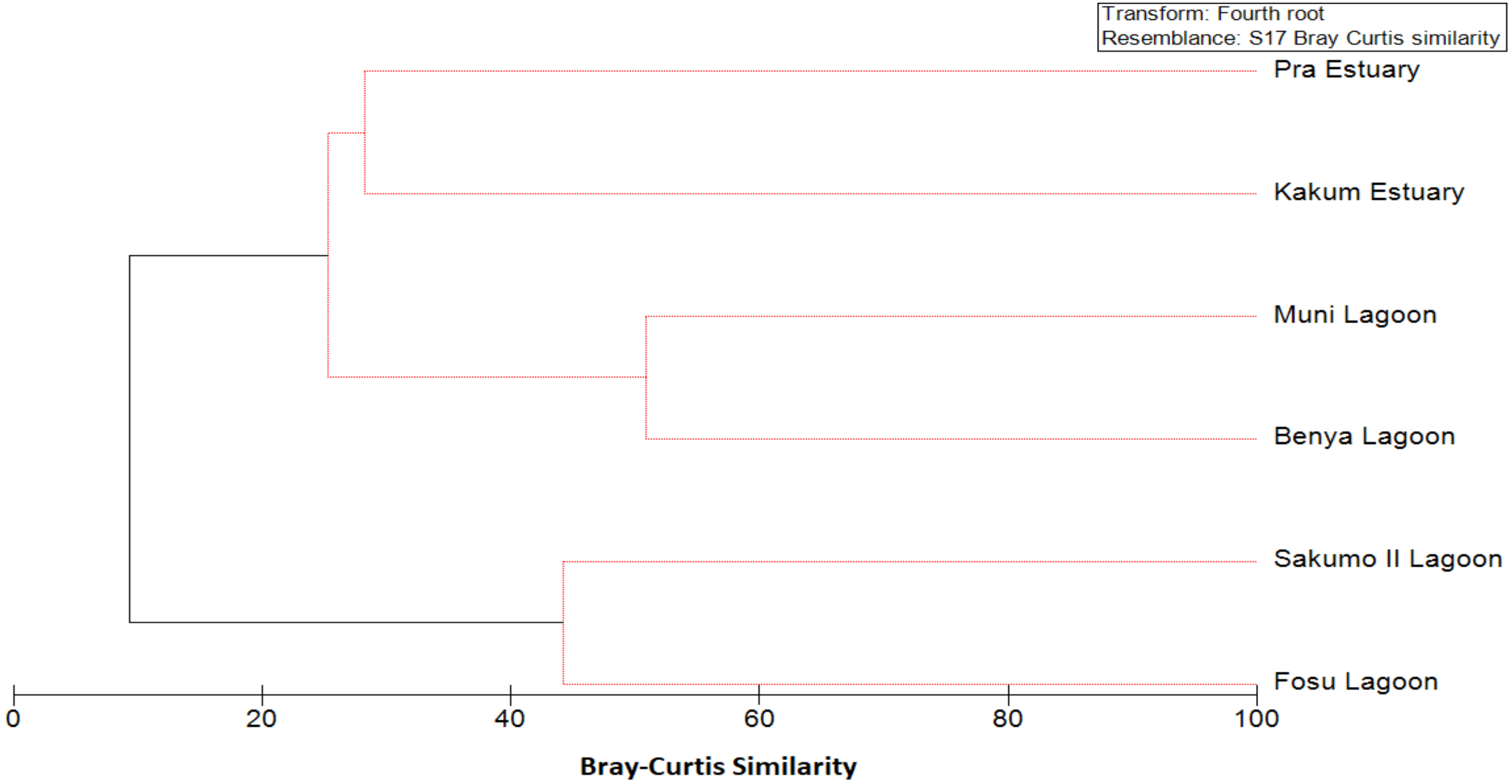

Figure 4.13: Complete linkage of Bray-Curtis similarity of benthic macroinvertebrate abundance in the six water bodies (joined red lines indicate significant clusters, $p < 0.05$ by SIMPROF analysis)

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4.6.6 Similarity percentages (SIMPER)

SIMPER in Table 4.17 shows species that were responsible for the average similarities within the two clusters. Only higher contributing species with a cumulative percentage ≥ 70 % were considered. *Chironomus* sp. and the backswimmer were responsible for the average similarity in the Sakumo II and Fosu lagoons (cluster 1). Seven species, namely *C. capitata*, *Chironomus* sp., *Pristina* sp., *Hipponoa* sp., *Lineus* sp., *Scoloplos madagascarensis* and *Tubifex* sp. were responsible for the average similarity in cluster 2. These species are hereafter referred to as influential species and were used for the environment-taxon relationship.

4.6.7 Environment-taxon relationship

The effects of abiotic factors on the abundance of influential species in the two clusters were determined and presented under this section. Abiotic factors that exhibited multi-collinearity were not included in the analyses. Two models were run; Model 1 shows the effects of physico-chemical parameters and sediment parameters on the abundance of influential species while Model 2 shows the effects of heavy metals concentrations, physico-chemical parameters and sediment parameters on the abundance of influential species. In the Sakumo II and Fosu lagoons (cluster 1), the abundance of influential species (*Chironomus* sp. and backswimmer) was significantly controlled by conductivity, and phosphate at $p < 0.05$ in Model 1 (Table 4.18). Decreased conductivity and phosphate resulted in increased abundance of these species. Abundance of the influential species increased with significant ($p < 0.05$)

Table 4.17 - *SIMPER Analysis Showing Species Contributing to the Average Similarity in the Clusters*

Species	**Average abundance**	**Average similarity**	**Similarity/SD**	**Contribution %**	**Cumulative %**
Average similarity in Cluster 1 (Sakumo II Lagoon and Fosu Lagoon): 44.29 %					
Chironomus sp.	6.39	27.34	-	61.73	61.73
Backswimmer	2.57	10.34	-	23.35	85.08
Average similarity in Cluster 2 (Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon): 34.21 %					
Capitella capitata	4.76	7.10	3.01	20.77	20.77
Chironomus sp.	2.69	4.36	3.04	12.74	33.51
Pristina sp.	3.01	4.19	0.89	12.25	45.76
Hipponoa sp.	1.62	3.12	5.77	9.12	54.89
Lineus sp.	1.62	2.16	0.86	6.31	61.20
Scoloplos madagascarensis	1.30	1.92	0.89	5.62	66.82
Tubifex sp.	2.07	1.87	0.78	5.47	72.29

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Table 4.18 - *Negative Binomial Model Showing the Effects of Abiotic Parameters on the Abundance of Influential in the Sakumo II Lagoon and Fosu Lagoon (Cluster 1)*

Abundance	**Model 1**						**Model 2**					
	IRR	**Robust S.E.**	**z**	**P>z**	**95% C.I.**		**IRR**	**Robust S.E.**	**z**	**P>z**	**95% C.I.**	
pH	1.6415	0.4798	1.70	0.09	0.9257	2.9108	0.6914	0.3350	-0.76	0.45	0.2674	1.7873
DO	1.0498	0.0612	0.83	0.40	0.9365	1.1768	1.0200	0.0949	0.21	0.83	0.8500	1.2239
Conductivity	0.9999	0.0000	-3.06	**0.01**	0.9998	0.9999	1.0000	0.0001	-0.52	0.60	0.9998	1.0001
Temperature	1.1449	0.0982	1.58	0.12	0.9677	1.3544	1.1951	0.2940	0.72	0.47	0.7379	1.9357
Turbidity	0.9993	0.0024	-0.29	0.77	0.9947	1.0039	1.0054	0.0051	1.05	0.29	0.9954	1.0156
Nitrate	0.9976	0.0189	-0.13	0.90	0.9612	1.0353	1.0120	0.0120	1.00	0.32	0.9887	1.0358
Phosphate	0.9326	0.0092	-7.05	**0.00**	0.9147	0.9509	1.2106	0.1620	1.43	0.15	0.9314	1.5736
OM	0.9757	0.0234	-1.03	0.31	0.9308	1.0227	1.0153	0.0311	0.50	0.62	0.9561	1.0782
MPS	1.4935	0.6869	0.87	0.38	0.6063	3.6788	5.6347	4.5887	2.12	**0.03**	1.1420	27.8012
As							1.2857	0.5239	0.62	0.54	0.5785	2.8574
Cr							3.7831	1.8399	2.74	**0.01**	1.4584	9.8137
Cu							1.4501	0.1877	2.87	**0.00**	1.1251	1.8690
Fe							0.9900	0.0032	-3.07	**0.00**	0.9837	0.9964
Hg							1.1463	0.5224	0.30	0.76	0.4693	2.8003
Mn							0.9865	0.0081	-1.67	0.10	0.9707	1.0024
Ni							0.9751	0.3044	-0.08	0.94	0.5288	1.7980
Pb							0.9844	0.0263	-0.59	0.56	0.9340	1.0374
Zn							0.5858	0.0739	-4.24	**0.00**	0.4575	0.7500
Constant	0.0396	0.1322	-0.97	0.33	0.0001	27.5593	0.5634	5.2165	-0.06	0.95	0.0000	4.29E+07

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increase in MPS, chromium and copper and a significant decrease in iron and zinc in Model 2.

Influential species in the other four water bodies (cluster 2) were *C. capitata*, *Chironomus* sp., *Pristina* sp., *Nereis* sp., *Notomastus* sp., *Nephtys* sp. and *Tubifex* sp. Abundance of these species in Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon increased when conductivity decreased and nitrate increased significantly ($p < 0.05$) in Model 1 (Table 4.19). In Model 2, abundance of the species increased when there was a significant increase in temperature, nitrate, organic matter, arsenic, lead and zinc and decrease in pH, DO, mercury and nickel ($p < 0.05$).

4.7 Benthic Macroinvertebrate Functional Groups

Macroinvertebrates in the six water bodies were categorised into various groups under the traits body form, feeding habit, mobility, sexuality and sociability (see Appendix L). This section covers the analysis of macroinvertebrate functional traits. It is important to note that all species in this study were small-sized, ranging between 0.5 cm and 4.0 cm.

4.7.1 Functional group richness

The Sakumo II Lagoon and Fosu Lagoon generally recorded the lowest number of groups under each functional trait (Table 4.20). Functional richness decreased in the order Kakum Estuary > Benya Lagoon > Muni Lagoon > Pra Estuary > Fosu Lagoon > Sakumo II Lagoon. No water body had all the groups identified under the traits ‘feeding habit’ and ‘body form’.

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Table 4.19 - *Negative Binomial Model Showing the Effects of Abiotic Parameters on the Abundance of Influential Species in the Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon (Cluster 2)*

Abundance	**Model 1**						**Model 2**					
	IRR	**Robust S.E.**	**z**	**P>z**	**95% C.I.**		**IRR**	**Robust S.E.**	**z**	**P>z**	**95% C.I.**	
pH	1.18570	0.15833	1.28	0.20	0.91267	1.54041	0.10702	0.05869	-4.07	**0.00**	0.03653	0.31353
DO	0.94637	0.02629	-1.98	0.05	0.89623	0.99933	0.70733	0.11035	-2.22	**0.03**	0.52098	0.96032
Conductivity	0.99949	0.00009	-5.77	**0.00**	0.99932	0.99967	1.00002	0.00016	0.09	0.93	0.99970	1.00033
Temperature	1.01458	0.02875	0.51	0.61	0.95977	1.07252	2.42050	0.34903	6.13	**0.00**	1.82458	3.21106
Turbidity	0.99925	0.00079	-0.96	0.34	0.99771	1.00079	0.99913	0.00127	-0.68	0.50	0.99664	1.00163
Nitrate	1.05050	0.02270	2.28	**0.02**	1.00695	1.09594	1.25554	0.12149	2.35	**0.02**	1.03864	1.51774
Phosphate	1.00069	0.04685	0.01	0.99	0.91295	1.09685	0.95622	0.10192	-0.42	0.67	0.77594	1.17838
OM	1.02384	0.01530	1.58	0.12	0.99430	1.05426	1.08196	0.03735	2.28	**0.02**	1.01119	1.15769
MPS	1.57288	0.46531	1.53	0.13	0.88080	2.80874	1.86979	1.51017	0.77	0.44	0.38398	9.10498
As							1.87937	0.32125	3.69	**0.00**	1.34435	2.62731
Fe							0.99761	0.00263	-0.91	0.36	0.99248	1.00277
Hg							0.34412	0.10481	-3.50	**0.00**	0.18943	0.62512
Mn							0.99547	0.01542	-0.29	0.77	0.96571	1.02615
Ni							0.73427	0.09587	-2.37	**0.02**	0.56849	0.94839
Pb							1.85081	0.43483	2.62	**0.01**	1.16782	2.93322
Zn							1.21185	0.10261	2.27	**0.02**	1.02654	1.43061
Constant	1.44390	1.35396	0.39	0.70	0.22980	9.07229	0.00017	0.00094	-1.54	0.12	0.00000	10.37533

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Table 4.20 - Functional Group Richness under the Various Functional Traits in the Six Water Bodies

Functional traits	**All water bodies**	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
Feeding habit	9	8	5	7	3	4	6
Body form	9	7	5	7	3	5	6
Mobility	6	6	4	5	3	4	4
Sociability	3	3	3	3	2	2	3
Sexuality	3	3	2	2	2	2	2

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4.7.2 Percentage composition

Numerical compositions were computed for the various functional trait groups. Under the trait body form, 'Cylindrical and elongate' organisms dominated the Benya Lagoon, Pra Estuary and Muni Lagoon with 84.5 %, 80.5 % and 52.3 % respectively, whereas Kakum Estuary, Sakumo II Lagoon and Fosu lagoon recorded 27.7 %, 5.2 % and 0.1 % respectively for that same trait (Figure 4.14). 'Conical' body forms dominated the Fosu Lagoon (59.7 %) while the other water bodies reported no individuals of this trait. Kakum Estuary and Sakumo II Lagoon were dominated by 'Threadlike' invertebrates with 47.0 % and 98.2 % respectively. 'Threadlike' forms showed 33.7 % representation in the Fosu Lagoon. 'Laterally compressed' forms were prominent in the Kakum Estuary (20.1 %) and Muni Lagoon (24.3 %). The group denoted 'Others' consists of species that are keel-shaped, stout, or have fused head and thorax.

Generally, 'Deposit feeder' and 'Deposit feeder+omnivore' groups were the most dominant in the feeding habit category (Figure 4.15). Deposit feeders dominated the Benya, Fosu and Muni lagoons with 84.1 %, 63.7 % and 57.2 % respectively with good representation in the Sakumo II Lagoon (47.6 %), Kakum Estuary (19.2 %) and Pra (26.2 %) Estuary. The 'Deposit feeder+omnivore' group dominated Sakumo II Lagoon (50.8 %) and Pra Estuary (61.0 %) with some representations in the remaining water bodies with compositions between 8.1 % and 34.9 %. Filter feeders were quite prominent in the Kakum Estuary (1.3 %) and Muni Lagoon (2.9 %).

In terms of mobility, burrowers were dominant in the Benya Lagoon (97.1 %), Pra Estuary (85.5 %), Muni Lagoon (70.6 %), Fosu Lagoon (64.3 %) and Kakum Estuary (45.8 %) (Figure 4.16). The Sakumo II Lagoon was co-

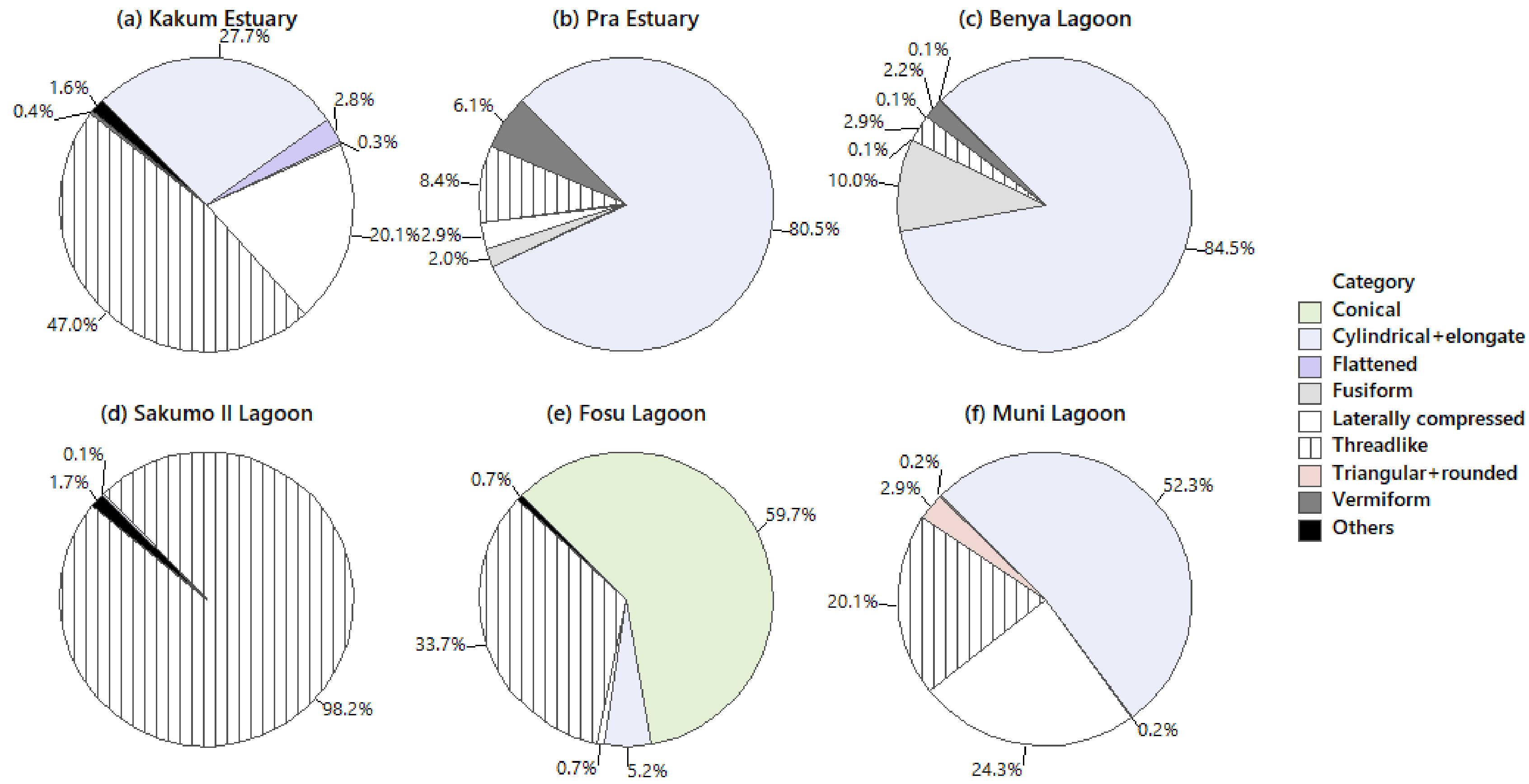

Figure 4.14: Percentage composition of numerical abundance of functional groups under the trait body form in the six water bodies

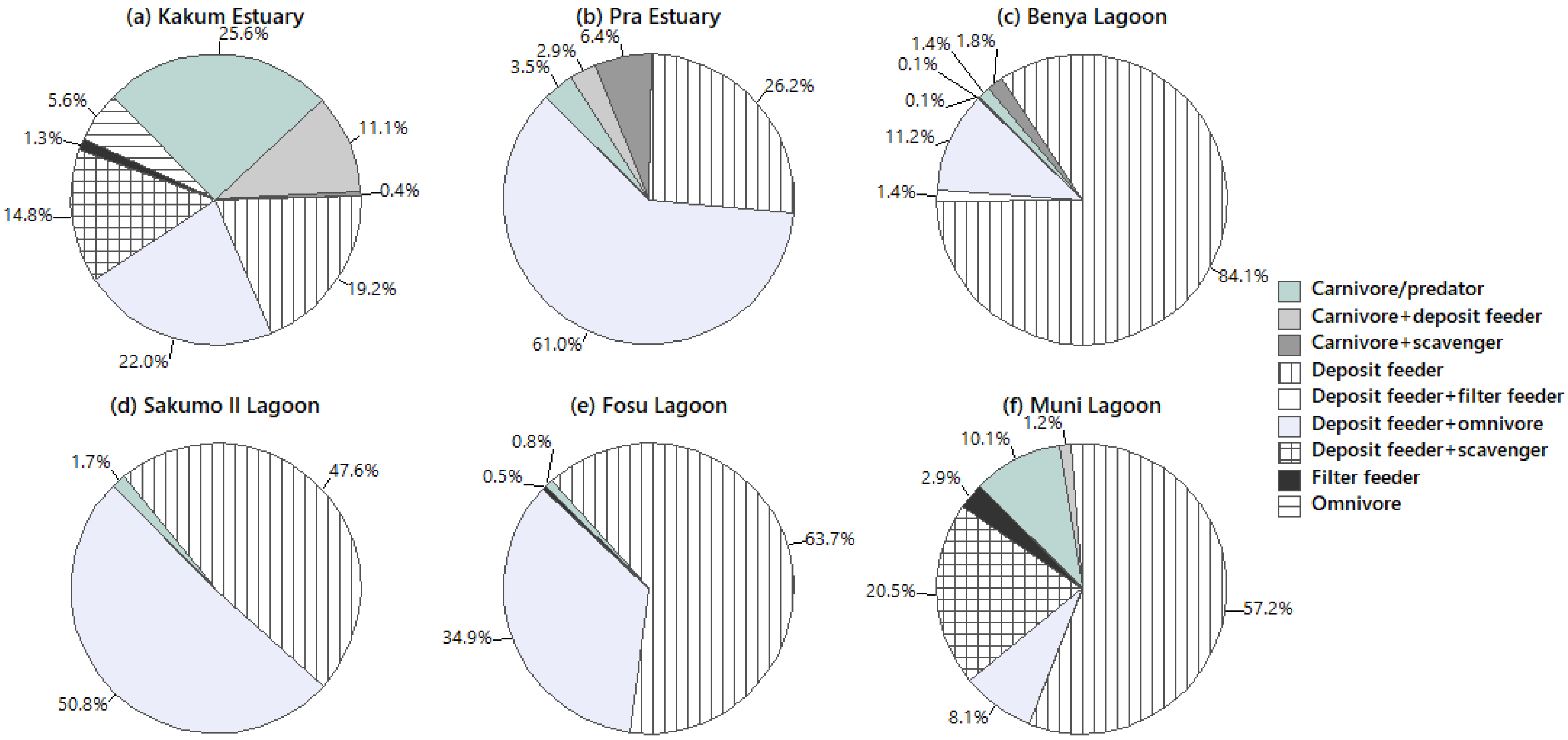

Figure 4.15: Percentage composition of numerical abundance of functional groups under the trait feeding habit in the six water bodies

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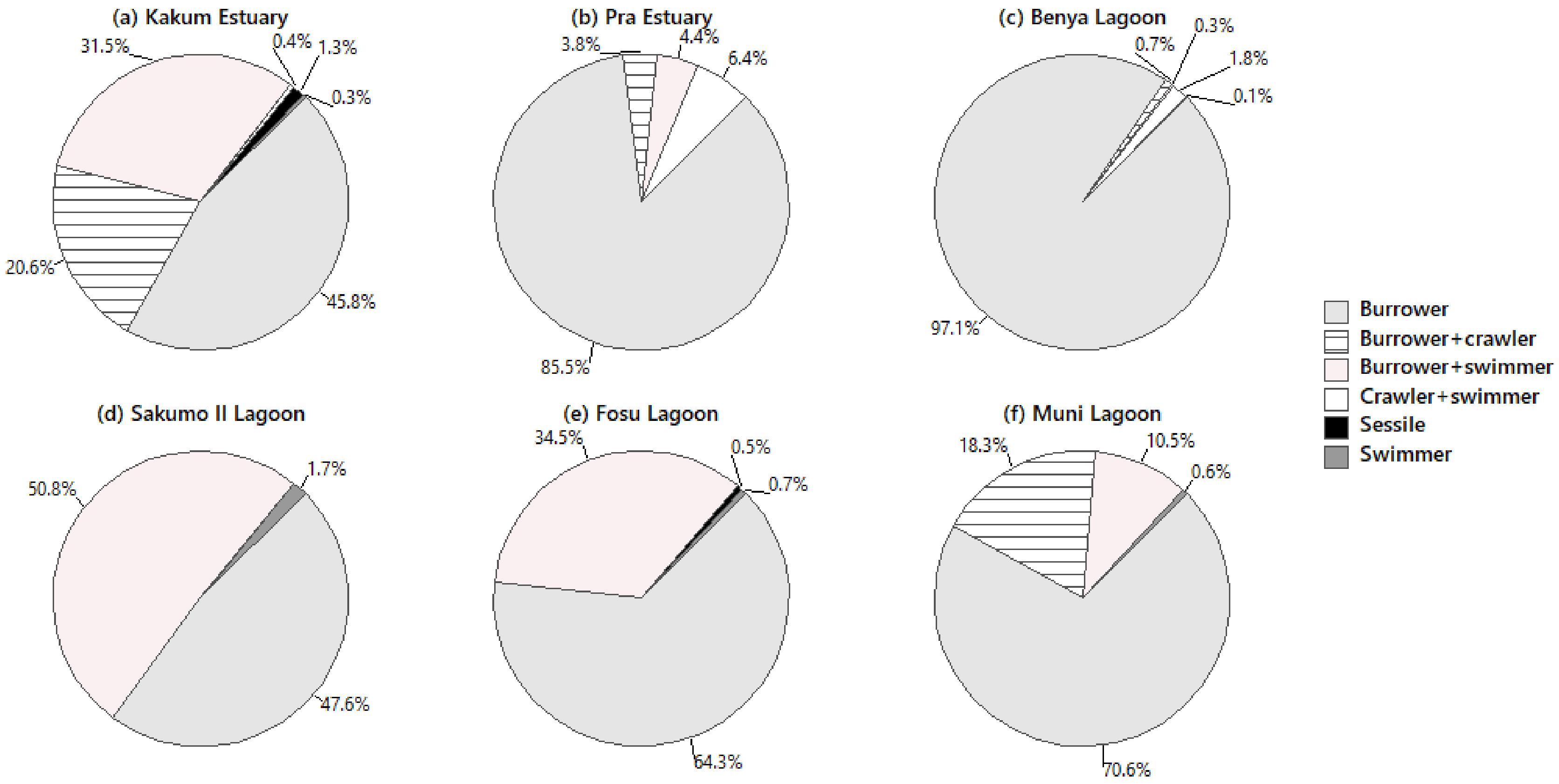

Figure 4.16: Percentage composition of numerical abundance of functional groups under the trait mobility in the six water bodies

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dominated by the groups ‘Burrower’ (47.6 %) and ‘Burrower+swimmer’ (50.8 %). The ‘Burrower+crawler’ group was quite prominent in the Kakum Estuary (20.6 %), Muni Lagoon (18.3 %) and Pra Estuary (3.8 %).

Under the trait sexuality, there was a co-dominance of hermaphrodites and gonochorists in the Pra and Kakum estuaries in the proportions of 53.0 % – 46.8 % and 47.4 % – 52.6 % respectively (Figure 4.17). ‘Gonochorist’ compositions were > 82 % in the rest of the water bodies.

Under the category sociability, solitary organisms dominated all water bodies with at least 57 % composition, except for Fosu Lagoon where 37.9 % was noted and ‘Solitary/Commensal’ dominated with 61.2 % (Fig. 4.18). The ‘Solitary/Commensal’ group was moderately prominent in the other water bodies but absent in the Sakumo II Lagoon.

4.7.3 Functional diversity

Water bodies were compared based on their functional diversities (using all functional groups) by adopting the Shannon-Weiner index. Functional diversity indices were 2.49 (Sakumo II Lagoon), 2.81 (Fosu Lagoon), 2.92 (Pra Estuary), 3.02 (Muni Lagoon), 3.14 (Benya Lagoon) and 3.28 (Kakum Estuary) (Figure 4.19).

Functional diversities were also computed separately with functional groups under the body form and feeding habit traits and the results shown in Figure 4.20 and Figure 4.21 respectively. For both functional traits, the water bodies show an increasing functional diversities in the order: Sakumo II Lagoon < Fosu Lagoon < Pra Estuary < Muni Lagoon < Benya Lagoon < Kakum Estuary.

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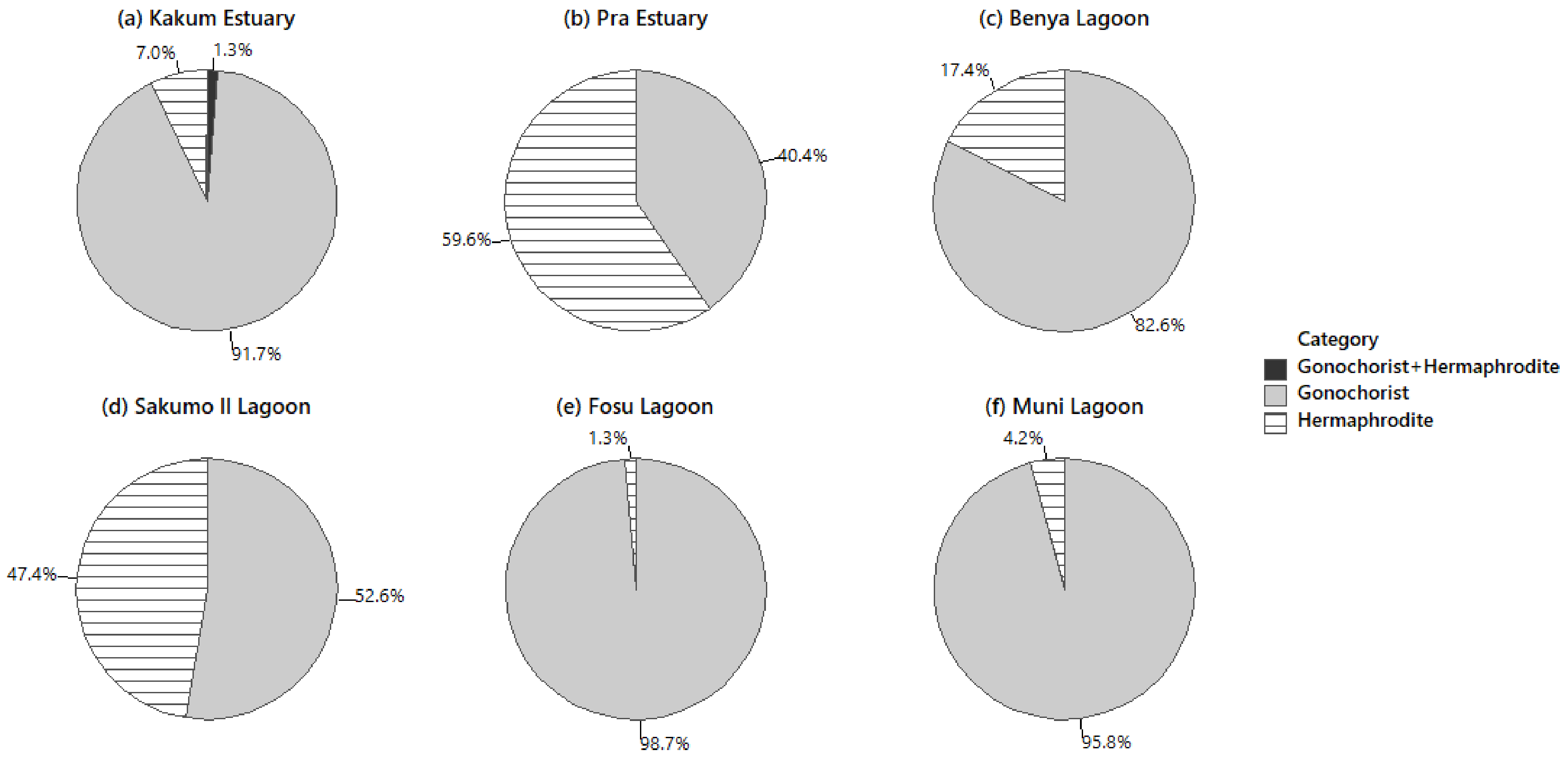

Figure 4.17: Percentage composition of numerical abundance of functional groups under the trait sexuality in the six water bodies

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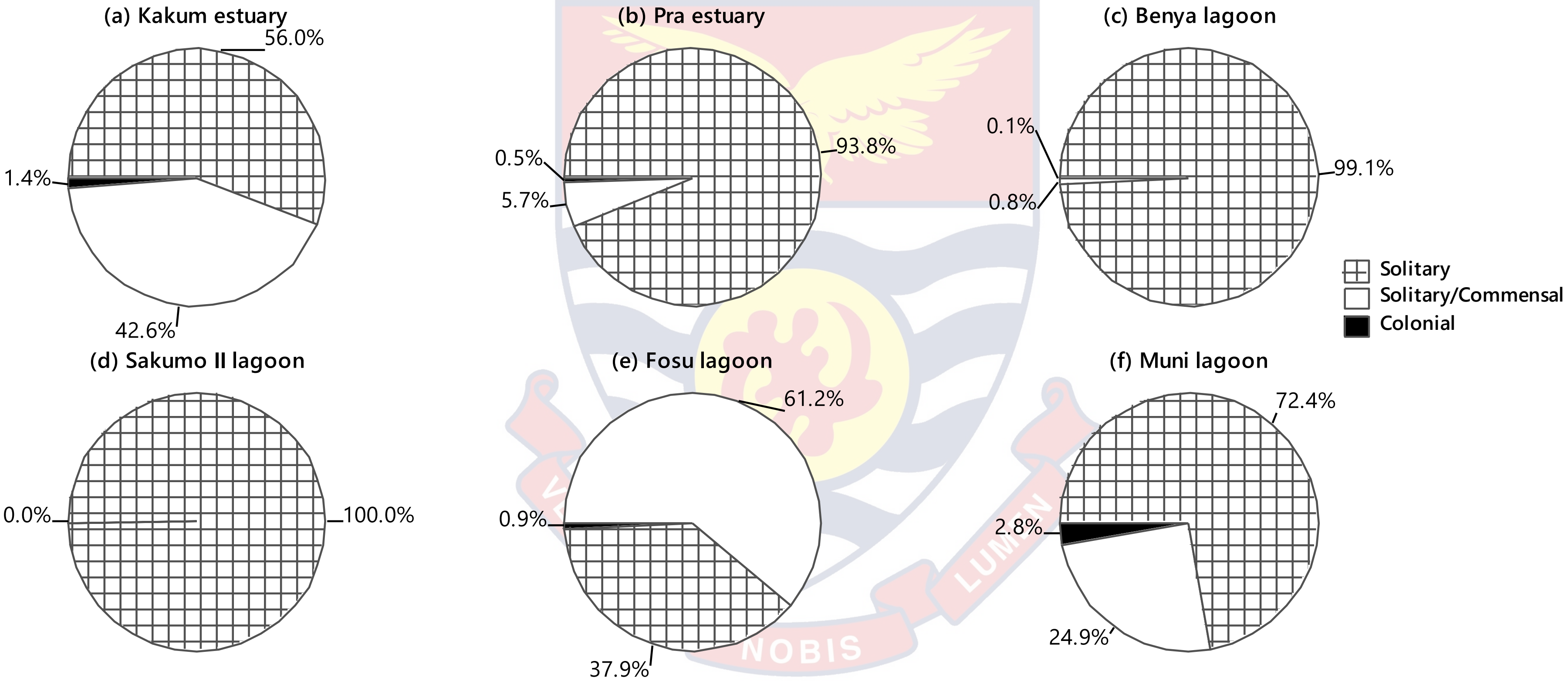

Figure 4.18: Percentage composition of numerical abundance of functional groups under the trait sociability in the six water bodies

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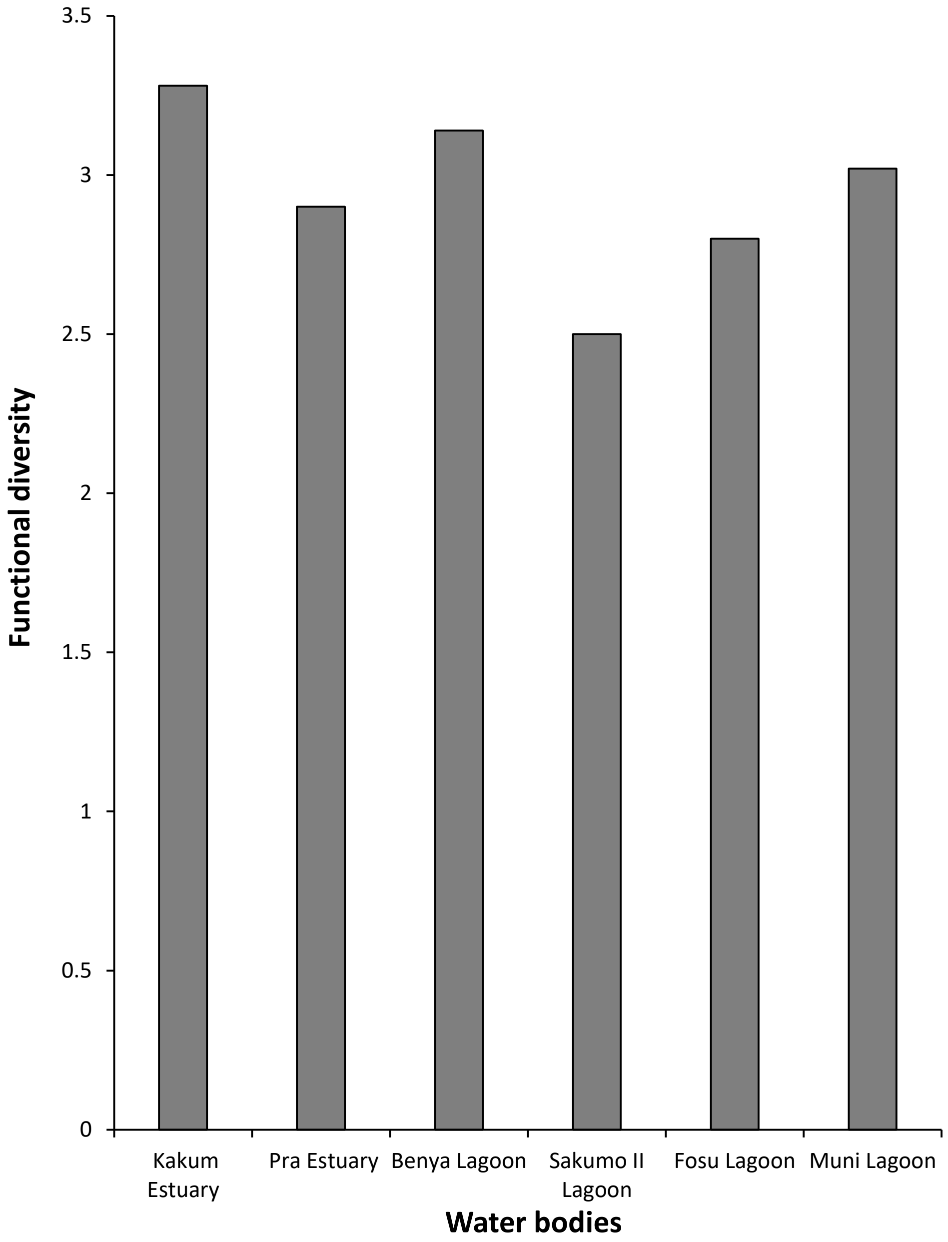

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Figure 4.19: Functional diversity for all functional traits in the six water bodies

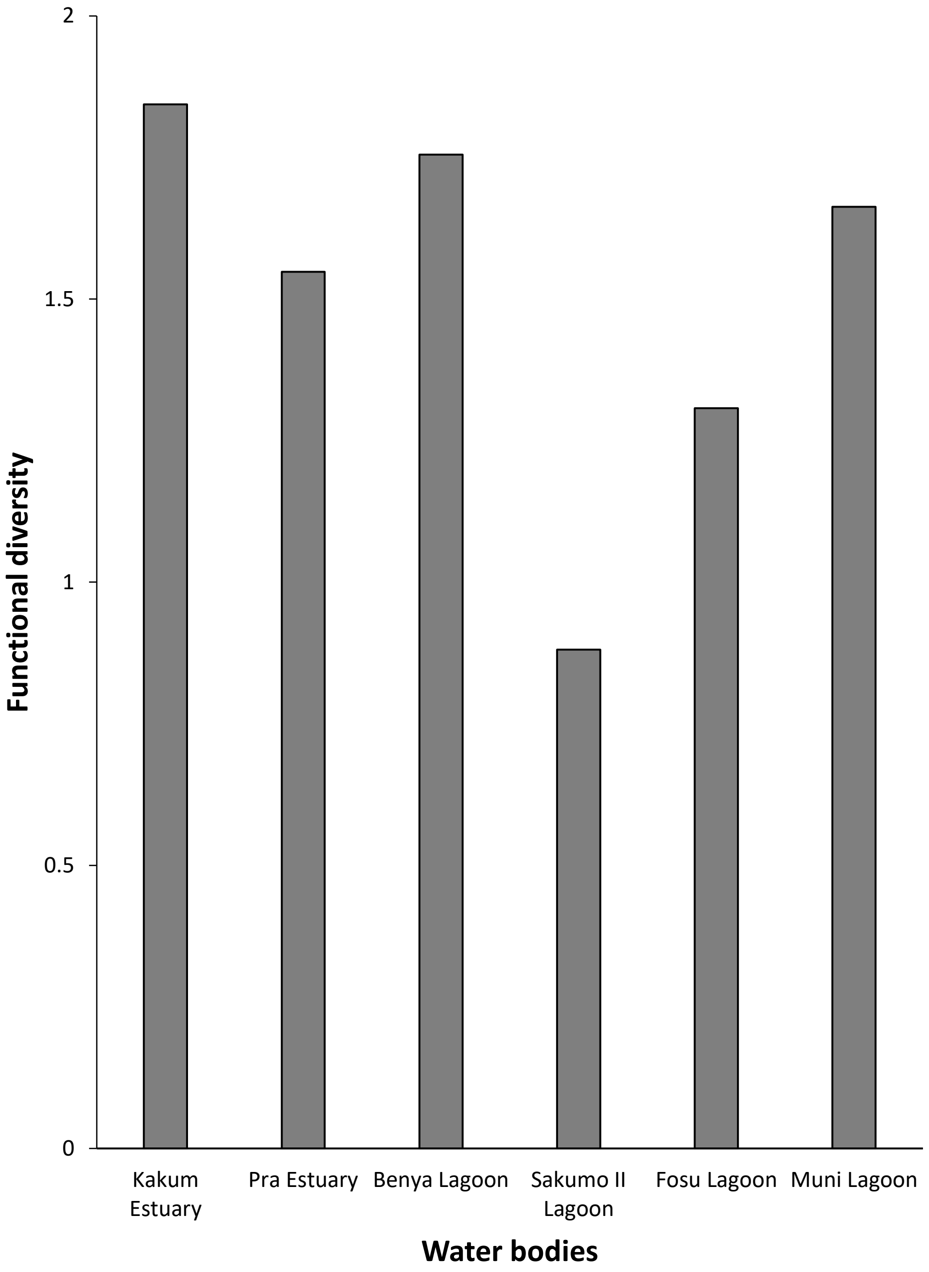

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Figure 4.20: Functional diversity for body form functional trait in the six water bodies

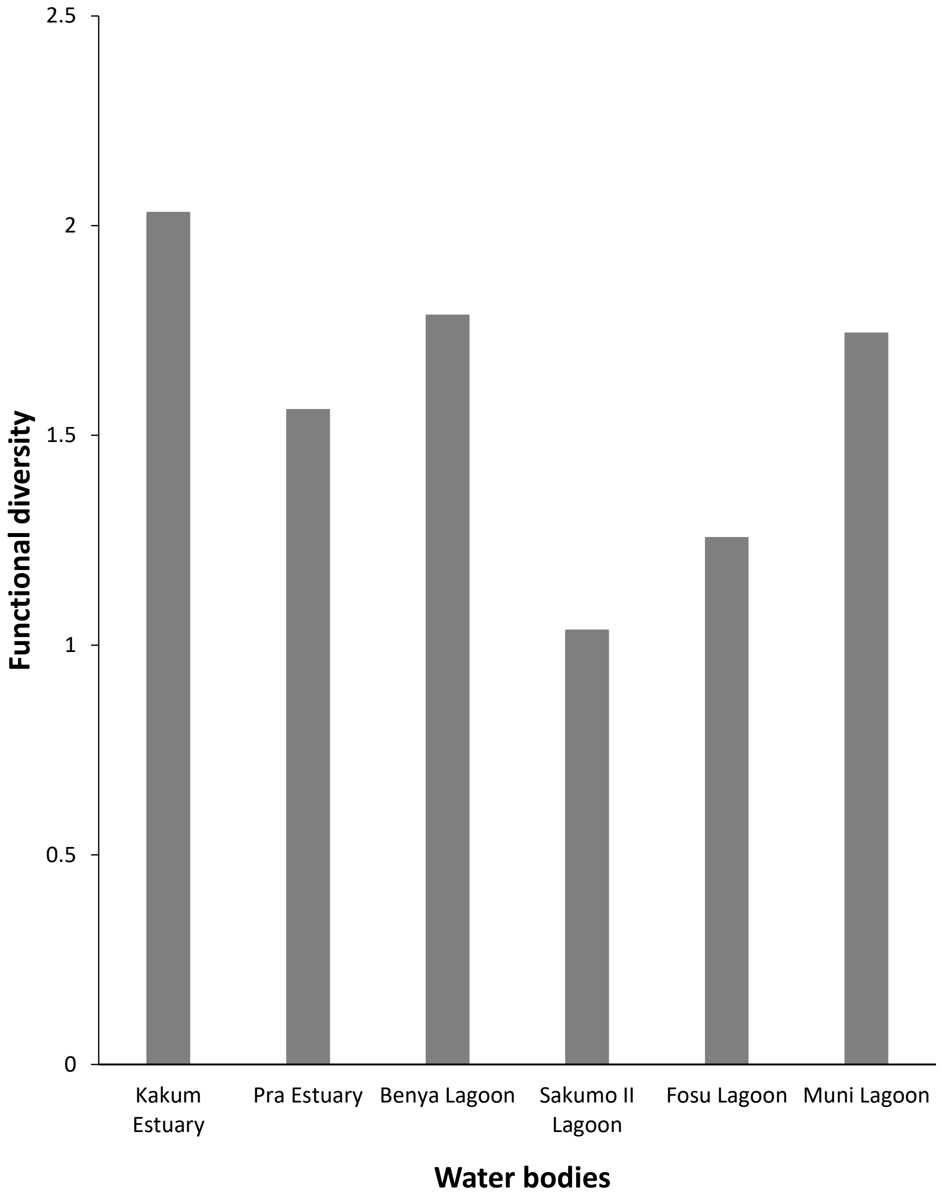

Figure 4.21: Functional diversity for feeding habit functional traits in the six water bodies

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4.7.4 Similarities in the water bodies

Bray-Curtis similarity among the water bodies based on composition and abundance of macroinvertebrate functional groups under the various functional traits namely body form, feeding habit, mobility, sexuality and sociability are presented under this section.

With regard to body form, two significant clusters were observed ($p < 0.05$) by SIMPROF analysis (Figure 4.22). Sakumo II and Fosu lagoons formed the first cluster at a similarity level of 58.96 %. The Benya and Muni lagoons were similar at level of 82.58 % while the Kakum Estuary and Pra Estuary were similar at level of 79.15 %. These four water bodies formed the second cluster at a similarity level of 62.7 %.

Under the feeding habit trait in Figure 4.23, SIMPROF separated the water bodies into two clusters ($p < 0.05$). The Sakumo II Lagoon and Fosu Lagoon formed cluster 1 at a similarity level of 73.26 %. Likewise, the Kakum and Pra estuaries (similar at level of 81.37 %) and Benya and Muni lagoons (similar at level of 75.28 %) formed the second cluster.

Figure 4.24 suggests that in terms of mobility, Kakum Estuary and Muni Lagoon were similar at 76.02 %, Sakumo II Lagoon and Fosu Lagoon at 74.91 %, and Pra Estuary and Benya Lagoon at 73.59 %. Only one significant cluster ($p < 0.05$) was identified by the SIMPROF analysis.

Figure 4.25 shows that based on sexuality, all six water bodies were statistically similar ($p < 0.05$) at level of 58.16 %. The Fosu Lagoon and Muni Lagoon were the most similar at 89.48 %. The Benya Lagoon and Sakumo II Lagoon were similar at level of 86.16 % while Kakum Estuary and Pra Estuary were similar at similarity level of 80.58 %.

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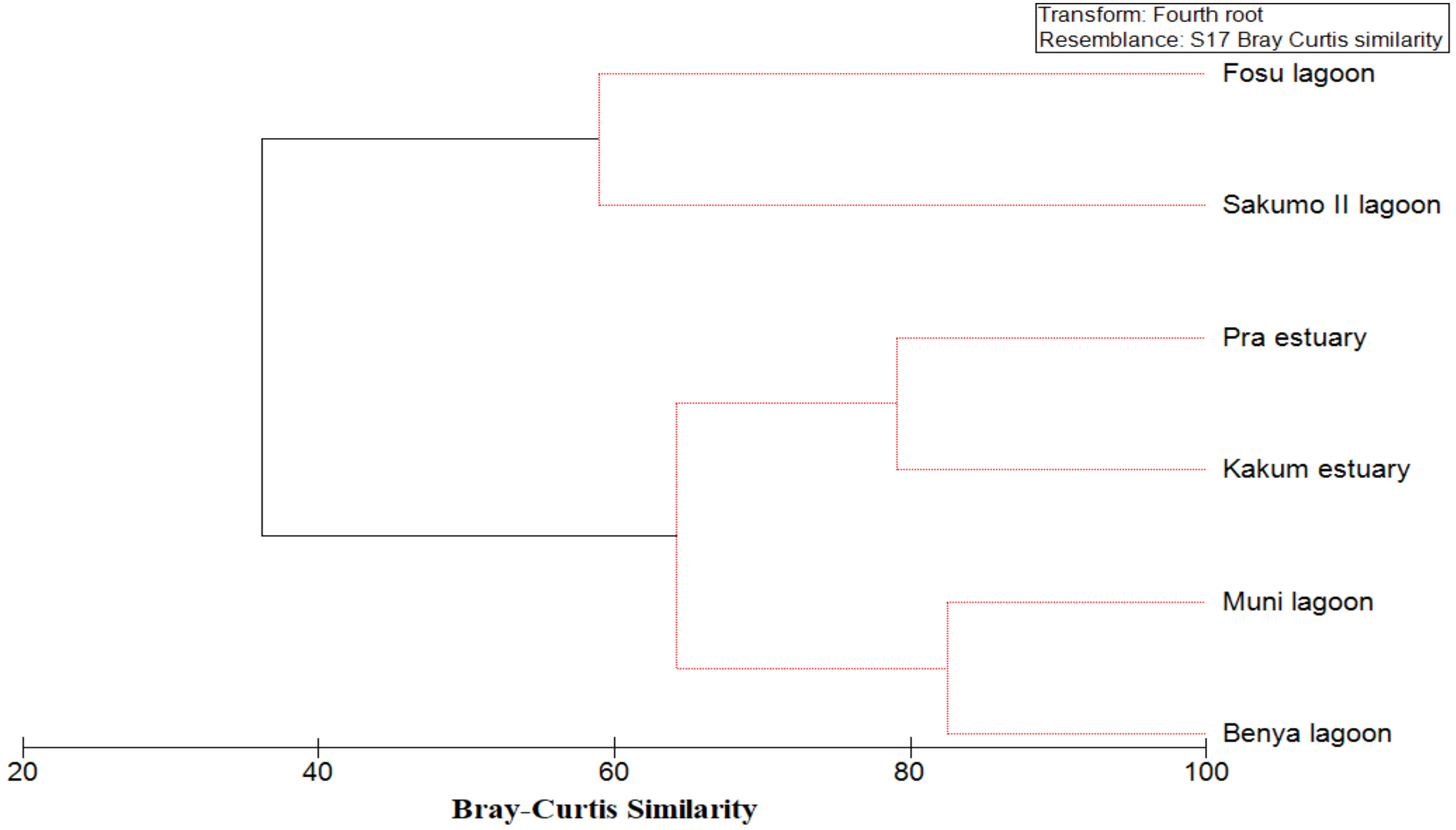

Figure 4.22: Complete linkage of Bray-Curtis similarity based on abundance of benthic macroinvertebrates body form in the six water bodies (joined red lines indicate significant clusters, $p < 0.05$ by SIMPROF analysis)

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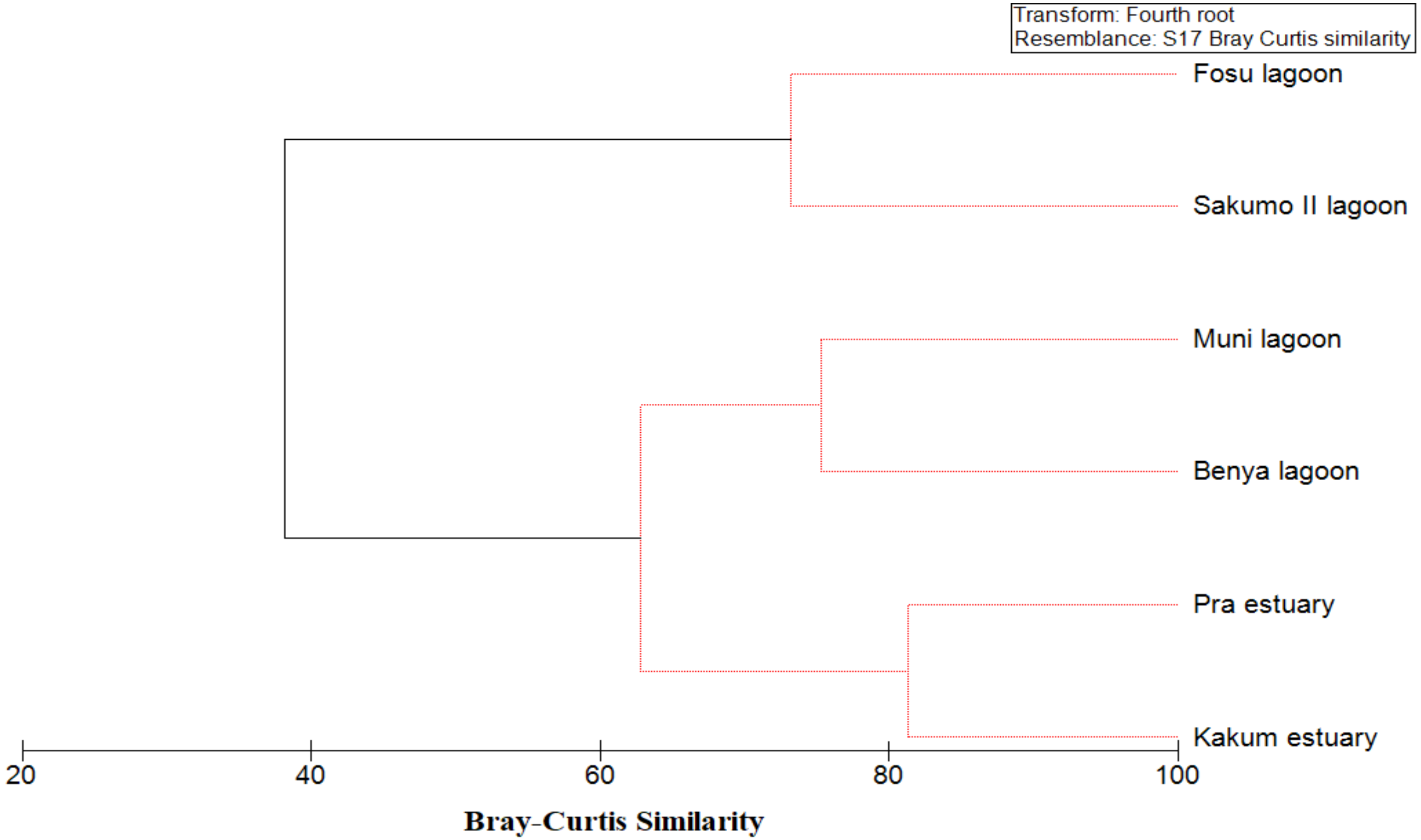

Figure 4.23: Complete linkage of Bray-Curtis similarity based on abundance of benthic macroinvertebrate feeding habit in the six water bodies (joined red lines indicate significant clusters, $p < 0.05$ by SIMPROF analysis)

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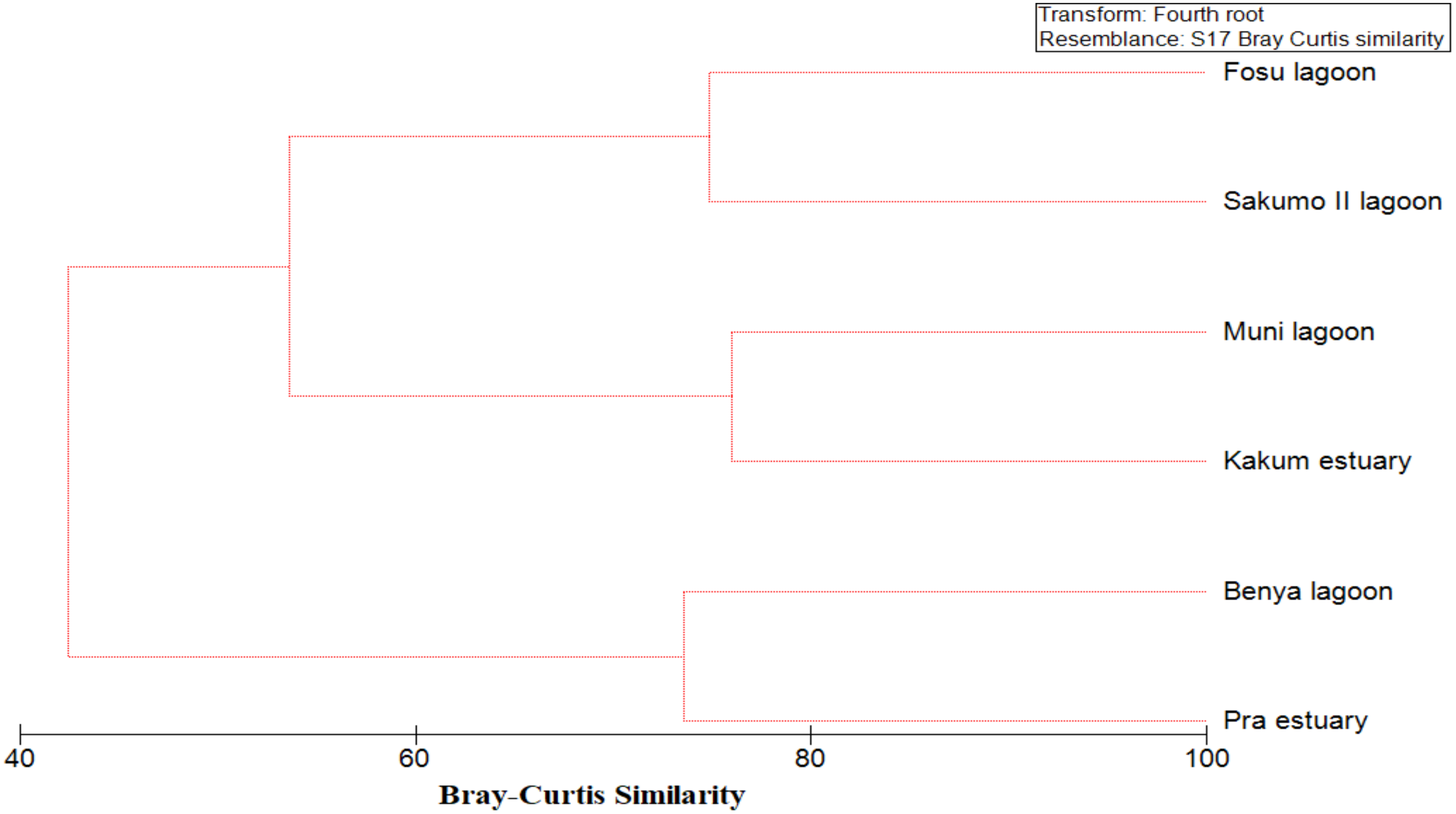

Figure 4.24: Complete linkage of Bray-Curtis similarity based on abundance of benthic macroinvertebrate mobility in the six water bodies (joined red lines indicate significant clusters, $p < 0.05$ by SIMPROF analysis)

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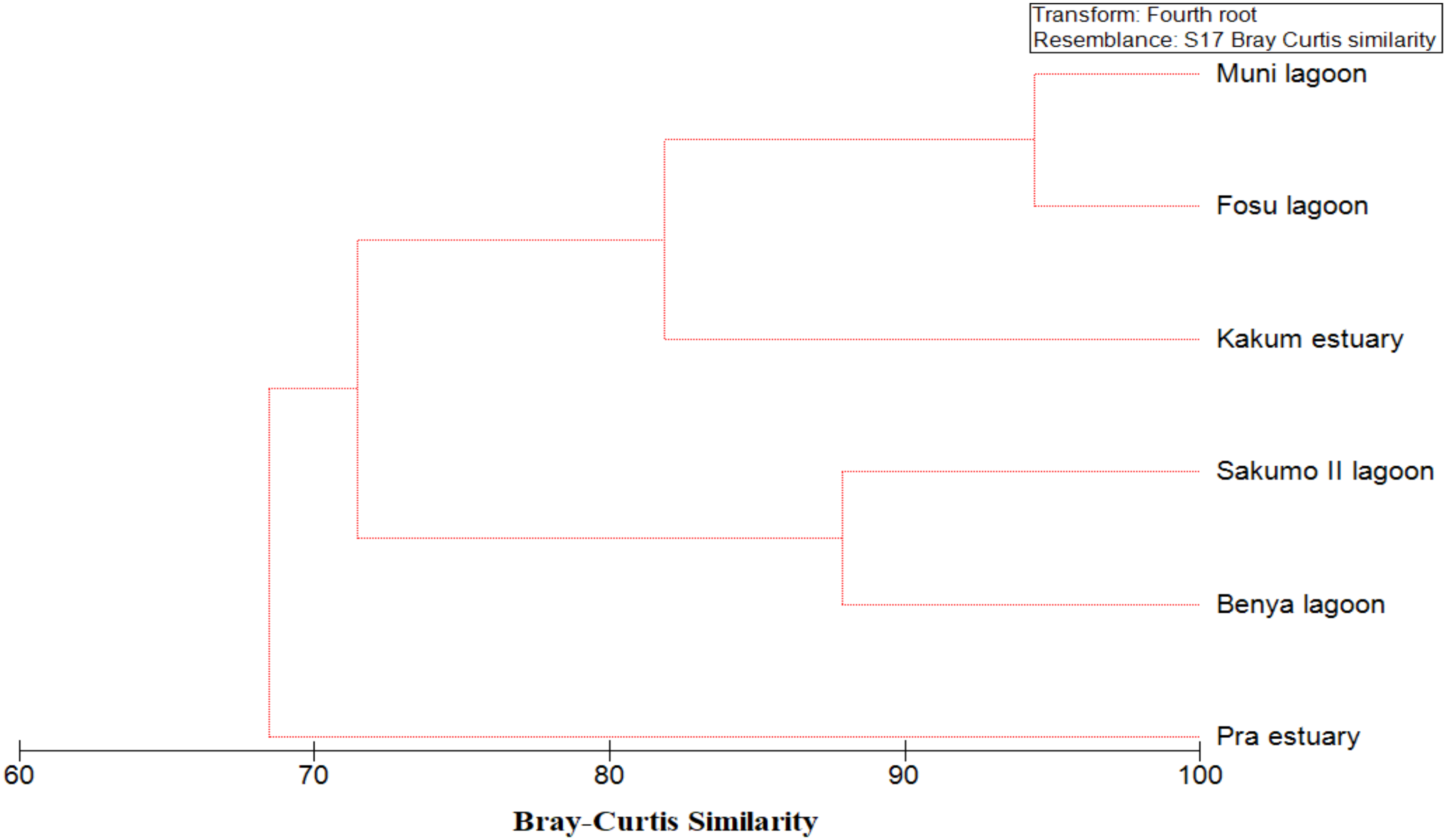

Figure 4.25: Complete linkage of Bray-Curtis similarity based on abundance of benthic macroinvertebrate sexuality in the six water bodies (joined red lines indicate significant clusters, $p < 0.05$ by SIMPROF analysis)

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Figure 4.26 showed a similarity between Fosu and Muni lagoons at 94.43 % under the trait sociability. The two water bodies were similar to the Kakum Estuary at level of 81.89 %. Benya Lagoon and Sakumo II Lagoon were similar at 87.89 %. All the water bodies showed statistical similarity ($p < 0.05$) by SIMPROF at level of 68.48 %.

Except for the trait sexuality and sociability, Sakumo II Lagoon and Fosu Lagoon formed one cluster for all of the functional traits while the other four water bodies formed another. However, the clusters were significantly different ($p < 0.05$) only with regards to body form and feeding habit traits.

4.7.5 Similarity percentages (SIMPER)

SIMPER was used to select functional trait groups that contributed most to the similarities that occurred among water bodies (Table 4.21). For brevity, only higher contributing functional groups with a cumulative percentage ≥ 70% are listed and used in the determination of environment-taxon relationships. These functional groups selected are hereafter referred to as influential functional groups. For the body form trait, ‘threadlike’ and ‘others’ categories were selected for cluster 1. ‘Others’ in the Sakumo II and Fosu lagoons refers to keel-shaped organisms. ‘Cylindrical and elongate’, ‘threadlike’ and ‘laterally compressed’ forms were selected for cluster 2.

Under the feeding habit trait, ‘deposit feeder’ and ‘deposit feeder+omnivore’ were selected for cluster 1 (Sakumo II and Fosu lagoons) while ‘carnivore/predator’ was selected in addition to ‘deposit feeder’ and ‘deposit feeder+omnivore’ in cluster 2 (the other four water bodies).

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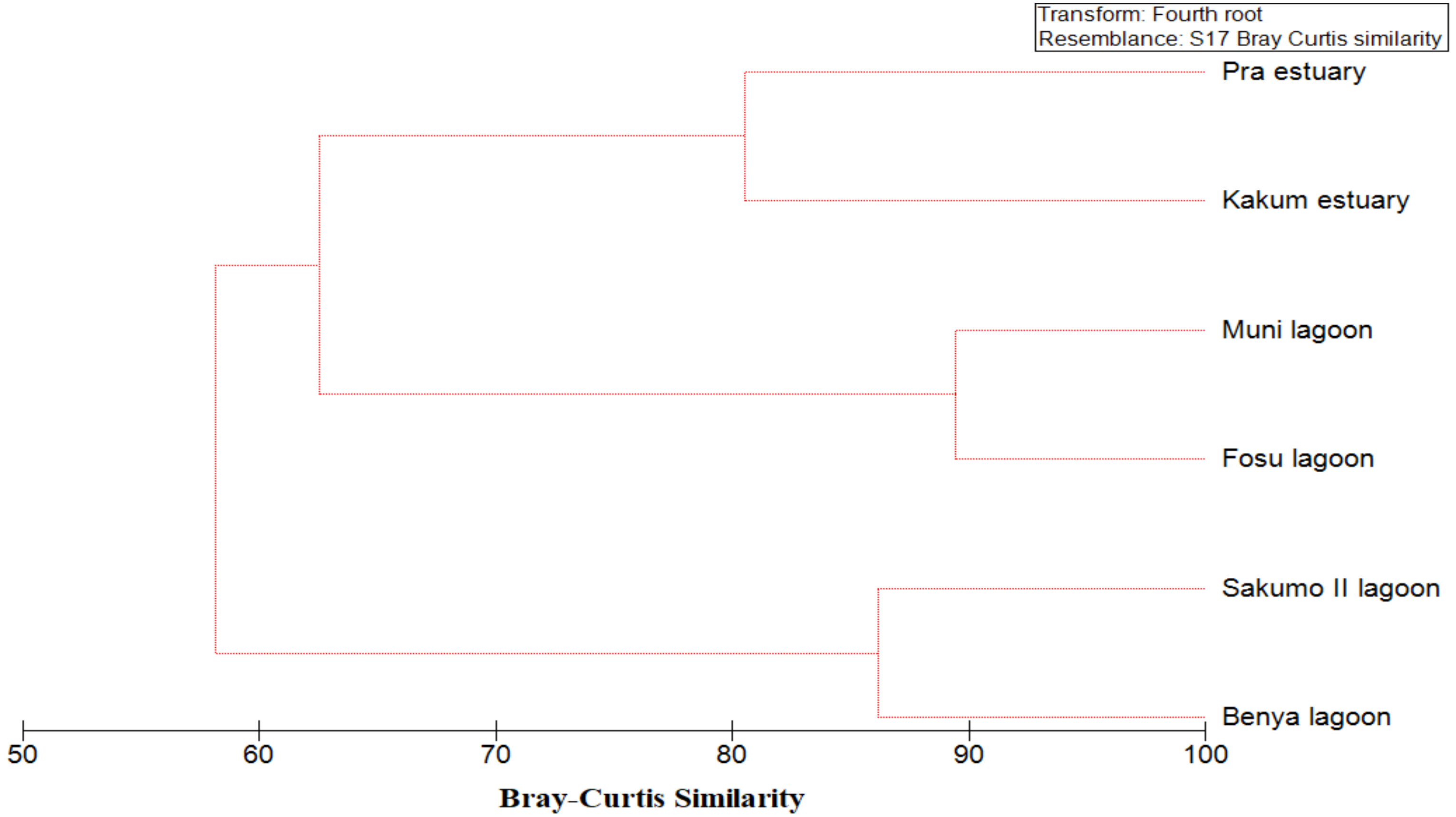

Figure 4.26: Complete linkage of Bray-Curtis similarity based on abundance of benthic macroinvertebrate sociability in the six water bodies (joined red lines indicate significant clusters, $p < 0.05$ by SIMPROF analysis)

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Table 4.21 - *SIMPER Analysis Showing Functional Groups Contributing to the Average Similarity in the Clusters*

Functional trait	**Functional group**	**Average abundance**	**Average similarity**	**Similarity/SD**	**Contribution %**	**Cumulative %**
Body form	***Average similarity in Cluster 1 (Sakumo II Lagoon and Fosu Lagoon): 58.96 %***					
	Threadlike	6.99	36.44	-	61.73	61.73
	Others	2.57	13.78	-	23.35	85.08
	Average similarity in Cluster 2 (Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon): 66.20 %					
	Cylindrical and elongate	5.69	23.05	5.53	32.82	32.82
	Threadlike	3.93	15.12	5.11	22.84	57.66
	Laterally compressed	1.18	9.76	2.46	14.74	72.41
Feeding habit	***Average similarity in Cluster 1 (Sakumo II Lagoon and Fosu Lagoon): 73.26 %***					
	Deposit feeder	6.88	38.18	-	42.81	42.81
	Deposit feeder+omnivore	6.42	36.71	-	41.16	83.97
	Average similarity in Cluster 2 (Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon): 59.89 %					
	Deposit feeder+omnivore	3.3	19.47	2.93	32.51	32.51
	Deposit feeder	2.49	15.02	2.21	25.08	57.59
	Carnivore/predator	1.81	8.51	1.48	14.21	71.8

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Table 4.21, continued

Functional trait	**Functional group**	**Average abundance**	**Average similarity**	**Similarity/SD**	**Contribution %**	**Cumulative %**
Mobility	***Average similarity: 66.23 % (All six water bodies)***					
	Burrower	6.32	32.91	5.44	49.69	49.69
	Burrower/swimmer	4.25	18.16	2.31	27.42	77.1
Sexuality	***Average similarity: 78.89 % (All six water bodies)***					
	Gonochorist	6.56	48.99	4.34	62.1	62.1
	Hermaphrodite	4.12	29.9	4.9	37.9	100
Sociability	***Average similarity: 61.06 % (All six water bodies)***					
	Solitary	3.86	44.64	2.74	70.75	70.75

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‘Burrower’ and ‘burrower/swimmer’ groups were selected under mobility functional trait, ‘gonochorist’ and ‘hermaphrodite’ were selected under sexuality while ‘solitary’ was selected under the trait sociability in all six water bodies.

4.7.6 Environment-functional trait/group relationship

Influence of abiotic factors on the abundance of functional groups under body form, feeding habit and mobility are presented under this section. Sexuality and sociability were not included because the groups under these traits were very few to merit analysis. Abiotic factors that exhibited multi-collinearity were eliminated. Higher contributing functional groups (influential functional groups) were used for this analysis. Similar to the environment-taxon relationship, abundance was predicted with two models; Model 1 shows the effects of physico-chemical parameters and sediment parameters on the abundance of influential functional groups while model 2 predicts the effects of heavy metals concentrations, in addition to physico-chemical parameters and sediment parameters on the abundance of influential functional groups.

In the Sakumo II and Fosu lagoons (cluster 1), abundance of threadlike and keel-shaped forms was influenced by significant changes in conductivity and phosphate in Model 1 (Table 4.22). Significant decrease ($p < 0.05$) in conductivity and phosphate resulted in increased abundance. In the presence of heavy metals in model 2, abundance increased when iron and zinc decreased and when copper and chromium increased ($p < 0.05$).

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Table 4.22 - *Negative Binomial Model Showing the Influence of Abiotic Factors on the Abundance of Influential Functional Groups under the Functional Trait 'Body Form' in Cluster 1 (Sakumo II Lagoon and Fosu Lagoon)*

Abundance	**Model 1**						**Model 2**					
	IRR	**Robust S.E.**	**z**	**P>z**	**95% C.I.**		**IRR**	**Robust S.E.**	**z**	**P>z**	**95% C.I.**	
pH	1.6394	0.4788	1.69	0.09	0.9248	2.9060	0.6472	0.3234	-0.87	0.38	0.2430	1.7232
DO	1.0355	0.0598	0.60	0.55	0.9246	1.1596	0.9934	0.0922	-0.07	0.94	0.8282	1.1917
Conductivity	0.9998	0.0000	-3.20	**0.00**	0.9998	0.9999	1.0000	0.0001	-0.58	0.56	0.9998	1.0001
Temperature	1.1435	0.0988	1.55	0.12	0.9654	1.3545	1.1522	0.2812	0.58	0.56	0.7141	1.8589
Turbidity	0.9992	0.0023	-0.36	0.72	0.9946	1.0037	1.0048	0.0051	0.94	0.35	0.9948	1.0149
Nitrate	0.9984	0.0193	-0.08	0.94	0.9614	1.0369	1.0132	0.0119	1.11	0.27	0.9901	1.0369
Phosphate	0.9325	0.0092	-7.06	**0.00**	0.9146	0.9508	1.2192	0.1624	1.49	0.14	0.9391	1.5828
OM	0.9735	0.0233	-1.12	0.26	0.9288	1.0203	1.0080	0.0304	0.26	0.79	0.9502	1.0694
MPS	1.3836	0.6346	0.71	0.48	0.5631	3.3996	4.8051	3.9070	1.93	0.05	0.9763	23.6488
As							1.1556	0.4782	0.35	0.73	0.5135	2.6005
Cr							3.8809	1.9164	2.75	**0.01**	1.4743	10.2156
Cu							1.4341	0.1822	2.84	**0.01**	1.1180	1.8396
Fe							0.9891	0.0032	-3.36	**0.00**	0.9829	0.9955
Hg							1.2762	0.5796	0.54	0.59	0.5240	3.1080
Mn							0.9869	0.0080	-1.62	0.11	0.9713	1.0028
Ni							0.9585	0.3049	-0.13	0.89	0.5138	1.7880
Pb							0.9945	0.0271	-0.20	0.84	0.9427	1.0490
Zn							0.5662	0.0702	-4.59	**0.00**	0.4441	0.7218
Constant	0.0465	0.1565	-0.91	0.36	0.0001	34.2398	5.7000	52.9096	0.19	0.85	0.0000	4.54E+08

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Abundance of ‘Cylindrical and elongate’ and ‘threadlike’ functional trait groups in the Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon (cluster 2) increased by significant increase and decrease in nitrate and conductivity respectively ($p < 0.05$) in model 1 (Table 4.23). In model 2, significant decrease in pH and mercury ($p < 0.05$) and significant increase in temperature, organic matter, arsenic, lead and zinc resulted in increased abundance.

Under the feeding habit trait, the abundance of ‘deposit feeder’ and ‘deposit feeder+omnivore’ groups in the Sakumo II and Fosu lagoons (cluster 1) increased when conductivity and phosphate decreased significantly ($p < 0.05$) in model 1 (Table 4.24). In model 2, abundance increased when iron and zinc decreased significantly ($p < 0.05$).

In the Benya Lagoon, Muni Lagoon, Pra Estuary and Kakum Estuary (cluster 2), abundance of the ‘deposit feeder’, ‘deposit feeder+omnivore’ and ‘carnivore/predator’ groups increased as conductivity increased and nitrate decreased significantly ($p < 0.05$) in model 1 (Table 4.25). In the presence of heavy metals (model 2), significant decrease in pH and Hg resulted in increased abundance ($p < 0.05$). Likewise, increase in temperature, organic matter, arsenic, lead and zinc significantly resulted in increased abundance.

The abundance of ‘burrower’ and ‘burrower/swimmer’ in all six water bodies was influenced by significant decrease in DO and turbidity and increase in pH and nitrate ($p < 0.05$) in model 1 (Table 4.26). In model 2, conductivity, temperature, turbidity, MPS and mercury significantly influenced abundance ($p < 0.05$). Abundance increased as conductivity, turbidity, nitrate and mercury decreased and MPS increased.

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Table 4.23 - *Negative Binomial Model Showing the Influence of Abiotic Factors on the Abundance of Influential Functional Groups under the Functional Trait 'Body Form' in Cluster 2 (Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon)*

Abundance	**Model 1**						**Model 2**					
	IRR	**Robust S.E.**	**z**	**P>z**	**95% C.I.**		**IRR**	**Robust S.E.**	**z**	**P>z**	**95% C.I.**	
pH	1.0633	0.1311	0.50	0.62	0.8350	1.3541	0.1671	0.0721	-4.15	**0.00**	0.0717	0.3894
DO	0.9534	0.0229	-1.99	0.05	0.9095	0.9993	0.7635	0.1106	-1.86	0.06	0.5748	1.0141
Conductivity	0.9995	0.0001	-6.39	**0.00**	0.9994	0.9997	1.0001	0.0001	0.78	0.44	0.9999	1.0003
Temperature	1.0161	0.0266	0.61	0.54	0.9653	1.0697	2.3809	0.3013	6.86	**0.00**	1.8579	3.0510
Turbidity	0.9989	0.0007	-1.54	0.12	0.9976	1.0003	0.9995	0.0013	-0.40	0.69	0.9970	1.0020
Nitrate	1.0472	0.0211	2.29	**0.02**	1.0066	1.0893	1.1280	0.0726	1.87	0.06	0.9942	1.2797
Phosphate	0.9882	0.0425	-0.28	0.78	0.9084	1.0751	0.8832	0.0912	-1.20	0.23	0.7214	1.0812
OM	1.0238	0.0142	1.69	0.09	0.9963	1.0521	1.0828	0.0312	2.76	**0.01**	1.0233	1.1457
MPS	1.3043	0.3646	0.95	0.34	0.7541	2.2559	0.8726	0.5405	-0.22	0.83	0.2592	2.9381
As							2.0330	0.3577	4.03	**0.00**	1.4401	2.8701
Fe							0.9986	0.0020	-0.71	0.48	0.9947	1.0025
Hg							0.2756	0.0732	-4.85	**0.00**	0.1638	0.4638
Mn							0.9939	0.0143	-0.43	0.67	0.9663	1.0223
Ni							0.8292	0.1046	-1.48	0.14	0.6476	1.0617
Pb							1.5546	0.2571	2.67	**0.01**	1.1242	2.1497
Zn							1.2340	0.0828	3.13	**0.00**	1.0819	1.4075
Constant	2.83708	2.51500	1.18	0.24	0.49923	16.12280	7.88E-06	3.75E-05	-2.47	0.01	0.0000	0.0879

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Table 4.24 - *Negative Binomial Model Showing the Influence of Abiotic Factors on the Abundance of Influential Functional Groups under the Trait 'Feeding Habit' in Cluster 1 (Sakumo II Lagoon and Fosu Lagoon)*

Abundance	**Model 1**						**Model 2**					
	IRR	**Robust S.E.**	**z**	**P>z**	**95% C.I.**		**IRR**	**Robust S.E.**	**z**	**P>z**	**95% C.I.**	
pH	1.8541	0.5015	2.28	0.02	1.0912	3.1503	1.5455	0.6339	1.06	0.29	0.6918	3.4529
DO	1.0169	0.0533	0.32	0.75	0.9176	1.1269	0.9392	0.0809	-0.73	0.47	0.7933	1.1119
Conductivity	0.9999	0.0000	-2.97	**0.00**	0.9998	1.0000	0.9999	0.0001	-1.58	0.12	0.9997	1.0000
Temperature	1.1523	0.0988	1.65	0.10	0.9741	1.3632	1.0984	0.2904	0.35	0.72	0.6542	1.8442
Turbidity	0.9986	0.0013	-1.13	0.26	0.9961	1.0010	1.0003	0.0049	0.06	0.96	0.9908	1.0099
Nitrate	1.0028	0.0193	0.15	0.88	0.9658	1.0413	0.9925	0.0139	-0.54	0.59	0.9656	1.0202
Phosphate	0.9352	0.0093	-6.73	**0.00**	0.9171	0.9536	1.0494	0.1266	0.40	0.69	0.8285	1.3294
OM	0.9771	0.0225	-1.00	0.32	0.9340	1.0223	1.0016	0.0300	0.05	0.96	0.9445	1.0623
MPS	1.4007	0.6195	0.76	0.45	0.5887	3.3327	2.1435	1.4347	1.14	0.26	0.5773	7.9585
As							1.4638	0.6611	0.84	0.40	0.6040	3.5474
Cr							0.9646	0.1234	-0.28	0.78	0.7507	1.2394
Cu							1.2272	0.1401	1.79	0.07	0.9812	1.5349
Fe							0.9897	0.0037	-2.73	**0.01**	0.9824	0.9971
Hg							1.3463	0.6349	0.63	0.53	0.5342	3.3930
Mn							0.9937	0.0076	-0.83	0.41	0.9788	1.0087
Ni							1.4576	0.3303	1.66	0.10	0.9349	2.2727
Pb							0.9993	0.0289	-0.02	0.98	0.9443	1.0575
Zn							0.7163	0.0938	-2.55	**0.01**	0.5542	0.9259
Constant	0.0133	0.0428	-1.34	0.18	0.0000	7.3647	0.0157	0.1592	-0.41	0.68	0.0000	6.44E+06

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Table 4.25 -Negative Binomial Model Showing the Influence of Abiotic Factors on the Abundance of Influential Functional Groups under the Functional Trait 'Feeding Habit' in Cluster 2 (Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon)

Abundance	**Model 1**						**Model 2**					
	IRR	**Robust S.E.**	**z**	**P>z**	**95% C.I.**		**IRR**	**Robust S.E.**	**z**	**P>z**	**95% C.I.**	
pH	1.0557	0.1329	0.43	0.67	0.8248	1.3512	0.1811	0.0918	-3.37	**0.00**	0.0670	0.4890
DO	0.9563	0.0236	-1.81	0.07	0.9111	1.0037	0.7515	0.1108	-1.94	0.05	0.5630	1.0032
Conductivity	0.9995	0.0001	-5.74	**0.00**	0.9993	0.9997	1.0000	0.0001	0.01	0.99	0.9997	1.0003
Temperature	1.0153	0.0271	0.57	0.57	0.9635	1.0700	2.4821	0.3287	6.86	**0.00**	1.9146	3.2177
Turbidity	0.9989	0.0007	-1.44	0.15	0.9975	1.0004	0.9996	0.0014	-0.32	0.75	0.9968	1.0023
Nitrate	1.0465	0.0210	2.26	**0.02**	1.0061	1.0885	1.1238	0.0747	1.76	0.08	0.9866	1.2801
Phosphate	1.0120	0.0458	0.26	0.79	0.9261	1.1059	0.8967	0.0952	-1.03	0.30	0.7283	1.1041
OM	1.0231	0.0147	1.59	0.11	0.9946	1.0524	1.0861	0.0311	2.89	**0.00**	1.0269	1.1488
MPS	1.4668	0.4250	1.32	0.19	0.8313	2.5883	1.1376	0.7764	0.19	0.85	0.2986	4.3342
As							2.0834	0.4006	3.82	**0.00**	1.4293	3.0369
Fe							0.9989	0.0020	-0.56	0.57	0.9949	1.0028
Hg							0.3082	0.0861	-4.21	**0.00**	0.1782	0.5331
Mn							0.9939	0.0152	-0.40	0.69	0.9646	1.0241
Ni							0.8172	0.1180	-1.40	0.16	0.6157	1.0847
Pb							1.5798	0.2620	2.76	**0.01**	1.1414	2.1866
Zn							1.1830	0.0769	2.59	**0.01**	1.0415	1.3437
Constant	3.2651	2.9432	1.31	0.19	0.5580	19.1064	0.0000	0.0000	-2.66	0.01	0.0000	0.0278

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Table 4.26 - *Negative Binomial Model Showing the Influence of Abiotic Factors on the Abundance of Influential Functional Groups under the Trait ‘Mobility’ in the Six Water Bodies*

Abundance	**Model 1**						**Model 2**					
	IRR	**Robust S.E.**	**z**	**P>z**	**95% C.I.**		**IRR**	**Robust S.E.**	**z**	**P>z**	**95% C.I.**	
pH	1.5876	0.1801	4.07	**0.00**	1.2710	1.9830	1.3857	0.3521	1.28	0.20	0.8421	2.2801
DO	0.9448	0.0190	-2.83	**0.01**	0.9084	0.9827	1.0239	0.0403	0.60	0.55	0.9479	1.1059
Conductivity	1.0000	0.0000	0.03	0.98	0.9999	1.0001	0.9999	0.0000	-2.56	**0.01**	0.9998	1.0000
Temperature	1.0430	0.0261	1.68	0.09	0.9930	1.0954	1.5407	0.1615	4.12	**0.00**	1.2546	1.8920
Turbidity	0.9973	0.0007	-4.12	**0.00**	0.9960	0.9986	0.9975	0.0008	-3.21	**0.00**	0.9960	0.9990
Nitrate	1.0454	0.0160	2.89	**0.00**	1.0144	1.0773	0.9994	0.0174	-0.03	0.97	0.9658	1.0341
Phosphate	0.9997	0.0192	-0.02	0.99	0.9627	1.0381	1.0127	0.0718	0.18	0.86	0.8812	1.1637
OM	1.0218	0.0125	1.77	0.08	0.9976	1.0465	1.0368	0.0264	1.42	0.16	0.9864	1.0897
MPS	1.0854	0.2568	0.35	0.73	0.6827	1.7258	2.0853	0.7194	2.13	**0.03**	1.0605	4.1005
As							1.4511	0.2812	1.92	0.06	0.9926	2.1215
Fe							0.9979	0.0019	-1.14	0.25	0.9942	1.0015
Hg							0.4794	0.1375	-2.56	**0.01**	0.2733	0.8409
Mn							1.0007	0.0050	0.14	0.89	0.9910	1.0105
Ni							1.2055	0.1234	1.83	0.07	0.9864	1.4732
Pb							0.9639	0.0190	-1.86	0.06	0.9273	1.0019
Zn							1.0732	0.0796	0.95	0.34	0.9279	1.2411
Constant	0.2041	0.1558	-2.08	0.04	0.0457	0.9113	0.0000	0.0000	-3.71	0.00	0.0000	0.0026

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4.8 Chapter Summary

This chapter highlights the results on various parameters studied in the six water bodies. Differences were observed in terms of physico-chemical parameters, sediment parameters and heavy metals across water bodies. Phosphate, nitrate, cadmium and mercury concentrations exceeded the recommended limits in all the water bodies. Extremely high conductivity values were recorded in the Fosu Lagoon, Sakumo II Lagoon and Pra Estuary. TDS values were high in the Muni and Fosu lagoons while the Pra Estuary was highly turbid. Benthic macroinvertebrates also showed differences taxonomically and functionally across the water bodies. Forty-five (45) species were encountered throughout the study, the highest number of species was recorded in the Benya Lagoon and the lowest in the Sakumo II Lagoon. Only *C. capitata* and *Chironomus* sp. were present in all six water bodies. Polychaetes dominated the water bodies generally except in the Fosu Lagoon where molluscs dominated and the Sakumo II Lagoon where oligochates and chironomids dominated. Low diversities were recorded in the Sakumo II and Fosu lagoons. 'Cylindrical and elongate' and 'threadlike' body forms, burrowers, deposit feeders, solitary forms and gonochorists dominated the functional trait groups. The Sakumo II and Fosu were much more similar to each other than to any other water body based on the Bray-Curtis similarity indices, SIMPROF and SIMPER tests. It was also shown in this chapter that, abiotic factors namely conductivity, nitrate, mercury, lead and zinc influenced the abundance of benthic macroinvertebrate taxonomic and functional groups most.

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CHAPTER FIVE

DISCUSSION

This chapter has been structured to primarily explain the observed trends in physico-chemical parameters, heavy metal concentrations, sediment parameters, benthic macroinvertebrate taxonomic and functional trait groups in the two estuaries and four lagoons studied. The findings have also been compared to other related works where necessary.

5.1 Physico-Chemical Parameters

According to Mustapha (2008), changes in physico-chemical characteristics like temperature, dissolved oxygen, nitrate and phosphate among others provide valuable information on water quality and their impacts on the functions and biodiversity of aquatic organisms. Key parameters considered in this research namely temperature, salinity, conductivity, DO, pH, turbidity, TDS, nitrate and phosphate showed levels of spatial and seasonal variations.

Mean temperatures between 23 ℃ and 34 ℃ recorded in this present study (Figure 4.1) is characteristic of shallow tropical coastal water bodies (Yap, Rahim Ismail, Azrina, Ismail & Tan, 2006; Davies et al., 2008; Tay et al., 2009; Abowei, 2010; Nirmal Kumar, George, Kumar, Sajish & Viyol, 2010; Okyere, 2010; Ewa et al., 2011; Dzakpasu & Yankson, 2015). High temperatures observed in the 1st quarter of 2017 and low temperatures in the 3rd quarters of 2016 and 2017 in all the water bodies reflect the climate conditions in southern Ghana where the hottest month is March and coldest is August. Similar trends were observed in the Kakum and Nyan estuaries by Dzakpasu and Yankson

(2015). Also, the highest temperatures recorded in the Muni Lagoon is perhaps due to the very shallow nature and the lack of shade compared to the other water bodies. The lagoon is about 0.15 – 3.5 m deep but most parts are less than 0.2 m. Low temperatures in the Kakum Estuary may be due to shading of this water body by mangrove vegetation on the banks. This estuary is narrow with a width of 8 – 25 m (Dzakpasu, 2012) making it possible for mangroves found on either side of the water body to form a canopy on most parts of the estuary. This estuary takes its source from the Kakum Forest which is generally a cool environment.

Salinity of water is closely linked to climatic conditions; it decreases through dilution from a freshwater source or rain and increases as a result of evaporation (Waller, Burchett & Dando, 1996). The higher salinity in the Muni and Benya lagoons could be attributed to several reasons. The Muni Lagoon, for instance, has been documented to be a hypersaline lagoon attaining salinity as high as 61.8 ppt during the dry season (Lamptey & Armah, 2008). Hence the current upper value of 47.2 ppt is within the range recorded by earlier authors. The Benya Lagoon, on the other hand, is a man-made open lagoon which is regularly inundated by the sea at high tides. Moreover, a number of salt pans are located around its upper reaches, contributing to its high salinity. Unlike the Sakumo II Lagoon which is also man-made open, the Benya Lagoon has a wider opening and lies lower than the sea allowing for much tidal forcing. The comparably high salinity in the 1st quarter of 2017 (Figure 4.2) can be associated with the hot ambient temperature during that time of the year and hence higher evaporation coupled with minimal rainfall. The highest temperatures in this study were also observed in the 1st quarter of 2017. McLusky (1989) noted that reduction in salinity could be a result of dilution when it rains while evaporation could increase salinity.

Poisson (1982) noted conductivity and salinity are strongly related. Fondriest Environmental Inc. (2014a) explained that dissolved salts contributed to conductivity. Interestingly, in this present study, the highest conductivity values were recorded in the less saline Fosu Lagoon, Sakumo II Lagoon and Pra Estuary while the more saline Benya and Muni lagoons had low conductivities (Figures 4.2 and 4.3). Other factors could be contributing to the high conductivities in the less saline water bodies. Das, Samal, Roy and Mitra (2006) explained that conductivity has strong interrelationship with water pollution. High conductivity within the range of 1000 to 10,000 µS/cm is an indicator of saline conditions or heavy impact by industry, while values less than 200 µS/cm indicate a healthy or clean conditions (Horne & Goldman, 1994). This suggests that Pra Estuary, Fosu Lagoon and the Sakumo II Lagoon are heavily impacted by industry.

High conductivity in the Pra Estuary could be attributed to mining activities and agriculture. The Pra River drains mining and farming areas before entering the sea. A common impact of mining on water quality is the oxidisation of sulphide minerals which occurs with the release of sulphate, leading to the formation of ‘acid mine drainage’ (AMD) (RoyChowdhury, Sarkar & Datta, 2015). Releases of AMD have been linked to high conductivities in water bodies (Ugya, Ajibade & Ajibade, 2018). The high conductivities in the Pra Estuary may therefore be coming from AMD.

According to Nazir et al. (2015), the presence of sodium, potassium, chloride or sulphate contributes to high conductivity values. Agriculture runoff and sewage leak has the potential of increasing conductivity due to the additional chloride, phosphate and nitrate ions (Fondriest Environmental Inc., 2014a). The Fosu Lagoon, for instance, receives effluents from the Cape Coast area in addition to direct discharges from the Cape Coast Metropolitan Hospital, St. Augustine College and the automobile garage at Siwdu located adjacent to it. Apart from the great deal of chemicals used in hospitals which have the potential of polluting surface waters, other wastes produced include blood and its products, pathologic wastes, tissues contaminated by microbial cultivation environments, syringe, nasal discharge, phlegm and excrements of patients, and other waste materials produced in emergency ward, surgery room, and hospitalization places (Ashouri & Sadhezari, 2016). Wastes from automobile shop may include batteries, solvents, oils, fuels, acids and alkalis, among others. These waste substances contain dissolved ions which may be contributing to the high conductivity in this lagoon. Similar values were recorded by other researchers in this lagoon (Blay & Asabere-Ameyaw, 1993; Eshun, 2011; Armah, Ason, et al., 2012).

High conductivities in the Sakumo II Lagoon, which lies between two industrial cities, Accra and Tema could be accounted for by wastes from industries. Like other harbours, the Tema Harbour (which is in close proximity to the lagoon) may be producing wastes such as oil, sewage, garbage, ballast water, contaminated dredge materials, etc. (O'Brien, 2009; Sciortino & Ravikumar, 1999) which may find their way into the lagoon contributing to high conductivity. The Mamahuma and the Gbagbla Ankonu streams, which feed the Sakumo II lagoon may also be contributing to high conductivities in the lagoon. These two streams have been reported to be polluted as a result of industrial and domestic activities (Tay et al., 2009). Values obtained in this present study however, appear lower than those in previous studies (Tay et al., 2009; Nonterah et al., 2015). Agriculture runoffs from farms along this water body may have also contributed to its high conductivities.

High DO concentrations in the water bodies during the 4th quarter of 2016 (around the harmattan period) may be as a result of settling of silt (Fondriest Environmental Inc., 2014b) which increases light penetration to enhance photosynthesis by phytoplankton. Longer photoperiod at this time of the year may be contributing factors. Low values in the 3rd quarter of 2016 and the 1st quarter of 2017 may be attributed to the major rains recorded in the vicinities of four out of the six water bodies in the 3rd quarter of 2016. Runoffs from rains possibly introduced organic materials which used up DO for decomposition and thereby reduced its concentration in the water bodies. Rainfall around this period also may have contributed to turbid nature of the water bodies and possibly causing reduced photosynthetic activities of phytoplankton and other aquatic plants. Low DO concentrations in the 1st quarter of 2017 could be accounted for by the high temperatures recorded around this period as solubility of oxygen in water reduces with increased temperature. DO ranges in this present study fall within the ranges suitable (< 2.0 to 11.0 mg/l) for aquatic organisms (Behar, 1997).

Generally, majority of aquatic organisms prefer a pH range of 6.5 – 9.0 (Fondriest Environmental Inc., 2013b). All six water bodies had pH within this range making them conducive for aquatic life. According to Waller et al. (1996), pH of a water body can be altered by the activities of living organisms as well as by pollution from the terrestrial environments. pH in the water bodies studied followed a similar trend as temperature, highest in 1st quarter of 2017 and lowest in 2nd and 3rd quarters of 2017 (Figure 4.5). Similar findings were made by other researchers. For example, Abowei (2010) recorded higher pH in the dry season compared to the wet season in the Nkoro River of the Niger Delta. A similar pattern was recorded in the Woji Creek of the Niger Delta (Davies et al., 2008). Photosynthesis, respiration and decomposition contribute to pH fluctuations due to their influences on carbon dioxide levels (Fondriest Environmental Inc., 2013b). Across water bodies, higher values in the Fosu and Muni lagoons may be due to various factors like the bedrock, presence of salt ions or other ions as well as influences from surrounding land (Fondriest Environmental Inc., 2013b).

Turbidity of water bodies can be influenced by phytoplankton, algal growth, re-suspension of sediments from the bottom, urban runoff, etc. (American Public Health Association, 1999). The high turbidity values recorded in the Pra Estuary compared to the other water bodies (Figure 4.6) may be a result of illegal artisanal mining (galamsey) activities reported upstream of this estuary (GhanaWeb, 2017; B&FTOnline, 2018). These activities disturb the bottom of the water body leading to suspension of silt particles in the water. High turbidity in the Pra Estuary has been reported by Okyere (2015), who recorded values > 150 NTU for most parts of the year. Turbidity values in the six water bodies somewhat reflected the rainfall values for the study vicinities suggesting that runoffs from rains played a role in the turbidity of the six water bodies.

Excessive TDS can reduce water clarity, hinder photosynthesis, and lead to increased water temperatures (USEPA, 1999). Scannell and Jacobs (2001)

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reported that TDS concentrations above 1500 mg/l affects the growth and survival of aquatic invertebrates. Consistently high TDS, above this range, in the Fosu Lagoon (Figure 4.7) could be attributed to possible influx of effluents from the hospital, school and automobile workshop located within its vicinity in addition to drainage pipes which have been directed into the lagoon. Fluctuations recorded in the Kakum and Pra estuaries could be due to runoff by rivers which possibly carry dissolved solids from their catchment areas. A sudden rise in TDS in the Muni Lagoon during the 2nd and 3rd quarters of 2017, coinciding with the same period of low salinity could be due to freshwater influx from runoffs. Some sources of dissolved solids are decaying organisms, urban and industrial runoff, industrial waste and sewage, in addition to weathering of rocks and erosion of the earth's surface (LEO Enviro Sci Inquiry, 2011; Fondriest Environmental Inc., 2014b). Agbemehia (2014) obtained values ranging from 779.25 mg/l to 6669.2 mg/l in the Sakumo II Lagoon, which were higher compared to 441.67 – 864.44 mg/l in the present study.

Nutrients such as nitrates and phosphates occur naturally in low concentrations in aquatic ecosystems, however, availability of excessive nutrients may result in eutrophication (Nartey et al., 2012). The significantly high concentrations of nitrate and phosphate in the Sakumo II Lagoon (Figures 4.9 and 4.10) could be coming from farms along the banks of the lagoon or may be introduced by runoffs carrying fertilizers and excreta from the catchment area. This is evident in the characteristic dark colour of the water and the presence of bloom of invasive weeds specifically the *Pistia* sp. in this water body. Several studies have recorded nutrient pollution in the Sakumo II Lagoon

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(Nixon et al., 2007; Ansa-Asare et al., 2008; Asmah et al., 2008; Nartey et al., 2012; Agbemehia, 2014; Nonterah et al., 2015).

It is worth noting that, all six water bodies had nitrate and phosphate values above the recommended levels of 1.0 mg/l and 0.1 mg/l respectively in estuarine and coastal waters (McCaffrey, 1997; Behar, 1997). All the water bodies studied are close to human communities and therefore prone to receive wastes containing phosphate and nitrates. Okyere (2015) recorded values above the permissible limits for both nitrate and phosphate in the Pra Estuary. Similar trends have been documented in the Fosu Lagoon (Biney, 1982; Baffour-Awuah, 2014), Benya and Muni lagoons (Nixon et al., 2007). Uncontrolled fertilizer applications on farms close to water bodies and within their catchment areas may be responsible for this kind of trend. Phosphates occur naturally in nature; other sources include fertilizers, detergents, and human and animal excrement (Smil, 2000). The most common source of nitrate contamination is runoff containing fertilizers. Other sources are leakage from septic tanks, erosion of natural deposits, animal manure (particularly cow manure), etc. (Davies, Reed & O’Brien, 2001).

5.2 Heavy Metals Concentrations

According to Tam and Wong (2000), heavy metals are among the persistent pollutants in the natural environment due to their toxicity, persistence and bioaccumulation problems; and therefore are important in the occurrence and diversity of macroinvertebrates. Higher concentrations of heavy metals in sediments compared to the water in this study is not surprising since sediments serve as reservoirs for contaminants (Suresh, Sutharsan, Ramasamy &

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Venkatachalapathy, 2012). This is because heavy metals are adsorbed to the sediment and thereby accumulate over time (Aderinola, Clarke, Olarinmoye, Kusemiju & Anatekhai, 2009). Also, most of the metals showed higher concentrations in the Fosu Lagoon, Sakumo II Lagoon and Pra estuary which are subjected to impacts from wastes of garage/mechanical workshop, industries, effluents from small scale mines respectively. The physico-chemical parameters show Sakumo II and Fosu lagoons, especially, recorded higher conductivity, nitrate, phosphate, pH and TDS. Relatively high levels in these parameters as seen in this study typically point to pollution. High heavy metals concentrations in these same water bodies corroborate the occurrence of polluting activities within their catchment areas.

Mercury and cadmium were above WHO/USEPA maximum permissible limits (0.002 mg/l in water and 0.3 mg/kg in sediment for mercury and 0.01 mg/l in water and 20 mg/kg in sediment for cadmium) in all the water bodies (see Tables 4.4 and 4.10). Cadmium concentrations being below the detection limit in sediments but above the maximum permissible limit in the water is not easy to explain. This trend is contrary to the expectation that sediments would have a higher level of pollutants as observed for the other metals. Perhaps inadvertent shortcomings in the processing protocol could be responsible. With regard to mercury, Sciortino and Ravikumar (1999) stated that it is a comparatively rare element although ubiquitous in the environment as a result of natural geological activity and man-made pollution. Sources of mercury in water bodies include weathering, dissolution and biological processes. Other sources include industrial effluents connected with chlorine and caustic soda production, pharmaceuticals, mirror coatings, mercury lamps, electrical appliances, mining and certain fungicides (Sciortino & Ravikumar, 1999; Verma & Dwivedi, 2013). Higher concentrations in the Fosu Lagoon compared to the rest of the water bodies could be attributed to wastes from the nearby hospital.

Arsenic concentration was highest in the Fosu Lagoon, followed by the Pra Estuary and lowest in the Muni Lagoon (Table 4.3). According to Verma and Dwivedi (2013), arsenic sources include natural processes, thermal power plants and fuel. The relatively high concentrations in the Fosu Lagoon may be coming from the automobile garage situated near this water body and effluents from the hospital while the mining activities upstream may be contributing to values in Pra Estuary. It is worth noting that, atmospheric concentration of arsenic gets into water bodies as a result of dry fallout and rain (Yadav et al., 2016). Concentrations in this present study were below the WHO/USEPA permissible limits of 0.1 mg/l for water and 20 mg/kg for sediment.

According to Sciortino and Ravikumar (1999), chromium is naturally highly insoluble, and the common soluble forms found in soils are mainly the result of contamination by industrial emissions. Chromium concentration below detection limit (Table 4.5) in the sediment in most of the water bodies may mean it is released into the water bodies occasionally. Relatively high concentrations and its presence throughout the study period in the Pra Estuary indicates a continuous source which may probably be attributed to the mining activities upstream. As stated by Verma and Dwivedi (2013), chromium sources include mining, leather tanning, chromium salts manufacturing and the use of industrial coolants. Concentrations reported in this study were below the WHO/USEPA permissible limit of 0.1 mg/l in water and 25 mg/kg in sediment.

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Copper concentrations in the sediments were generally higher in the Benya, Sakumo II and Fosu lagoons (Table 4.6). Mining, electroplating, smelting operations have been documented to be some sources of this metal (Verma & Dwivedi, 2013). These activities are common practices associated with the three water bodies which had relatively high concentrations. Copper was found throughout the study period in the Pra Estuary and Fosu Lagoon indicating a continuous source. According to Sciortino and Ravikumar (1999), copper is used in alloys, as a catalyst, in anti-fouling paints and as a wood preservative. Urban sewage contains substantial amounts of copper. Concentrations in the water bodies studied were however below the WHO/USEPA permissible limit of 2.0 mg/l in water and 25 mg/kg in sediment.

The relatively high iron concentrations in the Pra Estuary could be due to the clayey nature of the sediments. According to Carroll (1958), clay minerals have iron associated with them as an essential component, as a minor constituent within the crystal lattice or as iron oxide on the surface of the mineral platelets. Concentrations in this study were, however, below the WHO/USEPA maximum permissible limits of 2.0 mg/l in water and 25 mg/kg in sediment.

Lead concentrations in the sediments were higher in the Sakumo II and Fosu lagoons than the rest of the water bodies (Table 4.8). According to Verma and Dwivedi (2013), lead acid batteries, paints and electronic wastes are some common sources of lead in the environment. These are found within the catchment areas of the two lagoons with high concentrations. Lead is also one of the most abundant heavy metals occurring in nature (Sciortino & Ravikumar, 1999). Concentrations were, however, below the WHO/USEPA permissible limit of 0.05 mg/l in water and 40 mg/kg in sediment in the six water bodies.

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Nagpal (2001) stated that even though manganese is abundant and ubiquitous in the environment, additional concentrations originate from municipal sewage, sludge and landfills. This perhaps explains their relatively high concentrations in the Sakumo II Lagoon and Fosu Lagoon compared to the rest of the water bodies. Concentrations in this study were however, lower than the WHO/USEPA maximum permissible limit of 0.2 mg/l in water and 300 mg/kg in sediment (Sciortino & Ravikumar, 1999).

Nickel is a relatively non-toxic element; however, certain nickel compounds have been shown to be carcinogenic in animal experiments (Sciortino & Ravikumar, 1999). According to Verma and Dwivedi (2013), some sources of nickel include smelting operations, thermal power plants, battery industry, etc. The relatively high concentrations in the Sakumo II and Fosu lagoons (Table 4.11) may be due to their locations in heavy industrial area and adjacent to automobile workshop respectively. Concentrations in the six water bodies studied were however below the WHO/USEPA permissible limit maximum permissible limits.

Generally, high zinc concentrations in the Fosu Lagoon sediments could be attributed to domestic sewage, road surface runoff, combustion of fossil fuels and solid wastes (Eisler, 1993; Opaluwa et al., 2012; Verma & Dwivedi, 2013) due to its location near a large automobile workshop and a major road as well as being a receptacle for domestic waste.

5.3 Sediment Parameters

Sediment particle size and organic matter play a crucial role in the distribution of benthic macroinvertebrate populations (Allan, 1995; Ruellet &

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Dauvin, 2007). Harkantra (1982) noted that very fine sediments have a low benthic fauna which could be the case in the Pra Estuary. This estuary had the least number of macroinvertebrates and the finest particle sizes compared to the rest of the water bodies. The clayey nature of the bottom sediment in the Pra Estuary accounted for its fine particle sizes.

The relatively low organic matter content reported in the Muni Lagoon (Figure 4.10) compared to the other water bodies could be attributed to its larger particle sizes (coarse sand). According to Zink, Furtado, Casper and Schwark (2004), low organic matter are common with large particle sizes compared to smaller sizes. Bot and Benites (2005) noted that in well aerated soils, such as coarse sands, and soils in warm climatic regions, organic matter hardly increases because the added materials decompose rapidly.

Tsai et al. (2003) observed that, heavy metals concentrations in sediment increase as the amount of organic material increases. This was evident in the present study as higher concentrations for most of the metals were observed in the Fosu Lagoon, Sakumo II Lagoon and the Pra Estuary compared to the rest of the water bodies.

5.4 Benthic Macroinvertebrate Taxonomic Groups

Biological communities and physical habitat are closely linked in ecosystems (Jinyong et al., 2013). According to Allan (1995), environmental factors such as temperature, pH, electrical conductivity, dissolved oxygen, sediment particle sizes and organic matter content, among many others, determine the distribution of benthic macroinvertebrate communities. Changes within the environment are therefore reflected in the organisms living within.

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Sallenave (2015) mentioned that water quality can be evaluated by the number of species (or taxa) of benthic invertebrates present in a water body. Snelgrove (1997) explained that pollution, for instance, leads to high abundances of few species. It is therefore assumed that aquatic habitats with good water quality provide an optimum environment for the existence of a large number of species (high species richness) while polluted water imposes one or more limiting factors on the benthic community resulting in low species richness (Olive & Dambach, 1973; Reizopoulou et al., 2014). This suggests that the Sakumo II Lagoon (4 species) had the poorest quality, followed by the Fosu Lagoon (8 species) and the Pra Estuary (12 species) due to their low species richness, whiles the Benya Lagoon (21 species) had the best quality among the water bodies studied followed by Kakum Estuary (18 species) and Muni Lagoon (21 species) (Table 4.14). Armah, Ason, et al. (2012) also recorded a higher species richness in the Benya Lagoon (34 species) as compared to the Fosu Lagoon (7 species). The three water bodies with lower species richness also had high organic matter content and heavy metals concentrations in addition to conductivity values that fall within the heavily impacted range (1000 to 10,000 μS/cm) suggesting poor water quality.

The apparent high species richness in the 1st quarter of 2017 for all the water bodies could mean an improvement in water quality around this period. This was evident in the low conductivity values during that period. However, heavy metals concentrations, sediment mean particle sizes and organic matter content did not show any significant change during this period. High pH, temperature, salinity and phosphate recorded around this period may have also played a role.

Out of the total of 45 species encountered during the study, only *Capitella capitata* and *Chironomus* sp. were present in all water bodies. The presence of *C. capitata* and *Chironomus* sp. in all six water bodies is in line with their ubiquity reported in other studies (Grizzle, 1984; Jayaraj, Jayalakshmi & Saraladevi, 2007; Oliveira & Callisto, 2010; Balogun, Ladigbolu & Ariyo, 2011; Dzakpasu, 2012).

In agreement with Olive and Dambach (1973), species composition and relative abundance of each species are influenced by environmental changes. The dominance of *Chironomus* sp. (Insecta) and *Limnodrilus hoffmeisteri* (Oligochaeta) in the Sakumo II Lagoon (see table 4.15), accounting for about 98 % of total abundance raises concern. This is because *Chironomus* sp. is a well-known indicator of organic pollution and is tolerant to extremely low oxygen levels (Gerber & Gabriel, 2002; Xu, Wang, Duan & Pan, 2014). Similarly, *L. hoffmeisteri* is an indicator of organic pollution (Brinkhurst, 1971; Gamito, 2008). Several studies recorded high numbers of *L. hoffmeisteri* in heavily polluted areas (Yap et al., 2006; Martins et al., 2008; Rodriguez & Reynoldson, 2011; Xu et al., 2014). It is important to note that the other two species (*C. capitata* and backswimmer) present in the Sakumo II Lagoon are also pollution tolerant (Day, 1967; Yankson & Kendall, 2001; Gerber & Gabriel, 2002). This lagoon had high levels of heavy metals, nitrate, phosphate and a comparatively high organic matter.

Seven out of the eight species (with a member of the family: Melitidae as an exception) encountered in the Fosu Lagoon are pollution tolerant (refer to species list in Appendix J). The dominance of *Melanoides tuberculata* and *Chironomus* sp., constituting over 90 % of species abundance in the Fosu suggests this lagoon also has poor water quality. The high heavy metals concentration, conductivity and organic matter in this lagoon compared to the rest of the water bodies may be responsible for the preponderance of these pollution indicators. *M. tuberculata* has been reported to be a nuisance species and an invader of aquatic ecosystems because of its high dispersal rate among other traits (Vogler, Núñez, Gutiérrez Gregoric, Beltramino & Peso, 2013). In consonance to this present study, a dominance of *M. tuberculata* and *Chironomus* sp. have been reported in polluted water bodies in Nigeria (Aiwerioghene & Ayoade, 2016) and Indonesia (Patang, Soegianto & Hariyanto, 2018). Armah, Ason, et al. (2012) also recorded a dominance of *Chironomus* sp. (92.35 %) in the Fosu Lagoon.

In the Kakum Estuary, *Nephtys* sp., *Chironomus* sp. and *Nereis* sp. were the dominant invertebrates recorded. These species have been reported in the Kakum and Nyan estuaries where they contributed considerably to the total abundance (Dzakpasu et al., 2015). *Nephtys* sp. and *Nereis* sp. are euryhaline explaining their appearance and abundance in estuaries (Yankson & Kendall, 2001). It has been reported that *Nephtys* sp. prefers sandy substratum because of interstitial spaces (Jayaraj et al., 2008) accounting for its dominance in the Kakum estuary which had predominantly coarse sand. *Nereis* sp., just like the *Chironomus* sp., is a pollution indicator; however, their mere presence in this water body could not be associated with pollution (Ogunwenmo & Kusemiju, 2004; Balogun et al., 2011). Also, prominent numbers of amphipods seen in this water body suggest that there is little or no pollution in this estuary (Ramachandra, Rishiram & Karthick, 2006). The Kakum Estuary had conductivity and TDS within the ranges of healthy ecosystems. Nitrate, phosphate and heavy metals concentrations were also considerably low suggesting a relatively healthy environment as reported by Dzakpasu et al. (2015).

Pristina sp. and *C. capitata* have been documented among the infauna of muddy sediments (Day, 1967; Brinkhurst, 1986; Yankson & Kendall, 2001). This could explain why the two accounted to almost 70 % of the species abundance in the Pra Estuary which had predominantly fine sand.

In addition to its ability to survive in muddy waters, *C. capitata* is opportunistic and a good competitor for space and food (Grizzle, 1984) explaining its dominance in the Benya and Muni lagoons. While polychaetes dominated the Muni Lagoon in this present study, Lamptey and Armah (2008) reported molluscs forming more than half of macroinvertebrate abundance in the same lagoon indicating a shift in species composition and abundance. Also, contrary to this research, Armah, Ason, et al. (2012) found Nemertean worms dominating the Benya Lagoon (87.52 %) while its composition was < 2 % in this current study. A shift in species dominance in these lagoons is not easy to explain; perhaps there is a shift in water and sediment quality and/or food availability detrimental to the Nemertean worms. *Pristina* sp. and *Tubifex* sp. also occurred in fair abundances in the Benya Lagoon explaining their cosmopolitan nature (Brinkhurst, 1971, 1986).

The two species, *Ampithoe* sp. and *Tympanosyllis prampramensis* which were equally abundant in the Muni lagoon, in addition to *C. capitata*, have not been linked to ecological health of water bodies. Olive and Dambach (1973) explained that many organisms do not fit into pollution-tolerant or pollution-sensitive categories and are capable of living under a wide variety of conditions.

This could be said of *T. prampramensis.* The composition of *Ampithoe* sp. and the prominence of other crustaceans, high species richness, low organic matter content, generally low heavy metals concentrations and low conductivity and nutrient levels are all indications that the Muni Lagoon is not polluted (See Olive & Dambach, 1973; Horne & Goldman, 1994; Ramachandra et al., 2006).

Shannon-Wiener diversity indices were comparatively lower in the Sakumo II Lagoon and Fosu Lagoon (1.01 and 1.56 respectively) (refer to Figure 4.12), suggesting poor water quality. According to Turkmen and Kazanci (2010), Shannon-Wiener diversity index values range from 0 to 5 and values above 3 indicate stable and balanced habitats. Armah, Ason, et al. (2012) also had diversity as low as 0.346 in the Fosu Lagoon. The present findings, coupled with the dominance of pollution indicator species in these two water bodies give credence to the two lagoons being polluted.

Shannon-Wiener diversity values > 2.0 in the rest of the water bodies could be indicative of moderately stable environments. Okyere and Nortey (2018) recorded Shannon-Wiener diversity values of 1.0 – 2.3 in the Pra Estuary while Dzakpasu et al. (2015) had values ranging between 0.52 and 2.03 in the Nyan and Kakum estuaries. However, Armah, Ason, et al. (2012) recorded very low diversity of 0.71 in the Benya Lagoon unlike the 2.5 in the present study.

Low species richness and diversity may partly explain why the Sakumo II and Fosu lagoons were clustered together against the rest of the water bodies (Figure 4.13). The species responsible for the similarity in Sakumo II and Fosu were *Chironomus* sp. and the backswimmer (Table 4.17). These two pollution-tolerant species having > 70 % cumulative contribution to the similarity between these two lagoons corroborates the perception of Olive and Dambach

(1973) that, many pollution-sensitive species are eliminated in polluted water bodies and only a few pollution-tolerant organisms flourish in the absence of competition and in the presence of abundant food supply.

As part of the objectives of this study was to assess the influence of abiotic factors on benthic macroinvertebrates, negative binomial models were used to determine the effects of physico-chemical parameters, sediment parameters and heavy metal concentrations on the abundance of influential species in the water bodies studied. Model 1 ran the effects of physico-chemical parameters and sediment parameters on abundance while in Model 2, the effects of heavy metals, in addition to physico-chemical parameters and sediment parameters on the abundance of influential species was determined (Table 4.18). The effects of nitrate, turbidity, sediment mean particle sizes and chromium on the abundance of influential species in both clusters were not significant. However, pH, DO, conductivity, phosphate, copper, iron, manganese and zinc had significant effects on the abundance of the influential species in Sakumo II Lagoon and Fosu Lagoon.

When conductivity and phosphate decreased, abundance of influential species increased as seen in model 1 suggesting that even though these species are pollution tolerant, the ions contributing to the high conductivity may not be unfavourable for their abundance to increase. Generally, conductive ions come from sources such as dissolved salts and inorganic materials like alkalis, chlorides, sulphides and carbonate compounds (Fondriest Environmental Inc., 2014a). With respect to phosphate, high levels promote the proliferation of algae and other aquatic plants which subsequently decay and release toxins that are capable of causing harm to aquatic invertebrates (Kim et al., 2013) accounting

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for the increase in macroinvertebrate abundance following a decrease in phosphate concentrations.

Similarly, increase in abundance of chironomid larvae and backswimmer when iron and zinc decreased in model 2 may perhaps imply these organisms are not able to withstand high concentrations of these metals. Many aquatic invertebrates may be adversely affected from ingesting enough zinc-containing particulates (USEPA, 1987) explaining why abundance decreased with increased zinc concentrations. Generally, aquatic populations reduce drastically in zinc-polluted water bodies (Everall, Macfarlane & Sedgwick, 1989; Solbe & Flook, 1975). Similarly, iron concentrations have been reported to be detrimental to aquatic invertebrates (Verma & Dwivedi, 2013). This suggests that even though pollution tolerant organisms have developed special respiratory, food-gathering, and reproductive adaptations that enable them to survive in polluted water bodies (Olive & Dambach, 1973), high levels of some contaminants may result in a significant decrease in their abundance and in worse cases, their elimination.

It was also seen in model 2 that increased concentrations of chromium and copper, in addition to increased MPS (larger particle sizes) led to higher abundances of the two influential species in these lagoons. According to Oshida and Reish (1985), even though hexavalent chromium was extremely toxic to polychaetes and other aquatic fauna, trivalent chromium was not. Perhaps, the trivalent chromium was more available in the sediments. According to Oliviera (2012), trivalent chromium is mainly bound to organic matter in soil in the aquatic environment. It is possible that since the Sakumo II and Fosu lagoons had high organic matter content, more trivalent chromium was probably present

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in the sediments, hence its positive effect on abundance. Besides, concentrations were below the maximum permissible limits explaining why there was no adverse effect on abundance.

Copper was reported to act pathologically on the respiratory system by disruption of gill function resulting in internal hypoxia, but reparation could be accomplished even at "high" sub-lethal concentrations (Spicer & Weber, 1991). However, (Campana, Simpson, Spadaro and Blasco (2012) realised that sub-effects of copper were less in sediment with high organic matter content possibly explaining why abundance still increased when copper increased since Sakumo II and Fosu lagoons had high organic matter. The relationship between faunal assemblages and sediment types has been well documented (Jones, 1950). Very coarse sand and the very fine fraction of sediment have been reported to have a low benthic fauna whereas medium grain size has a rich fauna (Harkantra, 1982). The substrates in the Sakumo II and Fosu lagoons were predominantly coarse and medium sand encouraging the abundance of these species in both lagoons.

In the other four water bodies, namely Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon, decreased conductivity and increased nitrate significantly increased the abundance of influential macroinvertebrates in Model 1 (Table 4.19). The influential species in these water bodies were *C. capitata*, *Chironomus* sp., *Pristina* sp., *Hipponoa* sp., *Lineus* sp., *Scoloplos madagascarensis* and *Tubifex* sp. Decreased conductivity leading to increased abundance implies that conductivity possibly has a detrimental effect on benthic macroinvertebrates. This was, however, contrary to what was observed in the Sakumo II and Fosu lagoons when abundance of *Chironomus* sp. and backswimmer increased with increased conductivity. This may perhaps be as a result of the two species being sensitive to pollution. Other studies have reported the influence of conductivity on benthic macroinvertebrates (Horrigan, Choy, Marshall & Recknagel, 2005; Appiah, Etilé, Kouame & Kouamelan, 2017) with sensitive taxa disappearing as conductivity values increased (Horrigan et al., 2005; Shackleton, Holland, Stitz & McInerney, 2019). Increased nitrate levels leading to increased abundance in these four water bodies may be due to the fact that perhaps nitrate levels here were not up to detrimental limits.

In Model 2, abundance of influential species in the other four water bodies increased when there was a significant increase in temperature, organic matter, arsenic and lead and decrease in pH, DO, mercury and nickel. High temperature boosts primary productivity in water bodies (Lalli & Parsons, 1997). Organic matter controls nutrient availability in water bodies (Bot & Benites, 2005) hence increased values especially within the ranges observed in these four water bodies may positively influence the abundance of benthic macroinvertebrates. Organic matter also serves as food for some organisms (Levinton, 2001). According to Yadav et al. (2016), arsenic in excess quantities is detrimental as it destabilizes the ecosystem resulting in the biomagnification and consequently the death of the living organisms. Concentrations in the water bodies studied were probably too low to have any detrimental effects. Increased lead concentrations supporting more macroinvertebrates cannot easily be substantiated. Opaluwa et al. (2012), claimed lead is toxic at very low concentration and have no known functions in biochemical processes. Perhaps the concentrations in these water bodies were extremely low to have any toxic effect on macroinvertebrates.

Contrary to the observation in the Sakumo II and Fosu lagoons, abundance of the influential species in the other four water bodies increased when zinc increased. This perhaps is due to zinc being an essential metal playing a vital role in enzyme activity of aquatic organisms (Opaluwa et al., 2012). Concentrations in the other four water bodies were lower than those observed in the Sakumo II and Fosu implying that lower concentrations of this metal may be essential for the presence/abundance of macroinvertebrates.

Decreased levels of pH and DO leading to increased abundance in the study requires cautious interpretations. It is important to know that, DO concentrations in this study were hardly below 2.00 mg/l and therefore increased abundance of species when DO decreased may not necessarily point to high abundance during hypoxia/anoxia conditions. The same reason could apply to pH levels; pH in these four water bodies was in the range of 6.0 – 8.50 and therefore low pH resulting in high abundance does not mean extremely low pH outside of the range required for the survival of aquatic organisms.

Abundance of influential macroinvertebrates in the Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon decreased with increased mercury and nickel perhaps due to the toxic nature of these two elements (Wuana & Okieimen, 2011; Verma & Dwivedi, 2013). Ogundele, Adio and Oludele (2015) described nickel as an essential element for animal health but is toxic at high concentrations while mercury has no known essential role in living organisms (Kumolu-Johnson, Ndimele, Akintola & Jibuike, 2010). Kumolu-Johnson et al. (2010) noted that various studies have shown mercury may have toxic effects on fish, altering physiological activities and biochemical parameters both in their tissue and blood. Nickel is known to be absorbed easily and rapidly by plants (Ogundele et al., 2015).

5.5 Benthic Macroinvertebrate Functional Groups

Naeem et al. (1999) described ecosystem functioning as the collective life activities of organisms such as feeding, growing, moving, excreting waste, etc. and the effects of these activities on the physical and chemical conditions of their environment. It was emphasised that functioning means 'showing activity' and does not imply that organisms perform purposeful roles in ecosystem-level processes (Naeem et al., 1999). According to Mouillot et al. (2006), environmental factors could limit the presence of some of these activities at certain sites. Functional traits were generally limited in the Sakumo II Lagoon and Fosu Lagoon in the present study (Table 4.20). For instance, the feeding habit analysis shows species that are predominantly deposit feeders constituted > 98 % of total abundance in these lagoons (Figure 4.15). Omnivory was absent in both lagoons while filter feeding for instance, was completely absent in the Sakumo II. Beauchard, Veríssimo, Queirós and Herman (2017) reported that filter feeding corresponds to a diet composed of plankton and/or suspended particulate matter while carnivory corresponds to a diet of animals. They also noted that species sometimes switch from a specific diet to omnivory depending on food availability.

Deposit feeding macroinvertebrates dominating most of the six water bodies suggests a food chain predominantly based on detritus and decaying algae (Beauchard et al., 2017; De Broyer et al., 2001; Wurdig, Cenzano & Motta Marques, 2007). However, other groups were fairly represented in the other four water bodies except for the Sakumo II and Fosu lagoons where the other feeding groups accounted for < 3 % of total abundance. This perhaps explains why the Fosu Lagoon clustered together with the Sakumo II Lagoon under feeding traits while the other water bodies formed another cluster. Several authors have noted that in sediments with high organic content, deposit-feeding organisms dominate (Paiva, 1993; Frouin, 2000) which appears to be the case in this study where deposit feeding macroinvertebrates had higher compositions in the Sakumo II and Fosu lagoons where organic matter content was high in the sediments. Levinton (2001) believed the preference of most deposit feeders to fine grain sediments may be due to increased quantities of microorganisms, fine-grained particulate organic matter and ingestible inorganic particles. According to Jayaraj et al. (2007), high organic matter had an adverse effect especially on filter feeders which was the case in this study. The Muni Lagoon and Kakum estuary which had low organic matter content recorded more filter feeders than the other water bodies.

Generally, low composition of filter feeders in this study is in line with findings on the southeast coast of India (Manokaran, Khan, Lyla, Raja & Ansari, 2013) but contrary to Lamptey (2015) who recorded a high abundance of filter feeders in the mid-depth (31 – 50 m) compared to the shallow (11 – 30 m) and deep (51 – 70 m) waters of the GCLME. Perhaps, depth plays a role in the distribution and abundance of filter feeders. Lamptey (2015)also noticed in his study that filter feeders had body size in the range of 10.0 – 12.0 cm due to the possibility of greater energy needed to filter food particles in high water current. Based on this, it may be safe to assume that invertebrate filter feeders are mostly

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mega fauna explaining their small numbers in this current study and that of (Manokaran et al., 2013) which dwelled on macroinvertebrates.

The morphology of an organism determines the type of habitat in which it resides and its ability to colonize new habitats (Moore, 2001). Benthic macroinvertebrates with 'cylindrical and elongate' and 'threadlike' dominated most of the water bodies studied. These body forms may be a good adaptation to survival in the sediments of the water bodies investigated. Levinton (2001), for example, suggested that slender and elongated body forms may be related to uptake of dissolved organic matter for food as such body forms are designed to increase surface area for uptake of dissolved organic matter. Lamptey (2015) on the other hand, observed that species with elongated body form in the GCLME were predominantly carnivores or detritivores and their body form possibly facilitated their food acquisition mechanism. The dominance of conical body forms in the Fosu Lagoon may probably be controlled by factors other than sediment particles sizes since sediment particles in this lagoon did not vary much from the other water bodies in the present study. The conical body form could be an adaptation to the numerous pollutants in this lagoon perhaps. The prominence of laterally compressed body forms in the Muni Lagoon and the Kakum Estuary may be an adaptation to movement in a predominantly coarse sand environment.

In terms of mobility, all the water bodies were dominated by species that burrow, explaining why they formed one significant cluster based on their similarities. Likewise, similarities among these water bodies based on sociability and sexuality were significant since solitary forms and gonochorists were dominant. According to Palmer et al. (1997), burrowing organisms mix the sediments, aerate deeper layers of sediments, and increase rates of recycling of macro and micro-nutrients by bioturbation and faecal production.

As one of the objectives of this study, the effects of physico-chemical parameters, sediment parameters and heavy metals concentrations on the abundance of influential functional groups in the water bodies studied were determined using negative binomial models. Model 1 predicts the effects of physico-chemical parameters and sediment parameters on abundance while Model 2 predicts the effects of heavy metals, in addition to physico-chemical parameters and sediment parameters on the abundance of influential functional groups. Parameters such as pH, DO, conductivity, phosphate, copper, iron, manganese and zinc had significant effects on the abundance of the influential groups (deposit feeder and deposit feeder+omnivore) in Sakumo II Lagoon and Fosu Lagoon (Table 4.22). Decrease in conductivity and phosphate resulting in increase in abundance may mean better water quality which would favour more deposit feeding macroinvertebrates. Decrease in iron and zinc resulting in an increase in abundance may be associated with the toxicity of these metals since these organisms feed in the sediment.

The groups 'deposit feeder', 'deposit feeder+omnivore' and 'carnivore/predator' were influential in the similarity of Benya Lagoon, Muni Lagoon, Pra Estuary and Kakum Estuary. Abundance of these groups increased when conductivity increased and nitrate decreased in model 1 (Table 4.23). It is worth noting that conductivity values in these water bodies were generally within safe limits and hence may mean as long as conductivity is within a safe range, abundance will increase. Nitrate concentrations, however, were beyond the recommended limit for all the water bodies which poses a threat to the survival of organisms. With the introduction of heavy metals, abundance increased when pH and mercury decreased along with an increase in temperature, organic matter, arsenic, lead and zinc. High pH levels have the tendency of the feeding apparatus of some aquatic organisms (Fondriest Environmental Inc., 2013b). Mercury is also reported to be highly toxic (Sciortino & Ravikumar, 1999) and concentrations within these water bodies were above permissible limit for aquatic life.

Increase in abundance of 'threadlike' and keel-shaped body forms in the Sakumo II and Fosu lagoons was controlled by decreased conductivity and phosphate. Model 2 also showed abundance of above body forms increased with decreased iron and zinc and increased copper and chromium. As explained earlier, chromium in these water bodies may be in the trivalent form; and as the effects of copper is less in water bodies with high organic matter (Campana et al., 2012; Oliviera, 2012), these may explain why abundance increased with increased concentrations of these metals.

Abundance of 'cylindrical and elongate', threadlike and laterally compressed body forms in the Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon were influenced by the same factors that influenced feeding habits (deposit feeding – omnivory – carnivory) in these water bodies giving credence to Lamptey (2015)'s findings that body form possibly facilitated food acquisition mechanism.

In the present study, the abundance of burrowing macroinvertebrates increased when DO and turbidity decreased and pH and nitrate increased in model 1 while in model 2, abundance increased as conductivity, turbidity and mercury decreased and MPS increased (see Table 4.26). The effects of these

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parameters on abundance of macroinvertebrates have been mentioned earlier. Decreased conductivity, turbidity and mercury concentrations suggests good water quality. Perhaps, that was why macroinvertebrates abundance increased when these parameters decreased. Increased abundance of burrowers in larger sized sediment particles (i.e. medium to coarse sand) in the present study is supports the findings by De la Huz, Lastra and López (2002) that burrowing time is faster in medium to coarse sand compared to very coarse sand and fine sand. Burrowing activities promote the return of mineralised nitrogen nutrients to the overlying water at a greater rate (Rhoads, Aller & Goldhaber, 1977), explaining how increased levels of nitrate was associated with increased abundance of burrowers.

5.6 Comparison of Taxonomic and Functional Approaches

It is apparent from the results of the present study that both taxonomic and functional richness and diversities followed the same trend with Sakumo II and Fosu lagoons recording lower indices than the rest of the water bodies. This may imply that these two water bodies are more impacted/stressed compared to the other four water bodies. Similarity the relationship between taxonomic and functional richness and diversities have been observed by other authors who recorded a strong correlation between taxonomic and functional richness and diversity (Heino, 2008; Bazzanti et al., 2009; Uwadiae et al., 2012). Bazzanti et al. (2009) concluded that high taxonomic diversity maintains a high functional diversity.

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Also, the outcome of the Bray-Curtis analyses was similar for both approaches placing the Sakumo II and Fosu lagoons in one cluster and the other four water bodies in another cluster.

It was realised that the effects of abiotic factors on both taxonomic and functional groups were similar implying the functional approach also detects changes in the ecosystems, just like the taxonomic approach.

The functional approach presents some advantages over the taxonomic approach, in that it reduces taxonomic effort (i.e. there is no need to identify organisms to the lowest possible taxa). For example, using body form as a functional trait, a researcher simply has to group organisms of similar body shape/form together. It therefore saves time and reduces the chances of misidentification of organisms. The functional approach also gives a better understanding of the activities organisms perform in an ecosystem. Under conditions of limited resources, the use of the functional approach in ecological assessment would be a preferred option.

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CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The use of macroinvertebrate functional groups as surrogates for ecological assessment is common in streams and marine environments in the developed world. Studies on functional traits are uncommon in sub-Saharan Africa. Meanwhile, functional traits provide important information on water quality and ecosystem functioning. There is no record of the functional traits approach for assessing the quality of coastal water bodies in Ghana. Hence, this study is the first of its kind to concurrently use functional traits of macroinvertebrates and the taxonomic approach together with measurement of abiotic factors, to assess the ecological status of six coastal water bodies in Ghana, namely Kakum Estuary, Pra Estuary, Benya Lagoon, Sakumo II Lagoon, Fosu Lagoon and Muni Lagoon.

All physico-chemical parameters studied showed spatial and temporal variations. Temperature, DO, pH and salinity were within the ranges for shallow tropical coastal water bodies. Nitrates and phosphates were above the recommended limits in all the six water bodies. Higher values were recorded in the Sakumo II and Fosu lagoons. Turbidity was extremely high in the Pra Estuary compared to the other five water bodies. Conductivity values in Sakumo II Lagoon, Fosu Lagoon, and Pra Estuary were within the ranges of impacted/polluted ecosystems. TDS values were high in the Fosu Lagoon compared to the rest of the water bodies. Fluctuations in TDS were more pronounced in the two estuaries compared to the lagoons.

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Similar to the physico-chemical parameters, heavy metals namely arsenic, cadmium, chromium, copper, iron, manganese, mercury, nickel, lead and zinc concentrations varied spatially and temporally during the study period. Values, however, were lower than the maximum permissible limits except for mercury and cadmium. Heavy metals were generally higher in the Sakumo II and Fosu lagoons than the rest of the water bodies.

Sediment particle sizes and organic matter content also showed some spatial variations. Sediments in Muni Lagoon and Kakum Estuary were predominantly coarse sand. The rest of the water bodies alternated between coarse sand and medium sand whereas Pra estuary was dominated by fine sand. Sediment organic matter content was much higher in the Sakumo II and Fosu lagoons while the least was recorded in the Pra Estuary.

Forty-five (45) benthic macroinvertebrate species were encountered in the six water bodies studied. This highest number of species was recorded in the Benya Lagoon (21 species), followed by the Muni Lagoon (20 species), Kakum Estuary (18 species), Pra Estuary (12 species), Fosu Lagoon (8 species) and Sakumo II Lagoon (4 species). Shannon-Wiener diversity index was lower in the Sakumo II and Fosu lagoons while the Kakum Estuary and the Muni Lagoon had high diversity indices. *Capitella capitata* and *Chironomus* sp. were the most dominant species in this study and were the only species present in all six water bodies. Pollution indicator species, namely *Limnodrilus hoffmeisteri* and *Chironomus* sp. dominated the Sakumo II Lagoon while *Melanoides tuberculata* and *Chironomus* sp. dominated the Fosu Lagoon with > 90 % composition suggesting these lagoons may be polluted. *L. hoffmeisteri* was present inly in Sakumo II while *M. tuberculata* was present in Fosu only. The

Kakum Estuary was dominated by *Nephtys* sp., *Chironomus* sp. and *Nereis* sp. while *Pristina* sp. dominated the Pra Estuary. *C. capitata* was dominant in the Benya and Muni lagoons. The functional traits considered in this present study were body form, feeding habit, mobility, sexuality and sociability. Under the body form functional trait, cylindrical and elongate organisms constituted > 50 % in the Benya Lagoon, Pra Estuary and Muni Lagoon. Kakum Estuary and Sakumo II Lagoon were dominated by threadlike organisms whiles conical organisms dominated the Fosu Lagoon. Deposit feeders and those that are omnivorous in addition to deposit feeding together constituted > 98 % in the Sakumo II and Fosu lagoons. In addition to these two feeding groups, the other four water bodies had good representations of other feeding habit groups such as filter feeders, carnivores, etc. Most of the organisms encountered in all six water bodies were burrowers. Gonochoristic organisms were dominant in all water bodies except the Pra Estuary where hermaphroditic ones occurred. Regarding sociability, solitary organisms dominated the water bodies.

Species richness and diversity were generally low in the Sakumo II and Fosu lagoons, compared to the other water bodies. Functional richness and diversity showed a similar trend. Bray-Curtis similarity analysis clustered the Sakumo II and Fosu together using both taxonomic and functional groups compositions and abundance (body form, feeding habit and mobility).

The effects of abiotic parameters on taxonomic groups and functional groups were similar. Conductivity, phosphate, sediment mean particle sizes, chromium, copper and iron influenced species abundance and functional group abundance in the Sakumo II and Fosu lagoons while pH, DO, conductivity, temperature, nitrate, organic matter, arsenic, mercury, nickel, lead and zinc influenced species abundance and functional group abundance in the other four water bodies.

6.2 Conclusions

Based on the results of the present study, the following conclusions are made:

i. Physico-chemical parameters such as conductivity, TDS, nitrate, phosphate and sediment organic matter content indicate the Sakumo II and Fosu lagoons were heavily impacted by the anthropogenic activities around their catchment areas while the Kakum Estuary, Pra Estuary, Benya Lagoon and Muni Lagoon were generally in good ecological states. The study also showed the Pra Estuary was highly turbid.

ii. The Sakumo II and Fosu lagoons were polluted by heavy metals.

iii. All six water bodies studied had mercury and cadmium levels above permissible limits.

iv. Both the taxonomic and functional approaches for analysing aquatic macroinvertebrate communities produced similar results indicating pollution in the Sakumo II and Fosu lagoons. This was evident in species and functional diversities and richness analyses, as well as the Bray-Curtis similarity analyses for both approaches.

v. Based on the similar responses of macroinvertebrate taxonomic and functional groups abundance to changes in abiotic factors such as conductivity, nitrate, phosphate, organic matter, arsenic, copper, iron, mercury, lead, etc., it is concluded that abiotic parameters are

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key determinants of abundance of benthic macroinvertebrates taxa and functional groups.

6.3 Recommendations

In the wake of ecosystem degradation in Ghana, studies on ecosystem health are necessary to inform management policies. It is recommended that, similar studies should be extended to other coastal water bodies in Ghana for a holistic approach towards sustainable management.

This study measured parameters in water and sediment samples. Future research should consider determining the levels of contaminants in the tissues of benthic macroinvertebrates to determine how much pollutants these organisms take up since measuring heavy metals and other contaminants in water and sediment does not necessarily tell how much of these compounds are bioavailable (can be absorbed into a living system) to organisms living in the water.

The effects of heavy metals concentrations on the abundance of taxonomic and functional groups were significant despite concentrations (except mercury and cadmium) being lower than WHO/USEPA maximum permissible limits. A comprehensive research on heavy metals in water bodies in Ghana is therefore recommended in order to develop local standards for our water bodies.

In view of the high levels of mercury and cadmium (above the permissible limits) in all the six water bodies studied, it is recommended that measures should be put in place to control the sources of their discharge into aquatic ecosystems.

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This study shows knowledge on functional traits especially body form and feeding are good resources for ecosystem assessment. It is recommended that more studies be carried out on functional traits of benthic macroinvertebrates concentrating on body form and feeding habits in order to fill the dearth of knowledge on application of macroinvertebrates functional groups.

Furthermore, in view of the fact that the taxonomic and functional group approaches to macroinvertebrates analyses produced similar results in the present study, and considering the advantage of the latter approach, it is recommended that in situations where resources and time are limiting, the functional group approach should be considered the better option.

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APPENDICES

Appendix A: Physico-chemical Parameters

Appendix A: Variations in physico-chemical parameters in the water bodies

Water body	Parameter	Min	Max	Mean	S.E.
Kakum Estuary	Temperature (^{o}C)	24.41	29.58	26.8	0.16
Pra Estuary		26.60	29.91	27.89	0.10
Benya Lagoon		21.62	31.61	27.74	0.26
Sakumo II Lagoon		26.17	32.90	29.33	0.19
Fosu Lagoon		27.50	33.11	29.69	0.13
Muni Lagoon		25.93	37.62	30.54	0.28
Kakum Estuary	DO (mg/l)	2.12	7.92	4.33	0.15
Pra Estuary		1.77	7.45	4.38	0.20
Benya Lagoon		1.82	7.33	3.27	0.16
Sakumo II Lagoon		1.90	11.70	3.82	0.23
Fosu Lagoon		1.85	13.45	4.44	0.29
Muni Lagoon		2.30	13.01	4.32	0.25
Kakum Estuary	Turbidity (NTU)	3.06	177	38.11	3.97
Pra Estuary		14.35	902	379.86	24.21
Benya Lagoon		5.73	186	17.71	2.05
Sakumo II Lagoon		8.61	825	83.21	16.67
Fosu Lagoon		7.60	258	62.21	5.35
Muni Lagoon		3.14	115	19.44	2.00
Kakum Estuary	pH	6.64	8.09	7.13	0.06
Pra Estuary		6.19	8.50	7.33	0.05
Benya Lagoon		7.08	7.91	7.51	0.02
Sakumo II Lagoon		6.35	9.30	7.49	0.07
Fosu Lagoon		6.77	9.33	8.13	0.06
Muni Lagoon		7.15	8.70	8.03	0.04
Kakum Estuary	Salinity (ppt)	0.08	37.00	9.85	1.02
Pra Estuary		0.02	18.01	2.25	0.42
Benya Lagoon		4.00	31.55	26.68	0.82
Sakumo II Lagoon		0.38	8.00	1.36	0.19
Fosu Lagoon		1.95	13.31	4.36	0.22
Muni Lagoon		4.39	47.21	26.97	1.52

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Appendix A1, continued

Water body	Parameter	Min	Max	Mean	S.E.
Kakum Estuary	Conductivity (µS/cm)	16.89	6932.00	760.37	132.61
Pra Estuary		10.35	7166.00	1217.51	192.20
Benya Lagoon		42.52	54.50	46.79	0.24
Sakumo II Lagoon		760.00	2594.00	1539.52	43.74
Fosu Lagoon		11.00	9941.00	3983.93	329.88
Muni Lagoon		1.33	82.70	41.94	2.42
Kakum Estuary	TDS (ppm)	10.13	8091.00	621.07	143.70
Pra Estuary		10.12	6738.00	955.75	156.08
Benya Lagoon		21.45	27.07	23.10	0.07
Sakumo II Lagoon		387.00	1223.00	745.32	20.85
Fosu Lagoon		1863.00	9326.00	3878.13	176.79
Muni Lagoon		13.10	7625.00	2206.80	316.77
Kakum Estuary	Nitrate (mg/l)	0.00	18.60	2.19	0.25
Pra Estuary		0.00	17.60	3.05	0.40
Benya Lagoon		0.00	17.16	4.88	0.33
Sakumo II Lagoon		0.00	68.00	7.79	1.12
Fosu Lagoon		0.00	39.60	4.74	0.59
Muni Lagoon		0.00	13.97	3.69	0.34
Kakum Estuary	Phosphate (mg/l)	0.03	5.56	0.80	0.11
Pra Estuary		0.00	4.46	0.55	0.08
Benya Lagoon		0.00	9.08	0.82	0.12
Sakumo II Lagoon		0.00	49.10	8.36	1.27
Fosu Lagoon		0.00	9.46	0.97	0.16
Muni Lagoon		0.00	5.22	0.53	0.09

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Appendix B: ANOVA for Physico-chemical Parameters

Appendix B1: Within water bodies (95 % confidence level)

		Sum of Squares	df	Mean Square	F	Sig.
Temp	Between Groups	992.32	5	198.46	50.4	0.00
	Within Groups	2303.74	585	3.94		
	Total	3296.06	590			
DO	Between Groups	107.55	5	21.51	4.58	0.00
	Within Groups	2746.68	585	4.7		
	Total	2854.23	590			
Turbidity	Between Groups	9.41E+06	5	1.88E+06	135.79	0.00
	Within Groups	8.11E+06	585	1.39E+04		
	Total	1.75E+07	590			
pH	Between Groups	78.28	5	15.66	54.25	0.00
	Within Groups	168.83	585	0.29		
	Total	247.11	590			
Salinity	Between Groups	69884.49	5	13976.9	193.39	0.00
	Within Groups	42279.76	585	72.27		
	Total	112164.24	590			
Cond	Between Groups	1.09E+09	5	2.17E+08	76.83	0.00
	Within Groups	1.65E+09	585	2.83E+06		
	Total	2.74E+09	590			
TDS	Between Groups	1.00E+09	5	2.01E+08	67.71	0.00
	Within Groups	1.73E+09	585	2.96E+06		
	Total	2.74E+09	590			
Nitrate	Between Groups	1512.67	5	302.53	9.43	0.00
	Within Groups	17355.98	541	32.08		
	Total	18868.65	546			
Phosphate	Between Groups	4475.01	5	895	38.01	0.00
	Within Groups	13515.78	574	23.55		
	Total	17990.79	579			

Appendix B2: Within quarters (95 % confidence level)

		Sum of Squares	df	Mean Square	F	Sig.
Temp	Between Groups	1474.5	5	294.9	94.71	0.00
	Within Groups	1821.57	585	3.11		
	Total	3296.06	590			
DO	Between Groups	1088.58	5	217.72	72.14	0.00
	Within Groups	1765.65	585	3.02		
	Total	2854.23	590			
Turbidity	Between Groups	1.67E+06	5	334411	12.34	0.00
	Within Groups	1.58E+07	585	27091.9		
	Total	1.75E+07	590			
pH	Between Groups	83.63	5	16.73	59.86	0.00
	Within Groups	163.48	585	0.28		
	Total	247.11	590			
Salinity	Between Groups	9770.71	5	1954.14	11.17	0.00
	Within Groups	102393.5	585	175.03		
	Total	112164.2	590			
Cond	Between Groups	2.19E+08	5	4.4E+07	10.15	0.00
	Within Groups	2.52E+09	585	4311522		
	Total	2.74E+09	590			
TDS	Between Groups	7.68E+07	5	1.5E+07	3.38	0.01
	Within Groups	2.66E+09	585	4547709		
	Total	2.74E+09	590			
Nitrate	Between Groups	1528.44	5	305.69	9.54	0.00
	Within Groups	17340.21	541	32.05		
	Total	18868.65	546			
Phosphate	Between Groups	2390.44	5	478.09	17.59	0.00
	Within Groups	15600.35	574	27.18		
	Total	17990.79	579			

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Appendix C: Tukey's Post Hoc Test for Physico-Chemical Parameters

Appendix C1: Within water bodies (Mean ± SE)

Parameter	Water body					
	Kakum Estuary	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
Temp	26.80 ± 0.16^{d}	27.89 ± 0.10^{c}	27.74 ± 0.26^{c}	29.33 ± 0.19^{b}	29.69 ± 0.13^{b}	30.54 ± 0.28^{a}
DO	4.33 ± 0.15^{a}	4.38 ± 0.20^{a}	3.27 ± 0.16^{b}	3.82 ± 0.23^{a,b}	4.44 ± 0.29^{a}	4.32 ± 0.25^{a}
Turbidity	38.11 ± 3.97^{b,c}	379.86 ± 24.21^{a}	17.71 ± 2.05^{c}	83.21 ± 16.67^{b}	62.21 ± 5.35^{b,c}	19.44 ± 2.00^{c}
pH	7.13 ± 0.06^{c}	7.33 ± 0.05^{b,c}	7.51 ± 0.02^{b}	7.49 ± 0.07^{b}	8.13 ± 0.06^{a}	8.03 ± 0.04^{a}
Salinity	9.85 ± 1.02^{b}	2.25 ± 0.42^{c}	26.68 ± 0.82^{a}	1.36 ± 0.19^{c}	4.36 ± 0.22^{c}	26.97 ± 1.52^{a}
Cond	760.37 ± 132.61^{c}	1217.51 ± 192.20^{b,c}	46.79 ± 0.24^{d}	1539.52 ± 43.74^{b}	3983.93 ± 329.88^{a}	41.94 ± 2.42^{d}
TDS	621.07 ± 143.70^{c,d}	955.75 ± 156.08^{c}	23.10 ± 0.07^{d}	745.32 ± 20.85^{c}	3878.13 ± 176.79^{a}	2206.80 ± 316.77^{b}
Nitrate	2.51 ± 0.27^{c}	3.80 ± 0.46^{b,c}	5.08 ± 0.32^{b}	7.97 ± 1.14^{a}	4.83 ± 0.59^{b,c}	3.84 ± 0.34^{b,c}
Phosphate	0.80 ± 0.11^{b}	0.60 ± 0.08^{b}	0.82 ± 0.12^{b}	8.45 ± 1.28^{a}	0.99 ± 0.16^{b}	0.53 ± 0.09^{b}

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Appendix C2: Within quarters (Mean ± SE)

Parameter	**Quarter**					
	2nd Q. 2016	**3rd Q. 2016**	**4th Q. 2016**	**1st Q. 2017**	**2nd Q. 2017**	**3rd Q. 2017**
Temp	30.24 ± 0.25^{a,b}	27.96 ± 0.15^{c}	29.68 ± 0.16^{b}	30.51 ± 0.19^{a}	27.56 ± 0.14^{c}	26.01 ± 0.19^{d}
DO	5.12 ± 0.33^{b}	2.48 ± 0.05^{d}	6.10 ± 0.22^{a}	2.49 ± 0.06^{d}	4.26 ± 0.16^{c}	4.53 ± 0.19^{b,c}
Turbidity	203.50 ± 36.15^{a}	139.40 ± 16.76^{a,b}	107.71 ± 17.55^{b,c}	44.46 ± 6.29^{c,d}	80.31 ± 12.05^{b,c,d}	37.17 ± 6.32^{d}
pH	7.71 ± 0.05^{b}	7.73 ± 0.06^{b}	7.85 ± 0.05^{b}	8.08 ± 0.05^{a}	7.00 ± 0.04^{d}	7.23 ± 0.07^{c}
Salinity	12.71 ± 1.71^{b}	12.99 ± 1.15^{b}	13.42 ± 1.37^{a}	18.64 ± 1.56^{a}	6.45 ± 1.00^{c}	8.03 ± 1.19^{b,c}
Cond	1252.88 ± 229.96^{b}	730.19 ± 111.17^{b}	2486.86 ± 317.79^{a}	909.07 ± 197.11^{b}	914.47 ± 151.68^{b}	1293.70 ± 173.75^{b}
TDS	624.68 ± 114.50^{b}	1399.14 ± 220.23^{a,b}	1264.22 ± 159.03^{a,b}	1731.75 ± 237.31^{a}	1435.69 ± 206.98^{a,b}	1868.69 ± 278.68^{a}
Nitrate	3.07 ± 0.55^{c}	7.49 ± 0.89^{a}	4.15 ± 0.32^{b,c}	3.80 ± 0.29^{c}	3.03 ± 0.51^{c}	6.34 ± 0.82^{a,b}
Phosphate	0.09 ± 0.01^{b}	1.13 ± 0.12^{b}	2.18 ± 0.18^{b}	5.98 ± 1.14^{a}	0.46 ± 0.06^{b}	0.88 ± 0.19^{b}

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Appendix D: Heavy Metal Concentrations

Appendix D: Heavy metal concentrations in water (mg/l) and sediment (mg/kg)

Parameter	Water body	Min	Max	Mean	SE
Water					
As	Kakum Estuary	0.004	0.080	0.019	0.003
	Pra Estuary	0.005	0.103	0.013	0.002
	Benya Lagoon	0.002	0.097	0.021	0.003
	Sakumo II Lagoon	0.004	0.036	0.022	0.001
	Fosu Lagoon	0.008	0.100	0.028	0.003
	Muni Lagoon	0.005	0.080	0.019	0.003
Cd	Kakum Estuary	0.100	0.208	0.121	0.003
	Pra Estuary	0.002	0.150	0.085	0.008
	Benya Lagoon	0.015	0.222	0.108	0.022
	Sakumo II Lagoon	0.003	0.199	0.108	0.011
	Fosu Lagoon	0.003	0.135	0.074	0.004
	Muni Lagoon	0.027	0.143	0.107	0.006
Cr	Kakum Estuary	0.011	0.017	0.014	0.002
	Pra Estuary	BDL	BDL	-	-
	Benya Lagoon	0.028	0.042	0.034	0.004
	Sakumo II Lagoon	0.004	0.065	0.049	0.005
	Fosu Lagoon	0.002	0.052	0.012	0.005
	Muni Lagoon	0.004	0.015	0.009	0.001
Cu	Kakum Estuary	BDL	BDL	-	-
	Pra Estuary	BDL	BDL	BDL	BDL
	Benya Lagoon	0.002	0.036	0.014	0.003
	Sakumo II Lagoon	0.005	0.005	0.005	-
	Fosu Lagoon	0.025	0.031	0.028	0.003
	Muni Lagoon	0.018	0.042	0.032	0.002
Fe	Kakum Estuary	0.008	2.933	0.258	0.047
	Pra Estuary	0.016	4.069	0.629	0.080
	Benya Lagoon	0.004	1.163	0.130	0.027
	Sakumo II Lagoon	0.004	1.957	0.353	0.057
	Fosu Lagoon	0.003	1.582	0.144	0.034
	Muni Lagoon	0.004	0.736	0.166	0.014
Pb	Kakum Estuary	0.004	0.008	0.005	0.001
	Pra Estuary	0.003	0.030	0.013	0.001
	Benya Lagoon	0.002	0.054	0.027	0.003
	Sakumo II Lagoon	0.001	0.031	0.012	0.001
	Fosu Lagoon	0.004	0.034	0.017	0.007
	Muni Lagoon	0.006	0.523	0.046	0.021
Mn	Kakum Estuary	0.002	0.082	0.022	0.002
	Pra Estuary	0.002	0.100	0.032	0.004
	Benya Lagoon	0.002	0.137	0.018	0.003
	Sakumo II Lagoon	0.002	0.432	0.115	0.014
	Fosu Lagoon	0.001	0.121	0.053	0.004
	Muni Lagoon	0.002	0.165	0.022	0.002

Appendix D, continued

Parameter	Water body	Min	Max	Mean	SE
Water					
Hg	Kakum Estuary	0.001	0.035	0.018	0.002
	Pra Estuary	0.001	0.047	0.013	0.001
	Benya Lagoon	0.040	0.050	0.045	0.001
	Sakumo II Lagoon	0.001	0.020	0.004	0.000
	Fosu Lagoon	0.001	0.044	0.009	0.001
	Muni Lagoon	0.001	0.002	0.001	0.000
Ni	Kakum Estuary	0.003	0.034	0.011	0.003
	Pra Estuary	0.002	0.188	0.023	0.008
	Benya Lagoon	0.001	0.079	0.017	0.002
	Sakumo II Lagoon	0.001	0.061	0.029	0.003
	Fosu Lagoon	0.001	0.028	0.009	0.001
	Muni Lagoon	0.001	0.043	0.016	0.002
Zn	Kakum Estuary	0.002	0.022	0.011	0.000
	Pra Estuary	0.002	0.034	0.010	0.001
	Benya Lagoon	0.001	0.045	0.010	0.001
	Sakumo II Lagoon	0.002	0.113	0.020	0.003
	Fosu Lagoon	0.001	0.265	0.012	0.003
	Muni Lagoon	0.001	0.125	0.009	0.001
Sediment					
As	Kakum Estuary	3.000	4.760	3.866	0.059
	Pra Estuary	0.005	4.800	4.261	0.123
	Benya Lagoon	1.360	5.600	3.971	0.109
	Sakumo II Lagoon	0.018	5.160	3.775	0.184
	Fosu Lagoon	4.440	5.760	4.692	0.020
	Muni Lagoon	3.100	3.860	3.513	0.020
Cd	Kakum Estuary	BDL	BDL	-	-
	Pra Estuary	BDL	BDL	-	-
	Benya Lagoon	BDL	BDL	-	-
	Sakumo II Lagoon	BDL	BDL	-	-
	Fosu Lagoon	BDL	BDL	-	-
	Muni Lagoon	BDL	BDL	-	-
Cr	Kakum Estuary	0.120	3.280	0.562	0.126
	Pra Estuary	0.135	3.240	2.497	0.121
	Benya Lagoon	0.180	1.860	1.063	0.056
	Sakumo II Lagoon	0.120	19.360	1.493	0.458
	Fosu Lagoon	0.080	2.660	1.362	0.068
	Muni Lagoon	0.240	2.760	2.084	0.101
Cu	Kakum Estuary	0.080	3.600	1.020	0.355
	Pra Estuary	0.040	4.320	0.646	0.108
	Benya Lagoon	0.140	7.020	2.424	0.326
	Sakumo II Lagoon	0.400	11.820	3.521	0.362
	Fosu Lagoon	0.320	8.320	3.170	0.232
	Muni Lagoon	0.080	6.480	0.715	0.218

Appendix D, continued

Parameter	Water body	Min	Max	Mean	SE
Sediment					
Fe	Kakum Estuary	12.158	218.960	80.471	8.649
	Pra Estuary	0.026	219.360	83.792	9.229
	Benya Lagoon	16.132	218.160	76.311	8.487
	Sakumo II Lagoon	0.049	219.180	90.100	10.136
	Fosu Lagoon	17.514	219.240	46.682	6.755
	Muni Lagoon	18.298	217.660	89.838	8.809
Pb	Kakum Estuary	0.120	1.640	0.743	0.118
	Pra Estuary	0.013	1.420	0.533	0.034
	Benya Lagoon	0.260	3.480	0.980	0.121
	Sakumo II Lagoon	0.023	35.780	4.405	1.427
	Fosu Lagoon	0.800	26.200	5.222	0.489
	Muni Lagoon	0.580	1.100	0.743	0.016
Mn	Kakum Estuary	1.160	31.620	13.587	0.870
	Pra Estuary	0.035	48.060	12.044	1.635
	Benya Lagoon	0.500	31.120	12.407	0.954
	Sakumo II Lagoon	0.006	79.180	26.693	2.687
	Fosu Lagoon	7.500	99.800	38.026	2.140
	Muni Lagoon	3.520	48.940	18.179	1.064
Hg	Kakum Estuary	0.800	18.600	1.976	0.291
	Pra Estuary	0.008	2.360	1.633	0.082
	Benya Lagoon	0.160	2.060	1.488	0.067
	Sakumo II Lagoon	0.002	2.360	1.344	0.085
	Fosu Lagoon	1.760	4.040	2.106	0.036
	Muni Lagoon	4.000	4.000	4.000	0.000
Ni	Kakum Estuary	0.680	13.440	2.215	0.207
	Pra Estuary	0.140	4.140	0.994	0.113
	Benya Lagoon	0.060	3.220	1.564	0.098
	Sakumo II Lagoon	0.228	7.540	2.851	0.160
	Fosu Lagoon	0.860	4.540	2.875	0.083
	Muni Lagoon	0.080	4.140	0.772	0.114
Zn	Kakum Estuary	0.140	19.200	2.622	0.411
	Pra Estuary	0.007	4.980	3.191	0.151
	Benya Lagoon	0.880	9.780	3.302	0.231
	Sakumo II Lagoon	0.006	14.020	3.314	0.322
	Fosu Lagoon	2.800	12.860	6.256	0.259
	Muni Lagoon	0.280	7.680	2.184	0.165

**Cd in sediment was below detection limit in all water bodies throughout the period hence, no further analysis was carried out on it.

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Appendix E: ANOVA of Heavy Metals Concentrations

Appendix E1: Within water bodies (95 % confidence level)

		Sum of Squares	df	Mean Square	F	Sig.
Water						
As	Between Groups	0.01	5.00	0.00	4.28	0.00
	Within Groups	0.32	579.00	0.00		
	Total	0.33	584.00			
Cu	Between Groups	0.00	3.00	0.00	11.68	0.00
	Within Groups	0.00	33.00	0.00		
	Total	0.01	36.00			
Cd	Between Groups	0.07	5.00	0.01	5.25	0.00
	Within Groups	0.67	250.00	0.00		
	Total	0.74	255.00			
Cr	Between Groups	0.01	4.00	0.00	17.83	0.00
	Within Groups	0.01	33.00	0.00		
	Total	0.02	37.00			
Fe	Between Groups	15.58	5.00	3.12	14.31	0.00
	Within Groups	103.45	475.00	0.22		
	Total	119.03	480.00			
Hg	Between Groups	0.02	5.00	0.00	42.38	0.00
	Within Groups	0.03	292.00	0.00		
	Total	0.05	297.00			
Mn	Between Groups	0.48	5.00	0.10	32.46	0.00
	Within Groups	1.26	422.00	0.00		
	Total	1.74	427.00			
Ni	Between Groups	0.01	5.00	0.00	6.27	0.00
	Within Groups	0.05	187.00	0.00		
	Total	0.06	192.00			
Pb	Between Groups	0.02	5.00	0.00	1.97	0.09
	Within Groups	0.25	111.00	0.00		
	Total	0.27	116.00			
Zn	Between Groups	0.01	5.00	0.00	4.47	0.00
	Within Groups	0.18	551.00	0.00		
	Total	0.18	556.00			

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Appendix E1, continued

		Sum of Squares	df	Mean Square	F	Sig.
Sediment						
As	Between Groups	85.22	5.00	17.04	17.30	0.00
	Within Groups	576.31	585.00	0.99		
	Total	661.53	590.00			
Cr	Between Groups	126.98	5.00	25.40	11.17	0.00
	Within Groups	793.66	349.00	2.27		
	Total	920.64	354.00			
Cu	Between Groups	462.09	5.00	92.42	23.37	0.00
	Within Groups	1253.36	317.00	3.95		
	Total	1715.45	322.00			
Fe	Between Groups	1.31E+05	5.00	26215.79	3.54	0.00
	Within Groups	4.34E+06	585.00	7410.96		
	Total	4.47E+06	590.00			
Hg	Between Groups	39.56	4.00	12.02	5.46	0.00
	Within Groups	1038.31	469.00	2.20		
	Total	1077.87	473.00			
Mn	Between Groups	5.36E+04	5.00	10729.55	39.85	0.00
	Within Groups	1.58E+05	585.00	269.24		
	Total	2.11E+05	590.00			
Ni	Between Groups	384.20	5.00	76.84	44.18	0.00
	Within Groups	973.92	560.00	1.74		
	Total	1358.12	565.00			
Pb	Between Groups	1602.36	5.00	320.47	12.95	0.00
	Within Groups	8783.44	355.00	24.74		
	Total	10385.80	360.00			
Zn	Between Groups	1041.05	5.00	208.21	28.42	0.00
	Within Groups	4285.28	585.00	7.33		
	Total	5326.33	590.00			

**Post hoc analysis was not performed for Pb in water because there was no significant differences within sites.

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Appendix E2: Within quarters (95 % confidence level)

		Sum of Squares	df	Mean Square	F	Sig.
Water						
As	Between Groups	0.18	5	0.04	134.95	0.00
	Within Groups	0.15	579	0.00		
	Total	0.33	584			
Cu	Between Groups	0.00	1	0.00	2.81	0.10
	Within Groups	0.01	35	0.00		
	Total	0.01	36			
Cd	Between Groups	0.02	3	0.01	2.03	0.11
	Within Groups	0.72	252	0.00		
	Total	0.74	255			
Cr	Between Groups	0.01	2	0.00	23.98	0.00
	Within Groups	0.01	35	0.00		
	Total	0.02	37			
Fe	Between Groups	22.02	5	4.40	21.56	0.00
	Within Groups	97.02	475	0.20		
	Total	119.03	480			
Hg	Between Groups	0.02	5	0.00	49.87	0.00
	Within Groups	0.03	292	0.00		
	Total	0.05	297			
Pb	Between Groups	0.01	5	0.00	1.24	0.30
	Within Groups	0.25	111	0.00		
	Total	0.27	116			
Mn	Between Groups	0.22	5	0.04	12.33	0.00
	Within Groups	1.52	422	0.00		
	Total	1.74	427			
Ni	Between Groups	0.01	5	0.00	6.44	0.00
	Within Groups	0.05	187	0.00		
	Total	0.06	192			
Zn	Between Groups	0.01	5	0.00	4.26	0.00
	Within Groups	0.18	551	0.00		
	Total	0.18	556			

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Appendix E2, continued

		Sum of Squares	df	Mean Square	F	Sig.
Sediment						
As	Between Groups	102.09	5	20.42	21.35	0.00
	Within Groups	559.44	585	0.96		
	Total	661.53	590			
Cr	Between Groups	134.22	5	26.84	11.91	0.00
	Within Groups	786.43	349	2.25		
	Total	920.64	354			
Cu	Between Groups	168.94	5	33.79	6.93	0.00
	Within Groups	1546.50	317	4.88		
	Total	1715.45	322			
Fe	Between Groups	2.36E+06	5	472382.90	131.31	0.00
	Within Groups	2.10E+06	585	3597.56		
	Total	4.47E+06	590			
Hg	Between Groups	30.80	5	6.16	2.72	0.02
	Within Groups	1067.61	472	2.26		
	Total	1098.41	477			
Mn	Between Groups	14503.62	5	2900.72	8.63	0.00
	Within Groups	1.97E+05	585	336.16		
	Total	2.11E+05	590			
Ni	Between Groups	137.19	5	27.44	12.58	0.00
	Within Groups	1220.93	560	2.18		
	Total	1358.12	565			
Pb	Between Groups	444.40	5	88.88	3.17	0.01
	Within Groups	9941.40	355	28.00		
	Total	10385.80	360			
Zn	Between Groups	620.57	5	124.11	15.43	0.00
	Within Groups	4705.76	585	8.04		
	Total	5326.33	590			

**Post hoc analysis was not performed for Cu, Cd and Pb in water because there were no significant differences within quarters.

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Appendix F: Tukey's Post Hoc Test of Heavy Metals Concentrations

Appendix F1: Within water bodies (Mean ± SE)

	Kakum Estuary	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**
Water						
As	$0.019 \pm 0.003^{a,b}$	0.013 ± 0.002^{b}	$0.021 \pm 0.003^{a,b}$	0.022 ± 0.001^{a}	0.028 ± 0.003^{a}	$0.019 \pm 0.003^{a,b}$
Cd	0.121 ± 0.003^{a}	0.085 ± 0.008^{b}	$0.108 \pm 0.022^{a,b}$	$0.108 \pm 0.011^{a,b}$	0.074 ± 0.004^{b}	$0.107 \pm 0.006^{a,b}$
Cr	$0.014 \pm 0.002^{b,c}$	BDL	$0.034 \pm 0.004^{a,b}$	0.049 ± 0.005^{a}	0.012 ± 0.005^{c}	0.009 ± 0.001^{c}
Cu	BDL	BDL	0.014 ± 0.003^{b}	0.005	$0.028 \pm 0.003^{a,b}$	0.032 ± 0.002^{a}
Fe	$0.258 \pm 0.047^{b,c}$	0.629 ± 0.080^{a}	0.130 ± 0.027^{c}	0.353 ± 0.057^{b}	$0.144 \pm 0.034^{b,c}$	$0.166 \pm 0.014^{b,c}$
Hg	0.018 ± 0.002^{b}	$0.013 \pm 0.001^{b,c}$	0.045 ± 0.001^{a}	0.004 ± 0.000^{d}	$0.009 \pm 0.001^{c,d}$	0.001 ± 0.000^{d}
Mn	0.022 ± 0.002^{c}	$0.032 \pm 0.004^{b,c}$	0.018 ± 0.003^{c}	0.115 ± 0.014^{a}	0.053 ± 0.004^{b}	0.022 ± 0.002^{c}
Ni	0.011 ± 0.003^{b}	$0.023 \pm 0.008^{a,b}$	$0.017 \pm 0.002^{a,b}$	0.029 ± 0.003^{a}	0.009 ± 0.001^{b}	$0.016 \pm 0.002^{a,b}$
Zn	0.011 ± 0.000^{b}	0.010 ± 0.001^{b}	0.010 ± 0.001^{b}	0.020 ± 0.003^{a}	0.012 ± 0.003^{b}	0.009 ± 0.001^{b}
Sediment						
As	$3.866 \pm 0.059^{b,c,d}$	4.261 ± 0.123^{b}	$3.971 \pm 0.109^{b,c}$	$3.775 \pm 0.184^{c,d}$	4.692 ± 0.020^{a}	3.513 ± 0.020^{d}
Cr	0.562 ± 0.126^{d}	2.497 ± 0.121^{a}	$1.063 \pm 0.056^{c,d}$	$1.493 \pm 0.458^{b,c}$	$1.362 \pm 0.068^{b,c,d}$	$2.084 \pm 0.101^{a,b}$
Cu	1.020 ± 0.355^{b}	0.646 ± 0.108^{b}	2.424 ± 0.326^{a}	3.521 ± 0.362^{a}	3.170 ± 0.232^{a}	0.715 ± 0.218^{b}
Fe	$80.471 \pm 8.649^{a,b}$	83.792 ± 9.229^{a}	$76.311 \pm 8.487^{a,b}$	90.100 ± 10.136^{a}	46.682 ± 6.755^{b}	89.838 ± 8.809^{a}
Hg	$1.976 \pm 0.291^{a,b}$	$1.633 \pm 0.082^{a,b,c}$	$1.488 \pm 0.067^{b,c}$	1.344 ± 0.085^{c}	2.106 ± 0.036^{a}	-
Mn	13.587 ± 0.870^{c}	12.044 ± 1.635^{c}	12.407 ± 0.954^{c}	26.693 ± 2.687^{b}	38.026 ± 2.140^{a}	18.179 ± 1.064^{c}
Ni	2.215 ± 0.207^{b}	0.994 ± 0.113^{d}	1.564 ± 0.098^{c}	2.851 ± 0.160^{a}	2.875 ± 0.083^{a}	0.772 ± 0.114^{d}
Pb	0.743 ± 0.118^{b}	0.533 ± 0.034^{b}	0.980 ± 0.121^{b}	4.405 ± 1.427^{a}	5.222 ± 0.489^{a}	0.743 ± 0.016^{b}
Zn	$2.622 \pm 0.411^{b,c}$	$3.191 \pm 0.151^{b,c}$	3.302 ± 0.231^{b}	3.314 ± 0.322^{b}	6.256 ± 0.259^{a}	2.184 ± 0.165^{c}

**Hg in sediment in the Muni lagoon was not included in this analysis because standard deviation equals zero.

Appendix F2: Within quarters (Mean ± SE)

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	2nd Q 2016	3rd Q 2016	4th Q 2016	1st Q 2017	2nd Q 2017	3rd Q 2017
Water						
As	0.010 ± 0.001^{b}	0.014 ± 0.001^{b}	0.057 ± 0.003^{a}	0.014 ± 0.001^{b}	0.012 ± 0.001^{b}	0.009 ± 0.000^{b}
Cr	0.011 ± 0.001^{b}	0.049 ± 0.005^{a}	0.016 ± 0.003^{b}	BDL	BDL	BDL
Fe	0.177 ± 0.029^{b}	0.140 ± 0.013^{b}	0.269 ± 0.039^{b}	0.170 ± 0.029^{b}	0.756 ± 0.096^{a}	0.237 ± 0.050^{b}
Hg	0.009 ± 0.001^{b}	0.001 ± 0.000^{c}	0.024 ± 0.002^{a}	0.007 ± 0.001^{b}	0.008 ± 0.001^{b}	$0.006 \pm 0.001^{b,c}$
Mn	0.037 ± 0.005^{b}	0.082 ± 0.010^{a}	0.023 ± 0.002^{b}	0.037 ± 0.006^{b}	0.027 ± 0.003^{b}	0.038 ± 0.004^{b}
Ni	$0.012 \pm 0.002^{b,c}$	$0.022 \pm 0.002^{a,b}$	0.005 ± 0.001^{c}	$0.014 \pm 0.002^{b,c}$	0.029 ± 0.006^{a}	$0.014 \pm 0.001^{b,c}$
Zn	0.005 ± 0.000^{c}	0.017 ± 0.003^{a}	$0.014 \pm 0.002^{a,b}$	$0.010 \pm 0.001^{a,b,c}$	$0.014 \pm 0.001^{a,b}$	$0.009 \pm 0.002^{b,c}$
Sediment						
As	4.382 ± 0.074^{a}	4.234 ± 0.070^{a}	4.247 ± 0.062^{a}	4.178 ± 0.065^{a}	3.150 ± 0.172^{b}	4.010 ± 0.084^{a}
Cr	2.589 ± 0.405^{a}	$1.744 \pm 0.100^{a,b}$	0.931 ± 0.068^{b}	2.780 ± 0.106^{a}	0.822 ± 0.370^{b}	$1.737 \pm 0.099^{a,b}$
Cu	$2.020 \pm 0.384^{b,c}$	$1.608 \pm 0.185^{b,c}$	2.376 ± 0.228^{b}	0.735 ± 0.218^{c}	2.260 ± 0.289^{b}	3.895 ± 0.587^{a}
Fe	18.079 ± 0.173^{d}	$34.615 \pm 5.314^{c,d}$	116.150 ± 9.100^{b}	190.769 ± 4.488^{a}	57.036 ± 7.339^{c}	18.044 ± 0.180^{d}
Hg	$1.943 \pm 0.063^{a,b}$	$1.675 \pm 0.079^{a,b}$	2.001 ± 0.028^{a}	$1.657 \pm 0.052^{a,b}$	1.303 ± 0.107^{b}	$1.994 \pm 0.419^{a,b}$
Mn	$25.699 \pm 2.304^{a,b}$	$22.194 \pm 1.527^{a,b,c}$	26.646 ± 2.605^{a}	$15.421 \pm 1.579^{c,d}$	13.479 ± 1.514^{d}	$18.695 \pm 1.136^{b,c,d}$
Ni	1.827 ± 0.209^{b}	1.704 ± 0.138^{b}	2.826 ± 0.196^{a}	1.508 ± 0.088^{b}	1.801 ± 0.139^{b}	1.389 ± 0.125b
Pb	1.464 ± 0.262^{b}	$2.705 \pm 0.734^{a,b}$	$4.673 \pm 1.130^{a,b}$	1.762 ± 0.280^{b}	$3.820 \pm 1.255^{a,b}$	$1.797 \pm 0.314^{a,b}$
Zn	4.987 ± 0.375^{a}	4.607 ± 0.276^{a}	2.898 ± 0.191^{b}	2.464 ± 0.131^{b}	2.383 ± 0.219^{b}	4.192 ± 0.495^{a}

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Appendix G: Sediment Parameters

Appendix G: Sediment parameters in the six water bodies

Water body	Parameter	Min	Max	Mean	S.E.
Kakum Estuary	OM (%)	0.36	18.86	4.42	0.31
Pra Estuary		0.28	17.21	7.10	0.38
Benya Lagoon		0.59	21.58	6.68	0.50
Sakumo II Lagoon		0.27	43.27	8.41	0.78
Fosu Lagoon		1.60	28.26	10.31	0.39
Muni Lagoon		0.12	7.78	1.63	0.14
Kakum Estuary	MPS (mm)	0.19	1.11	0.53	0.03
Pra Estuary		0.03	0.96	0.23	0.02
Benya Lagoon		0.10	0.90	0.42	0.02
Sakumo II Lagoon		0.11	1.36	0.55	0.03
Fosu Lagoon		0.04	1.24	0.50	0.03
Muni Lagoon		0.22	0.95	0.58	0.02

Appendix H: ANOVA of Sediment Parameters

Appendix H1: Within water bodies (95 % confidence level)

		Sum of Squares	df	Mean Square	F	Sig.
OM	Between Groups	4626.27	5.00	925.25	47.03	0.00
	Within Groups	11508.70	585.00	19.67		
	Total	16134.98	590.00			
MPS	Between Groups	7.99	5.00	1.60	24.84	0.00
	Within Groups	37.62	585.00	0.06		
	Total	45.61	590.00			

Appendix H2: Within quarters (95 % confidence level)

		Sum of Squares	df	Mean Square	F	Sig.
OM	Between Groups	537.78	5.00	107.56	4.03	0.00
	Within Groups	15597.20	585.00	26.66		
	Total	16134.98	590.00			
MPS	Between Groups	7.40	5.00	1.48	22.67	0.00
	Within Groups	38.20	585.00	0.07		
	Total	45.61	590.00			

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Appendix I: Tukey's Post Hoc Test of Sediment Parameters

Appendix I1: Within water bodies (Mean ± SE)

Water bodies	OM (%)	MPS (mm)
Kakum Estuary	4.42 ± 0.31^{c}	0.53 ± 0.03^{a}
Pra Estuary	7.10 ± 0.38^{b}	0.23 ± 0.02^{c}
Benya Lagoon	6.68 ± 0.50^{b}	0.42 ± 0.02^{b}
Sakumo II Lagoon	8.41 ± 0.78^{b}	0.55 ± 0.03^{a}
Fosu Lagoon	10.31 ± 0.39^{a}	$0.50 \pm 0.03^{a,b}$
Muni Lagoon	1.63 ± 0.14^{d}	0.58 ± 0.02^{a}

Appendix I2: Within quarters (Mean ± SE)

Quarters	OM (%)	MPS (mm)
2nd Q. 2016	7.82 ± 0.56^{a}	0.75 ± 0.02^{a}
3rd Q. 2016	$5.97 \pm 0.52^{a,b}$	$0.45 \pm 0.03^{b,c}$
4th Q. 2016	5.24 ± 0.37^{b}	$0.42 \pm 0.02^{b,c}$
1st Q. 2017	$6.09 \pm 0.38^{a,b}$	0.49 ± 0.02^{b}
2nd Q. 2017	$6.10 \pm 0.47^{a,b}$	0.37 ± 0.03^{c}
3rd Q. 2017	7.91 ± 0.81^{a}	$0.41 \pm 0.03^{b,c}$

Appendix J: Inventory of Species Encountered

Appendix J1: Species encountered in the Kakum Estuary (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)

Species	**2nd Q. 2016**	**3rd Q. 2016**	**4th Q. 2016**	**1st Q. 2017**	**2nd Q. 2017**	**3rd Q. 2017**
Lineus sp. (N)	1		1	2		
Phoronida		2	8	3		
Capitella capitata (P)	23	8	1	23	10	1
Euclymene sp. (P)	10	9	4		2	
Eunice indica (P)	1			13		
Exogone sp. (P)				1	1	2
Hipponoa sp. (P)			2	1		
Marphysa sp. (P)					4	9
Nephtys sp. (P)	28	45	18	23	72	38
Nereis sp. (P)	24	17	11	18	24	14
Nicomache sp. (P)				10		18
Scoloplos madagascariensis (P)	1			3		
Tubifex sp. (O)	4	5	3	1	28	27
Ampithoe sp. (C)	60	11		19		
Crab zoea (C)	2	1				
Gammarus sp. (C)	10	44				
Mysid (C)	7			41	4	
Chironomus sp. (I)	37	40	26	14	71	13

Appendix J2: Species encountered in the Pra Estuary (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)

Species	**2nd Q. 2016**	**3rd Q. 2016**	**4th Q. 2016**	**1st Q. 2017**	**2nd Q. 2017**	**3rd Q. 2017**
Lineus sp. (N)			2	13	7	
Sphaerodorum gracile (P)				2		12
Scoloplos madagascariensis (P)		2		5		
Polyophthalmus pictus (P)		3		1		
Nereis succinea (P)	3	2		4		1
Nephtys sp. (P)				1	1	
Hipponoa sp. (P)				2	1	
Capitella capitata (P)	14	2		15	3	
Branchiomaldane sp. (P)			2	1	22	3
Pristina sp. (O)	3	120		22	60	
Melitidae (C)			3	6		1
Chironomus sp. (I)			1	1	3	

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Appendix J3: Species encountered in the Benya Lagoon (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)

Species	**2nd Q. 2016**	**3rd Q. 2016**	**4th Q. 2016**	**1st Q. 2017**	**2nd Q. 2017**	**3rd Q. 2017**
Lineus sp. (N)		58		1	4	7
Asychis capensis (P)				5	6	
Capitella capitata (P)	502	395	382	473	194	522
Cirriformia afer (P)		2			1	
Eteone ornata (P)			2	1		
Heteromastus sp. (P)		77	44	6		
Hipponoa sp. (P)		14			11	
Nephtys sp. (P)			1	1		
Notomastus sp. (P)	3	19	2	1	19	2
Parasclerocheilus capensis (P)			283	44	45	
Polydora sp. (P)	1	12	38			
Polyphysia crassa (P)				1		2
Prionospio pinnata (P)		11			1	
Rhodine gracilior (P)	4	1			16	
Scoloplos madagascariensis (P)		13		4	5	
Tympanosyllis prampramensis (P)	1	1		2	2	1
Pristina sp. (O)	79	135		86		130
Tubifex sp. (P)		193		4	61	
Peneaus notialis (C)			3	1		
Chironomus sp. (I)			4		7	
Anadara senilis (M)			3	2		

Appendix J4: Species encountered in the Sakumo II Lagoon (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)

Species	**2nd Q. 2016**	**3rd Q. 2016**	**4th Q. 2016**	**1st Q. 2017**	**2nd Q. 2017**	**3rd Q. 2017**
Capitella capitata (P)	4				1	
Limnodrilus sp.(O)	1	485	749	538	2	
Chironomus sp. (I)		1094	239	563	3	
Backswimmer (I)		45	14	3		

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Appendix J5: Species encountered in the Fosu Lagoon (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)

Species	**2nd Q. 2016**	**3rd Q. 2016**	**4th Q. 2016**	**1st Q. 2017**	**2nd Q. 2017**	**3rd Q. 2017**
Capitella capitata (P)			43	80	17	5
Pristina sp. (O)	18		21	2		14
Melitidae (C)			25	4		
Black fly larva (C)	22			1		
Dragonfly nymph (C)	1		4			
Backswimmer (I)	24				1	5
Chironomus sp. (I)	364	122	119	1	461	399
Melanoides tuberculata (M)	71	958	405	300	274	592

Appendix J6: Species encountered in the Muni Lagoon (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)

Species	**2nd Q. 2016**	**3rd Q. 2016**	**4th Q. 2016**	**1st Q. 2017**	**2nd Q. 2017**	**3rd Q. 2017**
Capitella capitata (P)	329	166	676	328	407	127
Exogone sp. (P)		6	2		23	3
Heteromastus sp. (P)	40	19			3	
Hipponoa sp. (P)	3	2				2
Nereis sp. (P)	19	1	2	11	2	21
Notomastus sp. (P)	6	13	1	22	10	18
Prionospio pinnata (P)	6			4		
Rhodine gracilior (P)	53	66	18	51	80	16
Tympanosyllis prampramensis (P)	3	219		67	100	35
Pristina sp. (O)	18	26		76	69	
Tubifex sp. (O)	1				3	
Chironomus sp. (C)	66		11	7	64	37
Ampithoe sp. (C)	4	77	192	10	398	99
Gammarus sp. (C)	90		12			19
Haustoridae (C)		13				3
Melitidae (C)		81	46	2	23	27
Penaeus notialis (C)		8			1	19
Tanaid (C)		1	2			
Anadara senilis (M)	1	3	3			
Tellina sp. (M)		5	119			2

Appendix K: Percentage Frequency of Occurrence

Appendix K: Percentage frequency of occurrence of benthic macroinvertebrates encountered in the six water bodies (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)

Species	Kakum Estuary	Pra Estuary	Benya Lagoon	Sakumo II Lagoon	Fosu Lagoon	Muni Lagoon	Composition (%)	Occurrence (%)
Capitella capitata (P)	66	34	2468	5	145	2033	26.42	100
Chironomus sp. (I)	201	5	11	1899	1466	185	20.95	100
Pristina sp. (O)		205	430		55	189	4.89	66.67
Hipponoa sp. (P)	3	3	25			7	0.21	66.67
Tubifex sp. (O)	68		258			4	1.84	50
Nephtys sp. (P)	224	2	2				1.27	50
Melitidae (C)		10			29	179	1.21	50
Lineus sp. (N)	4	22	70				0.53	50
Scoloplos madagascariensis (P)	4	7	22				0.18	50
Ampithoe sp. (C)	90					780	4.84	33.33
Tympanosyllis prampramensis (P)			7			424	2.4	33.33
Rhodine gracilior (P)			21			284	1.7	33.33
Heteromastus sp. (P)			127			62	1.05	33.33
Gammarus sp. (C)	54					121	0.97	33.33
Nereis sp. (P)	108					56	0.91	33.33
Notomastus sp. (P)			46			70	0.65	33.33
Backswimmer (I)				62	30		0.51	33.33
Exogone sp. (P)	4					34	0.21	33.33
Penaeus notialis (C)			4			28	0.18	33.33
Prionospio pinnata (P)			12			10	0.12	33.33
Anadara senilis (M)			5			7	0.07	33.33
Melanoides tuberculata (M)					2600		14.46	16.67
Limnodrilus sp. (O)				1775			9.87	16.67

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Appendix K, continued

Species	**Kakum Estuary**	**Pra Estuary**	**Benya Lagoon**	**Sakumo II Lagoon**	**Fosu Lagoon**	**Muni Lagoon**	**Composition (%)**	**Occurrence (%)**
Parasclerocheilus capensis (P)			372				2.07	16.67
Tellina sp. (M)						126	0.7	16.67
Mysid (C)	52						0.29	16.67
Polydora sp. (P)			51				0.28	16.67
Branchiomaldane sp. (P)		28					0.16	16.67
Nicomache sp. (P)	28						0.16	16.67
Euclymene sp. (P)	25						0.14	16.67
Black fly larva (I)					23		0.13	16.67
Haustoridae (C)						16	0.09	16.67
Eunice indica (P)	14						0.08	16.67
Sphaerodorum gracile (P)		14					0.08	16.67
Marphysa sp. (P)	13						0.07	16.67
Phoronida	13						0.07	16.67
Asychis capensis (P)			11				0.06	16.67
Nereis succinea (P)		10					0.06	16.67
Dragonfly nymph (I)					5		0.03	16.67
Polyophthalmus pictus (P)		4					0.02	16.67
Cirriformia afer (P)			3				0.02	16.67
Crab zoea (C)	3						0.02	16.67
Eteone ornata (P)			3				0.02	16.67
Polyphysia crassa (P)			3				0.02	16.67
Tanaid (C)						3	0.02	16.67

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Appendix L: Functional Trait Database

Appendix L: Functional trait database for benthic macroinvertebrates encountered in the six water bodies (N = Nemertea, P = Polychaeta, O = Oligochaeta, C = Crustacea, I = Insecta, M = Mollusca)

Major groups/Species	Body form	Feeding habit	Mobility	Sexuality	Sociability
Phoronida	Long with broad base	Filter feeder	Tube dweller	Gonochorist + Hermaphrodite	Colonial
Lineus sp. (N)	Threadlike	Carnivore+scavenger	Crawler+swimmer	Gonochorist	Solitary
Branchiomaldane sp. (P)	Cylindrical + elongate	Deposit feeder	Burrower	Gonochorist	Solitary
Capitella capitata (P)	Cylindrical + elongate	Deposit feeder	Burrower	Gonochorist	Solitary
Eteone ornata (P)	Threadlike	Deposit feeder+filter feeder	Burrower+crawler	Gonochorist	Solitary
Euclymene sp. (P)	Cylindrical + elongate	Deposit feeder	Burrower	Gonochorist	Solitary
Eunice indica (P)	Cylindrical + elongate	Carnivore	Burrower	Gonochorist	Solitary
Exogone sp. (P)	Threadlike	Carnivore	Burrower	Gonochorist	Solitary
Asychis capensis (P)	Cylindrical + elongate	Deposit feeder	Burrower	Gonochorist	Solitary
Cirriformia afer (P)	Fairly broad	Deposit feeder	Burrower+sessile	Gonochorist	Solitary
Heteromastus sp. (P)	Cylindrical + elongate	Deposit feeder	Burrower	Gonochorist	Solitary
Hipponoa sp. (P)	Fusiform	Carnivore	Burrower+crawler	Gonochorist	Solitary
Marphysa sp. (P)	Stout	Deposit feeder+omnivore	Burrower	Gonochorist	Solitary
Nephtys sp. (P)	Threadlike	Carnivore	Burrower	Gonochorist	Solitary
Nereis sp. (P)	Cylindrical + elongate	Carnivore/deposit feeder	Burrower+crawler	Gonochorist	Solitary + Commensal
Nereis succinea (P)	Cylindrical + elongate	Carnivore/deposit feeder	Burrower+crawler	Gonochorist	Solitary + Commensal
Nicomache sp. (P)	Cylindrical + elongate	Deposit feeder	Burrower	Gonochorist	Solitary
Notomastus sp. (P)	Cylindrical + elongate	Deposit feeder	Burrower	Gonochorist	Solitary
Parasclerocheilus capensis (P)	Threadlike	Deposit feeder	Burrower	Gonochorist	Solitary
Rhodine gracilior (P)	Cylindrical + elongate	Deposit feeder	Burrower	Gonochorist	Solitary
Scoloplos armiger (P)	Vermiform	Carnivore	Burrower	Gonochorist	Solitary
Sphaerodorum gracile (P)	Vermiform	Deposit feeder	Burrower	Gonochorist	Solitary

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Appendix L, continued

Major groups/Species	**Body form**	**Feeding habit**	**Mobility**	**Sexuality**	**Sociability**
Polydora sp. (P)	Vermiform	Deposit feeder+filter feeder	Burrower	Gonochorist	Solitary
Polyophthalmus pictus (P)	Fusiform	Deposit feeder	Burrower	Gonochorist	Solitary
Polyphysia crassa (P)	Stout	Deposit feeder	Burrower	Gonochorist	Solitary
Prionospio pinnata (P)	Vermiform	Deposit feeder	Burrower	Gonochorist	Solitary
Tympanosyllis prampramensis (P)	Threadlike	Carnivore	Burrower	Gonochorist	Solitary
Limnodrilus hoffmeisteri (O)	Threadlike	Deposit feeder	Burrower	Hermaphrodite	Solitary
Pristina sp. (O)	Cylindrical + elongate	Deposit feeder+omnivore	Burrower	Hermaphrodite	Solitary
Tubifex sp. (O)	Cylindrical + elongate	Deposit feeder	Burrower	Hermaphrodite	Solitary
Ampithoe sp. (C)	Laterally compressed	Deposit feeder/ scavenger	Burrower+ crawler	Gonochorist	Solitary + Commensal
Gammarus sp. (C)	Laterally compressed	Deposit feeder+scavenger	Burrower+swimmer	Gonochorist	Solitary + Commensal
Haustoridae (C)	Laterally compressed	Deposit feeder+scavenger	Burrower	Gonochorist	Solitary + Commensal
Crab zoea (C)	Slender, forked telson	Omnivore	Swimmer	Gonochorist	Solitary
Melitidae (C)	Laterally compressed	Deposit feeder	Burrower+swimmer	Gonochorist	Solitary
Mysid (C)	Laterally compressed	Omnivore	Burrower+swimmer	Gonochorist	Solitary + Commensal
Penaeus sp. (C)	Laterally compressed	Deposit feeder+scavenger	Swimmer	Gonochorist	Solitary
Tanaid (C)	Threadlike	Filter feeder	Burrower	Gonochorist	Solitary
Backwimmer (I)	Keel-like	Predator	Swimmer	Gonochorist	Colonial
Black fly larva (I)	Vermiform	Filter feeder	Clinger	Gonochorist	Colonial
Chironomus sp. (I)	Threadlike	Deposit feeder+omnivore	Burrower+swimmer	Gonochorist	Solitary
Dragonfly nymph (I)	Threadlike	Carnivore	Jet propulsion	Gonochorist	Solitary
Tellina sp. (M)	Triangular + rounded	Filter feeder	Burrower	Gonochorist	Colonial
Anadara sp. (M)	Triangular + rounded	Filter feeder	Burrower	Gonochorist	Solitary
Melanoides tuberculata (M)	Conical	Deposit feeder	Burrower	Gonochorist	Gregarious

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