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ASSESSMENT OF TONO AND VEA RESERVOIRS FOR SUSTAINABLE NILE TILAPIA (*Oreochromis niloticus*) CAGE AQUACULTURE DEVELOPMENT IN UPPER EAST REGION, GHANA

BY

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JUNE, 2019

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By

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DECLARATION

I hereby declare that this submission is my own work towards the PhD and that, to the best of my knowledge and belief, it contains no materials previously published by another person, nor material which has been accepted for the award of any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi or any other educational institution, except where due acknowledgement is made in the thesis.

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ABSTRACT

The use of man-made aquatic ecosystems such as reservoirs and dugouts originally built for water supply, irrigation and fish farming is an emerging trend in most developing countries.

Most reservoirs are being assessed for their potential for cage fish culture as a result of the high demand of fish. Northern Ghana has a number of reservoirs and dugouts which were originally constructed to conserve water for irrigated farming particularly the Tono and Vea reservoirs, however they seem to be under-utilized. This study was conducted to evaluate the potential of cage aquaculture on the reservoirs by assessment of the water quality, suitable zones, carrying capacity (CC) and development of aquaculture management areas (AMAs) within two major reservoirs in Upper East Region (UER) namely; Tono and Vea reservoirs. These reservoirs were monitored using linear stratified sampling technique and monthly sampling of eighteen water quality variables between 06:00 to 10:00 for fifteen months (February 2015 to April 2016). Three replicates of samples were obtained for each variable from each stratum of the reservoir. Water temperature, water depth, transparency, pH and conductivity were measured *in-situ* using combined portable meters. Water sampling and laboratory analysis were based on standard analytical methods for examination of water and waste-water. Temporal and spatial dynamics of the reservoirs were investigated using multivariate statistical methods to obtain three seasonality regimes from the water quality with total variance in both reservoirs < 88.5%. Water quality in both reservoirs could support Nile tilapia culture (temperature between 26.730 ^{0}C, dissolved oxygen > 5 mg l^{-1}, average water depth > 3 m but < 10 m, pH was slightly acidic to slightly alkaline). Geographical information system-based spatial multi-criteria analysis results indicate that 3.85 km^2 (39.05% suitability) and 2.15 km^2 (68.40% suitability) of reservoir area were suitable for the development of cage aquaculture in Tono and Vea reservoirs, respectively. Estimates of carrying capacity i.e. production, physical, ecological, and social were integrated to obtain the final aquaculture CC of 719.40 m^{-3} and 65.55 m^{-3} as production volume for Tono and Vea reservoirs, respectively. Results for trophic level index (TLI) indicate that Tono reservoir has very high nutrient enriched waters (TLI: 5.23; super trophic), whiles Vea reservoir has high nutrient enriched waters (TLI: 4.32; eutrophic). Based on the trophic status, percentage allocation of aquaculture CC and other secondary data; the three AMAs in Tono reservoir and the five AMAs in Vea reservoir could produce 107.91 and 9.83 metric tonnes of cultured Nile tilapia per production cycle respectively. The study postulate that the ecosystem approach to aquaculture could be pragmatic stepwise approach that has salient potential to deal with environmental, economic and social issues associated with cage culture in Tono and Vea reservoirs. Best management practices (BMPs), physical and biosecurity measures are needed to minimise aquatic animal health risk. The use of CC based suitable zones and identification of individual AMAs are recommended as useful for decision-making by fisheries and aquaculture regulators, managers of reservoirs and other aquaculture policy-makers for sustainable cage aquaculture in the two reservoirs.

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DEDICATION

This thesis is dedicated to God almighty for protection and provision, through my Master and Saviour of my life: The Lord Jesus Christ. To my parents, Mr. Alphonse Agbeko and Mrs. Margaret Ofori-Agbeko who continuously inspire me to excellence.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND ACRONYMS

AATs	Aquaculture Assessment Tools
ACC	Aquaculture Carrying Capacity
ACD	Average Culture Density
ACDEP	Association of Church-based Development Projects
ALK	Alkalinity
AMAs	Aquaculture Management Areas
B-C	Bray-Curtis
BMPs	Best Management Practices
BoG	Board of Government
CA	Cluster Analysis
CAP	Community Analysis Package
CC	Carrying Capacity
CHL-a	Chlorophyll-a
CL^-	Chloride
CoA	Correspondence Analysis
CON	Conductivity
Cp	Culture period
CSIR	Council for Scientific and Industrial Research
Cv	Expected Cage volume
DA	Discriminant Analysis
DO	Dissolved Oxygen
Ds	Down streams
EAA	Ecosystem Approach to Aquaculture
ECC	Ecological carrying capacity
FA	Factor Analysis
FAO	Food and Agriculture Organization
FCR	Feed Conversion Ratio
FL	Feed Load
Fr	Feed requirement

FR	Feeding Rate
GIS	Geographical Information Systems
Ha	Hectare
HDPE	High Density Polyethylene
ICOUR	Irrigation Company of Upper Region
IDW	Inverse Distance Weighted
Km	Kilometres
LODOS	Low Dissolved Oxygen Syndrome
LVHD	Low Volume High Density
MCE	Multi-Criteria Evaluation
Mp	Maximum production
Ms	Midstream
NH_4-N	Ammonium-Nitrogen
NO_2-N	Nitrite-Nitrogen
NO_3-N	Nitrate-Nitrogen
PAST	Paleontological Statistics
PCA	Principal Component Analysis
PCC	Physical carrying capacity
PHY.B	Phytoplankton Biomass
PO_4^{2-}	Phosphate-Phosphorus
ProCC	Production carrying capacity
RESULT	Resilient and Sustainable Livelihoods Transformation
SCC	Social carrying capacity
SDD	Secchi Disc Depth
SiO_2	Silicon dioxide
SMCE	Spatial Multi-Criteria Evaluation
SO_4^{2-}	Sulphate
SS	Standing Stock
SWT	Surface Water Temperature
T.HAR	Total Hardness
TDS	Total Dissolved Solid

TEM	Temperature
TLI	Trophic Level Index
TRA	Transparency
TUR	Turbidity
UER	Upper East Region
Us	Upstream
WD	Water Depth
Wg	Actual Weight gained

CHAPTER ONE

1. GENERAL INTRODUCTION

1.1 Overview of global aquaculture production

Aquaculture is an important venture that could increase fish production, generate income, minimize malnutrition and sustain livelihoods of people in riparian communities. The farming of finfish, crustaceans, molluscs, and other aquatic animals in inland freshwater, inland saline water, brackish water, or marine water referred to as aquaculture; has gained global attention as blue growth (FAO, 2018a). Aquaculture is the fastest growing agro sector (FAO, 2018b). Global fish production has grown steadily in the last five decades, with food fish supply increasing at an average annual rate of 3.2 percent, outpacing world population growth at 1.6 percent (FAO, 2014). However, recent global aquaculture production trends show a positive increase of 6.6 percent since 1995 (FAO, 2017). This was valued at US$ 163 billion for the first-sale value of 106 million tonnes of live weight, with additional 23 million tonnes required by year 2020 (FAO, 2017). The demand for fish as raw material for pharmaceutical, food and other industries averages over 299 million tons/year on the global market (Yulius *et al.*, 2009). Aquaculture production is projected to grow by 40% to satisfy the high demand for fish and fish products (TADAN, 2016). Thus, aquaculture growth is showing no sign of slowing down in absolute terms (Dean *et al.*, 2018) as it is essential for food security and economic development.

At continental level, African's aquaculture growth during 2001-2015 averaged 10.4%, followed by Asia (6%) and Americas (5.7%); while in Oceania and Europe aquaculture growth were only 2.9% and 2.5%, respectively (FAO, 2017). Africa's contribution to global fish production and growth could dwindle marginally compared to the rest of the world probably due to a myriad of problems associated with site selection, understanding water quality dynamics and management, poor fish seed (fingerlings), fish feed and feeding issues. Apart from feed being the highest input cost, challenges associated with suitable site selection, water quality deterioration and development of aquaculture management areas in lakes and reservoirs as a policy could hinder any progress being made in the aquaculture sector. There is a huge potential for the expansion of aquaculture even in the face of environmental, economic and societal changes due to high preference for fish (FAO,2018a), especially tilapia. Tilapia is a delicacy in most Ghanaian homes and serves as a source of protein in Ghana. Ghana is a net importer of fishery products. Ghana imported 151,541.25 metric tonnes (mt) of fish as the inland sub-sector produced only 46,601.17 mt of fish valued at GH 558,621,408.00 in 2018 (MoFAD MFEF PBB, 2019). Total aquaculture production target for 2018 was 88,512 mt but 62,718 mt, was the actual production obtained as at August, 2018, with tilapia and catfish accounting for 90.3% and 9.7% of the total aquaculture production respectively for this same period (MoFAD MFEF PBB, 2019).

1.2 Cage aquaculture trends and potentials in Northern Ghana

Ghana has considerable opportunities for commercial scale development of freshwater cage aquaculture, not only on the Volta Lake but also on the numerous reservoirs in the country. If well developed, cage aquaculture has the potential to produce seed for stocking inland waters and enhancing fisheries (Ofori *et al.*, 2010). Although, northern Ghana has a long history of aquaculture, it is limited to extensive systems in dug-outs and reservoirs which were constructed for irrigation purposes and as watering points for animals. Estimated contribution of reservoir culture-based fisheries is 150 kg/ha/yr (Agbeko *et al.*, 2014b), an indication that most reservoirs are under-utilised especially for fish production.

In the Upper West Region of Northern Ghana, Nile tilapia growth trials in cages have been conducted on selected reservoirs and dugouts (i.e. Busa, Sing, Vieri, Baleofiri, Guo and Kokoligu), with final fish harvest weight ranging from 200 – 400 g over six-months culture period using fingerlings with mean weight of 2g (E. Dery, pers. comm., August 28, 2018). The final fish harvest weight range obtained was good as it is within the weight range most consumers prefer in Ghana (Asmah, 2008). Most reservoirs in northern Ghana could have huge potential for cage aquaculture development using appropriate cage culture technologies such as Low Volume High Density cage technology (LVHD, 1x1x1 m^3 size cages). Asmah (2008) identified five irrigation reservoirs in northern Ghana that could be harnessed for aquaculture. However, not much has been done in terms of their suitability for cage culture. The major perennial reservoirs in Northern Ghana such as Bontanga, Golinga, Libga, Sankana, Tono, and Vea reservoirs have great potential for sustainable cage culture.

1.3 Prospects of Nile Tilapia Cage culture in the Upper East Region of Ghana

The Upper East Region (UER) has over 129 small ephemeral systems and 147 large perennial irrigation reservoirs, prominent among which are Tono and Vea (MoFA, 2009). These reservoirs are 7.5 and 15 km from populated towns such as Navrongo (from Tono) and Bolgatanga (from Vea) where fish products could be easily marketed. Supply of tilapia to these markets are sometimes augmented with fish produced in Burkina Faso and other neighbouring countries to meet the shortfall in supply.

Cage culture trials on irrigation reservoirs at Kordiabe and Michel Camp in the Greater Accra Region in Southern Ghana, using small cages (1 m^3) yielded between 84.5 - 99.5 kg m^{-3} after 3 months when juvenile fish (59g) were used. The final average weight of the cultured tilapia in the cages ranged between 335 – 394g (Veverica *et al.*, 2011). Pilot studies indicates that some dugouts and reservoirs in Ghana could be sustainably utilised for Nile tilapia production (Agbeko *et al.*, 2014b, Akongyuure *et al*., 2015, Alhassan *et al*., 2018). Thus, identifying and harnessing suitable areas in such reservoirs, provides opportunity for meeting the everincreasing demand for fish, especially for tilapia.

Commercial production trials in some selected reservoirs in Northern Ghana by the Council for Scientific and Industrial Research (CSIR)-Water Research Institute (Kumi *et al*., 2013; Agbeko *et al*, 2014a) had led to the adoption of Nile tilapia cage culture production on project basis in a number of shallow reservoirs in this part of the country. For example, few aquaculture intervention projects in the Upper-East Region produced a total of 19,498.4 kg (19.5 metric tonnes) (ACDEP-RESULT, 2018) of Nile tilapia valued at US$ 37,263.66 from 6 reservoirs at the community level (Table 1.4.1). Harvested average weight ranged between 284.3 - 302.0 g for Vea Reservoir (Agbeko *et al.*, 2014a) and 300 – 450 g for five other reservoirs selected from (P. Akpaglo, pers. comm., December 5, 2017) (Table 1.4.1). This production was from conventional cages of dimension (5x5x2 m^3), (4x4x2 m^3), and (5x5x4 m^3). In the past, most reservoirs were not considered for cage culture as they were considered to be shallow for fish cages. However, variation in cage depth can be done based on bathymetry of reservoir for effective mooring. It is posited that for good water exchange, the space between cage bottom and reservoir benthos should be 0.5-1.0 m.

Table 1.4.1. Production (kg) of Nile tilapia in cages in selected reservoirs and dugouts in Upper East Region, Ghana (Agbeko *et al.*, 2014a; ACDEP-RESULT, 2018).

Year	Community	District	Production (kg)	Value (GH₵)
2013/2014	Vea-Gowrie	Bongo	5,280.0*	36,960.00
2014/2015	Bon-Gurigu	Bongo	1,062.0	8,300.00
2015/2016	Bon-Gurigu	Bongo	5,327.3	32,696.00
2014/2015	Datoko	Talensi	1,544.0	13,860.00
2014/2015	Pusu-Namongo	Talensi	4,800.6	50,051.00
2016/2017	Soe-Yidongo	Bongo	1,484.5	10,914.00
Total			19,498.4 (19.5 mt)	152,781.00

GH₵4.10: US$1.00 (2017) *Calculated yield during pilot studies before poaching

1.4 Statement of problem

Aquaculture is an emerging sector that requires space and natural resources using technological innovation for addressing food security, environmental management, employment and poverty reduction (Falconer *et al*., 2013; FAO, 2015a; Dean *et al.*, 2018). Increase in human population and declining in reservoir capture-based fisheries had warranted intensification of culture-based fisheries. Aquaculture growth is attributed to several factors, including high market value and demand for fish, decline in protein food supply and food insecurity in developing countries, improvement of technology for cage culture in reservoirs and water bodies not suitable for conventional fisheries, and availability of technical support and high-quality inputs like fish feed or fry (Degefu *et al*., 2011).

However, some aquaculture development constraints still exist, which includes effects on the ecosystem and effects of other ecosystem components and external drivers on aquaculture emanates from ecological and socio-economic well-being issues (FAO, 2010). These issues are ripe in Tono and Vea reservoirs, which were purposely built for irrigation, domestic or municipal water supply and for capture fisheries with ponds for aquaculture (ICOUR, 1995). However, the availability of these fish production facilities seems not to have resulted in increased fish production from both reservoirs despite various re-stocking programmes and interventions. In recent years, the Tono and Vea reservoirs had come under increasing lobby for its utilisation for fish cage culture to boost fish production and economic returns for the

Upper East Region of Ghana. This additional use of these reservoirs could cause water quality deterioration, increase competition for fishing space and navigation which could heighten water-user conflicts among the multiple users of these reservoirs.

The high level of uncertainty over ecological impact of cage fish culture in shallow reservoirs has affected the harnessing of the full potentials of cage culture to augment capture fisheries. Production of fish by cage culture in existing water bodies could eliminate cost of pond construction though will incorporate the cost of cage production system whose capital investment requirement is relatively low compared to other intensive culture systems (ElSayed, 2006). Cages for tilapia production systems when properly sited poses a lot of advantages over other rearing systems, which includes relatively low capital costs, simple management, better quality of fish, and use of existing water bodies (Beveridge, 2004). To increase fish production without over-dependence on precautionary environmental approach, water quality monitoring is a pre-requisite for identifying patterns of variation or pollution to safeguard aquaculture and promote fish growth (Khalit *et al.*, 2017).

The lacuna created in lieu of sustainable aquaculture development causes adhoc siting of cages. In some cases, relocation of cages if unfavourable weather or environmental conditions (Pillay and Kutty, 2005), and /or with social objection or physical constrains occur. Specific spatial information from Geographical Information Systems (GIS) models and technological innovations inferred from scientific studies can be used in identifying suitable sites through modelling. GIS-based analysis provides rigorous and robust analysis that allows multiple factors to be considered for decision making which could minimise risk in aquaculture (Dean *et al.*, 2018), compared to other methods. The application of GIS-based modelling is emerging but less applied for decision making in freshwater aquaculture especially for Nile tilapia cage culture production systems (Radiarta *et al.*, 2008).

The incidence of fish poaching or theft causing economic losses, low tolerance of fish to poor water quality leading to greater risk of disease outbreak, and mass fish mortality (fish kills) within a shared water body or common water source could hamper aquaculture development and growth (Aguilar-Manjarrez *et al*., 2017), if Aquaculture Management Areas (AMA's) are not created within suitable zones Tono and Vea reservoirs. AMA refers to a cluster of fish farms, an aqua park or group of farms with a common shared water resource under coordinated management. Issues of water quality, selection of suitable sites and development of AMAs to make aquaculture more environmentally safe and economically rewarding will be fundamental to sustainability of aquaculture in Tono and Vea reservoirs in the Upper East region of Ghana, as such studies must deal with environmental, economic and social challenges in view of wateruser conflicts for sustainable aquaculture (FAO and World Bank, 2015).

1.5 Justification of the study

Aquaculture is an important venture that could increase local fish production, enhance nutrition and wealth creation as well as sustain livelihoods of communities (Shava and Gunhidziria, 2017; Alhassan *et al.*, 2018). Cage aquaculture has a high potential, especially in water bodies (lakes, reservoirs, large farm ponds, rivers, estuaries and micro dams) that cannot be drained or seined and that would otherwise be unsuitable for conventional fisheries (Degefu *et al.*, 2011). However, Cage aquaculture development in shallow reservoirs (mean depth < 10 m) could have both positive and negative impacts on ecosystem and social processes. Thus, efforts must be made to avoid or ameliorate negative impacts on reservoirs, as reservoirs are biodiversity hot-spots (Degefu *et al.,* 2011). The Ecosystem Approach to Aquaculture (EAA) recommended by Food and Aquaculture Organisation (FAO, 2010) for aquaculture development was adopted as the theorical framework for this study. EAA provides a strategy for the integration of the activities within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems (FAO, 2010).

In the context of reservoir development for cage aquaculture, the principles underlying the EAA framework will help generate empirical evidence that will enhance the understanding of the reservoir's ecosystem processes, provide the appropriate connection between aquaculture and water-related institutions to collaboratively make decisions to minimise water-user conflicts due to aquaculture development through a stepwise. The integration of EAA with GIS-spatial planning tools deployed in this study could progressively resolve some negative impacts owning to aquaculture development in tropical reservoirs. The benefits from spatial planning and management includes higher productivity and good returns for cage aquaculture investors and the effective mitigation of environmental, economic and social risks (AguilarManjarrez *et al*., 2017).

The paucity of scientific data for cage aquaculture decision making for most reservoirs in Northern Ghana had affected the development of these water storage systems for fish production. Zoning and expansion of local fish production through pragmatic research using

GIS-based models for decision making could be one of the approaches for up-scaling national fish production to reduce the high fish imports. GIS used in modelling is a useful tool for site selection, decision making and finding suitable zones for aquaculture. This is an important step in any aquaculture operation, affecting its success and sustainable development (Radiarta *et al.*, 2008). Deployment of scientific methods in site selection, could minimize environmental impacts such as water quality deterioration near cages as this could reduce fish growth performance rate and possibly lead to high fish mortality. Thus, further understanding of the water quality characteristics in reservoirs is fundamental to good aquaculture management and sustainability. Through the Ecosystem Approach to Aquaculture (EAA), Tono and Vea reservoirs could be zoned to increase fish production by harnessing the environmental and social interactions, using pragmatic research tools such as GIS-based models for sustainable aquaculture development (Ross *et al.*, 2013; FAO, 2015a; Prema, 2015). Thus, through the adoption of cage aquaculture, most reservoirs in Northern Ghana, especially in UER could be harnessed to boost Nile tilapia production. The study is expected to provide a reliable and empirical approach for cage culture development in shallow reservoirs as well as safeguard the aquatic ecosystem health in an environmentally and socially acceptable way. Thus, scientific studies on sustainable development of aquaculture are pragmatic to harness the full potentials of cage culture in lentic water bodies like Tono and Vea reservoirs. Hence, the need for this comprehensive study for informed decision making.

Nile tilapia (*Oreochromis niloticus*) was hypothetical considered for this study as the fish species of choice for suitability studies for aquaculture development in Tono and Vea reservoirs because it is the most preferred cultured species, have high market and economic returns, and is part of the mainstay in these reservoirs. Tilapias (Cichlidae) are widespread, fished and cultured in many other inland freshwater systems in Africa (Kolding *et al.*, 2019).

Fish cage culture, is considered the most efficient form of fish production system for Nile tilapia for inland freshwater systems like lakes and reservoirs (Schmittou, 2006), thus its usage for determination of suitable zones for the Tono and Vea reservoirs. Dues to the threats of pollution from aquaculture and water-use conflicts, aquaculture management areas (AMAs) were factored into the study as it was needed for sustainable aquaculture development (FAO, 2010; Aguilar-Manjarrez *et al.*, 2017) of the reservoirs.

1.6 Research Questions

This study sought to address the following research questions;

1. What is the water quality status of Tono and Vea reservoirs?
2. Where are the suitable areas and levels of suitability for cage culture of Nile tilapia?
3. What is the carrying capacity for these reservoirs for cage culture of Nile tilapia?
4. What is the trophic status and potential aquaculture management areas (AMA) within these reservoirs?

1.7 General Hypothesis and Objectives

The general hypothesis was "*Tono and Vea reservoirs have suitable characteristics for sustainable Nile tilapia cage culture development*"

The general objective of the study was to provide a scientific approach for sustainable development of cage aquaculture in shallow reservoirs by investigating the aquaculture potential of Tono and Vea Reservoirs, in the Upper East Region. Thus, specific objectives were formulated to provide a step-by-step approach of achieving the general objective.

The specific objectives of the study were to:

I. Determine the temporal and spatial characteristics of water quality using physicochemical and biological attributes in Tono and Vea reservoirs
II. Determine the most suitable zones in the Tono and Vea reservoirs for Tilapia cage culture using Multi Criteria Evaluation tools in GIS for sustainable aquaculture
III. Estimate the carrying capacity of Tono and Vea Reservoirs for tilapia cage culture system
IV. Assess the trophic status and develop potential Aquaculture Management Areas (AMAs) for Tono and Vea reservoirs

1.8 Organization of Thesis

The thesis is based on the Manuscript format. Chapter 1 presents the general introduction, statement of problem, Research questions and objectives, and justification of study. Chapter 2 is on literature review. General material and methods used in the study were stated in chapter 3. Chapter 4 is based on thematic areas derived from the four specific objectives of the study in the form of the publishable manuscripts. Chapter 5 is the general Discussion. Chapter 6 presents the conclusions and recommendations of the study. All references from each chapter were cited together and as well as appendices.

1.9 Publications

Five manuscript were prepared from this thesis and submitted to various peer-reviewed journals. Two had been accepted and published as stated below;

- Agbeko, E., Agbo, N. W., Agyemang, T.K., and Adjei-Boateng, D. (2019). Water quality status of Tono and Vea reservoirs for aquaculture development in the Upper East Region of Ghana. *Asian Journal of Fisheries and Aquatic Research.* 3(1): 1-14; article no. AJFAR.47536.

- Agbeko, E., Adjei-Boateng, D., Agbo, N., W, Agyemang T.K (2019). Trophic status and development of aquaculture management Areas (AMAs) for the two Major Reservoirs: Tono and Vea, in the Upper East Region of Ghana. *Journal of Aquaculture Research and Development*. 10: 563. doi: 10.4172/2155-9546.1000563

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Aquaculture and fish production

Aquaculture is an important food production sub-sector which involves the culturing of fin fish, shellfish and other aquatic plants. Aquaculture could be defined as the farming of aquatic organisms in inland and coastal areas, involving intervention in the rearing process to enhance production, with individual or corporate ownership of the stock being cultivated (Thorpe *et al.*, 2011). Aquaculture accounts for more than one-quarter of the total fish directly consumed by humans, using about 220 finfish and shellfish species (Naylor *et al.*, 2006), and currently produces 53 percent of global fish we consume which is expected to double the per capita fish consumption (FAO, 2018b). Contribution of aquaculture became significant to global food supply and rural livelihood about 30 years ago with the adoption being led by small-scale, small and medium-sized enterprises (SMEs) as aquaculture contribution to global fish production increased from 7% in 1974 to 26% in 1994 and 39% in 2004 (DEVCO-AFD-GIZ, 2017). Global Aquaculture volumes (weight) and values (monetary) estimates indicate that farmed food fish production included 54.1 million tonnes of finfish such as carp and tilapiine was USD 138.5 billion, 17.1 million tonnes of molluscs (USD 29.2 billion), 7.9 million tonnes of crustaceans (USD 57.1 billion) and 938 500 tonnes of other aquatic animals (USD 6.8 billion) such as turtles, sea cucumbers, sea urchins, frogs and edible jellyfish were produced (FAO, 2018b).

Recent study indicates that, there is an increasing consumer preference for fish probably due to the health benefits of fish (Wenaty *et al.*, 2018) compared to red meat. According to the United Nations Food and Agriculture Organization (FAO), fish consumption is projected to rise, as fish provides at least 15 percent of the average per capita animal protein intake for over 4.5 billion of the world's population (FAO, 2016). Fish consumption is increasing while capture fisheries is declining, hence aquaculture could be the panacea to meet the increasing global fish demand. Excluding aquatic plants, aquaculture contribution increased from 25.7 percent in 2000 to 46.8 percent in 2016 (90 million tonnes) of total global fish production, of which Africa's contribution was 9 million tonnes in 2016, representing an increase from 6 percent in 2000 to 17-18 percent in 2016 (FAO, 2018b). Recent joint report indicates that Africa's contribution had declined to less than 2 percent of global production as total production from the continent was around 1.74 million tonnes of aquaculture, as Americas are the second largest regional producer in terms of volume (around 3 million tonnes, representing over 3 percent of the global total) and Asia (largely from China since 1991) continues as the leading food fish producers with 92 percent of all aquaculture production (DEVCO-AFD-GIZ, 2017; FAO, 2018b).

Nile tilapia (*Oreochromis niloticus*) is one of the main species cultured commercially due to its good growth and its great potential for intensive fish farming (Sahu *et al*., 2017). Among the top 10 finfish and shellfish species cultured in 2014, the Nile tilapia accounts for 5 percent (3.7 million tonnes) of the total aquaculture species cultured in terms of global aquaculture volume (FAO, 2016b).

Various strategies can be used to manipulate the physical factors affecting fish production. Production systems usually require some investment in water management and environmental control (DEVCO-AFD-GIZ, 2017). Latitude determines the physical factors like climatic conditions, which again control variables such as temperature, light, annual insolation, seasonal variation, wind and precipitation. All these play a major role in the nutrient cycles and hence the regeneration of biomass for fish production. Fish production enhancements may be classified into edaphic, nutrient, hydrological and habitat enhancements. The edaphic conditions determine the chemical composition of the soil in the surrounding watershed, and thus the supply of nutrients and trace elements for organic synthesis (Ryder, 1978). Thus, the enhancements based on manipulations in edaphic factors depend on the nutrient status of the water body and soil along with the physical variables such as specific conductivity and total alkalinity (Craig, 2000). The morphology of a reservoir, particularly area, volume, depth, and shoreline development or gradient, is also of major importance to the productivity (Ryder, 1978). The mean water depth is a single morphometric parameter used to estimate the production potential of a reservoir (Agaypi, 2000).

Various culture systems such as ponds, cages, pens, tanks and raceways are being used to increase fish production worldwide. Cage culture is the raising of fish in water-suspended containers that are enclosed on all sides and the bottom by mesh material that secures the fish inside while allowing relatively free exchange of water with the surrounding environment (Schmittou, 2006). Cage culture has high potential, especially in water bodies that cannot be drained or seined and that would otherwise be unsuitable for conventional fisheries (Degefu *et al.*, 2011). A cage is a system that confines the fish or shellfish in a mesh enclosure. It has a completely rigid or flexible frame on all sides. Cage culture uses existing water resources (ponds, rivers, estuaries, open ocean, etc.) but confines the fish inside of mesh enclosures. The mesh retains the fish, making it easier to feed, observe and harvest them. In Ghana, materials for construction of cage frames are galvanized pipes, wood or bamboo. In the year 2000, the first cage culture farm was established as others culturing farms followed (Asmah *et. al.* 2016). The Upper East Region of Ghana has numerous small water storage systems i.e. dugouts and reservoirs (> 400) for run-off (rain water) storage. These dugouts and reservoirs are mainly for domestic use, animal watering, irrigation, capture fisheries, and seldom for aquaculture. This is because most of these reservoirs and dugouts are shallow (<10 m in depth) and for many years were perceived to be unsuitable for farming fish amidst potential environmental and water-use conflicts. Selection of suitable sites to make aquaculture environmentally safe and economically rewarding will be fundamental to sustainable of aquaculture.

2.2 Issues with Aquaculture development

Globally, the decline in capture fisheries, human population increase, unemployment, the demand for healthy protein-rich food alternatives, and possible good revenue from fish farming have been purported to encouraged the development of aquaculture. Contrarily to the strives being made in developing aquaculture globally, Africa's aquaculture has grown much more slowly compared to other regions due to numerous challenges including water quality and water resources conflicts, quality of fish seed and feed, the use of drugs for disease control, difficulties in accessing credit, farming innovations, technology and information (Finegold, 2009), that had affected aquaculture development. Most government institutions, fishery and aquaculture regulatory agencies, and aquaculture industry stakeholder may lack the applicable technology or funding to restore or ameliorate contaminated water bodies, nutrient pollution becomes a growing concern or issue (Healey *et al.*, 2016). A good approach to identify aquaculture issues is to focus on the different steps in the production process, including upstream (such as inputs) and downstream (such as post-harvest) aspects, and their related potential root causes explored (FAO, 2010).

2.2.1 Environmental and water quality challenges

Water quality deterioration is one of the factors underpinning the development of aquaculture in the aquatic ecosystem, especially in lentic water bodies like reservoirs. Cage culture enriches the surrounding water environment with metabolized feed waste as would organic fertilization (Schmittou, 2006). For cage aquaculture, site selection is key to avoiding water quality deterioration near cages (Braaten, 2007), other factors could cause negative effects due to the fish farming waste (Meijberg, 2016). Thus, water quality management (i.e. Physical, chemical and biological characteristics) possess a major concern to fish production. Temperature fluctuation and lake stratification (leading to water over-turn), Low dissolved oxygen syndrome (LODOS), nutrient loading and other water pollution issues are major water quality challenges (Sriyasak *et al.*, 2015), these have been observed as emerging challenges in some reservoirs and lake exploited for aquaculture in Ghana. These water quality issues often lead to fish kills (massive mortality) in cages mounted in certain portions of Lake Volta and in some reservoirs in northern Ghana.

In cages, the adverse water quality factors that most affect fish, and consequently limit fish production, are low dissolved oxygen (DO) levels and the high levels of metabolic wastes (Schmittou, 2006). Thus, the higher the fish biomass, the higher the oxygen demand and the higher the fish culture waste that can be produced within the culturing system. Also, excess or uneaten fish feed will increase the nitrogen and phosphorus concentrations in aquaculture systems which could exacerbate eutrophication (Talbot and Hole, 1994). There are three ways by which fish feed waste to a certain threshold is beneficial to the environment as it increases phytoplankton and other biomass in the following ways (stated below), but beyond a certain threshold which could not be easily predicted, the enriching elements become pollutants (Schmittou, 2006):

i. Important in maintaining good water quality (provides optimum physico-chemical balance)
ii. providing food to some caged fish, including the majority of tilapia
iii. Increasing production of non-caged fish that result from the enrichment.

Lakes and reservoirs do not maintain their fertility unless an external loading of nutrients is continually applied through their inflowing rivers and from rainwater. Typically, the nutrients tend to accumulate in the water basins due to evaporation, biological activities, and sediment interaction. Most of the reservoirs in Kerala (India) portray a low status in terms of nutrients, specific conductivity (<100 µs/cm) and total alkalinity (<100 ppm) with a low primary productivity and plankton diversity (Paul *et al.*, 2017), prior to its development for aquaculture. These authors noted that, phosphate very seldom exceeds 0.1 mg 1^{-1} in reservoirs free from pollution, as nitrate-nitrogen in water in Indian reservoirs exceeds 0.5 mg 1^{-1}. These authors further commented that, in India, the nutrient status of most of the reservoirs is low and this does not indicate low productivity from the system. Quick recycling of nutrients and rapid turnover rates of phosphate in the system makes it difficult to ascertain the reservoir productivity based on the status of phosphate (Sugunan, 1995; Paul *et al.*, 2017). Aquaculture effluents including development of land-based aquaculture related facilities could increase turbidity in reservoirs. Increasing turbidity was reported as a major constraint on primary production and potential fish yield (Ofori-Danson and Ntow, 2005), as this could invariable affect growth performance of cultured fish. According to Healey *et al.* (2016), an efficient aquaculture system not only limits its own environmental impact but it also helps repair the overfished oceans and lakes, and by making sure it is run properly it can be beneficial for the environment. The proper use of quality fish feed using appropriate feeding rates for a given fish species in a well-designed aquaculture system can minimize nutrient discharges by 50% (Miller and Semmens, 2002).

Site selection should not only be limited to water quality. There are many criteria or factors that determines the suitability of a proposed site; thus, the quality of water should not be the only indicator. Suitable zones must be able to deal with environmental, economic and social changes in view of water-user conflicts for sustainable aquaculture. The use of GIS for project management and as a tool for decision-making in aquaculture; can allow for more effective and proactive development, with strong dependence on the natural environment for success (Brandt, 2017). The use of GIS technology as a decision support tool, could be useful or efficient but probably expensive and require some skills to be used. Economically, application of GIS-models in aquaculture may not guarantee success unless it leads to a return in investment in a sustainable way at a proposed location.

For spatial planning of aquaculture, all aquaculture species have specific biological needs for dissolved oxygen, temperature and other good water quality thresholds that have to be satisfied to secure high production and to minimize stress and disease (Aguilar-Manjarrez *et al.*, 2017). A thorough analysis shows that the ecological threat of aquaculture is much lower compared to the trend of continuing to supply the majority of fish protein from wild capture (Tidwell and Allan, 2001).

2.2.2 Economic and Financial effects

Aquaculture could provide some economic benefits and financial reward or loss as expected in all agriculture production systems. Fish production can enhance the economic growth and generate wealth for riparian communities (Béné, 2006). There are over 200 million people in the world that derive direct and indirect income from fish (Tidwell and Allan, 2001). Due to the development of aquaculture globally, the number of fish farmers involved in the sector had tripled since the year 2000 from 6.1 million to 18.7 million (FAO, 2016b). Aquaculture production is worth around EUR 150 billion, of which around EUR 94 billion is from finfish, EUR 22 billion is from shellfish and EUR 5 billion from seaweeds (DEVCO-AFD-GIZ, 2017).

Input for fish production includes the fish production system (i.e. holding facilities such as cage, pond, raceway, tank, hapa), fish seed or fry, fish feed, fertilizer or manure, agriculture lime, equipment for sampling for feeding rate and growth analysis (weighing scales, scoop nets, bowls), tools for harvesting (various sizes and types of nets, graders and sorting tables), cost of labour, cost of energy/power supply and administrative cost. Thus, the initial investment cost for aquaculture development could be high. Although, cost of fish feed is high, fish has higher feed conversion rate compared to all common commercial livestock, as fish will readily consume feeds that are unpalatable or cannot be digested by most land animals (Kigeya, 1995). For cage culture, cost of various nets such as production nets, inner nets, protective nets and other harvesting technologies could be potentially high cost which needs to be considered (Jagger and Pender, 2001).

In countries like Rwanda, labour cost for aquaculture is relatively high compared to other land uses, although fish farming was the most profitable activity in terms of income above variable cost and net returns to land, labor and capital for fish ponds of 1 hectare or less (US$2118/ha/year for fish as compared with $141/ha/year for cassava), when the opportunity cost of family labor was accounted for in the analysis, fish farming became the least profitable of land uses (US$- 1424/ha/year and US$-847/ha/year for fish and cassava respectively) (Hishamunda *et al.*, 1998). Thus, the availability and cost of appropriate labour could affects investment for aquaculture development. Due to low labour mobility, ethnic heterogeneity and limited awareness of wage rate differences across regions, rural Uganda lacks a well-developed labor market, making labor scarce and costly in some places, and relatively cheap and abundant in others (Sserunkumma *et al.*, 2000). This situation is no different for Ghana’s aquaculture production hub, i.e. Eastern Region.

In Northern Ghana, livelihoods and income status of fisher-households were reported to be higher compared to non-fisher households (Abache, 2014; Alhassan *et al.*, 2018). The per capita income of fishers and fishmongers for Tono reservoir in the Upper East Region of Ghana was GH¢0.90 to GH¢8.60/person/day (equivalent to US$0.45 to US$4.30) from an annual average production of 61.2 metric tonnes from capture fisheries (Abache, 2014).

Aquaculture development is a capital-intensive venture, as capital is an essential tool for investment and is necessary for the commercialization and intensification of aquaculture (Brummet, 1995). However, fish farming can be a lucrative supplement to off-farm employment income if sufficient family labor is available to manage the fish ponds while other family members work off farm (Jagger and Pender, 2001).

2.2.3 Marketing issues

Marketing of fish is purported to be demand driven. A good understanding of consumer demand and supply could aid fish marketing as reiterated by studies in Uganda (KiremaMakusa and Reynolds, 1993). The demand for fish is projected to increase but Africa is lacking behind with supply from aquaculture to feed her increasing population (WorldFish, 2010a).

Most farmed fish are sold fresh at the farm gate, either through fish mongers or fish marketing merchants after harvesting. For cage culture of tilapia, most fish farmers prefer sale of the entire cage fish at a pre-determined and agreed price to wholesalers for cash. However, three channels have been established for marketing of fish by fish farmers (Rahman *et al.*, 2013). These channels are;

Channel I: Fish farmer → Consumer

Channel II: Fish farmer → Petty trader/Retailer → Consumer

Channel III: Fish farmer → Wholesaler → Retailer → Consumer

In Ghana, about 75 percent of farms sells fish at the farm gate with 13 percent selling at both farmgate and local market; of which prices are determined by large scale (big farms) who have marketing outlets in major towns and cities (Karikari and Asmah, 2016). These authors further stated the various marketing sizes for Nile tilapia as; size 3 (700-1000 g), size 2 (500 - 700 g), size 1 (300 - 500 g), regular (200 - 300 g), economy (150 - 200 g), school boys (<150 g). These marketing size categories seem to vary slightly from farm to farm, although prices are almost the same as most fish farmers compare prices from farm to farm to peg their prices in per kilogramme of fish.

Aquaculture has been successful in situations in which domestic markets, resources, and available technologies have combined to promote steady and substantial growth, as in Egypt and Nigeria (World Bank, 2007). Extrapolating knowledge from the health benefits of nutrients found in fish including n-3 polyunsaturated fatty acids (PUFAs), and claims that antioxidants and other substances are found in fish as against negative effects of some contaminants such as methylmercury and dioxins (Astley, 2003; Gunnarsson *et al.*, 2006), could be used for promotion and marketing of healthy farmed fish from aquaculture.

2.2.4 Socio-cultural challenges of aquaculture development

Some traditional norms and belief systems such as fishing norms, taboo and customs may help protect or destroy aquaculture investment. There are negative (theft, poaching, vandalization of cages) and positive (good neighborliness, hospitality) behaviours that could impact aquaculture development. Poaching is endemic across inland capture fisheries and aquaculture sectors in the central Asian regions (Thorpe *et al*., 2011), this situation is not different for Ghana. Compared to the capital-intensive aquaculture enterprises, where a good part of the profit goes to the investors, development of open water fisheries is highly labour-intensive (but risky due to poaching), although having the potential to provide gainful employment to the weaker sections (Sugunan, 1995). The interaction of aquaculture with stakeholders from other sectors can be synergistic, neutral or conflictual; for instance, if poorly managed aquaculture pollutes a water body, it imposes cost in terms of human health, restoration or finding an alternative source of clean water (FAO, 2010). If identification and consultation of relevant stakeholders are not done to address different issues properly (Aguilar-Manjarrez *et. al*., 2010), some socio-cultural issues could fester community relationship for sustainable aquaculture development.

2.3 Theoretical framework for sustainable aquaculture development

The ecosystem approach to aquaculture (EAA) is opined as principles that provides clear mechanisms for producers and government authorities to engage with one another for the effective and sustainable management of aquaculture operations and requires them to simultaneously embrace the environmental, socio-economic and governance objectives of the sector (Brugère, *et al.* 2018). EAA touches on inseparable planning and management issues and uniquely captures interactions between aquaculture and capture fisheries at multiple scales (Soto *et al.* 2012 a,b cited in Brugére *et al.*, 2018). An ecosystem approach to aquaculture (EAA) is a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems (FAO, 2010). Aquaculture must meet social, economic and environmental factors to be sustainable within the ecosystem (Barg and Philips, 1997). The Ecosystem approach to aquaculture (EAA) provides such integration. This approach that integrates all services for effective management decision, hinges on three principles which govern the implementation of the EAA (Aguilar-Manjarrez *et al.*, 2017) as follows:

(i) Aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience.

(ii) Aquaculture should improve human well-being with equity for all relevant stakeholders (e.g. access rights and fair share of incomes).

(iii) Aquaculture should be developed in the context of other sectors, policies and goals, as appropriate

The application of EAA had helped solved a number of real-world aquaculture situation with positive outcomes. For example, in Malawi, Nicaragua and Turkey, key stakeholders, including government, changed their way of planning by considering environmental, socio-economic and governance objectives and by better understanding the trade-offs that occur between different spatial and temporal scales (Brugére *et al.*, 2018). In Central America, a roadmap for the implementation of the ecosystem approach to shrimp fisheries and aquaculture has been prepared to strengthen fisheries and aquaculture planning, resource allocation and management (Gumy *et al.*, 2014).

However, there also seems to be some ambiguity regarding what the EAA means in practice: on the one hand, it is seen as an umbrella encompassing a number of 'tools' (aquaculture assessment tools (AATs)) to support the planning and management of the sector's development; on the other hand, it is seen as a tool itself (Brugére *et al.*, 2018). In spite of these ambiguity in EAA, its unequivocal that EAA is better compared to the conventional approach or the precautionary approach to environmental management of resources. Comparatively, the EAA is participatory, better suited to achieve multiple objectives, interact with other sectors, applicable at multiple (nested) scales, adaptive not just predictive, uses extended knowledge including scientific knowledge, incentives and allows public engagement and transparency

(FAO, 2010). Achieving sustainable food production, rural development, integrated water resource management and fair food supply chains will depend primarily upon improved policy, planning, regulation and implementing institutions – the critical issues faced by aquaculture development itself (Hambrey, 2017 cited in Brugére *et al.,* 2018).

2.4 Conceptual approach using spatial planning tools for aquaculture development

Spatial planning tools such as Geographical Information systems (GIS), remote sensing and mapping for data management, analysis, modelling and decision making are integral for multisectoral development and management of aquaculture (FAO, 2010). Geographical Information systems (GIS) can be used as a single decision support tool for spatial modelling for aquaculture, by allowing different environmental, socio-economic, infrastructural variable among other data sets to be spatially analysed (Nath *et al.*, 2000). The use of spatial analysis models has been promoted for nearly a decade under the ecosystems approach to aquaculture (EAA) for development of fisheries and aquaculture (Soto *et al*., 2008; FAO, 2010).

The ease of culturing, and the economic and social values of Nile tilapia have warranted expansion of aquaculture. Nile tilapia has become the preferred species of choice for aquaculture in most Africa countries, with a global share of 5 percent among the top 10 cultural species in the world (FAO, 2016b). However, there seem to be no recourse for suitability of proposed sites for aquaculture development using empirical evidence and emerging technologies. Environmental, social and economic factors affect sustainable cage culture but these can be combined in a logical way from primary data and sub models, as GIS allows integration of sophisticated analytical tools for multi-site aquaculture planning and management for sustainable development (Falconer *et al.,* 2013).

In view of the various challenges to aquaculture development, the multi-criteria evaluation (MCE) model has been suggested as good alternative to solving very complex problems with quantifiable indicators for decision making in the spatial environment (Zucca *et al.,* 2008; Lin, 2010). Geographic information system (GIS) based spatial multi-criteria evaluation (SMCE) provides various approaches and techniques with more reliability and advantages (Aliyu and Ludin, 2015), than the Boolean or fuzzy classification techniques. According to Andalecio (2010), the importance of developing evaluation criteria (such as MCE model) and performance indicators (structural and functional elements used to judge the success of management) for project appraisal, habitat restoration, management programs, ecosystem approach, and sustainability assessment and management are well-recognized, thus, criteria and related indicators are often derived from their goals and objectives. Therefore, the application of spatial multi-criteria evaluation (SMCE), could provide better understanding for the sustainable development of aquaculture, for fishery regulators, aquaculture scientist, policy-makers and aquaculture interest groups, aquaculture producers, processors and marketers, along the aquaculture value-chain. For sustainable aquaculture, suitability studies could help aquaculture industry players to maximise reservoir potential and minimise wateruse conflicts, as well as promote social benefits (FAO, 2015b). Application of multi-criteria evaluation (MCE) methods are widely used in natural resource management decision problems, its application to aquaculture is emerging, although other sectors have best-known examples found in the reviews of Romero and Rehman (1987) and Mardle and Pascoe (1999).

Issues of pollution from aquaculture can be minimised with the application of SMCE and GISbased software for identifying suitable sites through modeling. The application of GIS models in aquaculture planning and development is evolving (Yulius *et al.,* 2009; Falconer *et al.,* 2013; Nayak *et al.,* 2014; Wagdy and Kawi, 2015). Human activities such as poaching can be apprehended in the mariculture through the development and application of GIS-based software (Da Silva and Fulcher, 2006), such GIS-tools could be applicable in the inland freshwater cage culture systems to minimize theft, vandalism, and other societal risk involved in aquaculture production. However, tools to access the risk of aquaculture failure and escapes from aquaculture systems are rear, thus location tends to be assessed on relatively restricted spatial scale (Falconer *et al.,* 2013).

2.5 General characteristics and sustainable use of tropical reservoirs

Most reservoirs are public waters, thus the need for sustainable utilization of this water resource. Recent studies revealed that availability of small pelagic fishes steadily increased as a result of the creation of water bodies such as reservoirs in Africa, as reservoirs provide habitats for open water phytoplankton and zooplankton communities to establish pelagic fish growth (Kolding *et al.,* 2019). Similar study conducted indicates that, aquaculture in public waters and spaces, using net-tanks, pens or cages, are already the principal means of production of aquatic organisms in Asia, especially in rivers and reservoirs, with emphasis on China, Thailand, Cambodia and Vietnam (Bueno *et al.,* 2013).

A reservoir is a man-made ecosystem which is created when a dam is built on a river or a stream. Reservoirs may also be defined as man-made impoundments (of more than 10 ha) created by the obstruction of the surface flow by dams of any description on a river, stream or any water course (Sugunan, 1995). Another study states that, a reservoir is a water body contained by embankments or a dam, and subsequently managed in response to specific community needs; or any natural waters modified or managed to provide water for developing human activities and demands (Thornton *et al.*, 1996). For this study, the working definition of a reservoir is based on the above definition, whiles a "dam" refers to the physical structure.

Most reservoirs have vast areas which is not sustainably utilized, as in the case of over 3 million hectares of Indian reservoirs (Paul *et al.*, 2017). Although, reservoirs are an essential component of most irrigation systems worldwide and, together with those built for flood control and power generation, retain large volumes of water (Van Zwieten *et. al*., 2011), that can be exploited for aquaculture. Using reservoirs and other lentic water bodies such as lakes, China was able to produce 704,254 tonnes of aquatic organisms in 2005 (Chen e*t al*., 2007).

A reservoir may have co-existence of fluviatile (riverine) as well as lacustrine system, with transition system in the midstream of most reservoirs (Becker *et al.*, 2015). The river or stream water pack up behind the dam creates a reservoir which is used for various purposes. A reservoir is equipped with an outlet structure which is constructed with concrete or pipe. Most reservoirs have outlet structures called spill way. Smaller water storage systems (< 500 hectares) often referred as dugouts do not have outlet structure or spill ways. When water is retained in reservoirs they are made to go through a period of self-purification since sedimentation is allowed to take place. The water is then clear to some extent to be used for domestic purposes. Reservoirs hold water to prevent flooding when there is intense rainfall that can cause flooding to a community. Reservoirs commonly used for this purpose are called attenuation reservoirs and are used to prevent flooding of low-lying areas. They store water during periods with abnormally high rainfall and gradually release the water during periods of low rainfall. Therefore, spatial and temporal variability of water resources in Sub-Saharan Africa (SSA) is influencing agricultural development that can ultimately lead to food insecurity and poverty in the region (Anayah and Kaluarachchi, 2009).

Reservoirs can be used for various functionality and provision of ecosystem services. Due to growing populations and expanding economies, reservoirs are necessary for storage and transport of water, in order to cover the continuous, anthropogenic demand for water from the non-continuous, natural water supply, and to attain and preserve the fundamental human right for access to clean water (Nestmann and Stelzer, 2007).

Reservoir aid navigation of goods particularly agriculture products and passengers, for tourism, picnic or rituals activities and water sports. Thus, reservoirs hold water for domestic use, agricultural purposes (irrigation), industrial and/or religious use. These uses can be summaries as follows drinking and municipal water supply, industrial and cooling water supply, power generation, agricultural irrigation, river regulation and flood control, commercial and recreational fisheries, body contact recreation, boating, and other aesthetic recreational uses, navigation, canalisation, and waste disposal (Thornton *et al.*, 1996); or may serve as an environmental sink.

Reservoirs can also be used to hold water for the purposes of hydro-electric generation and for powering wind mills. Reservoirs for this purpose are equipped with turbines which generate the electricity. Reservoirs can be constructed for secondary purposes as recreation such as sailing, fishing and water skiing. For the purpose of fishery management, reservoirs are classified as small (< 1 000 ha), medium (1 000–5 000 ha) and large (> 5 000 ha), although different states provide slightly different classifications (Sugunan, 1995).

2.6 Reservoirs in Northern Ghana

Ghana has 755 reservoirs (dam) and 2,633 dugouts (non-perennial), out of which 22 formal irrigation schemes covering 8296.60 hectare are managed by Ghana Irrigation Development Authority (MoFA, 2009). Northern Ghana has over 359 reservoirs which are informal reservoirs (i.e. these were not built, managed or controlled by government agencies) with several dugouts in the three regions of the North of the country (Table 2.1). The major reservoirs (formal) which are also perennial in Northern Ghana are Sankana reservoir in the Upper West Region, Bontanga, Libga and Golinga in the Northern Region, and Tono and Vea reservoirs in the Upper East Region.

Tono and Vea reservoirs are among the largest man-made ecological water storage systems built across tributaries of the White Volta River, which is the second largest of the Volta's major sub-Basins. These reservoirs are considered as lentic water bodies that could support capture fisheries, irrigation for dry season crop farming, ruminant production (cattle, sheep, goat) and other domestic uses. Although fisheries in the Tono and Vea reservoirs had dwindled over the years, both reservoirs still support the livelihood of rural communities in its catchment (Okrah, 2010; Akongyuure *et al.*, 2017). As lentic water bodies, continuous water quality monitoring to understand the water quality changes over time and in space is needed for decision making relating to fish production. Thus, the major reservoirs in Northern Ghana could have great potential for both capture and culture fisheries (aquaculture) to support the socio-economic development of the Ghana.

Table 2.1 Area with number of informal reservoirs and dugouts in Northern Ghana (MoFA, 2009)

Region	Number of reservoirs	Number of dugouts	Total
Upper West	84	54	138
Upper East	147	129	276
Northern	128	398	526
Grand total	359	581	

2.7 Capture-based fisheries in tropical reservoirs

Although most reservoirs were built primarily for irrigation, soil conservation, flood control, domestic water supply and electricity generation, they also form important inland fisheries with substantial potential to increase output through improved management.

Total tilapia landings increased to 10 582 tonnes from 1966 to 1976, concomitant with the filling of the reservoir of the Akosombo dam and the increase in the number of fishing boats. In the next five years to 1981, landings increased to 30 529 tonnes, when the mean water level was kept at about 174 m and fishing effort was constant at 1 600 fishing boats (Kolding and van Zwieten, 2006). Thus, the water level was relatively high and considered suitable for tilapia reproduction. The high production could also result from the general fact that reservoirs have high production rates shortly after inundation (Kolding and van Zwieten, 2006).

Earlier report indicates that the tilapiines, *O. niloticus* and *S. galilaeus* (contributing about 85 percent of the total fish catch) inhabit shallow inshore areas that are profoundly affected by reservoir levels, a relationship can be expected between the total annual fish production and reservoir water level, particularly considering the large inter-annual fluctuations of 19 m between 1971 and 1996 and seasonal fluctuations of approximately 8 m in the reservoir section of the Akosombo dam (Ofori-Danson and Ntow, 2005). A significant relation that explained about 19 percent of the variation in anomalies was found between changes in water level and changes in total catch of tilapias with a lag of two years, meaning that the amplitude of annual change in water level appears to affect significantly the catch of tilapia two years later, as has also been described for Lake Kariba (Karenge and Kolding, 1995). An important caveat needs to be reiterated in relation to this analysis: the illegal unreported catches are assumed to be constant at about 50 percent, but more likely developed gradually from around the time that prices started to become fixed on the reservoir (van Zwieten *et al.,* 2011).

Reservoir fisheries enhancement methods using natural production basis in reservoirs vary with the size of the reservoirs. Mesh size and gear restrictions are among the most easily applied management regulations. Mesh size restriction involves regulation of the exploitation rate or the exploitation pattern through effort control and is practiced in Indian reservoirs during stocking programme. These regulations result in utilising maximum productivity of ecosystems by exploiting the small pelagics, or by fishing down the ecosystem or by reducing the predator masses (Jindal *et al.,* 2014). In Ghana, most reservoirs are re-stocked to enhance capture fisheries but to sustain it, fisher's community must adopt fishery enhancement strategy of maximising the output from the reservoirs by manipulating the mesh sizes of the gear used. This strategy is best suited for reservoirs managed under conservation strategy. Capture-based aquaculture, which is the practice of collecting 'seed' material from early life stages to adults from the wild, and on-growing these to marketable sizes using conventional aquaculture techniques (De Silva *et al.,* 2006) could also be practiced, if reservoir fisheries is not overexploited.

2.8 Cage culture and culture-based fisheries in reservoirs

Culture-based fisheries forms part of extensive aquaculture, or farming practice where small water bodies (< 100 hectares) are stocked with suitable species in pre-determined proportions, managed by ownership of stock (no supplementary/artificial feeding) and harvested when water recedes.

Fish catch from capture fisheries had dwindled over the years in most reservoirs and dugouts in Ghana due to over-exploitation, poor management, water pollution, and low water levels (Kwarfo-Apegyah *et al.,* 2008). Thus, the need for culture-based fisheries or aquaculture (cage, pen, pond, or tanks systems). Culture-based fisheries differ from traditional stock enhancement practices in large inland waters in that the group that manages the small water body will have ownership of the stock but in a large water body the fishery will have open access. Interventions using inland water bodies in China indicates that production from culture-based fishery in reservoirs is estimated to be 1,165,075 metric tonnes (from a total area of 1,567,971 ha), approximating 743 kg ha^{-1} $year^{-1}$, and which is reputed to have recorded a yearly growth of 52% from 1979 to 1997 (De Silva *et al*., 2003). Thus, culture-based fisheries are part of stock enhancement bordering on aquaculture (De Silva *et al.,* 2006). However, total capture fisheries for Ghana in 2018 was 46,601.17 metric tonnes declining from 86,268.00 metric tonnes in 2015 (MoFAD MTEF PBB, 2019), despite re-stocking of most of the reservoirs and dugouts between 2017-2018.

According to studies done by van Zwieten *et al.,* (2011), two possibilities exist to improve reservoir productivity: (i) introducing new species that are adapted to lake conditions; or (ii) stocking, of which almost all reservoirs in India are manage through some degree of stocking.

Introduction of new commercial fish species into reservoirs in India relation to the insufficiently utilized open water or pelagic area of reservoirs were done with fish species that were thought to be suitable. These fish species include freshwater herring (*Limnothrissa miodon*) from Lake Tanganyika, silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*), *Labeo* spp. (*Labeo rohita*) and tilapiine species (Paul *et. al.,* 2011). The later species, particularly Nile tilapia (*Oreochromis niloticus)* is the most widely used fish species for stocking most reservoirs in India as this species rarely migrate from its original habitat (van Zwieten *et. al.,* 2011). Pen and cage farming of fish in reservoirs are possible ways of increasing fish production for food security and socio-economic development in this era of blue revolution in aquaculture. Various studies have reported on the impact of cage culture or fish farming on reservoirs (Jia *et al.*, 2015; Alhassan, *et al*., 2018; ZaniboniFilho *et al.,* 2018). Few studies indicate that some reservoirs (Vea, Binaba) and dugouts in Northern Ghana could support Nile tilapia production in cages (Agbeko *et al.,* 2014a; Akongyuure *et al.,* 2015, Alhassan *et al.,* 2018). Tilapia production in reservoirs may require feeding with artificial or supplementary nutritionally balanced feed. Although caged Nile tilapia may obtain a few essential nutrients by filtering plankton from nutrient-rich waters, they still need a complete diet as if they were being cultured in food-free waters (Schmittou, 2006). Good feed and feeding enhances fish growth and survival, if appropriate stocking density is adhered.

2.9 Carrying capacity

The environmental carrying capacity (CC) or aquaculture carrying capacity and trophic status of any given water bodies needs to be known prior to its utilisation for cage culture. Under aquaculture CC, the total area available for cage farming would enable us to infer the total potential amount of production in cages for each reservoir; this could help set production targets with an incremental increase of production in a sustainable way. Eutrophication effects should be of great concern for utilisation of lentic water system such as lakes, reservoirs and dugouts for aquaculture. The Food and Agriculture organisation (FAO, 2010) proposed a strategy on "how it should be done" to ensure the sustainability of the aquaculture sector, known as the ecosystem approach to aquaculture (EAA). EAA is a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems (FAO, 2010). The EAA promotes spatial planning through aquaculture zoning, site selection, and the use of aquaculture management areas (AMAs) for the development of aquaculture (FAO and World Bank, 2015). The principal component of the EAA is carrying capacity; which is the level of resource use, both by humans or animals that can be sustained over the long term by the natural regenerative power of the environment (Asmah *et al.*, 2016). The lack of effective carrying capacity-based zonal planning represents a major risk to aquaculture producers and the entire value chain (Han and Immink, 2013). Thus, broader stakeholder consultation is required between fisher folks, aquaculture and fisheries scientist, fishery regulators and other related industry to collectively determine the aquaculture carrying capacity of a proposed suitable area or zone under EAA. The suitability technique postulated in this study based on the ecosystem approach to aquaculture (EAA) could be a pragmatic decision-making tool for up-scaling of the GIS-based SMCE methods for zonation and siting of cages in shallow reservoirs and other lentic water bodies for the development of aquaculture.

CHAPTER THREE

3. GENERAL MATERIALS AND METHODS

3.1 Study area

The study was conducted in Tono and Vea Reservoirs in the Upper East Region of Ghana. These reservoirs are among the major reservoirs of ecological and socio-economic importance in Ghana.

3.1.1 Profile of Tono reservoir

Tono reservoir is the largest reservoir in Upper East Region and in Northern Ghana as well. Tono reservoir is geographically located in the Kassena-Nankana Municipality of the Upper East Region of Ghana between Latitude $10^0$51'40'' and $10^0$54'30'' North and longitude $1^0$8'30'' and $1^0$10'50'' West (Figure 3.1). The reservoir which is near Navrongo is situated within the Guinea Savanna ecological zone, with a unimodal rainfall of 600-1000 mm of precipitation a year (Okrah, 2010). The vegetative cover around Tono reservoir is that of an open woodland savanna with shrubs and grasses (Abache, 2014). Woody tree species found around the reservoir are that of *Azadirachta indica* (Neem), *Adansonia digitata* (baobab), *Vitellaria paradoxa* (sheanut) and *Parkia biglobosa* (dawadawa trees).

The peak of the rainfall season is between August and September. Mean monthly atmospheric temperature fluctuates with maximum of 44 ^{o}C (hottest months of the year: March-April) and minimum of 10 ^{o}C recorded during the harmattan periods (December-February).

Tono reservoir was constructed for storage of water as part of an irrigation scheme that started in 1975 and was completed in 1985. The irrigation scheme was constructed by Taylor Woodraw International Limited (Aminini, 2019). The reservoir was constructed over River Tono, primarily to provide water for crop production on small scale and secondarily to support fish production using pond culture systems (ICOUR, 1995).

Water storage capacity of the Tono reservoir is 93 million cubic meters, out of which less than half can be used for irrigation of the irrigable lands (Dinye, 2013). The total length of the irrigable canal is about 42 km (Aminini, 2019). Currently, the irrigable lands of the reservoir are used for the production of rice, tomato, okra and for dry season (post-flood) vegetable cultivation of pepper (Plate 3.1) often in the littoral zone. Water flow for irrigation is by gravity through canals with night storage reservoirs located behind the dam (Figure 3.2, A). The irrigation scheme has an irrigation potential of 3,840 ha, out of which 2,490 ha is under irrigation.

Tono reservoir is under the management of Irrigation Company of Upper Region (ICOUR), with its head office within the Tono irrigation scheme (Figure 3.2, A). However, the fisheries resources mainly capture fisheries and few pond culture systems (downstream of the reservoir) are managed and regulated by the Fisheries Commission (FC) through the Ministry of Fisheries and Aquaculture Development (MoFAD). Tono capture fisheries is reported to be overfished, as a result of non-compliance in the use of the right fishing gear and methods, and due to the open access system being practiced and non-adherence for registration by the fishers (Okrah, 2010). During the study period, sizes of fish caught and number of fishes per fish landing per canoe was observed to be very small (< 30 individuals) and in some cases "no catch" was recorded as stated by some fishermen. Although, pond fish culture is re-gaining grounds around Tono reservoir, production levels are less than 20 tonnes (20,000 kg) of fish per annum (J. Ayamga, pers. comm., March 25, 2019). Fish species produced in these ponds are mainly Nile tilapia (*Oreochromis niloticus*) with less than 10% used for African catfish (*Clarias spp*.) farming. The sizes of fish ponds currently utilized for Nile tilapia production ranges between 20 m x 70 m and 15 m x 30 m.

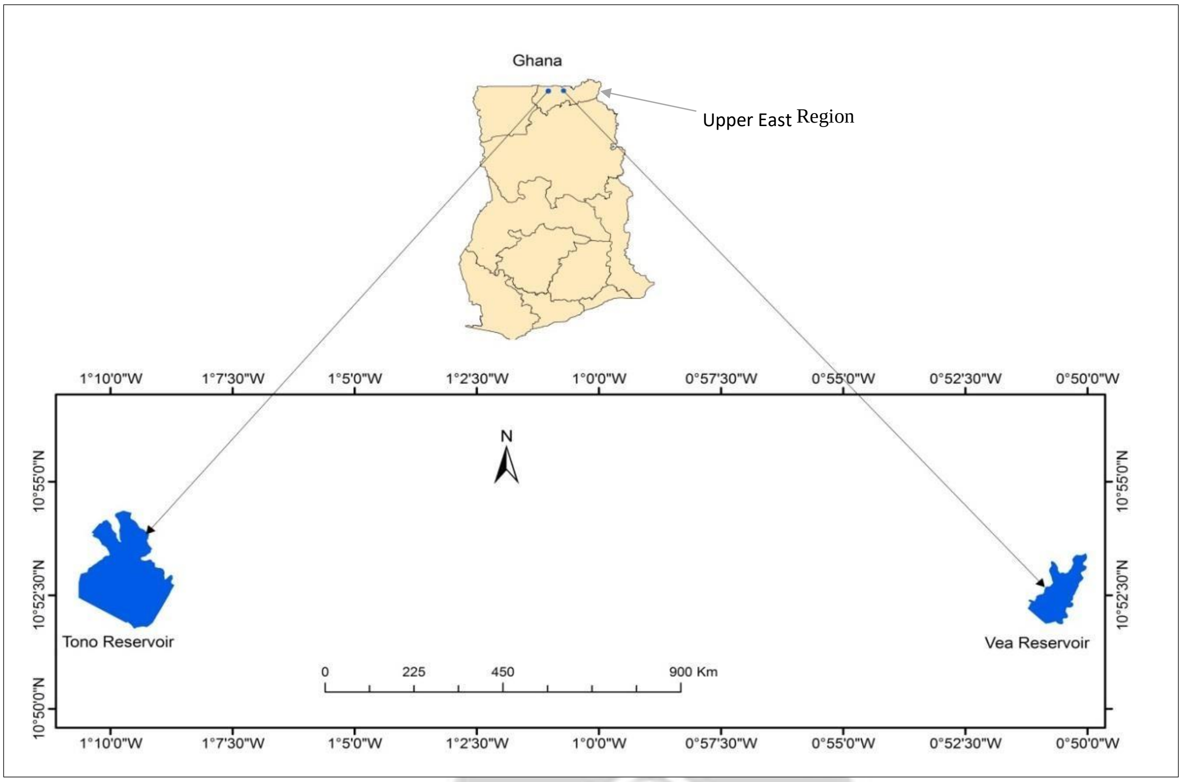

Figure 3.1 Location map showing Tono and Vea reservoirs in the Upper East Region, Ghana

3.1.2 Profile of Vea Reservoir

Vea reservoir is the second largest irrigation scheme in Upper East Region of Ghana. The reservoir is geographically located in Bongo District between latitude 10º 48` and 10º 56` North and 0º 44` and 0º 56` West (Figure 3.1). The vegetative cover around Vea reservoir is in the form of open woodland savanna with shrubs and grasses (Agbeko, 2012). Woody tree species found around the reservoir are that of *Azadirachta indica* (Neem), *Adansonia digitata* (Baobab), *Parkia biglobosa* (Dawadawa), *Vitellaria paradoxa* (sheanut) and some plantation of *Eucalyptus sp.* (Eucalyptus trees) along the banks of the reservoir.

Vea reservoir is near Bolgatanga (15 km) and situated within the Guinea Savanna ecological zone, with a unimodal rainfall of ranging between 600 mm and 1000 mm of precipitation a year. The peak of the rainfall season is between August and September, within which 79% of the total annual rainfall occurs (Amisigo *et al.*, 2011). Mean monthly maximum and minimum atmospheric temperature of 40 ºC and 12 ºC were recorded. Relative humidity is in the range of 20-30% in the dry season but averages about 80% in the wet season (Amisigo *et al.*, 2011).

Vea reservoir was constructed across river Yarigatanga, a tributary of White Volta River. Construction of the reservoir started in 1965 and was completed in 1980. The reservoir has a catchment area of 136 km^2, maximum lake surface area of 405 hectares, maximum storage of 17 x 10^6 m^3, live storage of 16 x 10^6 m^3, dead storage of 1 x 10^6 m^3, and crest length of 1585 m. The reservoir has two main canals (the right bank and the left bank canals) and a concrete spillway by the dam (Figure 3.2, B). The right bank canal is 9 km long and has 30 laterals that channels water from the main canals to irrigated fields. The left bank canal is 12 km long and has 31 laterals. Though it has a gross project area of 1,197 hectares, only 650 hectares is under cultivation.

Vea reservoir is also managed by Irrigation Company of Upper Region (ICOUR). Ministry of Fisheries and Aquaculture Development (MoFAD) manages the reservoir fisheries and ponds for aquaculture and integrated agriculture-aquaculture (IAA) farming such as rice-fish culture within the Vea irrigation scheme (Figure 3.2). The reservoir fisheries in Vea could be overexploited compared to Tono reservoir as relatively smaller sizes and weight (< 12 cm, < 50g) of fish (particularly tilapiine) and fewer catches (< 30 individuals) of fish were observed from the fish landing per canoe by fishers during the study. Vea reservoir is considered a multipurpose reservoir (Ampadu *et al.*, 2015), as it has several uses. Current uses of the reservoir are for water abstracting for potable water-supply by the Ghana Water Company, for irrigation of crops such as rice, tomatoes, garden eggs, okra, and pepper, and for capture fisheries. However, it was observed during this study that few ponds located downstream of the reservoir are being utilized for fish production and integrated agriculture-aquaculture. Fish species cultured in these ponds were` mainly Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias spp*).

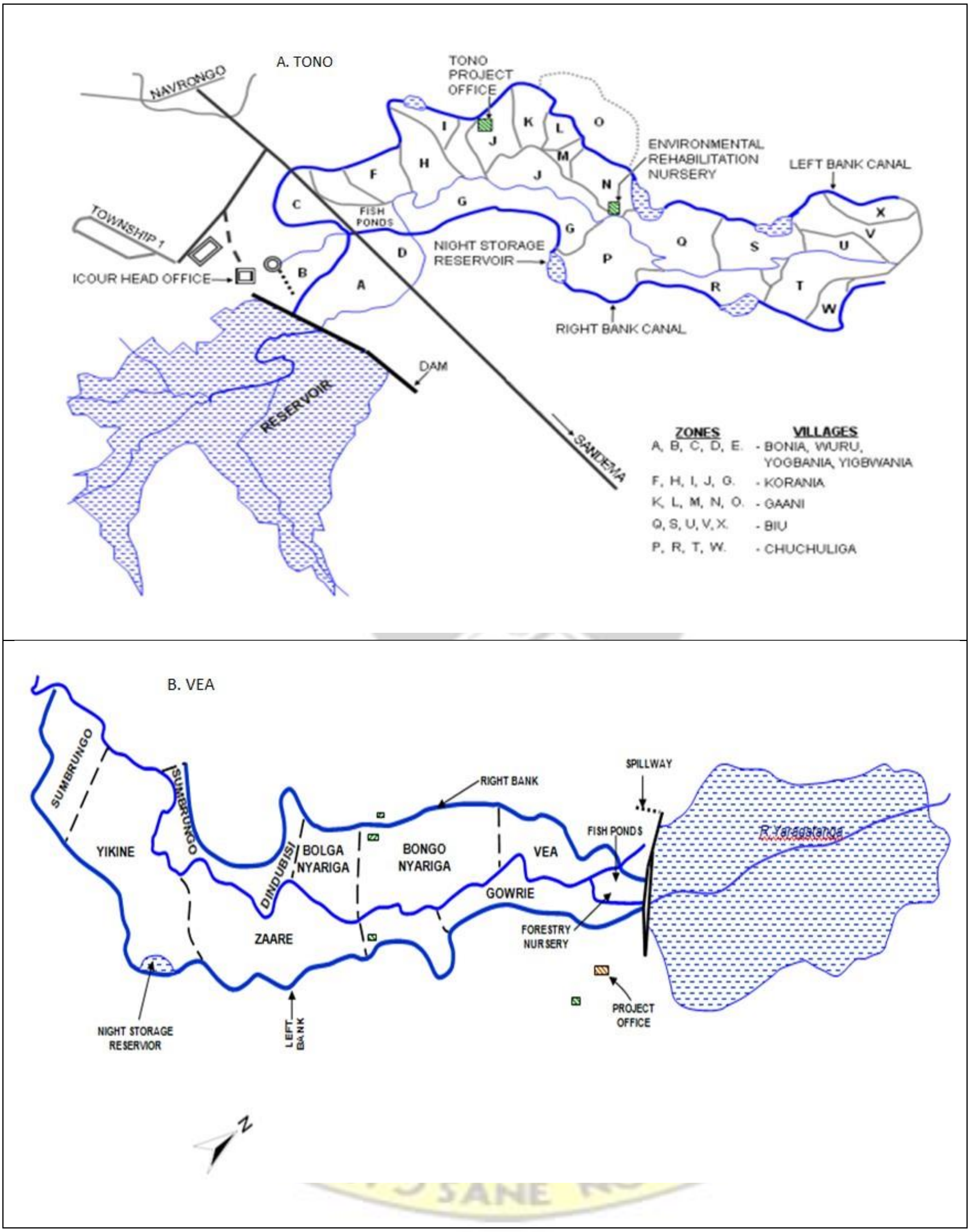

Figure 3.2 Features of Tono (A) and Vea (B) reservoirs with irrigation scheme (Source: DREF, 2014)

Plate 3.1 Post-flood vegetable cultivation within littoral sections of the East bank of Tono reservoir (January, 2016)

3.2 Data collection and preparations

Data acquisition was from primary and secondary sources relating to Tono and Vea reservoirs in the Upper East Region of Ghana. Materials to monitor the physical, chemical and biological attributes of Tono and Vea reservoirs for limnological studies and modelling for Nile tilapia cage culture development were deployed (Plate 3.2).

Plate 3.2 Water quality monitoring at a sampling station on the reservoir during the study

3.2.1 Water quality sampling and field measurements/observations

Primary data was obtained from field measurements and direct field observations within the reservoir and on the catchment areas. Water quality monitoring from the reservoir served as the primary data for the studies (Plate 3.2). Direct field observation was through transact walk and photo survey to ascertain anthropogenic activities within the catchment areas of Tono and Vea reservoirs.

Water samples for determination of water quality were collected monthly in the morning between 06:00 to 10:00 from February 2015 to April 2016 using linear stratified sampling technique (thus, zoning the reservoir into strata) with three replicates (i.e. three samples were taken from each zone). Stratification in the reservoirs was based on the direction of water flow for sampling purposes, namely; upstream (us), midstream (ms) and down streams (ds). Each reservoir had nine sampling stations for water quality monitoring. That is, a total of nine sampling stations in each reservoir. However, in January, 2016, additional representative sampling was done to cover more sections of the reservoir purposively for suitability studies (i.e. to obtain the suitable zone). Therefore, the sampling stations monitored in January, 2016 were twenty-seven (27) for Tono reservoir and nineteen (19) for Vea reservoir.

For determination of the reservoir water quality, *in situ* measurement of water temperature (TEM), atmospheric temperature and pH was done using combined portable meter (Hanna HI 83141), conductivity (CON) using Hanna HI 8733 portable meter, and transparency (TRA) in terms of Secchi disc depth (SDD) was measured using metric tape and Secchi disc, respectively on site. Water depth (WD) was measured using metric rope with weight attached.

Water samples for further laboratory analysis of the reservoir water quality were collected into the 1000 ml high density polyethylene (HDPE) bottles, which were pre-washed with dilute hydrochloric acid (10%) and re-washed three times on-site with the reservoir water before sampling. Water samples were collected at mid-depth (0.5-1.5 m). Physical parameters that were determined from the samples includes total dissolved solids (TDS), turbidity (TUR.), chloride (CL^-.), alkalinity (ALK.), total hardness (T.HAR), sulphate (SO_4^{2-}), phosphatephosphorus (PO_4^{2-}), silicon dioxide (SiO_2), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), and ammonium-nitrogen (NH_4-N). All samples were analysed based on recommended standard methods for analysis of water quality as detailed in section 3.4. For the dissolved oxygen (DO) sampling, clean re-washed 300 ml dark bottles were carefully used to collect water samples. The DO samples were immediately fixed with one (1) ml divalent magnesium sulphate and one (1) ml of alkali-iodide-azide to retain the oxygen in the sample, before transportation and laboratory analysis using the Azide modification of Winkler method (APHA, 1998).

For hdyro-biological sampling, chlorophyll-a (CHL-a) samples were collected into 500 ml bottles covered with black plastic sheets and stored in the dark in a cool ice box (4°C) to prevent deterioration of the chlorophyll pigment in sunlight or any light source. A plankton sampling net was towed horizontally to filter the water through the plankton mesh net over distance of 50 m for each stratum (upstream, midstream and downstream) to collect phytoplankton samples. Phytoplankton samples were fixed with Lugol's solution and formalin (about 4 drops to 250 ml).

Other laboratory reagents (chemicals) were also used to fix samples in the field and for laboratory analysis of water samples taken for water quality analysis (section 3.4). Life jacket as a buoyancy aid were used to enhance field safety during sampling on the reservoirs (Plate

3.2). Reservoir boundaries were delineated from Google map to determine the reservoir boundaries, prior to first sampling (February, 2015) and another map in January, 2016. The later map was adopted for suitability studies and development of aquaculture management areas as water quality was observed as unfavourable (i.e. worst-case scenario) for aquaculture based on the temporal water quality conditions from field data collected (Appendix I and II).

All samples were stored in cool box or "ice chest" (insulation boxes) chilling to 4°C to minimize temperature effects and microbiological decomposition of solids in samples during transportation before laboratory analyses. All samples were transported within 24 hours to CSIR-Water Research Institute (WRI) Environmental Chemistry Laboratory in Tamale for analysis, while phytoplankton analysis was conducted at the CSIR-WRI hydrobiology laboratory in Accra, Ghana. In all, eighteen (18) water quality variables were monitored, out of which fifteen (15) variables were selected for suitability studies due to their relative importance for Nile tilapia cage culture (WRC 2003; Radiarta *et al.* 2008; Thilza and Muhammad, 2010).

3.2.2 Secondary Data for modelling cage aquaculture development

Secondary data was obtained on water quality conditions, growth performance for Nile tilapia culture, reservoir physical characteristics including recharge and water storage capacity (for 2015/2016), location of fish landing sites and major navigation routes. The ecological, social and economic impact of cage culture on the reservoir were collated as stated in Table 3.2. These data (Table 3.2) were obtained from published journals, students' thesis, institutional reports and technical papers as literature review for the secondary data.

Table 3.2. Primary and secondary data considered for the studies on Tono and Vea Reservoirs in the Upper East Region, Ghana

Data criteria	Interpretation of criteria	Data source (s)
Ecological factors	Favourable water quality values	WRC, 2003
Fish growth	Indicate tilapia growth performance	Alhassan *et al.* 2018
Bathymetry	Favorable depth for mooring cage	ICOUR
Social– infrastructural	Distance to town/link roads	ICOUR/FC/FO
Distance to piers	Fish landing site	FC/Fishermen/FO
Distance to land-based facility	Support services/offices	ICOUR/FC
Town/industrial	View shed and pollution	ICOUR/FC Stream
mouth	Water pollution/suspended matter supply	ICOUR/FO

ICOUR: Irrigation Company of Upper Region, FC: Fisheries Commission, FO: Field observation

3.[1] Methods for determination of water quality variables

In the laboratory, physico-chemical and hydro-biological analysis of water samples were done according to recommended standard methods for water quality analysis. These methods used stated below.

[1] .3.1 Determination of Dissolved Oxygen (DO), Turbidity, Alkalinity, Total Dissolved Solid (TDS) and Total Hardness

Determination of dissolved oxygen was by the Azide modification of Winkler method (APHA 1998). Exactly, 2 ml of manganous sulphate ($MnSO_4$) (Winkler 1 solution) and 2 ml of Akali –iodide Azide were added to each of the collected sample in the bottle. It was corked and swirled gently to mix. The sample was left to stand for a few minutes, and then 2 ml of concentrated H_2SO_4 was added to it. The mixture was corked and swirled gently. Hundred (100) ml of the above sample was measured using a measuring cylinder into a flask and titrated against a 0.0125 M sodium thiosulphate ($Na_2S_2O_3$) solution (Burette). At a peel yellow colour, 2 g of dissolved laboratory-grade soluble starch was added as the indicator, after a blue-black

Turbidity was determined with a turbidimeter (HACH 2100P) using distilled water as a blank. The conductivity meter was used to determinate the total dissolved solids (TDS) levels through a Gravimetric method.

For alkalinity, strong acid titration (visual titration using indicators) as described by APHA (1995) was used. Sampled water of 200 ml was used since alkalinity value obtained in preliminary samples was low in the reservoirs (i.e. < 100 mg l^{-1}). The sample was mixed with three drops of phenolphthalein indicator. If the sample turns orange without the addition of acid, the total alkalinity is zero. When the sample turns pink or red, the sample was titrated against a sulfuric acid until the pink colour just disappears. The determination was continue using the sample to which phenolphthalein had been added by adding 3 drops of methyl orange indicator. When the sample turned orange without the addition of acid, the total alkalinity was noted as zero. But when the sample turned yellow, titration continued with standard acid until the first perceptible colour change towards orange was detected as the end-point. Hydroxyl ions present in a sample as a result of dissociation or hydrolysis of solute react with additions of standard acid. Alkalinity thus depends on the end-point pH used. Titration to the end point of pH 8.3 determined the phenolphthalein alkalinity (P); titration to the end point of pH 4.5 gave the total (methyl orange) alkalinity (T). The end point of pH 4.5 indicated by the methyl orange gave the accurate result for the alkalinity.

For total hardness, the Ethylene diamine tetra-acetic acid (EDTA) titration was performed. For that 50 ml of sample water was poured into a conical flask and 0.1 – 0.2 g crystals of Eriochrome black T was added as indicator. The purple colour titrate were mixed constantly until the last trace of purple colour disappeared, turning into light blue colour for the end point of the titration and values determined as described by APHA (1995). Laboratory analysis were completed within one (1) week after sampling and low levels (less than 5 mg L^{-1}) of total hardness were not obtained during the study.

3.3.2 Determination of nutrient levels in water column

Nutrients levels of the reservoir in the samples taken were determined by filtering 1000 ml (1 litre) of the samples through Whatman GF/C (0.45 µm pore size) filter paper for analysis of

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colour developed the mixture was titrated to a colorless endpoint by dropping carefully at this point, the sodium thiosulphate ($Na_2S_2O_3$).

dissolved inorganic nutrients. The nutrients and methods used for determination varied. Ammonia-nitrogen (NH_4 –N) was determined by direct nesslerization method, nitrite – nitrogen (NO_2-N) was determined by diazotization method, nitrate – nitrogen (NO_3-N was determined by hydrazine reduction method, and phosphate (PO_4-P) was determined by Stannous Chloride Method. The above nutrients were determined by the colorimetric analysis following procedures stated in standard methods for the examination of water and wastewater (APHA, AWWA, WEF, 2012). Sulphate (SO_4^{2-}) was determined by the turbidimetric method as described by APHA, AWWA, WEF (1975). Chloride levels was determined by Titrimetric by Silver Nitrate method as described by Rohrbough *et al.* (1986).

3.3.3 Determination of biological variables in water column

For chlorophyll-a (as surrogate for primary production), was determined following the visible spectrophotometer method (APHA, 1998). A 1000 ml (1 litre) of the water sampled was filtered through Whatman GF/C (0.45 µm pore size) filter paper. The filter paper with the trapped phytoplankton was then placed in 90 ml of 90% aqueous acetone with 10 ml magnesium carbonate solution to prepare 100 ml of solution to extract the chlorophyll-a overnight and centrifuged at 3200 rpm for 10 minutes to obtain a clear extract. Chlorophyll-a levels were determined using a spectrophotometer with the 90% acetone as a blank. For instrument analysis, 4 ml of the supernatant from centrifugal processing was poured into cuvettes at measured at wavelengths of 663, 645, and 630 nm, extinction, respectively using PG Instruments T60 UV- Each extinction was corrected by a small turbidity blank by subtracting the 750 nm absorption from 663, 645, 630 nm absorptions. The chlorophyll-a values were obtained based on the following equations: Mg pigment / $m^3 = \frac{Ca \times Ve}{Vs \times L}$

Where, Ca = 11.64 (E663) – 2.16 (E645) + 0.1 (E630)

Vs = Volume of sample in litres

Ve = Volume of acetone in ml

L = Light path in centimetres of cell

From the final chlorophyll-a values, the phytoplankton biomass (PHY.B) was derived through estimation from the equation;

PHY.B = CHL-a x 67; based on (APHA, 1980).

Where the value 67; is a constant

Phytoplankton identification was by examination of water samples microscopically in counting chambers of 25 ml cuvette (1ml of sample: 24ml distilled water) with a slide cover under a Carl Zeiss inverted light microscope (BDS 300) as described by (Lund *et al*., 1958). Minimum settling time of 4 hours per every 1 cm height of sample in the chamber was observed (Wetzel and Liken, 1992). Sedimentation was carried out in tubular counting chambers (Outer diameter 47/42 mm), cell counts were made in duplicate and average cell counts per ml computed. Identification of algae taxa (phytoplankton) was aided with a guide to study of freshwater biology Needham *et al*., (1966) and the manual of algae species drawings for laboratoire D'Ichtyologie Museum National D'Histoire Naturelle, Paris (Sevrin-Reysec, 1988).

3.4 Statistical analysis and modelling approach

Different statistical analyses and modelling were performed based on each research objective. Descriptive analysis was performed using various statistical methods and modelling using GISbase spatial models as stated below for each objective.

For research objective one, multivariate statistical methods were used for the assessment of the reservoir water quality to explore similarities and identify patterns associated with water quality changes in Tono and Vea reservoirs. For the similarity measure, Cluster analysis using Ward's method **(**Bray-Curtis <30) was run in Community Analysis Package (CAP, Version 1.52) software. To obtain the important variables (most significant) that influence spatial variation in Tono and Vea reservoirs, Principal Component Analysis (PCA) was used to reduce the water quality parameter data set from initial eighteen (18) to six (6) water quality parameters using PAST analytical software, version 3.11. Correspondence Analysis (CoA) was performed to compare associations, as corresponding eigenvector with eigenvalues more than one or close to one were considered significant in obtaining new groups of factors, as recommended (Khalit *et al.* 2017). Factor Analysis (FA) was performed to explain variance in the dataset using XLSTAT software, version 2018. The variables that were considered for the water quality dataset were water temperature (TEM), pH, conductivity (CON), water depth (WD), transparency (TRA) in terms of Secchi depth (SDD), Dissolved Oxygen (DO), Total dissolved solid (TDS), Turbidity (TUR.), Chloride (CL^-.), Alkalinity (ALK.), Total Hardness (T.HAR), Sulphate (SO_4^{2-}), Phosphate-phosphorus (PO_4^{2-}), Silicon dioxide (SiO_2), NitrateNitrogen (NO_3-N), Nitrite-Nitrogen (NO_2-N), Ammonium-Nitrogen (NH_4-N), Chlorophyll-a (CHL-a) and phytoplankton obtained for Tono and Vea reservoirs during the study (from February 2015 to April 2016). These variables when statistically analyzed with the multivariate methods, as these methods served as important pattern recognition techniques (Jiang-Qi *et al*., 2013) for sustainable management of the reservoir water resources for aquaculture development.

For research objective two, GIS-based modelling for cage culture suitability was applied. Spatial multi-criteria evaluation (SMCE) was used to determine the suitability levels for cage culture in reservoirs Tono and Vea. From fifteen (15) water quality variables recommended as factors that influence the growth of Nile tilapia (WRC, 2003; Radiarta *et al.* 2008; Thilza and Muhammad, 2010), mean for field values were obtained and denoted as point 'z'. Field values for each factor (z) that influence the growth of tilapia at sampled locations (based on representative sampling, 27 and 19 stations on the Tono and Vea reservoir, respectively) i.e. 513 and 361 data points were exploited. Geographic coordinates of the sampled locations (X, Y) were taken within delineated boundary of each reservoir given the worst case-scenario period or season (i.e. In January, water quality was not good for aquaculture in the temporal water condition). These values were converted into a point shape file in ArcGIS (version 10.2) via ArcMap layer tool with computation in table attributes. For each sampled point, the measurement values for all 15 factors were populated. Inverse distance weighted (IDW) interpolation method was used to obtain measurement values for unknown areas for each factor. Interpolated outputs were exported to GIS-based software called ILWIS for a Spatial Multi-Criteria Evaluation (SMCE). The use of SMCE is highly promoted by Food and Agriculture Organization (FAO, 2008, 2013, 2014). ILWIS was most preferred for this analysis because it has a tool built purposely for spatial multi-criteria evaluation.

For research objective three, aquaculture carrying capacity (ACC) of Tono and Vea reservoirs were determined from four (4) types of carrying capacities (CC). Namely, data from the physical, production, ecological and social carrying capacities. Mean values from selected water quality parameters obtained from monthly water quality monitoring (February, 2015 to April, 2016) were used. An integrated approach derived from textual database (Schmittou, 2006) as recommended by Prema (2015), and other reservoir characteristics derived from secondary sources with reservoir water quality data were the factors considered for estimation. Spreadsheet computation was used for estimation of final aquaculture carrying capacity for both reservoirs. This integrated approach for estimation of ACC was selected for this study because the approach helps to minimise water pollution and water-user conflicts due to aquaculture development (Asmah, 2013; FAO, 2015a). Detailed statistical analysis for aquaculture carrying capacity are stated in chapter 4, sub-section 3.

For the final research objective, mean values from these water quality parameters: reservoir water depth, water transparency (Secchi disc depth), chlorophyll-a, nitrate-nitrogen, nitritenitrogen, ammonium-nitrogen and phosphorus concentration levels monitored for 15 months, were assess the eutrophication potential of Tono and Vea reservoirs. Thus, the trophic status of Tono and Vea reservoirs were estimated using a trophic level index (TLI) model according to Pavluk and bij de Vaate, 2017 and results were compared with Trophic Level thresholds. The TLI estimation as stated below, is more robust and reliable than the conventional estimation of trophic status using the Carlson index which has three independent variables (Lee and Liu, 2018). Thus, the trophic level index equation;

$$TLI = (TL_{nitrogen} + TL_{phosphorus} + TL_{transparency} + TL_{chlorophyll\text{-}a})/4$$

Where, TL: trophic level

Based on the trophic status obtained, direct (aquaculture carrying capacity, number of cages and annual production) and indirect (feed delivered to an aquaculture zone) measurements were performed. Social conflict as an indicator of local attitudes to management was inferred alongside other constraints. Areas suitable for aquaculture obtained from objective 2 were demarcated into clusters or zones called aquaculture management areas (AMAs) based on several factors. The factors considered during the demarcation for the development of AMAs in the Tono and Vea reservoirs were trophic status, aquaculture carrying capacity (from Objective 3), feed conversion rate (FCR) (Agbeko *et al.,* 2014a, Akongyuure *et al.,* 2015, Alhassan *et al.* 2018), stocking density (Veverica *et al.*, 2011), expected bulk fish weight or fish yield from cages and average weight of fish for the two reservoirs (estimated base on Schmittou, 2006).

3.5 Validation and verification of data source

Most of the data collated and results obtained were verified and validated through field observation and photo-layer comparison via informal interview with key-informants and fisher-folks with more than five (5) years working experience within the reservoirs, Fisheries Commission (FC) officers and Officers of Irrigation Company of Upper Region (ICOUR).

Further validation and verification were done for inference using secondary data from text books, published journal articles, technical reports and policy briefs from institutions or organizations.

CHAPTER FOUR

4. TOPICAL OR THEMATIC CHAPTER

4.1 Water Quality Status of Tono and Vea Reservoirs for Aquaculture Development

4.1.1 Introduction

Globally, the demand for fish has increased and fish farming has been proposed as the solution to meet the ever-increasing demand for fish whiles managing capture fisheries (Naylor, 2004; Omoare *et al.,* 2013). Despite having numerous inland fresh water bodies and/or coastal brackish or marine water resources, fish production in Africa had a steady growth, averaging 10.4% over the last one and half decades (FAO, 2017). However, reservoirs especially in Ghana could be harnessed to provide some comparative advantage since inland fisheries and aquaculture contribute only 30 percent of the total fish production (Aseidu *et al*., 2017). Aquaculture production in Ghana is mainly on the lake Volta. Small water bodies such as reservoirs and dugouts are often overlooked due to the quantity and quality of water within such systems. Water quality is one of the most important factors that affect fish health and performance in any aquaculture production system Towers, (2015) and for that matter cage culture. Poor water quality could lead to stunted fish growth, increase the incidence of diseases, and can cause high fish mortality. Changes in the composition and abundance of phytoplankton may impact the water quality status over the spatial-temporal scale (Lund *et al*., 1958). Deteriorated waters could lead to algal blooms which may produce cyanobacteria toxins that affects fish and other aquatic organisms (Qu *et al*., 2013; Karikari and Asmah, 2016). Some cyanobacteria release substances that affect the taste of fish produced due to off-flavour compounds that accumulates in the fish (Tucker, 2000). Water temperature and dissolved oxygen levels helps in determining the feeding rate per the percentage body weight of fish (Towers, 2015; Marimuthu *et al*., 2011). Thus, the first guiding principle for sustainable aquaculture is water quality. The use of physico-chemical properties of water to assess water quality give a good impression of the status, productivity and sustainability of such water bodies.

Currently, reservoirs, dugouts, and other small water bodies in semi-arid zones are being considered and exploited for aquaculture. Formerly, cages were mostly constructed and mounted on large water bodies such as lakes and rivers, but in recent times reservoirs purposely built for irrigation are utilized (FAO, 2017; Agbeko *et al*., 2014; Alhassan *et al.,* 2018). Culture-based fisheries in reservoirs is being promoted in countries such as Burkina Faso, Guinea, Madagascar, Malawi, Mali, Niger, Nigeria and Senegal to maximize water use efficiency (FAO, 2017).

Most reservoirs in northern Ghana were seldom used for cage culture. Although few studies recommended exploitation of these reservoirs for aquaculture (Agbeko, 2012; Agbeko *et al.*, 2014; Akongyuure *et al*., 2015), little was being done. Recent tilapia cage culture production in some reservoirs and dugouts (Datoko, Pusu-Namongo, Soe-Yidongo, Bon-Gurigu) yielded 19.5 metric tonnes of fish (Akpaglo, 2018 pers. comm.). Feasibility studies conducted in selected dugouts in the Bongo District of the Upper East Region, indicated that Nile tilapia culture can serve as an alternative livelihood for rural communities as the fish had good growth even in eutrophic waters (Alhassan *et al.,* 2018).

In order to increase fish production in reservoirs, intensification of tilapia cage culture on the Tono and Vea reservoirs in UER is envisaged. This could be based on successful cage culture production trials in some selected reservoirs and dugs in the UER from 2011-2015 (Agbeko *et al.,* 2014; Akongyuure *et al.,* 2015), coupled with the high demand by the populace for tilapia. Thus, Tono and Vea reservoirs earmarked for cage culture needs extensive water quality studies to understand the water quality dynamics as the first pragmatic step for prudent decision making on its water resources utilization and for sustainable aquaculture. The quality of culture water determines the growth, health and quality of fish produced. Water pollution could be exacerbated by aquaculture if the reservoir assimilative capacity is exceeded. Environmental occurrences i.e. drought and water pollution from industrial effluent from manufacturing companies, urban runoff, sewerage and agro-chemicals, which are threats to water quality cannot be understated. This is because fish are totally reliant on water. Tilapias are more tolerant than most commonly farmed freshwater fish to high salinity, high water temperature, low dissolved oxygen, and high ammonia concentrations (Popma and Masser, 1999). The state, feeding intensity and growth rate of fish is intensely affected by the physical and chemical situations of their environment. Hence, the need to have constant monitoring of the water quality. The aim of this study, was to determine the seasonal characteristics in terms of spatial variability and patterns in reservoir water quality. This could serve as baseline information for aquaculture development using the physico-chemical and biological attributes of the Tono and Vea reservoirs.

4.1.2 Materials and Methods

4.1.2.1 Study Area

The study was conducted on the Tono and Vea reservoirs in Upper East Region (UER), Ghana (Figure. 4.1.1). Tono and Vea Reservoirs are among the largest man-made water storage systems of ecological and socio-economic importance in the Sudan-savanna ecological zone of Northern Ghana. Tono Reservoir is located in the Kassena Nankana District between Latitude $10^0$51’40’’ and $10^0$54’30’’ North and longitude $1^0$8’30’’ and $1^0$10’50’’ West on River Tono, while Vea Reservoir is located between latitude 10^0 00’00’’ and $11^0$01’00’’ North and longitude $0^0$45’30’’and $0^0$56’30’’ West on River Yarigatanga in the Bongo District, UER. Tono and Vea reservoirs are irrigation schemes under the management of Irrigation Company of Upper Region (ICOUR) with irrigable areas of 2,490 and 468 hectares, respectively. As perennial reservoirs, water volume of 92.6 and 17 million cubic meters for Tono and Vea reservoirs was reported Okrah, (2010) with mean water depth < 10 meters in both reservoirs.

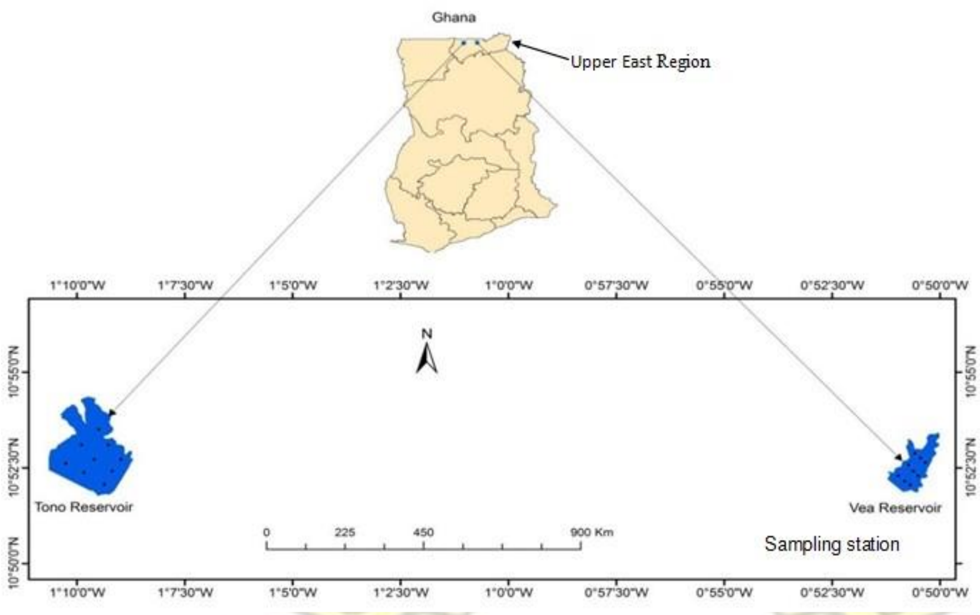


Figure. 4.1.1 Tono and Vea reservoirs in the Upper East Region, Ghana

These reservoirs were built for irrigation and livestock watering with few earthen ponds for rice and fish culture (ICOUR, 1995). It was noted that, the fish landing sites in Tono reservoir are known as bay, of which four (4) out of the five (5) of these fish landing sites are in use, whiles Vea reservoir had all three (3) fish landing sites in use. Both reservoirs are not directly exploited for culture fisheries (particularly cage aquaculture). Although, Tono and Vea reservoir fishery resources had dwindled over the years, it remains the hub for capture fisheries for Navrongo, Bolgatanga and other communities in the Upper East Region of Ghana. A large number of riparian communities and hundreds of people depend on these two major reservoirs for food, employment, income and livelihood (Abache, 2014).

4.1.2.2 Water Sampling and Quality Assurance

The Tono and Vea Reservoirs were divided into three sections based on the direction of water flow for sampling purposes, namely; Upstream (us), midstream (ms) and down streams (ds). Water samples were collected monthly from February 2015 to April 2016 (06:00 – 10:00) using linear stratified sampling technique with three replicates from each section. That is, a total of nine sampling stations on each reservoir. In-situ measurement of water temperature (TEM) and pH was done using Hanna HI 83141 portable meter, conductivity (CON) using Hanna HI 8733 portable meter; and water depth (WD) and transparency (TRA) in terms of Secchi depth (SDD) were measured using metric tape and Secchi disc, respectively on site. Water samples were collected into the 1000 ml high density polyethylene (HDPE) bottles, which were pre-washed with dilute hydrochloric acid (10%) and re-washed three times on-site with the reservoir water before sampling. Water samples were collected at mid-depth (0.5-1.5 m). The collected water samples were analyzed for dissolved oxygen (DO), Total dissolved solid (TDS), Turbidity (TUR.), Chloride (CL^-.), Alkalinity (ALK.), Total Hardness (T.HAR), Sulphate (SO_4^{2-}), Phosphate-phosphorus (PO_4^{2-}), Silicon dioxide (SiO_2), Nitrate-Nitrogen (NO_3-N), NitriteNitrogen (NO_2-N), Ammonium-Nitrogen (NH_4-N). For hdyro-biological samples, water samples for Chlorophyll-a (CHL-a) determination were collected into 500 ml bottles covered with black plastic sheets and stored in the dark in an insulated ice box to prevent deterioration of green chlorophyll pigment in sunlight. Plankton net was towed within each designated zone or strata to collect phytoplankton samples. Phytoplankton samples were fixed with acid lugol's solution and formalin (4 drops to 250 ml). All samples were stored in cool box or "ice chest" (insulation boxes) at 4°C to minimize temperature effects on samples during transportation for laboratory analyses. All samples were transported (< 24 hours) to CSIR-Water Research Institute's Laboratory in Tamale for analysis.

4.1.2.3 Laboratory Analysis

Standard protocols for water stabilization, storage and water quality analysis were followed according to standard analytical methods for examination of water and waste-water (APHA, 1998). Out of the 1000 ml of sampled water, 50 ml is utilized or an aliquot diluted to 50 ml is taken until preparation of standard are completed through titration and colour indicator methods (APHA, 1998). Except for phytoplankton samples, all other samples were kept in a refrigerator at 4°C until analyses were completed (approximately in 3 days).

Hydro-biological samples were analyzed to determine the algal chlorophyll a (CHL-a), phytoplankton phyla and phytoplankton biomass. Algal chlorophyll a (chlorophyll-a) was determined spectrophotometrically. Final chlorophyll-a values were calculated as recommended in (APHA, 1998). The phytoplankton biomass (PHY.B) was derived through estimation from the equation;

PHY.B = CHL-a x 67; based on (APHA, 1980).

The value 67; is a constant

Phytoplankton identification was by examination of water samples microscopically in counting chambers of 25 ml cuvette (1ml of sample: 24ml distilled water) with a slide cover under a Carl Zeiss inverted light microscope (BDS 300) as described by (Lund *et al.,* 1958). Minimum settling time of 4 hours per every 1 cm height of sample in the chamber was observed (Wetzel and Liken, 1992). Sedimentation was carried out in tubular counting Chambers (Outer diameter 47/42 mm), cell counts were made in duplicate and average cell counts per ml computed. Identification of algae taxa (phytoplankton) was aided with a guide to study of freshwater biology Needham *et al.,* (1966) and the manual of algae species drawings for laboratoire D'Ichtyologie Museum National D'Histoire Naturelle, Paris (Sevrin-Reysec, 1988).

4.1.2.4 Data Analysis

Multivariate statistical methods were employed to explore similarities and identify patterns associated with water quality changes in the reservoirs. Multivariate methods such as cluster analysis (CA), principal component analysis (PCA), correspondence analysis (CoA), discriminant analysis (DA), factor analysis (FA); provides important pattern recognition techniques for reliable management of water resources (Jiang-Qi et al., 2013). Thus, these analyses were conducted to elucidate the impact on water quality for aquaculture development in reservoirs.

In this study, cluster analysis (CA) using Ward's method and Bray-Curtis (B-C) similarity measure was run in Community Analysis Package (CAP, Version 1.52) software. During the analysis, transformation of data was performed using log base 10 to reduce the range of the data. Groups clustering at B-C <30% was employed to display similarity of samples across a wide range of scale with clusters to aid understanding of Tono and Vea Reservoirs' system response over temporal scale. Similarity was identified through the linkages between months represented by a tree diagram or dendrogram.

Paleontological statistics (PAST, version 3.11) software was employed to run a principal component analysis (PCA) on the physico-chemical parameters (environmental variables) and phytoplankton phylum distribution (biological variables) to detect spatial relationship among the variables. PCA was used to reduce the water quality parameter data set from initial eighteen (18) water quality parameters to obtain the important variables (most significant) that influence spatial variation in Tono and Vea reservoirs. Further PCA and FA statistical analysis were performed in XLSTAT version 2018 software to explain the variance obtained in the original dataset.

Correspondence Analysis (CoA) compared associations between phytoplankton phylum and most significant environmental variables at various zones (us, ms and ds) of the reservoirs for unimodal spatial response. In these analytical approaches, the less significant variables were omitted from the whole data set with a very minimum loss of its original information in the analysis. The percentages of similarity accounted for by the eigenvectors are provided. Thus, corresponding eigenvector with eigenvalues more than one or close to one are considered significant in obtaining new groups of factors, as recommended (Khalit *et al*., 2017). Results were presented in dendrograms, triplot charts, and tables and graphs using Microsoft Excel (2013).

4.1.3 Results

4.1.3.1 Water Quality Characteristic of Reservoir

Mean values and standard error of eighteen (18) water quality variables monitored in the Tono and Vea reservoirs are presented in Table 4.1.1. The monthly values of these water quality variables as obtained are stated in appendices I and II. During the study period, it was observed that the atmospheric temperature was 27 °C - 31.9 °C, while the dry season produced fluctuating atmospheric temperature of 15 °C – 44 °C, characterized with hazy winds during the harmattan period (December - Mid March). Both reservoirs had dissolved oxygen levels > 5 mg L^{-1}. The pH of the reservoir water was neutral, ranging between 7.74 - 7.56 and 7.92 - 7.82 for Tono and Vea Reservoirs, respectively. Total alkalinity recorded in both reservoirs were > 45 mg L^{-1}, with conductivity levels > 500 µs cm^{-1}. Tono reservoir had deeper water depth with mean water depth of 5.50 m compared to 3.65 m for Vea reservoir. Transparency of water in the reservoirs were 0.55 m (Tono reservoir) and 0.43 m (Vea reservoir) as velocity of water runoff and land use of reservoir watershed varied (Table 4.1.1). Using chlorophyll-a as a proxy for primary production indicates that Tono reservoir (1.37 mg m^{-3}) could have higher primary productivity than Vea reservoir (0.08 mg m^{-3}).

Table 4.1.1 Water quality parameters (Means ± S.E) monitored in Tono and Vea reservoirs in the Upper East Region of Ghana (Feb.2015-Apr.2016)

	Reservoir			
	Tono		**Vea**	
Parameters (Units)	**Means ± S. E**	**Range**	**Means ± S. E**	**Range**
TURB. (NTU)	147.06 ±24.17	327.60-38.50	157.73 ±33.52	371.00-14.17
W. TEMP (°C)	27.64 ±0.63	32.60-21.98	26.67 ±0.69	29.94-20.50
DO (mg/L)	8.66 ±0.45	13.40-6.78	7.64 ±0.26	10.08-6.79
Cl- (mg/L)	3.19 ±0.23	4.07-0.88	5.69 ±0.18	7.88-5.01
SO_4^{2-} (mg/L)	19.64 ±1.71	28.01-5.80	10.64 ±0.96	14.46-6.05
PO_4^{2-} (mg/L)	0.09 ±0.01	0.19-0.03	0.05 ±0.01	0.11-0.001
SiO_2 (mg/L)	18.36 ±2.55	29.85-4.40	9.17 ±0.97	15.49-2.99
NO_3-N (mg/L)	3.05 ±0.98	11.13-0.01	2.49 ±0.80	9.11-0.16
NO_2-N (mg/L)	0.26 ±0.08	1.05-0.01	0.03 ±0.004	0.06-0.01
NH_4-N (mg/L)	3.17 ±0.64	7.83-0.25	0.79 ±0.02	0.89-0.73
COND. (µs/cm)	742.65 ±55.69	1079.50-430.90	1025.15 ±30.22	1205.00-770.56
pH	7.74 - 7.56	8.70-6.50	7.92 - 7.82	8.30-6.86
SDD (m)	0.55 ±0.06	1.00-0.35	0.43 ±0.03	0.56-0.20
W. DEPTH (m)	5.50 ±0.56	8.90-3.22	3.66 ±0.25	5.43-2.45

ALK. (mg/L $CaCO_3$)	48.47 ±1.11	57.00-42.50	58.39 ±1.50	69.30-48.70
T.HAR. (mg/L)	66.45 ±0.73	71.46-63.37	68.067 ±1.91	80.15-53.33
CHL-a (mg/m^3)	1.37 ±0.04	1.74-1.21	0.061 ±0.003	0.08-0.05
PHYTO. Biomass	91.48 ±2.91	116.58-81.07	4.060 ±0.197	5.29-3.35

S.E: Standard Error; W: Water; T: Total; TURB: Turbidity; TEMP: Temperature; DO: Dissolved Oxygen; COND: Conductivity; SDD: Secchi Disc Depth; D: Depth; HAR: Hardness; CHL-a: Chlorophyll-a; PHYTO: Phytoplankton.

4.1.3.2 Temporal Characteristics of Reservoir Water Quality

The results of cluster analysis (CA) for the fifteen (15) months of sampling in Tono and Vea Reservoirs shows temporal similarity in groupings (Figure. 4.1.2) in water quality. Monthly groups clustering aided identification of seasonal changes in water quality parameters monitored in Tono and Vea Reservoirs. Bray-Curtis (B-C) similarity of clustering at < 30% (Figure. 4.1.2) used quantified the difference between samples on seasonal basis based on their relative counts, as four-clusters were formed with respect to temporal grouping of Tono reservoir: Cluster 1 – December 2015, November 2015, July 2015, May 2015 and June 2015; Cluster 2 – April 2016 and March 2016; Cluster 3 – October 2015, September 2015, and August 2015; Cluster 4 – February 2016, January 2016, April 2015, March 2015 and February 2015.

For Vea reservoir with respect to temporal grouping, groups clustering at B-C < 30% considered to exhibit similar community structure produced three-clusters (Figure. 4.1.2). These are: Cluster 1 – November 2015, October 2015, December 2015 and August 2015; Cluster 2 – September 2015, July 2015 and June 2015; Cluster 3-February 2016, May 2016, March 2016, April 2016, April 2015, January 2016, March 2015, and February 2015.

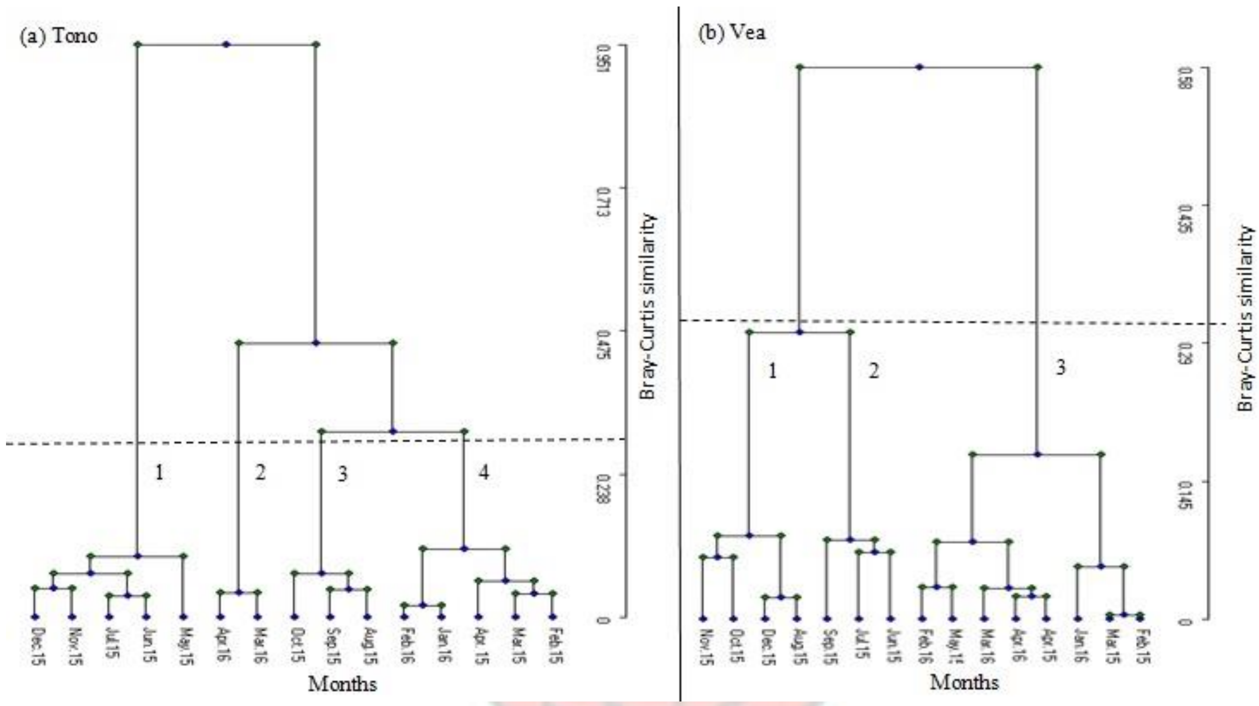


Figure. 4.1.2 Hierarchical dendrogram showing temporal variations (cluster analysis) of monitoring periods in (a) Tono reservoir and (b) Vea reservoir in the Upper East Region, Ghana. Ward's method, Bray – Curtis (b-c) similarity measure, groups clustering at b-c < 30% were considered to exhibit similar community structure

4.1.3.3 Spatial Characteristics of Environmental and Biological Variables

Pre-analysis of entire water quality dataset using Principal Component Analysis (PCA) was performed to obtain a correlation matrix of the eigenvalues plotted (Figure. 4.1.3). This plot called scree plot are eigenvalues associated with each of the factors extracted, against each other. That is, each eigenvalue corresponds to a factor, and each factor to a one dimension. Thus, at the point that the plot begins to level off, the additional factors explain less variance than a single variable.

For Tono reservoir, there were five factors with eigenvalues more than 1; F1: 6.370, F2: 4.397, F3: 2.559, F4: 1.398, F5: 1.163 (Figure. 4.1.3). The first five of the eigenvalues correspond to a high percentages of the variance, assuring us that the scree plot based on the first five factors are good quality projection of the initial multi-dimensional water quality structure. In the Figure. 4.1.3 below, the first five factors allow us to explain 88.26% of the initial variability of the data. This indicates a very good result (>50%). That is, eighteen water quality parameters were reduced to five (F1, F2, F3, F4, F5) factors.

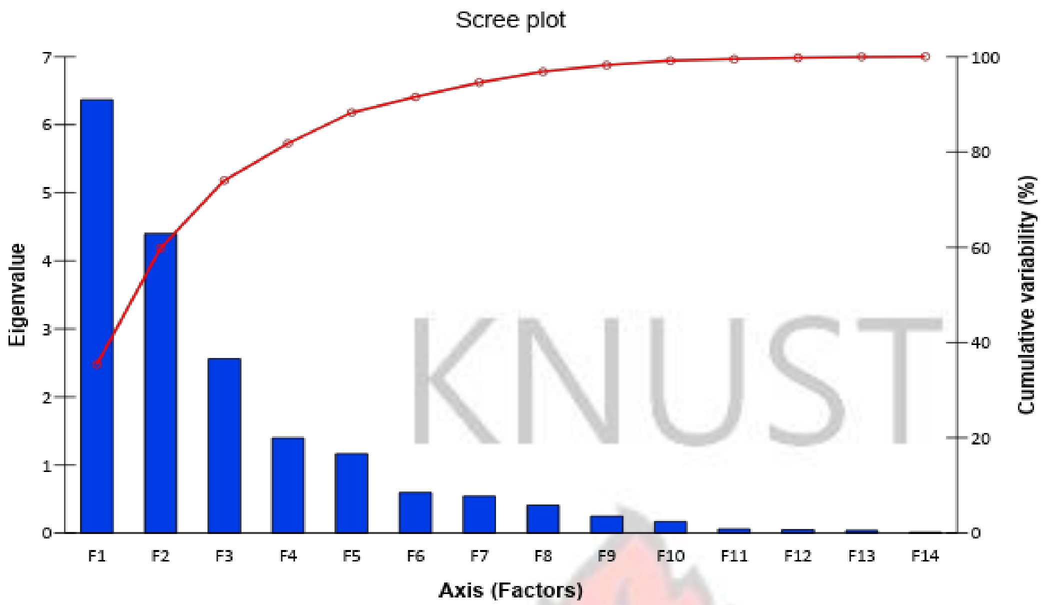


Figure. 4.1.3 Scree plot of eigenvalues from principal component analysis (PCA) for Tono reservoir in the Upper East Region, Ghana

Similarly, for Vea reservoir, from Figure. 4.1.4, the first eigenvalue (F1) equals 9.669 which represent 53.72% of the total variability. This means that if data are represented on only one axis, a percentage (%) of the total variability of the data can still be obtained. As such each eigenvalue correspond to a factor, and each factor to a dimension. The second (F2: 2.791) and third (F3: 1.814) of the eigenvalues in addition to F1; correspond to a high number of percentage of the variance assuring us that the scree plot based on the first three factors (F1 - F3) are good quality projection of the initial multi-dimensional water quality structure. In the scree plot, the first three factors allow us to represent 79.30% of the initial variability of the data which also indicates a good result. That is, eighteen water quality parameters were reduced to three factors (F1, F2, F3).

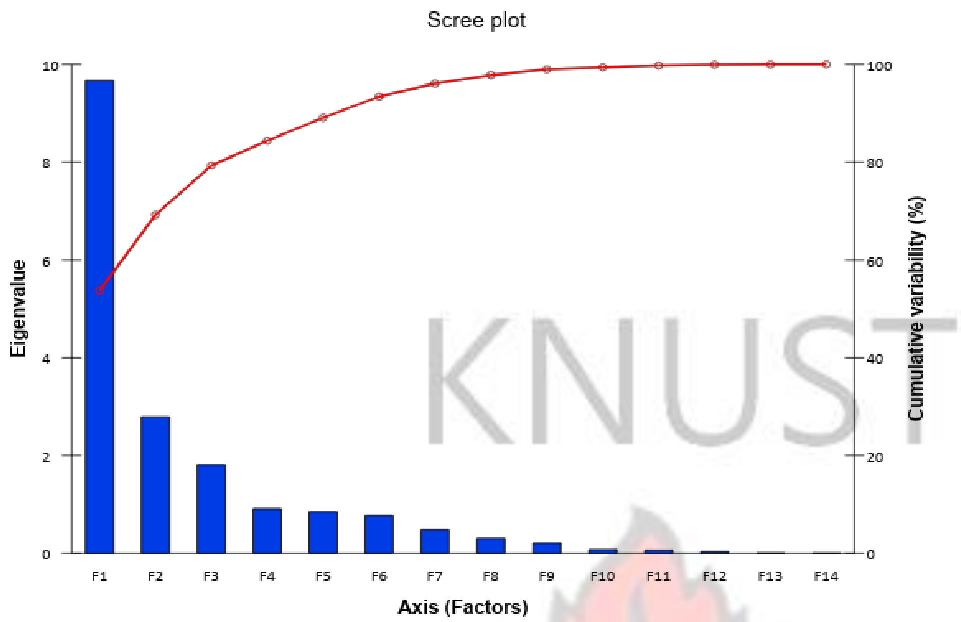


Figure. 4.1.4 Scree plot of eigenvalues from principal component analysis (PCA) for Vea reservoir in the Upper East Region, Ghana

Land use characteristics of the reservoir's watershed shows wide spread post-flood period anthropogenic activities (Dry season; October-December). Dry season farming mostly vegetable cultivation is dominant on the catchment areas for both reservoirs. However, sandmining and moulding of cement blocks were observed as pre-dominant pre-flood activity within the receded littoral section the Vea reservoir. However, vegetable cultivation was predominant in Tono reservoir than in Vea reservoir. These anthropogenic activities could impact on the water quality especially on nutrient loading in the reservoir and possible cascading effect on phytoplankton abundance in the reservoir.

Phytoplankton were identified to the level of phylum. Three (3) phyla of phytoplankton identified in Tono and Vea reservoirs were Chlorophyta (Green algae), Bacillariophyta (Diatoms) and Cyanophyta (Blue-Green algae). The dominant phylum was Chlorophyta (72%) and Cyanophyta (52%) for Tono and Vea reservoirs, respectively (Figure 4.1.5). Bacillariophyta had the lowest and same percent abundance in both reservoirs. These could suggest that both reservoirs' response to nutrients changes in the water column could be low (El-Serehy *et al.*, 2017).

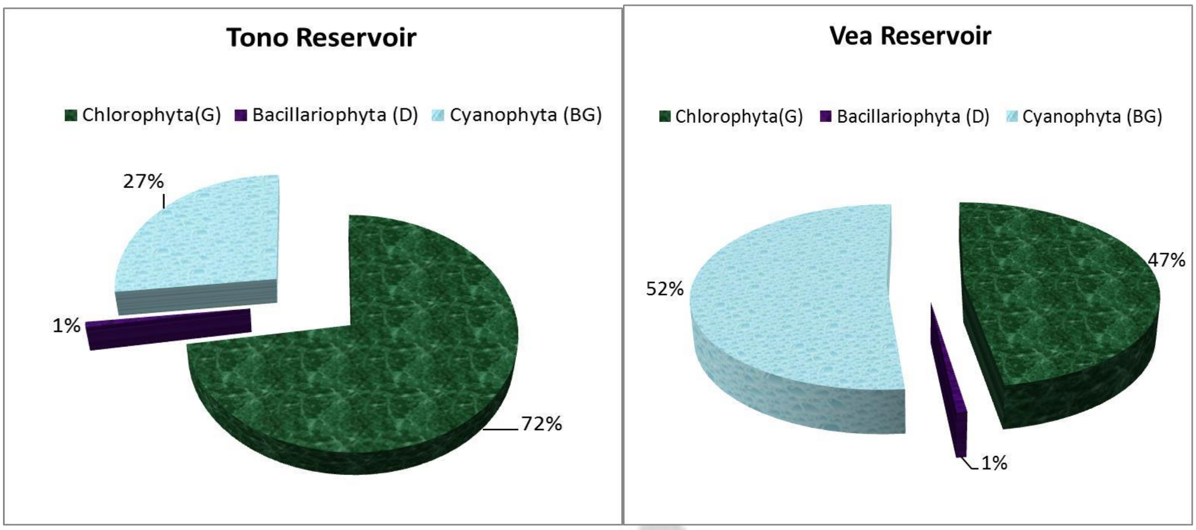


Figure 4.1.5 Percent abundance of phytoplankton (phyla) in Tono and Vea Reservoirs in the Upper East Region, Ghana. Quarterly monitored (cell counts ml^{-1}) from February 2015 – April 2016. G: Green algae, D: Diatom, BG: Blue-Green algae

These phyla from various sampling zones were the biological variable analyzed with the environmental variables. From interrogation of the factors obtained from PCA, further analysis of environmental factors for both reservoirs cumulatively produced six water quality parameters as best variables (from eigenvalues), extracted from the pre-analysed data set. The best variables were; conductivity, turbidity, nitrate, sulphate, water depth and total hardness. Although, dissolved oxygen (DO) was not part of extracted best variables, DO was included into the correspondence analysis (CA) due to its relative importance as an environmental factor to fish survival and growth in aquaculture. The best variables are relevant for water quality monitoring.

Table 4.1.2 shows CA results of similarity accounted for by the corresponding eigenvectors and percentages of similarity accounted in each reservoir from the CA performed. The important environmental gradient (spatially varying aspect) indicative as the first CA axis explained 84.2% and 64.3% of the total variance in relative abundance of 3 phyla of phytoplankton for Tono reservoir and Vea reservoirs, respectively (Figure 4.1.6). For Tono reservoir, Bacillariophyta, conductivity, turbidity, nitrate, sulphate, water depth, total hardness and dissolved oxygen were positively related; showing strong relationship between phytoplankton score and environmental scores (Table 4.1.2; Figure 3.1.6, a). Chlorophyta and water depth showed positive association in Vea reservoir (Figure 3.1.6, b). Comparatively, CA axis 2 in Vea reservoir showed stronger positive association between Bacillariophyta, conductivity, Turbidity, Nitrate, Sulphate, water depth, total hardness and dissolved oxygen, although contributing to (<50%) of the total variance (Table 4.1.2).

Table 4.1.2 Summary of correspondence analysis (CA) eigenvectors, relating relative abundance of 3 phyla of phytoplankton to environmental variables in Tono and Vea reservoirs, Upper East Region, Ghana, following Chi-squared distances

	Tono CA axis		Vea CA axis	
Parameters	1	2	1	2
Chlorophyta	-0.2115	0.08883	**0.71769**	-0.2252
Bacillariophyta	**2.46079**	**1.07226**	-0.2576	**2.18201**
Cyanophyta	0.12037	-0.1479	-0.7102	-0.1011
Conductivity	**0.65489**	-0.0326	0.3103	**1.54408**
Turbidity	**0.97482**	0.20534	0.27032	**1.56357**
Nitrate	**0.99888**	0.22528	0.30074	**1.47528**
Sulphate	**0.97847**	0.24182	0.30595	**1.55751**
Water depth	**1.0951**	0.42172	**0.53832**	**1.96392**
Total hardness	**0.97659**	0.18858	0.30763	**1.53156**
Dissolved oxygen	**1.09939**	0.31976	0.30163	**1.59256**
Eigenvalue	0.10466	0.01965	0.47131	0.2619
% of total variance	84.196	15.804	64.281	35.719
Cumulative % variance	84.196	100	64.281	100

Bold valves shows strong positive relationship

Results of biological variables at each section of the reservoirs viz. upstream, midstream and downstream assessed in terms of phytoplankton abundance in phyla (cell counts/ml) are presented in Table 4.1.3. Spatial variation for site score CA axis 1 indicates strong positive association between Phytoplankton phyla and midstream sections (TOMS: 2.98, VEMS: 1.32) in both reservoirs, as shown in Table 4.1.3. Thus, midstream sections had relatively more phytoplankton abundance.

Table 4.1.3 Summary of site score for biological variables at various sampling zones in Tono and Vea reservoirs in the Upper East Region, Ghana

Correspondence analysis

Zones (site)	Axis 1	Axis 2
TOUS 1	0.498311	-1.4337
TOMS 2	**2.97785**	1.73251
TODS 3	-0.616874	0.48309
VEUS 1	-0.790337	-0.132128
VEMS 2	**1.31593**	-0.302956
VEDS 3	0.413316	5.09611

TO: Tono, VE: Vea, US: up-stream, MS: mid-stream, DS: down-stream

An integration of the principal components (from PCA) of environmental and biological factors (Table 4.1.2), and site score (Table 4.1.3) for spatial relationship using correspondence analysis (CA) are presented in triplot chart (Figure. 4.1.6). Based on the first axis of CA for Tono reservoir, axis I alone explained 84.2% of phytoplankton spatially varied distribution in the three zones (Figure. 4.1.6). From the triplot chat, Bacillariophyta had positive association with water depth, dissolved oxygen, sulphate, turbidity, nitrate and total hardness at the midstream zone of Tono reservoir (TOMS 2) due to disturbances from anthropogenic activities. Similarly, conductivity and Cyanobacteria seem to have a weak association with the Upstream zone (TOUS 1), whiles Chlorophyta was negatively associated with downstream zone (TODS 3) (Figure. 4.1.6, a). Comparatively, a lower percentage variability of 64.3% based on first axis of CA for Vea reservoir (axis I) showed strong positive association with Vea downstream.
Phytoplankton had a spatially varied distribution in the three sites (Figure 4.1.6).

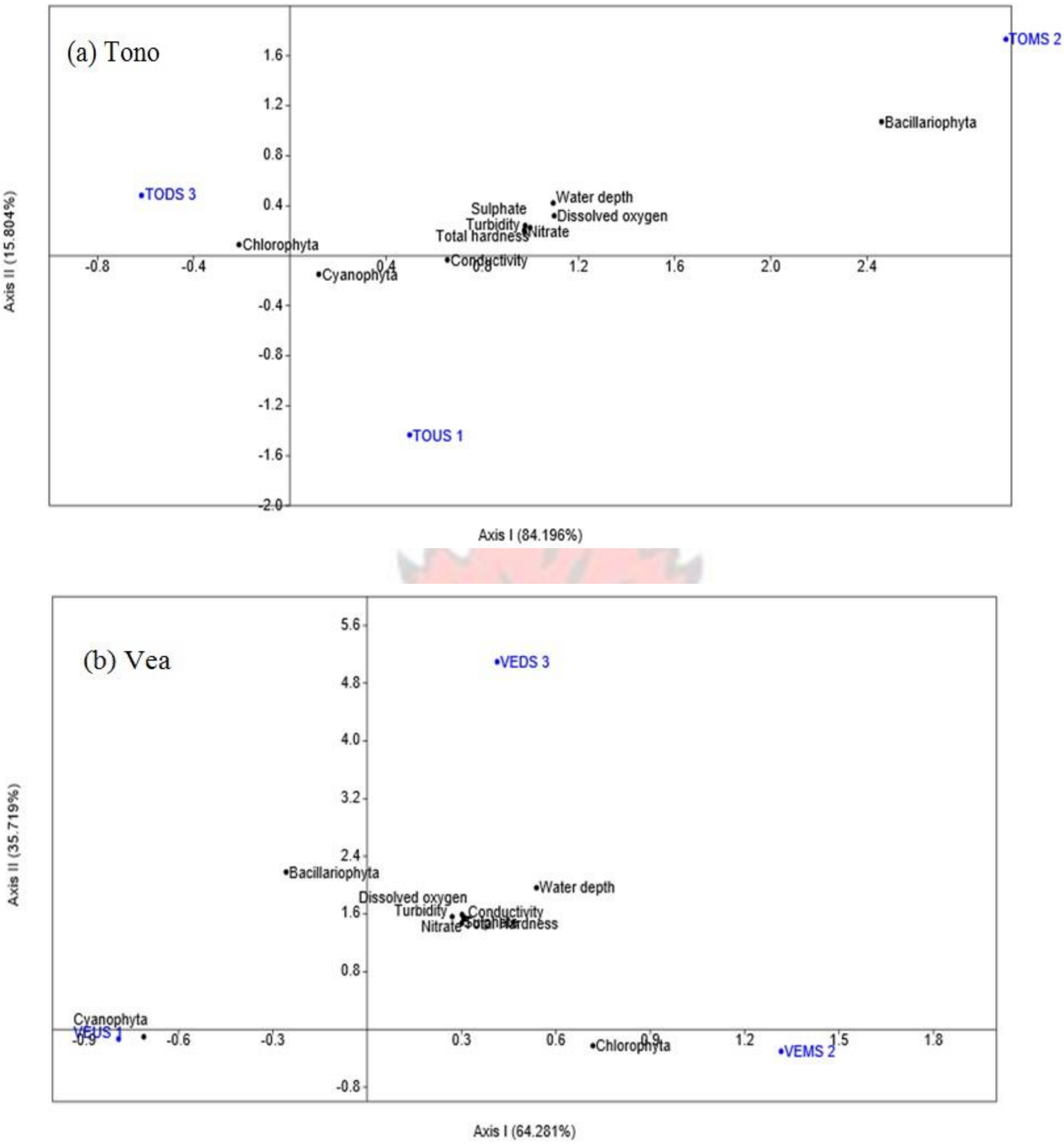


Figure 4.1.6 Triplot chart of correspondence analysis (CA) ordination indicating the relationship among relative abundance of phytoplankton in phyla and environmental variables at various zones/sites in (a) Tono reservoir and (b) Vea reservoir, in the Upper East Region, Ghana

4.1.4 Discussion

4.1.4.1 Temporal Variation and Seasonality Regime of Reservoir Water Quality

The temporal trends exhibited by the various clusters of temporal grouping were compared with empirical seasonality regimes (dry and rainy seasons) in the Upper East Region of Ghana

Previous studies on the Tono and Vea reservoirs categorized the dry season into two; the first category from November to mid-February which is characterized with cold and dry dusty harmattan winds (Okra, 2010). The second category (Mid-February to March) is characterized by hot, less windy and high atmospheric temperature (> 33 ºC). In this study, based on limnological results obtained over temporal scale; the empirical dry season was divided into two periods; namely pre-flood and post-flood seasons. Whiles the peak periods of the rainy season are called flood season. These assertions were based on the premise that most lentic water bodies like Tono and Vea reservoirs are perennial. That is, these water bodies do not completely dry out. It was inferred that, after impoundment, there had been no period where these reservoirs became literally dry (with-out water). Preceding from the premise in this study, similarity of temporal variance (Figure. 4.1.2, a) in cluster 1 revealed mixed correspondence in line with post-flood period (December, November) and flood period (May - July). This postflood period accounted for 33.3% of temporal variance in water quality in the Tono reservoir.

The results of grouping “May, June and July” as part of cluster 1 (post-flood season), instead of it being flood season for Tono reservoir could be due to variation in the amount of rainfall (runoff received) and water quality in those particular months. Recent studies cited May to October as rainy season within the catchment of the Vea and Tono reservoirs (Okra, 2010).

From this current study, the cluster obtained as “May, June and July” was re-classified in line with previous observation as flood season. Thus, anthropogenic activities and seasonal variation could have altered the water quality (Sharma *et al.*, 2016). Cluster 2 closely corresponding with the dry season, was probably an outlier due to few dissimilarities of unexplainable variation in water quality over the period but could be considered. Cluster 3 resonates closely with the flood periods where there is high rainfall (August, September, October), accompanied by water run-off into the reservoir. Thus, the rainy season accounts for 20% of the temporal variation in the reservoir. The study observed that the flood season in the reservoirs usually lasted for 3 months. Cluster 4 denotes the typical dry season periods with virtually no rain fall. Thus, cluster 2 and 4 have similarity in seasons were considered as one season; post-flood period of the dry season. This season which is also referred to as Harmattan accounted for 46.7% of the temporal variation in water quality in Tono reservoir.

Correspondence of cluster 1 to pre-Harmattan/Harmattan season (October-December). Cluster 1 could also be referred to as post-flood periods for limnological purposes. During this period, dry dusty winds blow causing early morning turbulence, thereby improving dissolved oxygen levels into the reservoir water. However, the season only accounted for 26.7% of the observed temporal changes in water quality. Cluster 2 produced similarity groupings typical for months with peak rainfall in Upper East Region (Akongyuure *et al.*, 2015; Okra, 2010) characterized by increased water volume in the reservoir. However, this season accounted for least variance in seasonality dynamics (20%). With cluster 3 accounting for 53.3% of variation in seasonality, it corroborates with the pre-flood season. Thus, pre-flood season (January-April) plays important role in observed changes in water quality over time in these reservoirs. This study observed that temporal changes in Tono and Vea reservoirs could be linked to seasonal regimes. Natural drivers of change in most streams had been reported to be associated with flooding regime, as fish responses vary by season and spatiotemporal scale (Nsor, 2016). For planning purposes, management strategies should be put in place for expected water quality changes during the pre-flood season (dry season) for fish farming in reservoirs.

4.1.4.2 Spatial Variation and Responsible Factors for Reservoir Water Quality

Multivariate relationships play important roles in discovering the key factors that influence association and changes in water quality. The Principal Component Analysis (PCA) employed reduced eighteen water quality variables to five and three factors in Tono and Vea reservoirs, respectively. These factors had more variance (>50%), allowing a good representation of the initial variability of the reservoir water quality. Thus, the first few factors produced better variance (Khalit *et al.*, 2017).

Three phyla of phytoplankton were identified in Tono and Vea reservoirs; Chlorophyta (Green algae), Bacillariophyta (Diatoms) and Cyanophyta (Blue-Green algae). This was consistent with previous study in Vea reservoir where three phyla were observed (Agbeko, 2012). Similar findings were reported on Baldi stream in India from thirty-four species of phytoplankton obtained (Sharma *et al.*, 2016). Percentage abundance of Cyanophyta (Cyanobacteria) was higher in Vea reservoir (> 50%) compared to Tono reservoir, while the Diatoms had equal percentage abundance in both reservoirs (Figure 4.1.5). There is little compelling evidence to support reasons for equal percentage abundance of the latter phylum (Diatoms) stated. However, calcareous rocks, calcium carbonates or bicarbonates in the reservoir could have enhance the growth of diatoms (Sharma *et al.*, 2016).

The high levels of Cyanophyta in Vea reservoir compared to Tono reservoir, was contrary to observed land use activities such as vegetable farming. Tono was expected to have higher levels of cyanophyta due to direct dry season vegetable farming activities and other anthropogenic activities on the riparian zone of the reservoir catchment area. The high levels of Cyanophyta in Vea reservoir indicated that the reservoir could be receiving higher pollution load, apart from nutrient enrichment as asserted by other studies (Sharma *et al.,* 2016). Permanent cyanobacterial prevalence is regarded as the ultimate phase of eutrophication (Boelee *et al*., 2009). The hydrology and water chemistry of seasonal ponds are governed by the landscape features and changing characteristics, such as landform or soil type; therefore, varying macro invertebrates' communities (Batzer, *et al*., 2004) as well as altering its food quantity and quality. This could explain observed changes in phytoplankton abundance (phyla dominance) in Tono reservoir. Based on temporal variation in this study, post-flood periods are characterized by higher water temperature. Higher temperature and adequate nutrition elements lead to increased algae activities (Jiang-Qi, *et al*, 2013). Studies indicates that due to the relatively short life cycle of diatoms, the diatoms respond rapidly to the physico-chemical changes and eutrophication thus indicating information on nutrient changes, as diatoms are strongly correlated to total phosphorus (TP) concentrations (El-Serehy *et al.*, 2017).

From correspondence analysis performed following principal component analysis, relatively strong positive relationship between the phylum Bacillariophyta and key environmental variable from water quality parameters was detected. Most of the water quality variables obtained during this study were within acceptable limits for aquaculture (WRC, 2003). Observed monthly mean conductivity level of 742.65 µs cm^{-1} for the Tono reservoir was lower than that for Vea reservoir (1025.15 µs cm^{-1}). Nitrate-nitrogen levels were higher for Tono reservoir (3.05 mg L^{-1}) compared to 2.49 mg L^{-1} for Vea reservoir. High Nitrate levels in Tono reservoir may be due to nutrient loading from the reservoir catchment. Nitrate which is a byproduct of ammonia or nitrite but elevated levels are results from agricultural runoff, plant and animal decomposition and excreta (both domestic animals and human). These activities were observed during the study. Higher nitrate–nitrogen levels (> 5 mg L^{-1}) may be linked to eutrophication via nutrient enrichment. Therefore, the positive association between conductivity and cyanobacteria in upstream zone of Tono reservoir in this study, could trigger an imminent phytoplankton bloom. A study suggested conductivity may have no discernible effects on phytoplankton even in the presence of nitrogen and phosphorus (Davis, 2016). However, the impact of conductivity on phytoplankton could be beneficial for herbivorous fish growth at a given threshold as increased conductivity may decrease zooplankton population whilst increasing phytoplankton population, especially when pH and dissolve oxygen increases above 7.5 and 3 mg L^{-1}, respectively (WRC, 2003; Towers, 2015; Sharma *et al.*, 2016;). Phosphorus considered as a limiting nutrient in most lakes and reservoirs was not detected as a principal component of the reservoir water quality. The presence of nitrate, sulphate, turbidity and total hardness as key variables of reservoir water quality could be linked to anthropogenic activities such as farming which was observed on the littoral section of the reservoir, are responsible for the changes in reservoir water quality. Agricultural activities had been reported to be linked to similar effects in other lentic water bodies (Suratman *et al.*, 2014; Nsor, 2016). In addition, Chlorophyta as a primary productivity phylum preferred as food for fish showed positive relationship with water depth in Vea reservoir. Water depth is affected by sedimentation of the reservoir bed from loose soils during run-off. Turbid conditions cause light attenuation with water depth with the cascading (negative impact) effect on photosynthesis and Chlorophyta production. As observed from the triplot chart from correspondence analysis (CA), of which the principal environmental factors had good affinity for Bacillariophyta association in the Tono midstream zone and Vea downstream. The dynamics and structure of phytoplankton of an aquatic ecosystem is influenced by the physicochemical parameters, thus affects distribution and composition (Suratman *et al.*, 2016). Elucidating on this study result, spatial characteristics in reservoir water quality arguably affect phytoplankton abundance, for that matter the natural productivity within the natural food web could be linked to specific sections or sites within a reservoir.

4.1.5 Conclusions and Recommendations

4.1.5.1 Conclusions

From this study, limnological evidence from temporal variation and seasonality influences produced three distinct clusters that were characterized as Pre-flood season, flood season and post-flood season. The post-flood period had dominant negative effect on reservoir water quality. This study indicates (from first correspondence analysis axis) that the important environmental variable that influenced reservoir water quality and hence needs regular monitoring for aquaculture in Tono and Vea reservoirs are conductivity, turbidity, total hardness, water depth, sulphate, nitrate and dissolved oxygen. These environmental gradients related spatially with phytoplankton abundance in both reservoirs, thus entire reservoir could be productive for fish farming.

4.1.5.2 Recommendations

- Pre-flood to flood seasons are ideal periods for cage culture in Tono and Vea reservoirs as temporal variance in water quality changes are good. Post-flood periods are critical periods and not recommended as it needs regular monitoring to further understanding of the temporal variation and impact on fish production. However, both Tono and Vea reservoirs can support cage aquaculture.
- The community and stakeholders should be sensitized and trained to exploit the potential of these reservoir for sustainable aquaculture.
- Considerably, multivariate statistical methods could be useful pattern recognition tools for water quality assessment for aquaculture-use. Thus, recommended for managers of reservoirs and dugouts.

4.2 Modelling the Suitability of cage aquaculture zones on the Tono and Vea reservoirs

4.2.1 Introduction

Aquaculture is an emerging agro sector that needs spatial technological innovation to enhance selection of suitable sites to maximize fish production. Planning aquaculture development spatially using adequate technology has a major advantage of enabling the grouping of farms in suitable areas with the sharing of facilities. These facilities include the sharing of equipment, fingerling production infrastructure, cold stores, transport to retail markets, the establishment of fish sale outlets and the collective solving of problems among other benefits. The idea of establishing clusters has been promoted by the World Bank as an aquaculture spatial planning process (FAO and World Bank, 2015). This is for the development of area management plans through participatory activities, engaging the best available knowledge, including local interest with other relevant stakeholder consultation.

An aquaculture zone consists of a hydrological system which is suitable for aquaculture that encompasses part of or an entire catchment area from the source of a waterway to the estuary, water body (lake or dam), or coastal area, or off the coastal area, that has been allocated to develop aquaculture (FAO, 2016). The development of an aquaculture zone through spatial planning could further enhance the siting and operations of fish packaging and freezing facilities, as well as availability of fish health and pharmaceutical service providers. Major aquaculture actors in the sector could be aggregated to access common physical resources like roads and markets to boost their fish trade from an aquaculture zone. With spatial zonation, regulatory agencies such as the Fisheries Commission, Water Resources Commission and Environmental Protection Agencies could monitor where, how and which areas are being polluted through aquaculture for management decision making and futuristic planning for aquaculture development. For governance and revenue mobilisation, a spatially planned aquaculture zone could help in allocating only suitable portions to aquaculture under a quota system for a fee, while allowing the remaining areas for capture fisheries and other uses. The trickle-down effect leads to improved accountability and transparency for increased public confidence, minimising water-use conflicts and encouraging the viability of aquaculture investments. Suitable zones must be able to deal with environmental, economical and societal changes in view of water-user conflicts for sustainable aquaculture. The adaptation and application of Geographical Information System (GIS) models for aquaculture planning and development is evolving (Yulius *et al.,* 2009; Falconer *et al*., 2013; Nayak *et al.*, 2014; Wagdy and Kawi, 2015). Selection of suitable zones for cage culture in reservoirs and dugouts using GIS tools is not common in Ghana. Application of GIS in aquaculture development could serve as a decision support tool for better prediction of the suitable zones for aquaculture (Kapetsky, 2002).

The bulk of farmed fish is produced in cages on Lake Volta, with 85,000 metric tonnes produced by capture fisheries (FAO, 2016). The Tono and Vea reservoirs are the two major water bodies created in Upper East Region that supports fisheries and irrigation activities in Northern Ghana, but dwindling fish catch from these reservoirs had warranted the determination of its aquaculture suitability potential. The objective of this study is to identify suitable zones for Nile Tilapia cage culture using site specific water quality data and socioeconomic consideration with spatial multi criteria evaluation (SMCE) in GIS for sustainable aquaculture development on the Tono and Vea reservoirs in the Upper East Region of Ghana.

4.2.2 Materials and Methods

4.2.2.1 Study area

The study was conducted on the Tono and Vea reservoirs in Upper East Region (UER), Ghana (Figure 4.2.1). Tono and Vea reservoirs are among the largest man-made water reservoirs of ecological and socio-economic importance in the arid zones of Northern Ghana. Tono reservoir is located in the Kassena Nankana District between Latitude 10^0 051’40’’ and 10 054’30’’ North and longitude 1^0 08’30’’ and 1 010’50’’ West along the tributaries of River Sissile, while Vea reservoir is located between latitude 10‘000’00’’ and 11^0 001‘’00’’ North and longitude 0^0 045’30’’, 0^0 056‘’30’’ West on River Yarigatanga in the Bongo District, UER.

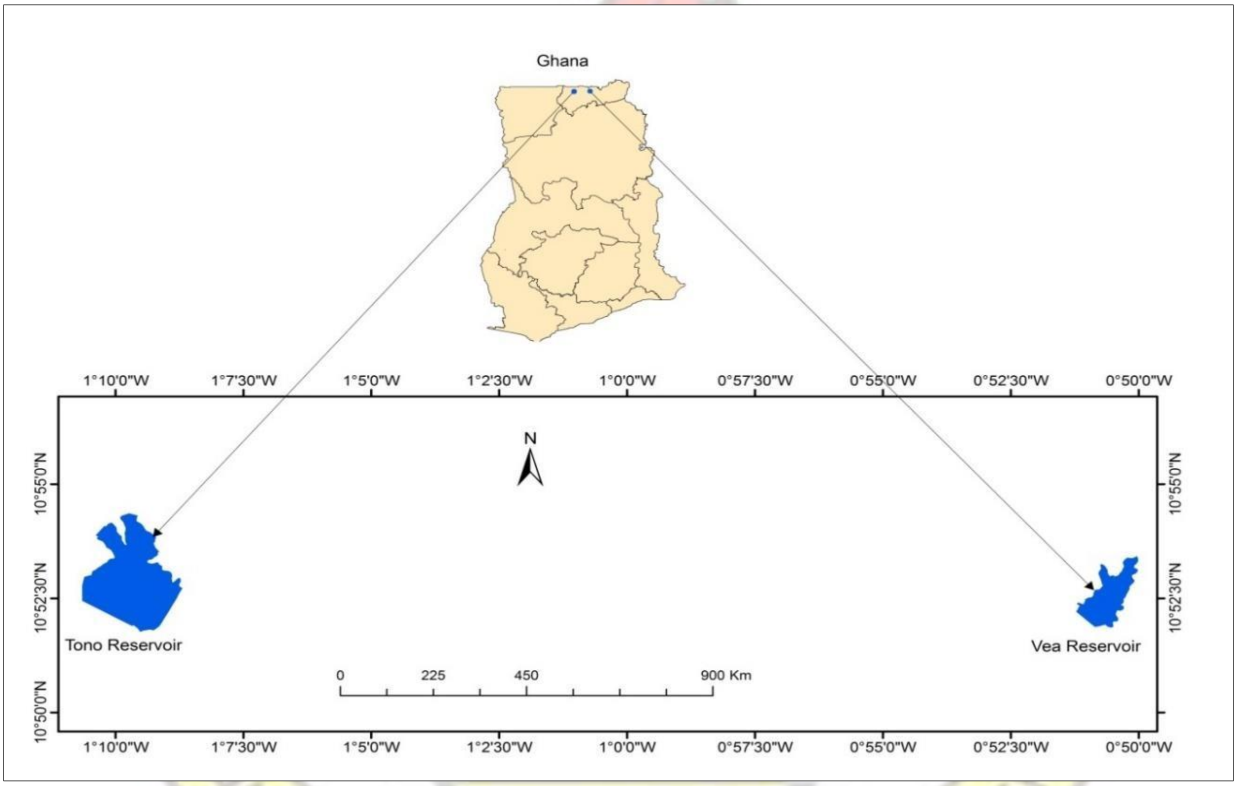


Figure 4.2.1 Tono and Vea Reservoirs in the Upper East Region, Ghana

These reservoirs are located within the Volta Riverine Basin and are the main hub for capture fisheries that produce the bulk of fish that feed the people of Navrongo, Bolgatanga and its environs. These reservoirs are managed and operated by Irrigation Company of Upper Region (ICOUR). The total catchment area of the reservoirs with their riparian communities (Okrah, 2010) are indicated in Table 4.2.1.

Table 4.2.1 Characteristics of Tono and Vea Reservoirs (Modified from Okrah, 2010)

Characteristics of Reservoir	Tono	Vea
Catchment Area (Km^2)	650	136
Reservoir Area (Km^2)	186	40.5
Volume (10^6 m^3)	92.6	17
Mean Water depth (m)	<10	<10
Total Project Area (ha)	3,860	1,197
Riparian communities/Fishermen	Chuchuliga, Wuru, Navrongo, Bonia	Balunge, Vea, Gowrie, Bongo Kukua

Mean annual rainfall ranges from 850 to 1000 mm occurs in the months of May-October, followed by a prolonged dry season. The first part of the dry season from November to midFebruary is characteristically cold and dry weather with dusty harmattan winds. The rest of the dry season is usually characterized by a wide temperature range from 14°C at night and to over 35°C during the day (Pelig-Ba, 2011).

4.2.2.2 Data requirement and collection

Primary and secondary data were obtained as inputs for GIS-based site suitability modeling (Table 4.2.2). Based on the delineated boundaries of Tono and Vea reservoirs, several transects at regular intervals (≥ 200 m) apart of each other, across the entire reservoir surface was made to identify sampling stations. The sampling stations were geo-referenced with a hand-held GPS. Primary data were collected from 27 and 19 sampling stations in Tono and Vea reservoirs, respectively. Preliminary monthly survey involving in-situ measurements and water quality monitoring were carried out once a month from February 2015 to April 2016 to observe monthly seasonality trends in water quality and water depth. From these monthly water quality data observed, January 2016 was adopted for this study as the worst-case condition based on limiting factors (i.e. the month that water quality including water depth, fluctuated and deteriorated most in both reservoirs). This was followed with an extensive water quality sampling, with a total of 513 and 361 data points analyzed from sampling stations spread over the entire Tono and Vea reservoirs, respectively in January 2016. Water temperature, pH and conductivity were determined in-situ using HANNA probe meter, (version HI991002 and HI98192). Water transparency was measured with Secchi disc and water depth with metric robe. Water for chlorophyll-a determination was sampled into dark bottles and analysed using the acetone extraction method, while phytoplankton biomass was derived from chlorophyll-a values based on analysis of APHA (1980). Other water parameters such as dissolved oxygen (DO), turbidity (NTU), NO_3-N, NO_2-N, NH^{2}-N, PO_4-, TDS, SO_4^{2-}, and Cl^- were sampled and geo-referenced at each sampling station. Water was sampled into 1 litre high density polyethylene bottles which were prewashed with diluted HCL (10%) and rinsed three times with the sampled water. All water samples collected were transported in cool box (< 4 °C) and analysed at CSIR-Water Research Institute laboratory in Tamale in the Northern Region of Ghana according to standard methods (APHA, 2005).

Table 4.2.2 Sub model considered for cage culture area suitability selection

Sub model Criteria	Interpretation of criteria	Data sources
Bathymetry	Favourable depth for mooring cage	Primary
Water temperature	Favourable temperature for Tilapia culture	Primary
Ecological factors	Favourable DO, Nutrients, pH	Primary
Chlorophyll-a	Availability of natural food (phytoplankton)	Primary

[2] .2.2.3 Modeling and Weighing of sub-models

The integrative methodology as described by Silva et al. (2011), which determines suitable aquaculture areas through 3 stages of analysis, was used. These include: (i) analysis of regulatory and social spatial restrictions using GIS to generate a constraints map involving reservoir boundary; (ii) a Multi-Criteria Evaluation that considers the criteria as in Table 3 and its constituent factors such as physical, growth and survival, and environmental sensitivity to generate a final map showing the most appropriate areas using GIS tools; and (iii) detailed analysis of production, socio-economic outputs and environmental effects on suitable areas. The above methodology emphasizes the application in data-poor environments, where there are combinations of social difficulties, data scarcity and aquaculture expansion pressure. Recommended standard values for water quality that influence the development and growth of Nile tilapia were derived from secondary data obtained from review of published research articles (Table 4.2.3) and from personal information gathered from key informants (Table 4.2.4). These information were considered as factors towards the development of final aquaculture suitability output.

Suspended solids	Indicate level of water clarity (turbidity)	Primary
Constraints/societal	Wildlife/water abstraction/sensitive area	Secondary

Table 4.2.3 Water quality criteria and standardization values for suitability modelling of cage aquaculture

	Range	Standard *	Interpretation/Comments	
Temperature (°C)	23-32	26-30.6	Better when higher than 25	
pH	6 -9	6.5-8.0	Moderate, it should not be too high or lower than 7	
Turbidity (NTU)	55-150	<80	Lower the better	
Dissolved oxygen (mg L^{-1})	3 - 8.53	5	Higher the better	
NO_3-N (mg L^{-1})	0.535-1.105	<1	Lower the better	
				<1
NO_2-N (mg L^{-1})	0.005-0.088		Lower the better	<1
NH_4-N (mg L^{-1})	3.9-8.7		Lower the better	<1.0
PO_4 (mg L^{-1})	0.01 – 0.05		Lower the better	≤2.5
CHL-a (mg m^{-3})	0.8-1.85		Moderate, it should not be too high or too low, i.e. above/lower than 2.5	
Transparency (m)	0.2-1.0	0.5	Moderate, it should not be too high or too low, i.e. above/lower than 5	
E. Conductivity (mg L^{-1})	30-5,000	60-2,000	Moderate, it should not be too high or too low	
Water depth (m)	1.5-3.0	≥2	Higher the better	
TDS (mg L^{-1})	50-1500	1000	Lower the better	
SO_{42} (mg L^{-1})	0-1000	<500	Lower the better	
Cl_{-} (mg L^{-1})	10-100	<70	Lower the better	

*Adapted and modified from WRC (2003), Radiarta *et al.* (2008), Thilza and Muhammad (2010), E: Electrical, TDS: Total Dissolved Solids

Table 4.2.4 Institution and type of information provided towards development of final aquaculture suitability output or map

Institution	Type of Information provided
MOFAD/FC	Fish landing sites, navigation route for canoe
Chief fishermen	Fish landing sites, navigation route for canoe
GWCL	Water abstraction site
EPA	Ecologically sensitive area for aquatic birds/wildlife
ICOUR	Water allocation and reservoir management
GIDA	Issues on water use rights
WRC	Water Use permits and water allocation
Chief/Opinion leaders	Possible social objection site

MoFAD: Ministry of Fisheries and Aquaculture Development, FC: Fisheries Commission, GWCL: Ghana Water Company Limited, EPA: Environmental Protection Agency, ICOUR: Irrigation Company of Upper Region, GIDA: Ghana Irrigation Development Authority, WRC: Water Resources Commission

4.2.2.4 Data Preparation and Analysis for suitability modeling

All statistical analyses were performed using Microsoft Office Excel 2013 and PAST 3.1 version 2015 software. Water quality data were prepared in ArcGIS version 10.2 and exported to GIS-based software ILWIS version 3.8.5 for spatial analysis. The X, Y locations of the sampled stations from which measurements were done were converted into a point shape file in ArcGIS. For each sampled station, the measured values for all 15 water quality parameters were populated i.e. to distribute the quantity of points. To obtain measurement values for unknown areas for each factor, inverse distance weighted interpolation method was applied.

Interpolated outputs were exported to ILWIS for spatial multi-criteria evaluation (SMCE). ILWIS was most preferred for this analysis because it has a tool built purposely for SMCE and analytically recommended (Wagdy and Kawi, 2015). The data processing was run four times in succession using the SMCE in ILWIS. These are structuring of factors (also known as criteria tree), standardization of factors, and weighting of factors and generation of composite index map. The criteria tree was created with 15 factors (Table 4.2.3) as depicted in the criteria tree in Figure 4.2.2. Standardization was also carried out to help normalize all measurement values between 0 (Unsuitable) and 1 (highly suitable). Various standardization methods ranging from interval, maximum and goal standardizations were applied. The weighting of the factors also allows for prioritization of the relative importance of factors. In this study, all factors were weighted equally with the assumption that these factors were equally important for tilapia production in these reservoirs.

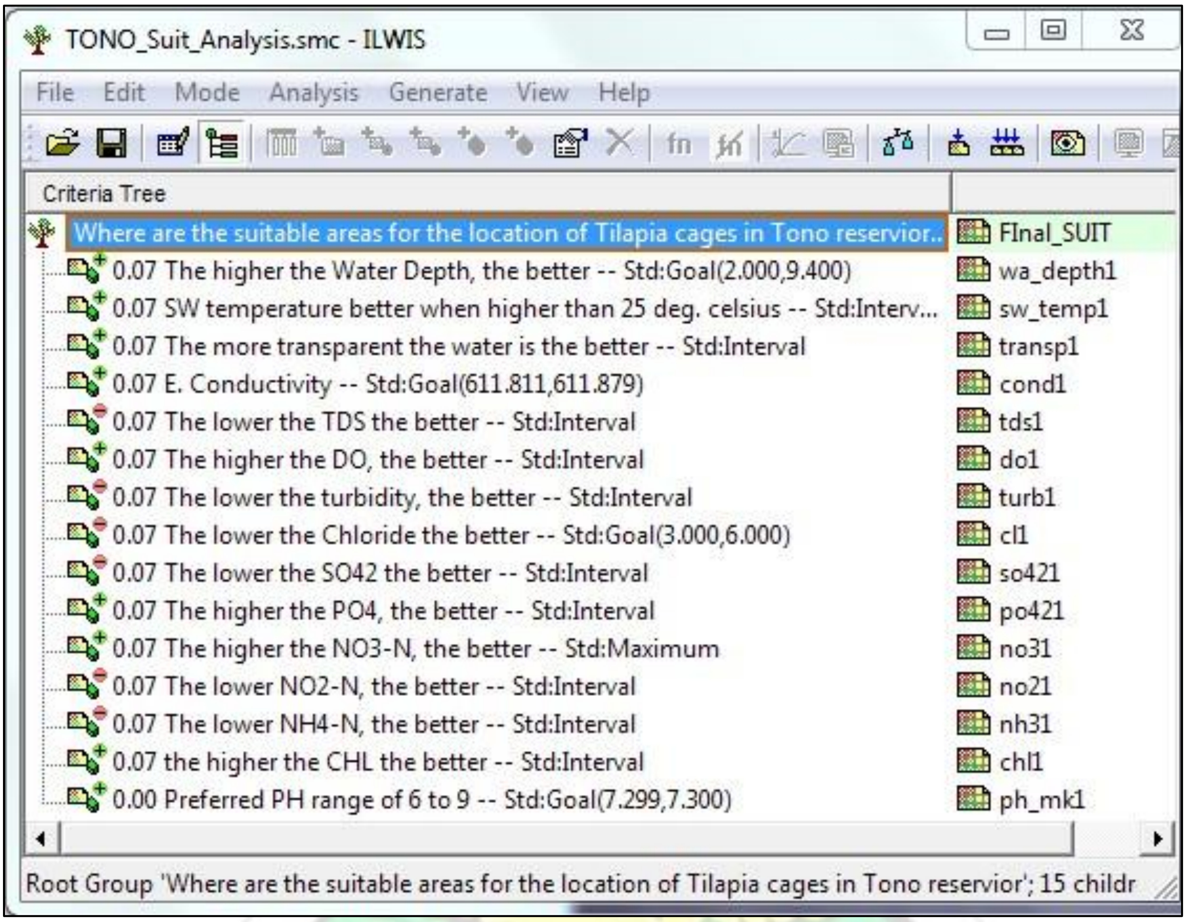


Figure 4.2.2 A pictorial view of criteria tree built in ILWIS from suitability analysis performed

After standardization and weighting, a composite suitability map was generated showing the suitability of areas for the growth of tilapia. The composite indices range from 0.44 to 0.75. This was classified into five (5) classes ranging from moderately unsuitable, poorly suitable, moderately suitable and highly suitable using equal interval classification method. The fifth class labeled as unsuitable was based on several major concerns' parameters including site likely to attract social objection, water abstraction zone and scenic view were considered as constraint area. These constraint areas are out of bounds for cage fish farming.

4.2.2.5 Validation of suitability areas

The model output of suitable area was selected for validation. This area was then subjected to validation through further field data survey involving selected water quality parameters i.e.

dissolved oxygen (DO), temperature, pH, water depth and transparency. Most studies on aquaculture site selection recommend similar validation approach (Radiarta *et al.*, 2008; Silva *et al.*, 2011) with ground-truthing as a further step and a reality check (Pérez *et al.*, 2005). For this study, ground-truthing was done by comparing the levels of suitability from the model with field observation and photo verification. Cross-checks with stakeholders including experts (≥ 5 years' experience) and Fisheries Commission officials consulted affirmed the output of levels of suitability obtained for Tono and Vea reservoirs (Table 4.2.4). Similar confirmatory assertion was made by fishermen from each reservoir during the validation survey. Accuracy of the reservoir modelling based on qualitative assessment was not applicable, thus was not considered in this study.

4.2.3 Results

4.2.3.1 Reservoir Water quality for suitability studies

Water depth at Tono and Vea reservoirs were over 3 m as shown in Table 4.2.5. For the two reservoirs, the water depth and the concentration of dissolved oxygen (DO) showed similar values, while water temperature, transparency, alkalinity ($CaCO_3$), and phytoplankton biomass among the two sites differed significantly. From the study, DO levels are optimum for growing Nile tilapia in the two reservoirs (7.09- 6.79 mg O_2 l^{-1}). Turbidity value of 87 NTU in Vea reservoir was slightly higher than the permissible level for aquaculture. Nutrient levels namely nitrate, nitrite and ammonium were low (< 2.0 mg l^{-1}) in both reservoirs. Phytoplankton biomass for Vea reservoir was extremely low (3.43 mg m^{-3}) compared to 81.07 mg m -3 for the Tono reservoir. Mean and range values observed in reclassification for each thematic layer of water quality parameter for modeling suitable areas for January 2016 in both reservoirs are presented in Table 4.2.5. Monthly averages of the reservoir water quality from which the worst case month (January) was adopted are presented in appendices I and II.

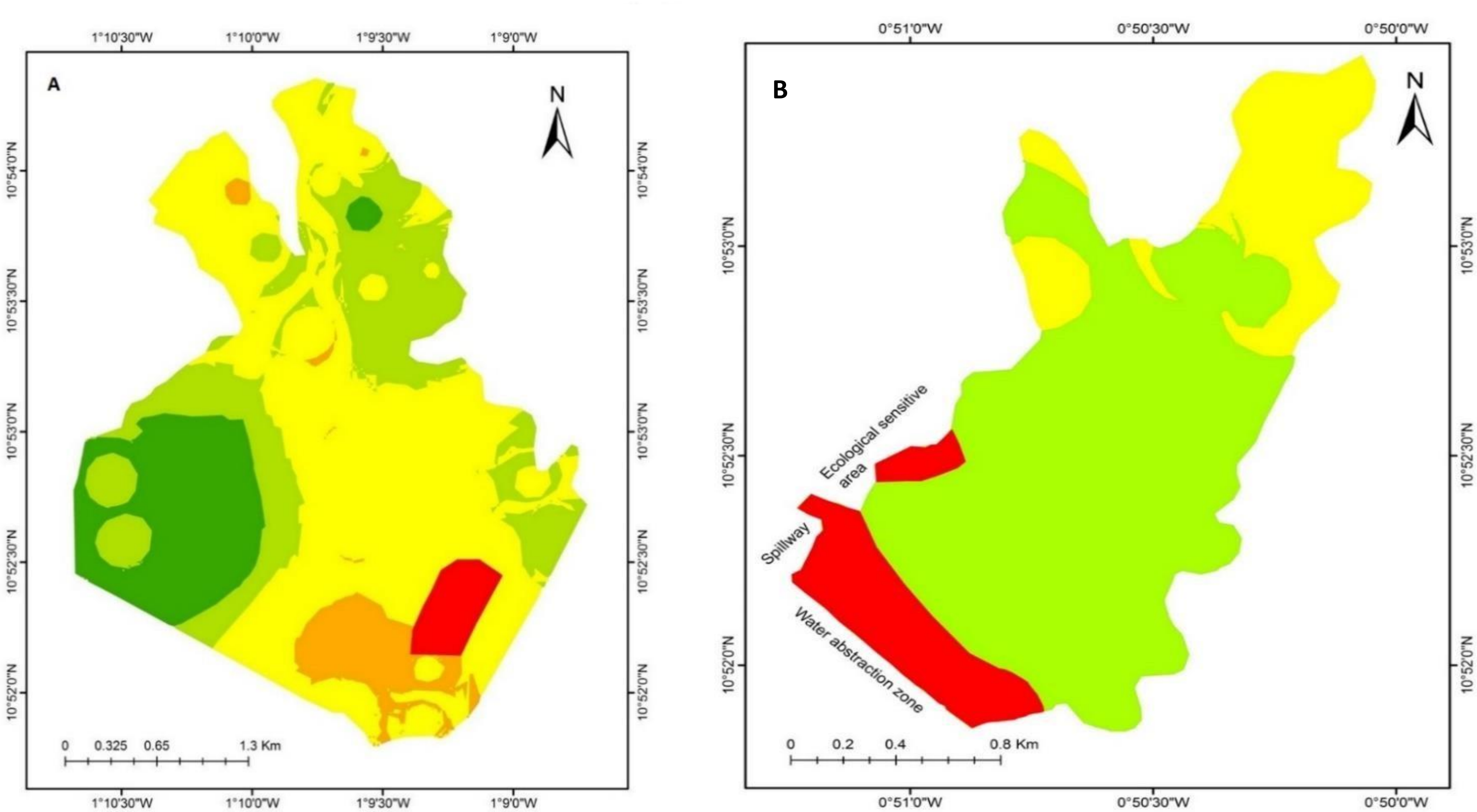
Table 4.2.5 Summary statistics of water quality parameters monitored at various sampling stations in Tono (n=27) and Vea Reservoirs (n=19), respectively (January 2016) in the Upper East Region, Ghana

	Tono reservoir		Vea reservoir	
Parameters	Mean±s.e.	Range (min-max)	Mean±s.e.	Range (min-max)
Water depth (m)	3.80±0.46	1-9.4	3.41±0.55	0.82-8.50
S.W. Temperature (°C)	21.98±0.09[a]	21.1-22.50	20.24±0.13[a]	19.2-20.9
Transparency (m)	0.50±0.03 [a]	0.19-0.75	0.44±0.03	0.3-0.87
pH		7.40-8.70		7.59-8.08
E. Conductivity (μs cm^{-1})	645.33±4.41	612-680.00	870.79±2.49[a]	835-889
TDS (mg L^{-1})	419.47±2.86	397.80-442.00	566.01±1.62[a]	542.75-577.85
DO (mg L^{-1})	7.09±0.14[a]	5.49-8.53	6.79±0.15[a]	5.1-7.89
Turbidity (NTU)	42.89±0.66	36-50	87.79±1.36[a]	80-94
Chloride (mg L^{-1})	4.05±0.19	2.96-5.98	5.27±0.13	4.94-6.95
Alkalinity* (mg $CaCO_3$ L^{-1})	48.33±1.00	42-59	59.89±1.43	52-74
Total Hardness* (mg $CaCO_3$ L^{-1})	63.37±1.30	54-76	68.42±3.19	54-94
SO_4^{2-} (mg L^{-1})	10.51±0.29	8.00-14.00	14.46±0.49	12-18.62
PO_4^{2} (mg L^{-1})	0.07±0.01	0.03-0.21	0.11±0.01	0.07-0.18
SiO_2* (mg L^{-1})	8.26±0.25	6.05-10.42	10.53±0.19[a]	9.02-12.4
NO_3-N (mg L^{-1})	0.10±0.01	0.01-0.28	0.20±0.02	0.07-0.3
NO_2-N (mg L^{-1})	0.04±0.01	0.004-0.19	0.04±0.01	0.032-0.06
NH_4-N (mg L^{-1})	0.57±0.70	0.15-2.28	0.76±0.02[a]	0.52-0.87
Chlorophyll-a (mg m^{-3})	1.21	1-1.85	0.05	0.05-0.06
Phytoplankton biomass* = Chl-a 67 (mg m^{-}3	81.07	67-123.95	3.43	3.40-3.95

N: number of samples s.e.: standard error [a]: not skewed *Not used in modelling suitable areas, E: Electrical, S.W.: Surface Water

4.2.3.2 Location of area suitability for Nile tilapia cage culture

The conceptual model created for this study generated the various suitability zones from the water quality ranges, standards and interpretation that were performed. Apart from water quality of the reservoirs as stated in Table 4.2.5; the social, economical, environmental and conservational concerns collated as cage culture development constraints (Table 4.2.6) indicates that the entire reservoir surface could not be demarcated for aquaculture purposes. The total area surveyed into portions of areas deemed more or less suitable according to a scale of suitability, ranging from 0 to 1. The model calculated the suitability based on the data on water quality, according to its ranges, the standards and the interpretation provided. For each suitability criterion for Nile Tilapia farming that was built in ILWIS, the main thematic layers generated a model output of comparative suitability for mounting the cages. Comparing the two reservoirs, Tono and Vea, it appears that the Vea reservoir is more homogeneous than the Tono reservoir, where the areas designated suitable for farming are patchier or less uniform (Figures 4.2.3).



Legend

Levels of suitability

- Unsuitable Constrains zone
- Moderately unsuitable
- Moderately suitable
- Poorly suitable
- Highly suitable

Legend

Levels of suitability

- Unsuitable constraint zone
- Moderately suitable
- Poorly suitable

Figure 4.2.3 The map of suitable area or suitability with four levels in (A) Tono and (B) Vea reservoir in the Upper East Region, Ghana

The value 0 represented constrain areas (out of bounds). Constrain areas were deemed unsuitable for cage culture when they were subjected to a range of criteria. These criteria include areas with potential social objection, points for water abstraction, areas that could mar-aesthetic view and/or environmentally sensitive location such as rocky zones or high portions for aquatic birds' roost, amphibians and other wild animal conservation. The total study area for potential cage aquaculture was 9.86 and 3.14 square kilometres for Tono and Vea reservoirs, respectively (Table 4.2.6). Results of levels of suitability ranging from unsuitable to highly suitable are presented in Table 4.2.6. Tono reservoir had 0.28 km^2 being unsuitable compared to Vea Reservoir's 0.38 km^2, representing 2.84 % and 12.10 % aquaculture zones under this study, respectively. Vea reservoir had no moderately unsuitable or highly suitable zones. The total suitable area for cage culture development was relatively larger for Tono reservoir (3.85 km^2, 39.05%) compared to Vea reservoir's 2.15 km^2 representing 68.40% (Table 4.2.6).

Table 4.2.6 Suitability index and levels of suitability for Nile tilapia cage culture

		Tono Reservoir		Vea Reservoir	
Index range	Levels of Suitability	Area (sq. km)	% area	Area (sq. km)	% area
Constrain area	Unsuitable	0.28	2.84	0.38	12.10
0 – 0.25	Moderately unsuitable	0.63	6.39	0.00	0.00
0.26 -0.50	Poorly suitable	5.10	51.72	0.61	19.50
0.51 – 0.75	Moderately suitable	2.40	24.34	2.15	68.40
0.76 – 1.0	Highly suitable 1.45	0.00 Total suitability	14.71 3.85	2.15	0.00
			39.05		68.40

4.2.3.3 Field Verification and Validation

Field surveys were conducted to verify and validate the levels of suitability modelled on the reservoir as shown in the photo layers (Plate 4.2.1). Poorly suitable and moderately suitable areas on the suitability maps were compared physically to features existing in the reservoir through ground-truthing. Ground-truthing allowed to confirm more suitable zones as provided by the data analysis (Subjective comparison of photo layers during ground-truthing). That is, Tono and Vea reservoirs had more suitable zones as depicted on the final suitability map. The study was able to exclude a small (< 0.1 km ^{2}) rocky area located in Central Eastern section of Vea reservoir (Plate 4.2.1).

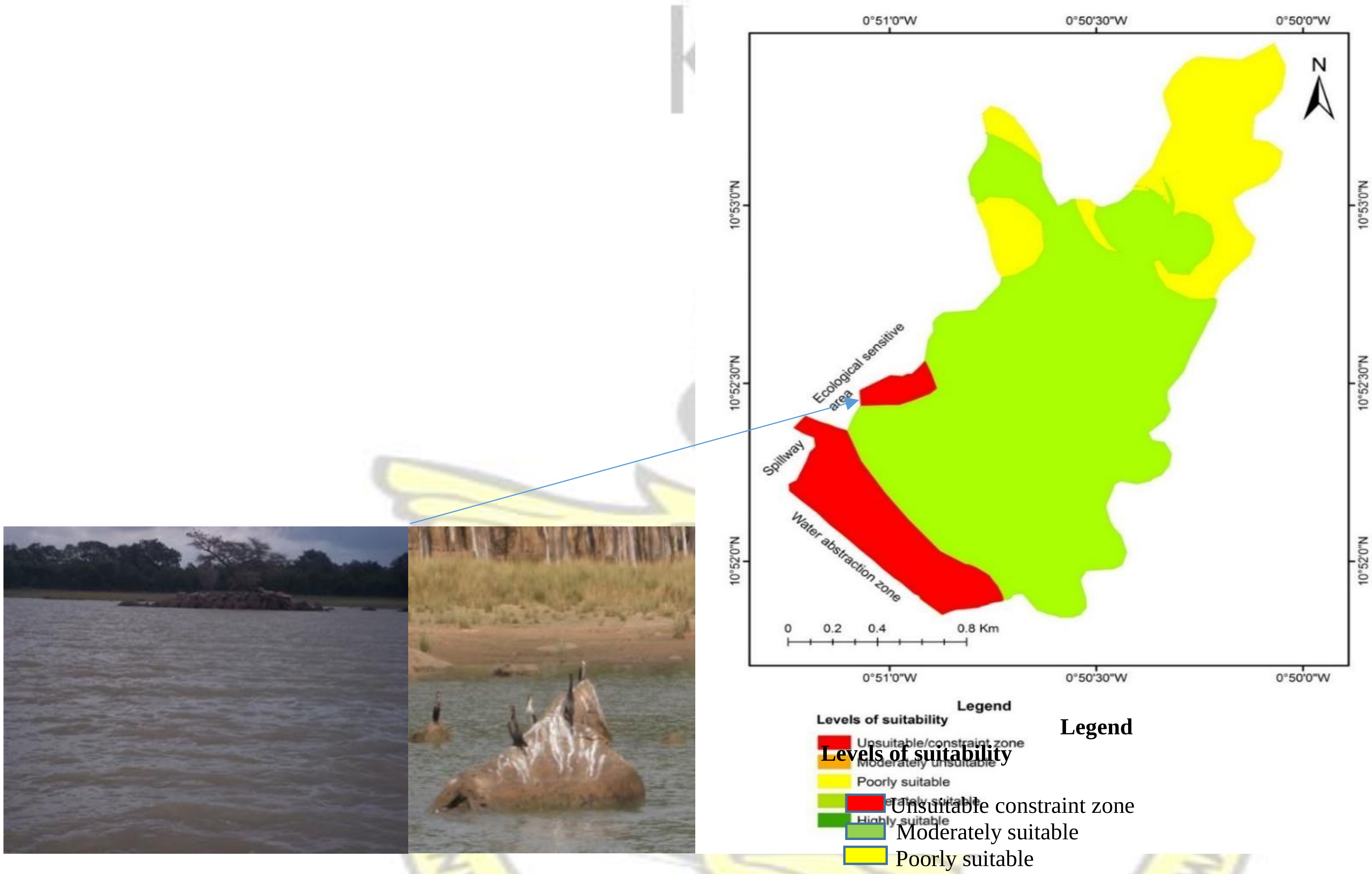


Figure 4.2.4 Photo layer verification and validation through ground truthing in Vea Reservoir in the Upper East Region, Ghana

4.2.4 Discussion

4.2.4.1 Water quality conditions for cage culture

Some optimum water quality parameters existed even under the worst-case condition adopted for both Tono and Vea reservoirs. It was observed that over a one-year study period, water quality deteriorates from the beginning of the dry season known as harmattan (November to March) with January as worst-case month. The data gathered indicates that the conditions of the two reservoirs are suitable for growing tilapia and match the requirements of the farmed fish. Tilapia can tolerate a wide range of changes in environmental conditions including water temperature (El-Sayed, 2006), can be culture in shallow water bodies (depth $\geq$ 1 m) in smaller cages (Lim and Webster, 2006). Mean water level of 3.80 m and 3.41 m, and transparency of 0.5 m and 0.44 m, measured for the Tono and Vea reservoirs, respectively were good for mooring of small size cages such as Low Volume High density cages (LVHD). Average phytoplankton biomass in Vea Reservoir (3.43 mg m^{-3}) was relatively low compared to Tono Reservoir (81.07 mg m^{-3}). As the reservoirs are used by local communities, there is no information on the seasonal changes in the multiple human activities on and around the reservoirs. These activities will eventually affect the water parameters, the nutrient loading and the phytoplankton mass as it changes. Besides these, there are inter-annually meteorological changes that do not appear in a one-year study. Increases in water evaporation or rainfall will modify the water masses and their quality. The impact of all these factors on phytoplankton abundance is not clear. However, if there is algae bloom, this could lead to the clogging of the mesh of fish cage, thereby adding to the maintenance cost of these cages due to the need for regular cleaning. Contrarily, algae bloom could be contributing to availability of natural food for wild species of tilapia in the reservoir. A recent study indicates that Nile tilapia can suppress phytoplankton and zooplankton biomass in tropical lakes and reservoirs (Vasconcelos *et al*., 2018). The conflicts of interests resulting from access to the reservoirs, directly or indirectly, coupled with fish feeding as an issue could be minimized if reservoirs are harnessed based on the utilization of suitable areas, especially for Nile tilapia culture. Since tilapia could feed on algae, the assertion from studies on Brazilian reservoirs that concluded that control or exclusion of tilapia species populations to improve water quality was problematic (Figureueredo and Giani, 2005), could be improbable.

Surface water temperature (SWT) range of 20.24 – 22.00 °C encountered (in January as the worst case scenario) for Tono and Vea reservoirs could support fish survival but may be too low to enhance physiological growth of Nile Tilapia. Due to the large air-water surface interaction and Harmattan wind mixing in the morning over Tono and Vea reservoirs (07:00 – 10:00 hrs.), dissolved oxygen (DO) levels of 7.09 - 6.79 mg L^{-1} encountered was relatively good for fish production. DO levels >5 mg L^{-1} is optimum for good tilapia growth (Lloyd, 1992). The pH range of 7.4-8.7 and 7.6-8.1, neutral to slightly alkaline was optimum for ecosystem health and fish growth. Total dissolved solids (TDS), total hardness and alkalinity (mg $CaCO_3$ L^{-1}) were within levels recommended by Ghana National Aquaculture code of practice and guidelines (2003), except turbidity which was slightly higher in Vea Reservoir (> 75 NTU).

Dissolution of inorganic nutrients in the Tono and Vea reservoirs were generally low during the study period contrary to the expected high levels due to anthropogenic activities on the catchment area. Nitrite-Nitrogen (NO_2 -N) mean concentration was stable, 0.04 mg L^{-1} at almost all zones within the reservoir but nitrate-nitrogen (NO_3 -N) varied from 0.10 to 0.20 mg L^{-1} as a result of varying degree of nutrient loading from adjoining catchment area and the long residence time for reservoir water. The variation could also be due to high oxygen inputs during the dry periods when harmattan wind stimulates the reservoir water, coupled with mineralisation-nitrificationdenitrification within organically rich sediments (Furnas, 1992). Ammonium-nitrogen levels were higher than recommended safe concentration of 0.05 mg/l for freshwater fish (Lawson, 1995). Based on the phosphate level of 0.07 and 0.11 mg L^{-1} in Tono and Vea reservoirs, respectively; both reservoirs are already eutrophic over the last twenty-four months since levels exceeds 0.02 mg L^{-1} (Muller and Helsel, 1999). Previous studies indicated that Vea reservoir was becoming eutrophic (Agbeko, 2012). Although phosphates are not toxic to aquatic organisms, increased levels could lead to excessive algal bloom which depletes the dissolved oxygen in the water for respiratory and other physiological functions of the fish. However, nutrient utilization through cage aquaculture could be beneficial at various suitable zones. This is because plankton growth stimulated by phosphates could serve as natural food for cultured fish. Thus, cages mounted in eutrophic waters could be managed through semi-intensive system involving practices such as zero feeding or provision of supplementary feeding using extruded floating pelletized feeds.

4.2.4.2 Suitability for cage culture

The selection of suitable zones is a prioritized criterion required for specific farming. The choice of tools for this exercise must be made considering efficiency and cost. Managers of reservoirs, fishery and aquaculture regulatory agencies, or the Water Resources Commission must serve as duty-bearers to enhance cost-efficiency. Based on this suitability study; three levels of suitable zones for cage culture were inferred. This study corroborates with a reclassified three tier zoning scheme for Lake Volta (Ross and Falconer, 2016). Levels of suitability may not necessarily be related to the size of reservoirs but rather the depth of the water body being considered for cage culture. This study spatial modelled the entire Tono and Vea reservoirs, with some similarities in terms of levels of suitability compared to studies on Lake Volta which modelled prioritized areas of the lake (Ross *et al.* 2016), which were larger than Tono and Vea reservoirs.

Despite these two reservoirs were relatively shallow (< 10 m of average water depth) and smaller in size in terms of surface area (<50 km^2), total percentage suitability was higher for Vea reservoir (68.40%) compared to Tono reservoir (39.05%) for cage aquaculture. Tono reservoir being thrice larger in size (surface area) than Vea reservoir, had more than half (51.72 %) of its total percentage area being unsuitable for cage culture. This higher level of poorly suitability encountered in this study for Tono reservoir could be due to illegal and unregulated anthropogenic activities on the reservoir catchment, which affected the overall potential suitability of the reservoir. Some anthropogenic activities coupled with fish farming in reservoirs could trigger eutrophication in reservoirs (Degefu *et al*., 2011). However, the poorly suitable levels can be improved upon to become moderately suitable for cage culture through appropriate aquaculture management interventions and regulation of human activities (farming and sand mining) on the reservoir catchment. The total area available for cage farming was 9.58 km^2 and 2.76 km^2 for Tono and Vea reservoirs, respectively. The potential amount of fish production in cages for each reservoir can be inferred from the total suitable area. This could help set production targets. Vea reservoir will be more preferred for cage culture than Tono reservoir in terms of suitability levels. With little complementary evidence from this suitability study, the size of a reservoir may not necessarily guarantee a better suitability level. This provides information for decision-making as reiterated by previous studies that indicates that, GIS-based models could be reliable tools for assessment of suitable zones for floating cage culture (Baxter *et al.*, 2008; Bekkby *et al.* 2008, Falconer et al., 2013).

The results of this study indicate that site specific spatial and temporal GIS-based models developed could be a predictive tool applicable in shallow reservoirs in Africa for siting cages for Nile Tilapia culture. The fisher folks confirmed that the poorly suitable area predicted in Vea reservoir often experiences higher water recession rate and noted to have less concentration of fish, thus would probably not support aquaculture. Out of the five fish landing bays in Tono reservoir, three bays were within the suitable zone which could minimize the potential areas available for cage farming. Areas close to the spillway in Tono reservoir was moderately unsuitable with no scenic view objection concerns. Comparatively, similar location in Vea reservoir was unsuitable because it had water abstraction zone and scenic view objection concerns. Thus, the entire downstream section in Vea reservoir was demarcated as constrain zone for cage culture. According to Radiarta *et al.* (2008), management option will be required when water-user conflict occurs in the same location following suitability analysis of the area. In such situation, the choice has to be based on environmental requirements for the activity. For example, Pérez *et al.* (2003) analyzed the potential area for development of marine fish cages in terms of their co-existence with the tourism industry in the Canary Islands.

The multi-criteria technique used in this study, may provide some empirical evidence for decision-making where cage aquaculture in reservoirs could probably not be acceptable, although such areas could be environmentally suitable for cage culture. For larger freshwater ecosystems such as Lake Volta, moderately suitable areas are probably considered marginal for aquaculture use (Ross and Falconer, 2016). This study posits that smaller reservoirs like Tono and Vea that had moderately suitable areas that are idle could be readily developed with better aquaculture management intervention and strategies for Nile tilapia cage culture, to sustainably produce fish.

4.2.5 Conclusions and Recommendations

4.2.5.1 Conclusions

This GIS-based study indicates the existence of suitable conditions and zones for Nile tilapia cage culture in Tono and Vea Reservoirs. The potential for aquaculture development through

Nile tilapia farming in cages in these reservoirs is enormous as Tono and Vea reservoirs under worst-case condition had total suitability of 39.05% (3.85 kilometer square) and 68.40% (2.15 kilometer square), respectively. Thus, Vea reservoir was more suitable for cage aquaculture than Tono reservoir probably due to the intensification of anthropogenic activities on the Tono reservoir catchment area.

4.2.5.2 Recommendations

- To harness the full potential of suitable zones for freshwater fish production, it is recommended that an aquaculture management area (AMA) plan could be developed by Ministry of Fisheries and Aquaculture Development (MoFAD), Irrigation Company of Upper Region (ICOUR) and the Water Resources Commission (WRC) to notch up sustainable aquaculture.
- This study recommends further comparative case-study of Nile tilapia growth performance between unsuitable and moderately suitable zones modelled, so as to improve upon future suitability studies using expanded GIS-based methods.
- Further studies on the cost-benefit analysis of this GIS approach postulated in this study for Nile tilapia cage culture suitability in reservoirs is needed for better decision making.

4.3 Aquaculture carrying capacity determination for Tono and Vea reservoirs

4.3.1 Introduction

Reservoirs are artificial lakes that store surface and ground water. Most tropical reservoirs are created from the impoundment of streams and rivers in order to store water for domestic use, irrigation and to control floods during the rainy season. Current trends in the utilization of tropical reservoirs includes sediment and nutrient retention in reservoirs; where these reservoirs act as active bio-filters, in which the hydrological, ecological and biogeochemical processes work together to retain a significant fraction of these elements (Okuku *et al.,* 2018). Apart from the provision of ecosystem services such as the provision of fish, optimum water quality, a medium for growth and waste treatment, most tropical reservoirs are under increasing pressure for cage fish culture as in the case of the Tono and Vea reservoirs. However, the supply of ecosystem services by reservoirs could be limited by their carrying capacity (CC). The carrying capacity of an ecosystem unit (i.e. reservoir, lake, pond) is the maximum population of a given organism that the environment can sustain indefinitely within a given habitat. Carrying capacity is an important concept for ecosystem-based management which facilitates defining the upper limits of production, ecological limits, and the social acceptability of the venture without causing any unacceptable change to both the natural ecosystem, social functions and structures (Byron and Costa-Pierce, 2010).

Most studies are encouraging the use of perennial reservoirs and lakes for cage aquaculture (Boyd, 2007; WorldFish Center, 2010; Agbeko, 2012; Akongyuure *et al.,* 2015; Alhassan *et al.,* 2018) and non-perennial reservoirs (those that often dry up completely during dry season) for culture-based fisheries (De Silva *et al.,* 2006; De Silva and Amarasinghe, 2009). To harness the potential of reservoirs for cage aquaculture, it is necessary to improve understanding of the processes influencing reservoir productivity in such a way as to involve biological principles and stakeholder participation, as each reservoir has different properties (van Zwieten *et al.,* 2011). The lack of effective carrying capacity-based zonal planning presents a major risk to potential aquaculture producers and the entire supply chain (Han and Immink, 2013). Most analyses do not factor in the impacts of fluctuating reservoir levels or long-term changes in productivity resulting from continuing sediment loading and associated changes in carrying capacity (van Zwieten *et al.,* 2011). Scientists, regulators, aqua industries and other stakeholders should jointly determine the carrying capacity (CC) for all areas under an administration's control (Han and Immink, 2013). Integration of more than two types of CC could provide a more robust strategy for sustainable development and management of aquaculture. Several authors have recommended four types of carrying capacity, which are; physical, production, ecological and social (Soto et. al., 2008; Ross et al., 2013; FAO, 2015a). Physical carrying capacity (PCC) refers to the potential of an area/site to sustain aquaculture in the appropriate physical characteristics (including minimum infrastructure and access). This is the primary selection criterion for an aquaculture activity, for site selection and aquaculture zoning. Production carrying capacity (ProCC) deals with the maximum yield that can be produced in a selected water body (Ross *et al.,* 2013; FAO, 2015a).

Estimates of maximum aquaculture production given the source of food is considered typically at the farm level but should go beyond this. Ecological carrying capacity (ECC) is the population or biomass of a species that a specific habitat can sustain without damaging the ecosystem or the magnitude of aquaculture production that can be supported by the environment. Social carrying capacity (SCC) assesses the quantity and type of aquaculture (total production, number and density of farms, species and systems) that a social system can take without incurring significant negative social changes (FAO, 2015a; Prema, 2015). The integrated estimation of these four carrying capacities is postulated as the aquaculture carrying capacity (ACC) for this study.This study seeks to estimate the optimum aquaculture carrying capacity for cage culture development on the Tono and Vea Reservoirs.

4.3.2 Materials and Methods

4.3.2.1 Study area

The study was conducted on the Tono and Vea reservoirs in Upper East Region (UER), Ghana (Figure 4.3.1). The Tono and Vea Reservoirs are among the largest man-made water storage systems of ecological and socio-economic importance in the Sudan-savanna ecological zone of Northern Ghana (Figure 4.3.1). The Tono reservoir is located between geographical coordinates of 10^{0}53′39″ North and 1^{0}9′57″ West, in the Kassena-Nankana District, UER. Whiles, Vea reservoir is located between geographical coordinates of 10^{0} 52′0″ North and 0^{0}51′0″ West, in the Bongo District, UER. Tono and Vea reservoirs were created by impounding tributaries of the Sissile and Yarigatanga rivers, respectively. The area generally has an average temperature of 27°C - 31.9 °C. However, the dry season experience extreme temperatures ranging between 15 – 44°C, characterized with hazy winds (December-Mid March).

Tono and Vea reservoirs are irrigation schemes under the management of Irrigation Company of Upper Region (ICOUR) with irrigable areas of 2,490 and 468 hectares, respectively. Thus, these reservoirs were built for irrigation and livestock watering with a few earthen ponds for fish culture. The ponds are located downstream of the dam, most of which have been abandoned or under-utilised due to operational difficulties during the study period (Field observation: March 2016).

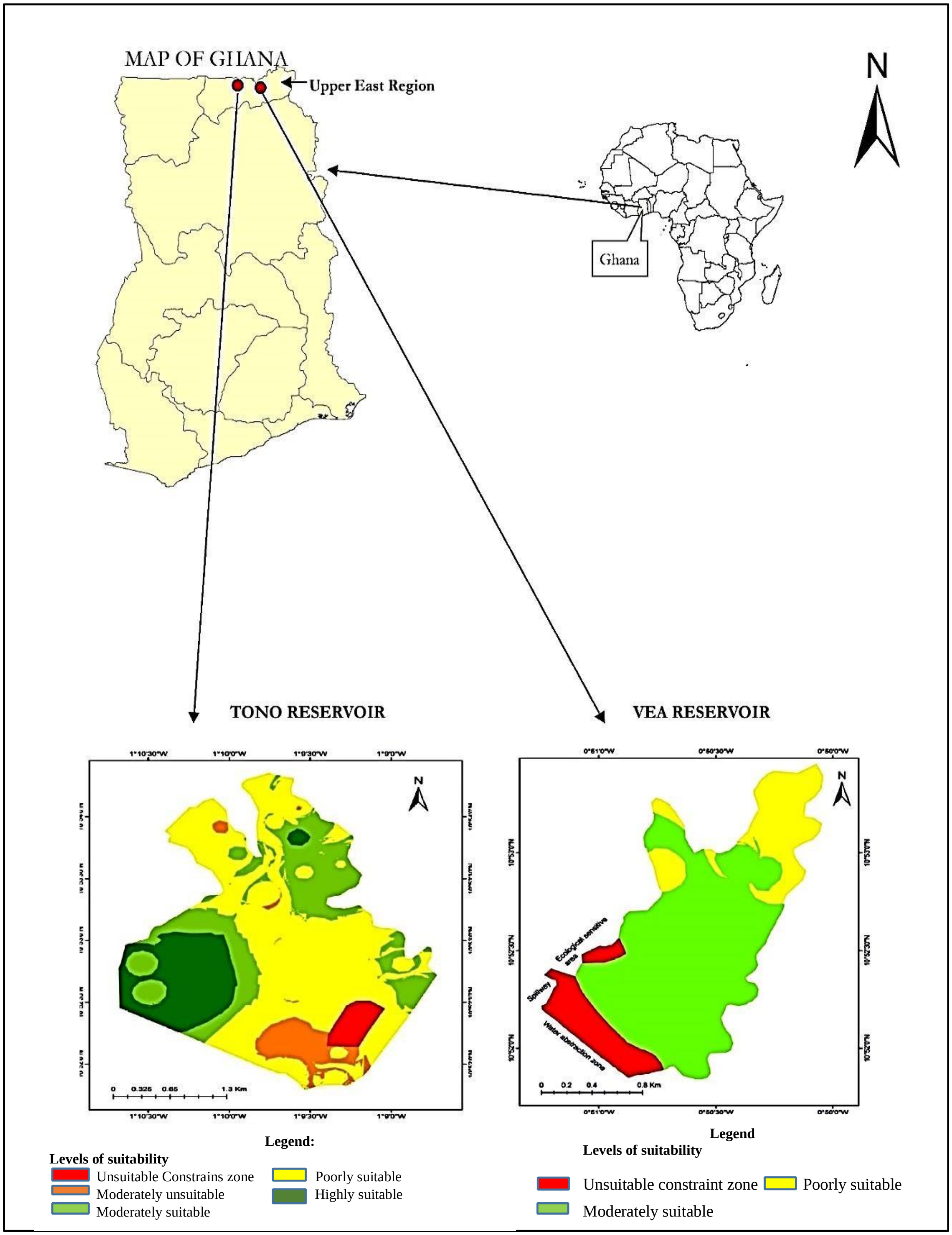


Figure 4.3.1 Tono and Vea reservoirs showing suitable aquaculture zones in green colour (obtained from sub-section 4.4.2).

There are five fish landing sites in Tono (i.e. bay 1-5), out of which four are operational, whiles Vea has three fish landing sites all operational; for capture fisheries. In recent times, these reservoirs have come under increasing pressure for culture-based fisheries (cage aquaculture). The Vea reservoir serves as source of raw water which is abstracted, treated and supplied to the Bolgatanga township and its environs, although, the water storage potential of Vea reservoir is smaller than that of Tono reservoir (Table 4.3.1).

Table 4.3.1 Water storage characteristics for Tono and Vea reservoirs, Upper East Region, Ghana.

Characteristics	Reservoir		
	Tono	Vea	Units
Maximum reservoir storage capacity (Live storage)	$83x10^6$	$17x10^6$	m^3
Minimum reservoir storage capacity (Dead storage)	$10x10^6$	$1x10^6$	m^3
Maximum surface area of main reservoir	1,860	405	Ha
Catchment Area	650	136	km^2
Fish pond (number of ponds: p)	4.8 (23 p)	3.8 (16 p)	Ha

Sources: Author's construct (Modified from Kumah *et al.*, 1990; Abache, 2014; ICOUR, 2015)

4.3.2.2 Data Collection

For the estimation of carrying capacity for aquaculture, data describing the physical, biological, economic, social and infrastructure for fish production in cages were considered and adopted (Table 4.3.2). These data were derived from primary and secondary sources. Primary data was obtained from in-situ measurement of water depth using metric tape measure, transparency using Secchi disc, water temperature and pH using HANNA probe meter (version H+I991002 and HI98192), and some selected water quality parameters such as phosphorus concentration (P), turbidity and dissolved oxygen were obtained from monthly water quality monitoring for 18 months from February 2015 to April 2016. All water samples were taken between 06:00 to 10:00 and were analysed according to standard methods (APHA, 1998).

Secondary data sources include; reservoir maps obtained from suitability studies (Sub-section 4.2), feed conversion rate (FCR) obtained from previous cage culture studies on Vea reservoir (Agbeko *et al.*, 2014a), phosphorus concentration in fish feed that could be released into the water as phosphorus loading from cage culture was obtained from textual databases (Schmittou, 2006) as recommended by Prema (2015), reservoir volume for the year 2015 and 2016 as inputs for estimation of flushing rate (ICOUR, 2016) and information on access rights including visual effects of proposed "cage culture undertaken" were inferred from personal interviews with key informant as detailed in section 2.3 were used.

These primary and secondary information were factored as an integrated approach involving five determinants from the four types of carrying capacities (PCC, ProCC, ECC, and SCC). This approach is postulated as a framework to obtain overall aquaculture carrying capacity (ACC) estimates for lentic water bodies such as reservoirs (Figure 4.3.2).

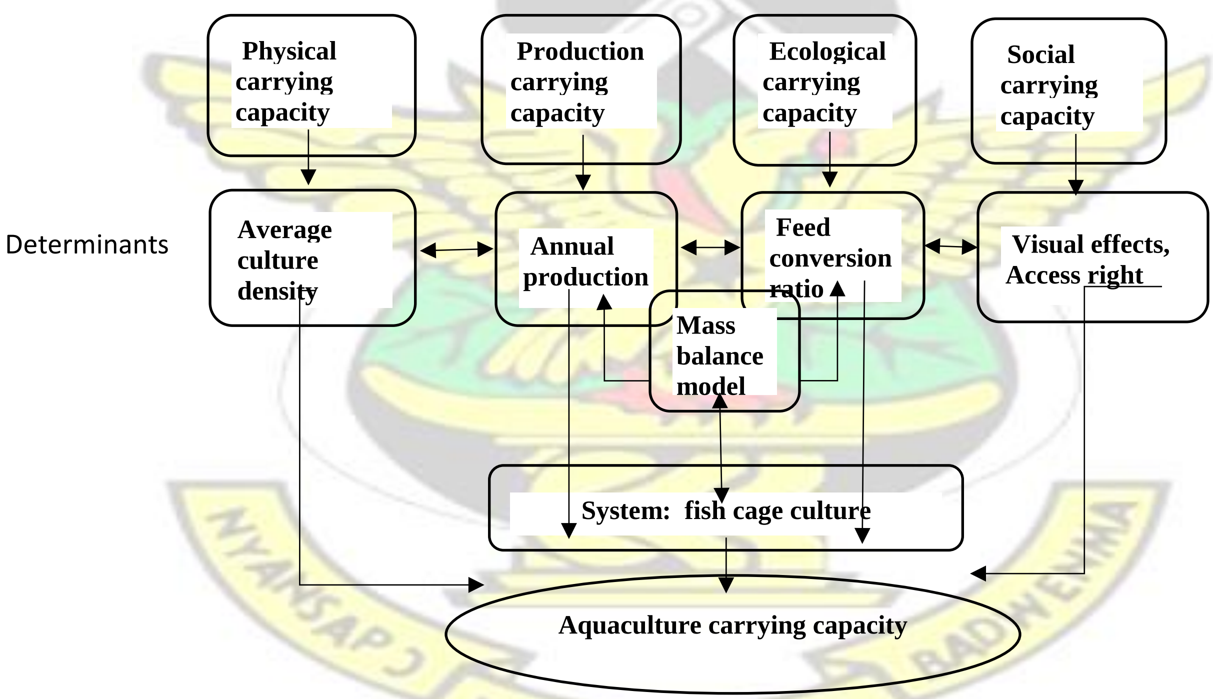


Figure 4.3.2 Conceptual framework showing determinants for aquaculture carrying capacity estimation in Tono and Vea Reservoirs, Upper East Region, Ghana

4.3.2 Spreadsheet computation for carrying capacity

Actual values for carrying capacity determinants were computed in a spreadsheet. The spreadsheet used in this analysis is presented in Table 4.3.3. Computations in spreadsheet for the determinants were based on water quality measurements (particularly nutrient concentrations and water depth). Additionally, estimates from feasibility studies on cage culture on Vea reservoir (Agbeko *et al.*, 2014a) and by extrapolation for the Tono reservoir, information based on expert knowledge of the reservoirs such as reservoir volume was obtained from the Irrigation Company of Upper Region (ICOUR) and personal observations in the field. Personal interviews with key informant such as fisheries officers, researchers and managers of these two reservoirs under ICOUR was done to solicit information on possible or expected aquaculture (fish) production target, reservoir volume and other physical characteristics of the reservoir. Data for social carrying capacity consideration were collated from a total of 30 fisher and fish-folks through oneon-one randomized informal interview on a monthly basis during water quality sampling (February 2015 – April 2016), to have an idea of the amount of space and access right needed for capture fisheries on each reservoir. These CC determinants were quantified and formularized into equations 1-7, below. For nutrient concentrations, phospohorus is one of the limiting factors of water quality for most freshwater systems. Thus, total phosphorus was chosen because it is often used in the determination of carrying capacity for aquaculture purposes (Hidrosfera, 2003; Ekpeki and Telfer, 2016).

Table 4.3.2 Data sources for production carrying capacity (CC) estimation with Social carrying capacity consideration for Tono and Vea reservoirs: (a) modified from mass balance equation of Dillon and Rigler (1974) to obtain production and social carrying capacity (b) integration of models to obtain final aquaculture carrying capacity.

Phosphorus (P) Mass Balance Calculations	Formula/Calculation /Source

(a) [P] initial (Field measurement)	Direct field measurement
[P] final (Standard / stakeholder guesstimates)	500
Δ [P]	=[P] final – [P] initial
Volume (V)	Estimated (Water budget: ICOUR, 2015/2016)
Mean depth (z)	Direct field measurement
Reservoir surface area (A), Social CC	Direct Field measurement
Flushing rate (ρ)	= net Increase / (z*A)
P losses to the sediment (R)	= V (1 + 0.515 ρ0.551), V=0.2
P released by caged fish retained in sediment (Rfish)	Rfish = x + [(1-x) R] ; x=0.5
Predict allowable loading of P from cage culture (Lfish)	Δ[P] z ρ / (1 – Rfish)
Apply loading estimate to the area of the reservoir (Lrev.)	Lfish x A
P production per ton feed (Pload)	(Schmittou, 2006)
Production CC (Pr. CC) and Social CC (So. CC)	Lrev./Pload per tonne of fish
Integration of CC for final aquaculture CC	Formula/Calculation /Source
(b) Annual carrying capacity (Pr. CC and So. CC)	Calculated from Table 3(a) above
FCR, Actual (Ecological CC)	(Agbeko *et al.*, 2014a)
Feed rate as % of body weight (6 months culture)	Cummulative %ABW for 6 months
Feeding rate (FR)	20% average, 27-28 °C, guesstimates
Average culture density (ACD)	(Veverica *et al.*, 2011)
Physical CC or Feed load per year (Fl.yr)	Pr.CC*FCR
Feed load per day (Fl.d)	Fl.yr/365 days
Standing stock (SS)	Fl.d/FR
Final aquaculture CC (Cage volume)	SS/ACD
Total Cage volume per reservoir (1m-3 cages)	

P: Phosphorus; ICOUR 2016: Sebastian Bagna, Personal communication, 27 March 2018.

The general equation used for estimation of production carrying capacity (ProCC) was derived through the application of simple mass balance model of Dillon and Rigler (1974). This equation (Equation 1) is a derivative based on phosphorus and other smaller equations to obtain the ProCC as shown below:

$P = L\,(1-R) / \bar{z}.p$ Dillon and Rigler (1974) …………. (Equation 1)

Where; [P] = total phosphorus concentration (µg/L), L = total phosphorus loading (g/m^2 per yr), R = fraction of total phosphorus retained by sediments (0-1), $\bar{z}$ = mean depth (m), ρ = flushing rate (reservoir volume/yr) and P is phosphorus.

Due to the small size of the reservoirs relative to other lentic water bodies such as lake Volta, each reservoir was considered as one ecological unit, and not sections or site. This approach was to ensure a holistic estimation of the carrying capacity in each reservoir and for sustainable management of the reservoir ecosystem.

To provide inputs into the general production carrying capacity equation, the following smaller or simple equation below (Equation 2 to 6) were deployed to obtain their respective input values for Equation 7. The following procedures were implemented and equations were computered for each reservior (adopted and modified from Hargreaves, 2017) as follows:

I. Concentration of phosphorus in the Reservior: Direct or field measurement was 0.068 mg l^{-1} and 0.104 mg l^{-1} for Tono and Vea Reservoirs, respectively.

II. Establish the phosphorus (P) concentration limit for each reservoir: 1.0 mg l^{-1},

III. Determine the allowable increase in total P concentration from cage culture

$$\Delta [P] = [P]_{final} - [P]_{initial}, \quad \text{(Equation 2)}$$

IV. Determine the sedimentation rate (R): proportion of P released by caged fish that is retained by the sediment, (a) -a function of flushing rate

-sediment is the ultimate place for most P

$$R = 1 / (1 + 0.747\, \rho 0.507) \quad \text{(Equation 3)}$$

(b) Determine the proportion of phosphorus (P) released by caged fish that is retained by the sediment (Rfish).

$$R_{fish} = x + [(1-x)\ R] \quad \text{(Equation 4)}$$

where x = 0.5

V. Predict the allowable loading of P from cage culture.

Re-arranging the Dillon and Rigler equation:

$Lfish = \Delta\ [P]\ z\ \rho\ /\ (1 - Rfish)$ ……………………………………………… (Equation 5)

Units are mg/m^2 per yr

VI. Apply loading estimate to the area of the reservoir.

$Lrev. = Lfish \times A$ ………………………………………………………… (Equation 6)

Units: mg P / yr

P Loading estimate was applied to the whole reservoir

VII. The P released per unit tilapia production in cages (kg/t) depends on:

- P content of feed (0.5-1.0%) form (digestibility) of P in feed
- Feed Conversion Ratio (FCR)
- P concentration of fish (0.75-0.80% wet weight)

VIII. Calculate production (ProCC) and social (SCC) carrying capacity:

= allowable loading / fish excretion

$CC = Lp\ /\ EP$ …………………………………………………………………… (Equation 7)

units: t fish/yr

IX. Integrate ProCC and SCC with ECC (using FCR) and PCC (using feeding rate, average culture density, standing stock) to obtain final aquaculture Carrying capacity (ACC) ACC = Standing stock /Average culture density

The above formulae (equations I-IX) were computed on spreadsheets as summarized in the Table 3. The spreadsheet models were adapted and modified from mass balance equation (Dillon and Rigler, 1974; Hargreaves, 2017) with other secondary data that were collated from other authors, personal experience and observations made studying these reservoirs in the Upper East region of Ghana. The values and inferences obtained were formulated into the spreadsheet as model for the determination of the final aquaculture carrying capacity (Table 4.3.3).

4.3.3 Results

4.3.3.1 Reservoir water quality in relation to carrying capacity

This study results indicated that Tono and Vea reservoirs are shallow with a mean water depth of 5.5 m and 3.7 m, respectively. There was a gradual monthly increase in water depth, with a peak (8.9 and 5.4 m in Tono and Vea reservoirs, respectively) in the month of October, followed by a gradual decrease in both reservoirs (Figure 4.3.3). Transparency in terms of Secchi disc depth (SDD) was relatively stable, < 2 m in both reservoirs (Figure 3). Water temperature ranged from 26.7 and 27.6 °C, with dissolved oxygen (DO) concentration of 7.6 and 8.7 mg L^{-1} (06:0010:00) and turbidity of 147.1 NTU and 157.7 NTU were recorded for Tono and Vea reservoirs, respectively. The pH ranged between 6.5 - 8.7 and 6.86 - 8.17 for Tono and Vea Reservoir, respectively. The concentration of nitrite-nitrogen and phosphorus (N: P) were 0.03: 0.09 mgl^{-1} and 0.26: 0.05 mg L^{-1} for Tono and Vea reservoirs, respectively.

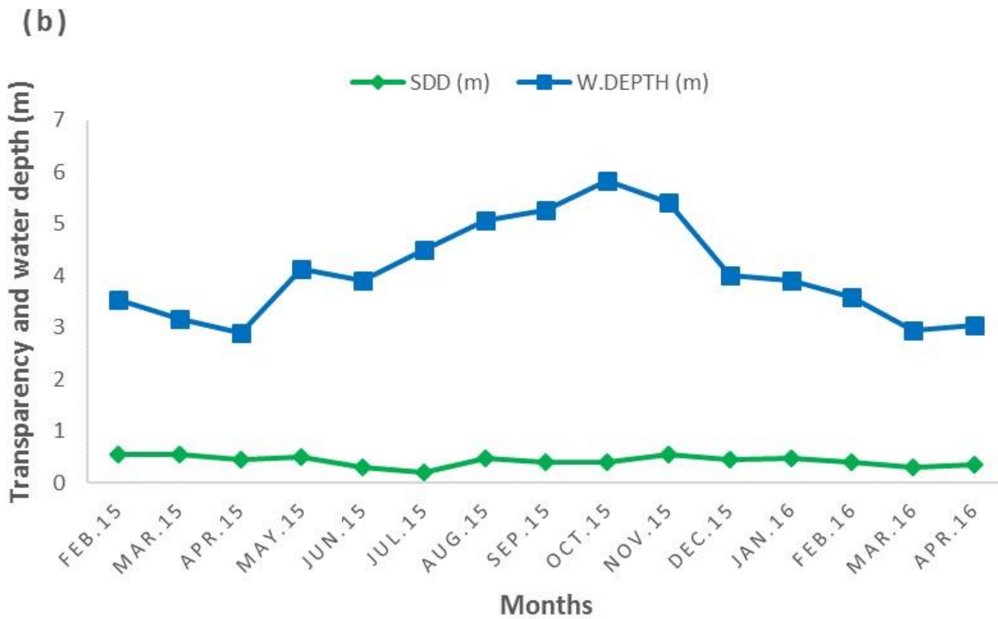


Figure 4.3.3 Transparency (SSD) levels and water depth trends from February 2015 to April 2016 in (a) Tono reservoir and (b) Vea reservoir, in the upper East Region, Ghana.

4.3.3.2 Carrying capacity for Tono and Vea Reservoirs

Summarised in Table 4.3.4 are the results of the production carrying capacity (ProCC) and social carrying capacity (SCC) estimates obtained for the Tono and Vea reservoirs. The Tono reservoir is almost three times larger than Vea reservoir. Although, water flashing rate (ρ) and phosphorus (P) losses to the sediment (R) per year were almost the same for both reservoirs, P released by caged fish retained in sediment (Rfish) varied for Tono (0.64) and Vea (0.15) reservoirs (Table 4.3.4). Thus, the integration of production and social carrying capacities estimate obtained were 2,902.98 and 264.51 metric tonnes of cultured fish per year for Tono and Vea reservoirs, respectively. However, for sustainable aquaculture involving the integration of ecological carrying capacity (ECC) and physical carrying capacity (PCC) (Table 4.3.5); the results indicate that the Tono and Vea reservoirs could have a standing stock of 71.58 and 6.52 metric tonnes of fish per year, respectively. These translates into final aquaculture carrying capacity (cage volume) estimates of 719.40 and 65.55 cubic metres for Tono and Vea reservoirs, respectively (Table 4.3.5).

Table 4.3.3 Estimation of production and social carrying capacities for the Tono and Vea reservoirs, Upper East region, Ghana (modified from mass balance equation of Dillon and Rigler (1974).

Phosphorus (P) Mass Balance Calculations	Reservoir values		
	Tono	Vea	Units
[P] initial (Field measurement)	91.53	51.5	mg m^{-3}
[P] final (Standard / stakeholder guesstimates)	500	500	mg m^{-3}
Δ [P]	408.47	448.5	mg m^{-3}
Volume (V)	123.3*10^6	23*10^6	m^{3}
Mean depth (z)	5.5	3.66	m
Reservoir surface area (A), Social CC	9.86	3.14	km^{2}
Flushing rate (ρ)	0.75	0.7	flushes yr^{-1}
P losses to the sediment (R)	0.29	0.28	-
P released by caged fish retained in sediment (Rfish)	0.64	0.15	-
Allowable loading of P from cage culture (Lfish)	4710.71	1347.82	mg m^{-2} yr^{-1}
Loading estimate to the area of the reservoir (Lrev.)	46447.64	4232.17	mg P yr^{-1}
P production per ton feed (Pload)	16	16	kg P feed $^{-1}$
Production CC (Pr. CC) and Social CC (So. CC)	2902.98	264.51	T yr^{-1}

P: Phosphorus, -: Not applicable,

Table 4.3.4 Integration of estimated production and social carrying capacities with ecological and physical carrying capacities for the estimation of final aquaculture carrying capacity for the Tono and Vea reservoirs, Upper East Region, Ghana.

Integration of CC for Final aquaculture CC	Reservoir values		
	Tono	Vea	Units
Annual carrying capacity (Pr. CC and So. CC)	2,902,977.36	264,510.34	kg fish yr $^{-1}$
FCR, Actual (Ecological CC)	1.8	1.8	-
Feed rate as % of body weight (6 months culture)	20%	20%	kgfeed/kgfish/d
Feeding rate (FR)	0.2	0.2	-
Average culture density (ACD)	99.5	99.5	kg fish m $^{-3}$
Physical CC or Feed load per year (Fl.yr)	5225359.25	476118.62	kg feed yr $^{-1}$

Feed load per day (Fl.d)	14316.05	1304.43	kg feed d^{-1}
Standing stock (SS)	71580.26	6522.17	kg fish
Final aquaculture CC (Cage volume)	719.40	65.55	m^{-3}
Total Cage volume per reservoir (1m-3 cages)	719	66	cages

-: Not applicable

4.3.4 Discussions

4.3.4.1 Water Quality

The quality and quantity of water in a given lentic ecosystem could affect the carrying capacity for fish culture (Beveridge, 1984). Some reservoirs in Northern Ghana such as Bontanga, Libga, Golinga and Sankana reservoirs are characterised by low water depth similar to the mean values measured for the Tono and Vea Reservoirs (5.5 m and 3.7 m). The low water depth encountered in this study shows that both reservoirs are shallow (<10m). Fluctuation in water depth in most tropical reservoirs are related to quantity of run-off (rainfall) in the catchment of the reservoir.

Differences in water quantity and quality could cause natural productivity of reservoirs to change over time, particularly the general hydrodynamic variability in reservoirs (Kolding and van Zwieten, 2006). Reservoirs share a number of attributes with natural lakes and are in general, subjected to water quality requirements in relation to a variety of human uses (Thornton et al., 1996).

When water bodies are assessed for cage aquaculture, transparency in terms of Secchi depth (SDD) > 0.5 m is ideal for cage culture. In this study, transparency levels were relatively stable as the mean SSD were 0.6 and 0.4 m for Tono and Vea reservoirs, respectively. This could be attributed to the fact that, suspended solids (organic and inorganic matter) in turbid flood waters flowing into Tono and Vea reservoirs had shorter settlement time. According to van Zwieten et al. (2011) the arrival of flood waters from River Nile in Lake Nasser, resulted in the lowering of the Secchi depth 0.7 – 1.40 m to 0.2–0.3 m or even to 0.5 –0.1 m within a few hours. For fishes that are confined in cages, a relative shorter settlement time in terms of changes in water transparency is idea to minimize stress that could be triggered by sudden changes in sunlight penetration into the cage and cascading photosynthetic effects. This process could lead to changes in fish behaviour and growth performance in cages (Schmittou, 2006). Seasonality could have influenced quantity of water available for fish cage culture as high water levels were recorded in September and October (flood season) for Tono and Vea reservoirs. However, monthly fluctuations in water depth ranging between 3.2 - 8.9 m and 2.5- 5.4 m for the Tono and Vea reservoirs, respectively, corresponded with the dry season and rainy seasons regimes in Northern Ghana. This is corroborated by the observed seasonal fluctuations in water levels in most tropical reservoirs (van Zwieten et al., 2011).

Although, Tono and Vea reservoirs are considered shallow with tropical limnological conditions, they have good water quality i.e., water temperature of 27.6 - 26.7 °C and high dissolved oxygen levels (7.6 - 8.7 mg l^{-1}). The above water temperature and dissolved oxygen (DO) levels (> 5 mg l^{-1}) recorded in this study are optimum for Nile tilapia growth (Lim and Webster, 2006). According to Thornton et al. (1996), hypolimnetic deoxygenation is more common in tropical and sub-tropical reservoirs because of the higher rates of decomposition occurring at the high ambient temperatures of those reservoirs. High levels of DO and optimum temperature, should not warrant high carrying capacity or high stocking density in cages in such reservoirs without explicitly calculating the carrying capacity for cage aquaculture. In most reservoirs and lakes, particularly in lake Volta, Ghana, it is purported that high stocking densities, acute periods of high water temperature (>28°C) and other environmental stressors were predisposing fish in cages to disease outbreaks. Both reservoirs under this study had a pH range that is (pH 6.5 – 8.7), optimum for fish culture (Jobling, 1995). There should be a pragmatic reservoir management strategy for sustainable cage fish production which should hinge on other water quality parameters as indicators for determination of aquaculture carrying capacity.

Further analysis indicates that, although the Tono and Vea reservoirs are within the same water basin (i.e. White Volta basin), variability in water level and nutrient loading were observed. This variability was due to differences in the quantity of rainfall received in each reservoir coupled with the type and level of intensity of anthropogenic activities in the watersheds (Jiang-Qi et al., 2013). For example, Tono reservoir had more dry season vegetable farming activities taking place on the littoral zone than in Vea reservoir. Thus, anthropogenic activities could affect the physical and ecological carrying capacities of a reservoir, apart from the size of the reservoir.

According to Béné et al., (2009), the patterns of water level fluctuations and existing anthropogenic situation of the Dahob and Pahuj reservoirs (India) resulted in variability in key biophysical parameters, which strongly affected the overall production potential of the ecosystems. Mean values of water quality encountered in both reservoirs during this study can support any aquaculture carrying capacity development programs or activities.

4.3.4.2 Aquaculture carrying capacity

Estimation of carrying capacity for most lentic water bodies such as reservoirs, have not been conducted for aquaculture development due to the perception that these water bodies may not be ideal for cage culture because they are shallow (<10 m) in terms of water depth and threat from pollution which could lead to conflicts (Beveridge,1984; FAO, 2010). From the phosphorus mass balance calculation, phosphorus loading into the reservoirs was higher in Tono (46,447.64 mg P yr^{-1}) compared to Vea (4,232.17 mg P yr^{-1}). The social carrying capacity (SCC) and production carrying capacity (ProCC) obtained was 2902.98 t yr^{-1} and 264.51 t yr^{-1} for Tono and Vea Reservoirs, respectively. These were congenial to studies on three sites (Akosombo, Asikuma, Kpeve) within lake Volta, where the carrying capacities obtained were 229 t yr^{-1}, 1278.8 t yr^{-1} and 82.9 t yr^{-1}, respectively (Ekpeki and Telfer, 2016). From the above CC values, Tono and Vea reservoirs, although shallow have good SCC and ProCC that can be exploited for aquaculture development. For sustainable aquaculture carrying capacity (ACC), the final decision process involving the ECC and PCC integrated into the SCC and ProCC were estimated to be 719 m^{-3} and 66 m^{-3} (cage size of 1x1x1 m) of cage volume for Tono and Vea reservoirs, respectively. These estimates provide the total cage volume per reservoir that can be harnessed in synergy with the production, social, physical, and ecological carrying capacities for Nile tilapia production on the two reservoirs in the Upper East Region of Ghana. Fish production performance per volume of cage is much higher and economically more efficient (200 kg fish per m^3 cage) in smaller cages of about 1 to 4 m^3 due to frequent complete water exchanges in smaller cages (Schmittou, 2006). Thus, smaller cages of 1 – 4 m^3 would be ideal for cage aquaculture in shallow tropical reservoirs such as Tono and Vea. Based on the above premise and using an effective (actual) cage depth of 1 m; a total of 719 and 66 units of floating cages of 1x1x1 m^3 cage size, or 180 and

17 units of floating cages of 2x2x1 m^3 cage size, or 80 and 7 units of floating cages of 3x3x1 cage size could be mounted on Tono and Vea reservoirs, respectively.

Within a catchment area, the amount of rainfall (precipitation) affects the carrying capacity for reservoirs, thus carrying capacity thresholds could be increased with projected higher water depth and/or volume, if PCC is not exceeded. The harmonisation of carrying capacities estimation at localised scale was reiterated in recent studies as pragmatic approach for sustainable cage aquaculture (Ross and Falconer, 2016; Brugèrel *et al.*, 2018).

4.3.5 Conclusions and Recommendations

4.3.5 Conclusions

The Tono and Vea reservoirs have optimum water quality conditions that can support aquaculture development, from the standing stock estimates, a total of 78,102.43 kg fish per production cycle could be sustainably produced in both reservoirs using approximately 785 m^{-3} of cages for each production cycle for Nile tilapia (*Oreochromis niloticus*). Aquaculture carrying capacity was approximately 719 m^{-3} and 66 m^{-3} for Tono and Vea reservoirs, respectively.

4.3.5.2 Recommendations

- It is recommended that the number of cages to be mounted should be based on an annual quota system as a precautionary measure for sustainable development of the estimated aquaculture carrying capacity of the reservoirs.

- Other factors that may affect carrying capacity such as rainfall pattern, temperature profile and tidal height that were not analyzed in this study, should be monitored to minimize risk associated with increased intensification of aquaculture in the reservoirs.

- Use best management practices (BMPs) such as the use of extruded floating feed and conservative feeding, moving cages per year to fallow bottom, disposal of dead fish and trash on land could ensure sustainable cage culture in reservoirs.

- This study further recommends that continuous impact studies on water quality should be carried out on the reservoirs to characterize the aquaculture carrying capacity at different seasons of the year.

4.4 Trophic Status and Development of Aquaculture Management Areas (AMAs)

4.4.1 Introduction

Reservoirs are often considered as artificial lakes created by the impoundment of rivers or streams, primarily for water storage, irrigation, flood control and domestic use as well as supporting capture fisheries. Generally, most reservoirs have high productivity shortly after inundation (FAO, 2015a). Recently, the use of reservoirs and other lentic water bodies (lakes, dugouts) for culture-based fisheries or aquaculture development is increasingly being promoted (van zwieten *et al*., 2011; Mustapha, 2014; Bueno *et al.*, 2015; Agbeko *et al.*, 2019). These studies have highlighted the potential adverse environmental impacts of aquaculture development on reservoir water quality. Most of these studies, however, did not emphasize the importance of aquaculture management areas (AMAs) for sustainable fish production in reservoirs.

Eutrophication is one of the challenges of aquaculture development, particularly with cage culture in most lentic water bodies. Thus, the trophic status in terms of primary productivity or the trophic relations between organisms are often investigated. In the aquatic environment, water bodies are distinguished as oligotrophic, mesotrophic, eutrophic, and dystrophic according to their nutrient status. The nutrient status of a water body is commonly used as an index of the general health of the aquatic ecosystem - especially, those systems that have been severely altered as result of anthropogenic activities such as water pollution and other physical disturbances (Lim and Webster, 2006). Development of aquaculture management areas (AMAs) in shallow reservoirs could threaten the aquatic ecosystems and the livelihoods of riparian communities that depend on it, if the trophic status is not known.

Aquaculture management areas (AMAs) can be aquaculture parks, clusters or any aquaculture area within a zone where farms share a common water body or water source and where farms may benefit from a common management system aimed at minimizing environmental, social and fish health risks (FAO, 2015a). AMAs can also be beneficial for groups of small farmers seeking joint access to feed, seed and technical support services. Other important considerations in the designation of AMAs are the provision of access to markets and very importantly, conflict resolution with other users of common resources. AMAs require an administrative structure and a management system that includes setting limits to the maximum production per area according to carrying capacity, distance among the farms, and density of fish within farms. Such a system should include monitoring and remedial action plans for environmental quality, fish health, and other relevant parameters (Aguilar-Manjarrez *et al*., 2017). The creation of AMAs could be a significant step forward for sustainable growth in aquaculture in regions where the farms are already operating and having difficulty with diseases and/or negative environmental impacts. AMAs also (Aguilar-Manjarrez *et al*., 2017). Thus, an aquaculture zone could be an area where aquaculture is formally allowed after appropriate participatory process to design the zone and its use, taking into consideration the economic, social and environmental objectives and related risks. AMAs provide aquaculture opportunities in a coordinated manner under an aquaculture management area plan and offer an opportunity for collective certification of products under an ecosystem perspective (Aguilar-Manjarrez *et al*., 2017). The study could provide individual fish farmers, Fisheries Officers, aquaculture stakeholders and policy makers, a sustainable approach for allocation of individual fish farms in a given demarcated area. It can also be important for collective certification of fish and fish products.

Previous studies in most reservoirs and dugouts including Tono and Vea reservoirs in Upper East Region, Ghana (Agbeko, 2012; Alhassan, *et al*., 2018) indicates that, the trophic status of these reservoirs and dugouts had not been explicitly studied to warrant zonation and implementation of AMAs for cage fish farming. The objective of this study was to determine the trophic status of the Tono and Vea reservoirs and explore potential aquaculture management areas in these two reservoirs for cage culture to enhance sustainable aquaculture.

4.4.2 Materials and Methods

4.4.2.1 Study area

The Tono and Vea reservoirs are the two major reservoirs of ecological and socio-economic importance in the Upper East Region, Ghana, West Africa. The Tono reservoir is located at 10°53′39″ north and 1°9′57″ west whiles Vea reservoir is 10˚0 52′0″ north and 00 51′0″ west (Figure 4.4.1). Tono and Vea reservoirs were created by impoundment of the Sissile and Yarigatanga rivers, respectively. These reservoirs are public water resource managed by the Irrigation Company of Upper Regions (ICOUR), a governmental agency. The reservoirs had previously been studied for cage culture and suitable zones for cage placement (APHA, 1980) (Figure 4.4.1).

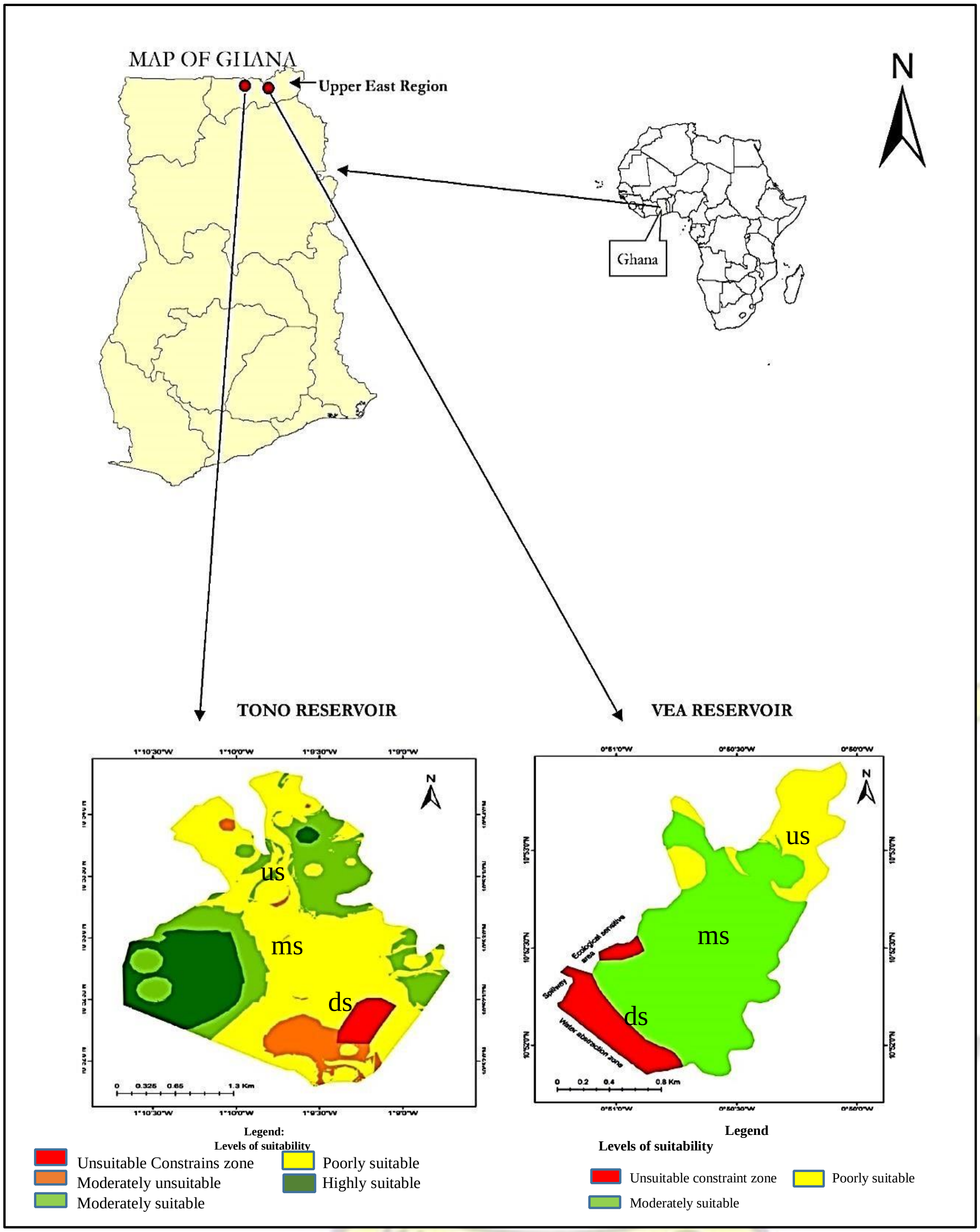


Figure 4.4.1 Tono and Vea reservoirs showing suitable aquaculture zones (in green colour) for development of aquaculture management areas (obtained from sub-section 4.2).

4.4.2.2 Water sampling and quality assurance

The Tono and Vea Reservoirs were zoned into three sections based on the direction of water flow for sampling purposes, namely; Upstream (us), midstream (ms) and down streams (ds) zones.

Water samples were collected monthly from February 2015 to April 2016 using linear stratified sampling technique with three replicates from each zone or strata. That is, a total of nine sampling stations in each reservoir.

In-situ measurement of water temperature (TEM) and pH using the Hanna HI 83141 portable water meter, water depth (WD) measured with a metric tape and transparency (TRA) in terms of Secchi disc depth (SDD). Water samples for nutrient analysis were collected into 1000 ml high density polyethylene (HDPE) bottles, which were prewashed with dilute hydrochloric acid (10%) and re-washed three times onsite with the reservoir water before sampling. Water samples were collected at mid-depth (0.5-1.5 m). The nutrients that were analysed were phosphate-phosphorus ($PO4^{2-}$), nitrate-nitrogen (NO_3 -N), nitritenitrogen (NO_2 -N), and ammonium-nitrogen (NH_4 N). For hydrobiological analysis, chlorophyll-a (CHL-a) samples were collected into 500 ml bottles covered with black plastic sheets and stored in the dark in a cool ice box to prevent deterioration of chlorophyll pigments in sunlight. All water samples were stored in cool box (insulation boxes) at 4°C to minimize temperature effects on samples during transportation for laboratory analysis. All samples were transported (<24 hours) to CSIR Water Research Institute's Laboratory in Tamale for analysis.

4.4.2.3 Laboratory analysis

Standard protocols for water stabilization, storage and water quality analysis were followed according to standard analytical methods for examination of water and waste-water (Bueno, et al., 2015, Mustapha, 2014). Water quality samples consisting of nutrients for laboratory analysis were done using 50 ml of the sample with appropriate reagents through titration and colour indicator methods. The analytical methods used are summarized in Table 4.4.1. Samples were kept in a refrigerator at 4°C until analysis were completed (approximately in 3 days).

Table 4.4.1 Summary of analytical methods used for water quality determination of samples from Tono and Vea reservoirs in Upper East Region, Ghana (February 2015 – April 2016)

Parameter	Method
PO_4^2 - P	Stannous chloride method

NO_3-N	Hydrazine reduction method
NO_2-N	Diazotization method
NH_4-N	Direct nesslerization
CHL-a	Spectrometry by acetone extraction

Algal chlorophyll (chlorophyll-a) as surrogate for primary production was determined using the visible spectrophotometric method as recommended by APHA, 1998 (Table 4.4.1). Further details for the determination of chlorophyll-a in the water column for Tono and Vea reservoirs were stated in section 3.4.3.

4.4.2.4 Estimation of Trophic status

The trophic status of the Tono and Vea reservoirs were determined from the trophic level index (TLI). Concentration of total phosphorus (PO_4^2 –P), total nitrogen (nitrate-nitrogen, nitritenitrogen, and ammonium-nitrogen), transparency (SDD) and chlorophyll-a levels were combined to construct the TLI for both reservoirs. Estimation were based on these four trophic state indicator variables (Equations 1-4) and computed into the final TLI (Equation 5), as indicated below. These formulae were derived from the equations recommended by Lim and Webster (Lim and Webster, 2006). The TLI values obtained were compared with trophic level thresholds accordingly (Lim and Webster, 2006). Thus, the higher the TLI value, the worse the water quality.

$TL_{nitrogen} = -3.61+3.01 \log (N_{total})$ Equation (1)

$TL_{phosphorus} = 0.218+2.92 \log (P_{total})$ Equation (2)

$TL_{transparency} = 5.10+2.27 \log (1/\text{Secchi disc depth} – 1/40)$ Equation (3)

$TL_{chlorophyll}\text{-a} = 2.22+2.54 \log (\text{chl-a})$ Equation (4)

$TLI= (TL_{nitrogen} + TL_{phosphorus} + TL_{transparency} + TL_{chlorophyll-a})/4$ Equation (5)

Where,

TL: Trophic Level, N_{total}: Total Nitrogen, $P_{total:}$ Total Phosphorus

4.4.2.5 Development of aquaculture management areas (AMAs)

Areas suitable for aquaculture obtained from previous studies APHA (1998) were demarcated into clusters or zones called aquaculture management areas (AMAs) based on several factors. The factors considered during the demarcation for the development of AMAs in the Tono and Vea reservoirs were trophic status, aquaculture carrying capacity, feed conversion rate (FCR), stocking density, expected bulk fish weight (fish yield) and average weight of fish for the two reservoirs (Figure 4.4.2). Ecologically sensitive areas for wildlife or aquatic birds were avoided. Site or zones for social good such as areas near water abstraction points and navigation routes were demarcated to avoid social conflicts. Allocation of existing and potential fish landing sites were inferred from key informants: fishers operating on the reservoir more than 5 years, fishery officers from Fisheries Commission, managers of the reservoir from the Irrigation Company of Upper Regions and riparian community members. Based on these factors, AMAs were generated within the suitable zones in the reservoirs (Figure 4.4.2).

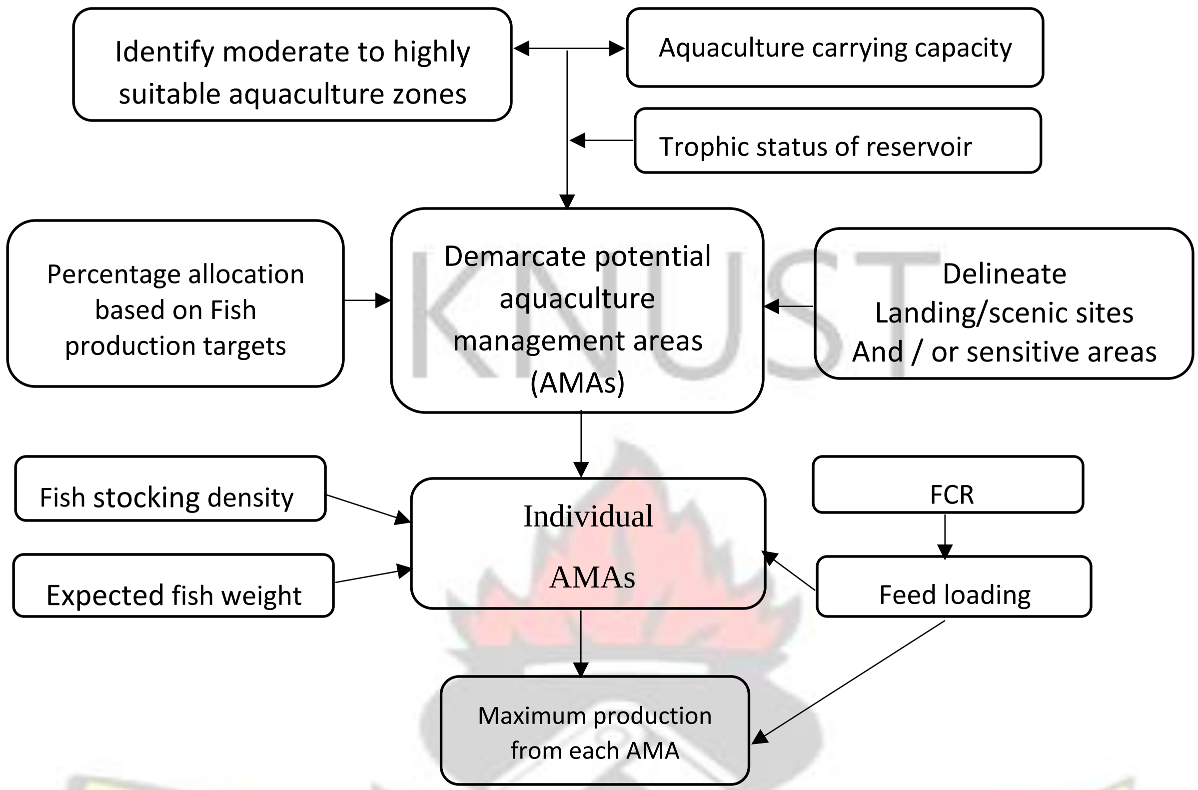


Figure 4.4.2: Conceptual model for development of aquaculture management areas (AMAs) at Tono and Vea reservoirs in Upper East Region, Ghana

The number of fish to stock was calculated from the simple equation: $Ns = Wc/W$

Where; Ns is the number of fish to stock per m^3 of cage,

W_c is the expected total fish weight per cubic meter of cage at harvest,

W is the desired mean fish weight at harvest.

Expected total (bulk) weight was proposed as 150 kg per cubic meter based on the low volume High Density (LVHD) cage culture Technology adopted for this study (Schmittou, 2006). The LVHD cages have higher productivity and better water exchange efficiency (>50%) compared to conventional cages with bigger volume (Schmittou, 2006). Also, LVHD cage culture could be more suitable for shallow reservoirs like Tono and Vea. The expected average weight was set at 250 g based on cage culture feasibility studies conducted in Vea reservoir (Agbeko, 2014a) and observed fish market demands of the area.

Expected cage volume (Cv) per AMA was estimated from the equation: Cv = % A × CC,

Where, % A is the percentage area allocation, CC is aquaculture carrying capacity of the reservoir.

Under the assumption of 180 days' culture period (Cp) to produce 150 kg m-3 of fish, feed conversion rate of 1.5, Ns = 600 individual fish (fingerlings), initial stocking weight of fish: 5 g,

Thus, 600 × 5 = 3000 g ≡ 3 kg of fish, Actual weight gained (Wg):150-3 = 147 kg,

Feed requirement/m (Fr): (Wg/FCR)/Cp, [(147/1.5)/180 = 0.54 kg m^{-3}]

Therefore, feed loading as allowable feed (Fl) per day in each AMA was estimated from the equation: Fl = Cv × Fr

The maximum production (Mp) of fish per AMA was estimated from equation: Mp = Wc × Cv, where, Wc is expected weight per cubic metre (m^3) and Cv is the expected cage volume

Data analysis for water quality variables to obtain mean values, ranges, standard error, and summation were performed in Microsoft excel (Version 2013). The outputs were presented in tables and Figures. Suitable zones generated, demarcated and identified as potential AMAs were further verified by ground-truthing and multi-stakeholder confirmation

4.4.3 Results

4.4.3.1 Trophic status of reservoirs

Four water quality variables; transparency, total phosphorus, total nitrogen and chlorophyll-a representing the physical, chemical and biological components in relation to trophic status of reservoirs and lakes were identified and computed as inputs for trophic level index (TLI) estimation (Table 4.4.2).

Table 4.4.2 Descriptive statistics of water quality variables for trophic level index (TLI) estimation in Tono and Vea reservoirs in the Upper East Region, Ghana (February 2015 – April 2016)

	Tono reservoir	Vea reservoir

Parameters	Mean (SE)	Range	Mean (SE)	Range
SSD (m)	0.5507 (0.0546)	0.35-1	0.4256 (0.027)	0.2-0.56
Chl-a (mg m^{-3})	1.3653 (0.0434)	1.21-1.74	0.0606 (0.003)	0.079-0.5
PO_4^{2-} (mg m^{-3})	101.7 (12.9)	33-191	51.8 (12.6)	1-110
NH_4-N (mg m^{-3})	3174 (643.5)	250-7830	786.7 (15.2)	730-890
NO_3^{2}-N (mg m^{-3})	2990.33 (966.8)	12-11130	2486.1 (803.5)	160-9110
NO_2-N (mg m^{-3})	256.33 (83.2)	8-1050	32.8 (3.8)	9-50
T. Nitrogen (mg m^{-3})	6420.66 (1693.5)	270-20010	3305.6 (822.5)	899-10050

SE: standard error, Mean values were used in estimation of TLI, T: total, SSD: Secchi disc depth, Chl-a: Chlorophyll-a

Results from the water quality and nutrient loading (total nitrogen and total phosphorus) indicated that the Tono and Vea reservoirs were ultra-micro and oligo trophic, respectively (Tables 3 and 4). The combined effects of four trophic indicators showed that Tono reservoir has a trophic level index (TLI) of 5.23, which indicates that the reservoir had very high nutrient enrichment, and thus super trophic (Table 4.4.3). Similarly, the Vea reservoir with the trophic level index (TLI) of 4.32, indicates that the reservoir was high in nutrient and thus eutrophic (Table 4.4.4). But the primary productivity in terms of chlorophyll-a indicated meso-trophic and ultra-micro trophic status for the Tono and Vea reservoirs, respectively (Tables 4.4.3 and Table 4.4.4).

Table 4.4.3 Estimated trophic state (values in bold parenthesis) and corresponding quantitative parameters of the trophic level index (Pavluk and Bij de Vaate, 2017) for Tono reservoir in the Upper East Region, Ghana

Trophic state	Nutrient E.C.	TLI	Chl-a (mg m^{-3})	SDD (m)	T. phosphorus (mg m^{-3})	T. nitrogen (mg m^{-3})
Ultra-micro trophic	Practically pure	0.0-1.0	<0.33	>25	<1.8	<34 **(7.85)**
Micro trophic	Very low	1.0-2.0	0.33-0.82	25-15	1.8-4.1	34-73
Oligo trophic	Low	2.0-3.0	0.82-2.0	15-7	4.1-9.0 **(4.81)**	73-157
Meso trophic	Medium	3.0-4.0	2-5 **(2.56)**	7.0-2.8 **(5.68)**	9.0-20	157-337
Eutrophic	High	4.0-5.0	5.0-12.0	2.8-1.1	20-43	337-725
Super trophic	Very high	5.0-6.0 **(5.23)**	12-31	1.1-0.4	43-96	725-1558
Hyper trophic	Saturated	>6.0	>31	<0.4	>96	>1558

E.C: enrichment category TLI: Trophic level index Chl-a: Chlorophyll-a SDD: Secchi disk depth

Table 4.4.4 Estimated trophic state (values in bold parenthesis) and corresponding quantitative parameters of the trophic level index (Pavluk and Bij de Vaate, 2017) for Vea reservoir for Tono reservoir in the Upper East Region, Ghana

Trophic state	Nutrient E.C.	TLI	Chl-a (mg m^{-3})	SDD (m)	T. phosphorus (mg m^{-3})	T. nitrogen (mg m^{-3})
Ultra-micro trophic	Practically pure	0.0-1.0	<0.33 **(-0.87)**	>25	<1.8	<34 **(6.98)**
Micro trophic	Very low	1.0-2.0	0.33-0.82	25-15	1.8-4.1	34-73
Oligo trophic	Low	2.0-3.0	0.82-2.0	15-7	4.1-9.0 **(5.22)**	73-157
Meso trophic	Medium	3.0-4.0	2-5	7.0-2.8 **(5.93)**	9.0-20.0	157-337
Eutrophic	High	4.0-5.0 **(4.32)**	5.0-12.0	2.8-1.1	20-43	337-725
Super trophic	Very high	5.0-6.0	12-31	1.1-0.4	43-96	725-1558
Hyper trophic	Saturated	>6.0	>31	<0.4	>96	>1558

E.C: enrichment category TLI: Trophic level index Chl-a: Chlorophyll-a SDD: Secchi disk depth

4.4.3.2 Development of potential Aquaculture Management Areas (AMAs) in reservoirs

Suitable zones identified from previous studies APHA (1980) were inferred and further delineated. The re-mapping produced sub-zones or clusters called aquaculture management areas (AMAs) that can be managed under a given management option which is socially acceptable to all stakeholders. Having considered various social-infrastructural factors (delineation of sites for water abstraction, navigation route, fishing areas and fish landing sites), three potential AMAs for the Tono reservoir and five potential AMAs for Vea reservoir were generated in the suitable zones within the reservoirs (Figures 4.4.3 and 4.4.4). From these areas, different sizes of AMAs would have varying degrees of fish production potential based on the aquaculture carrying capacity.

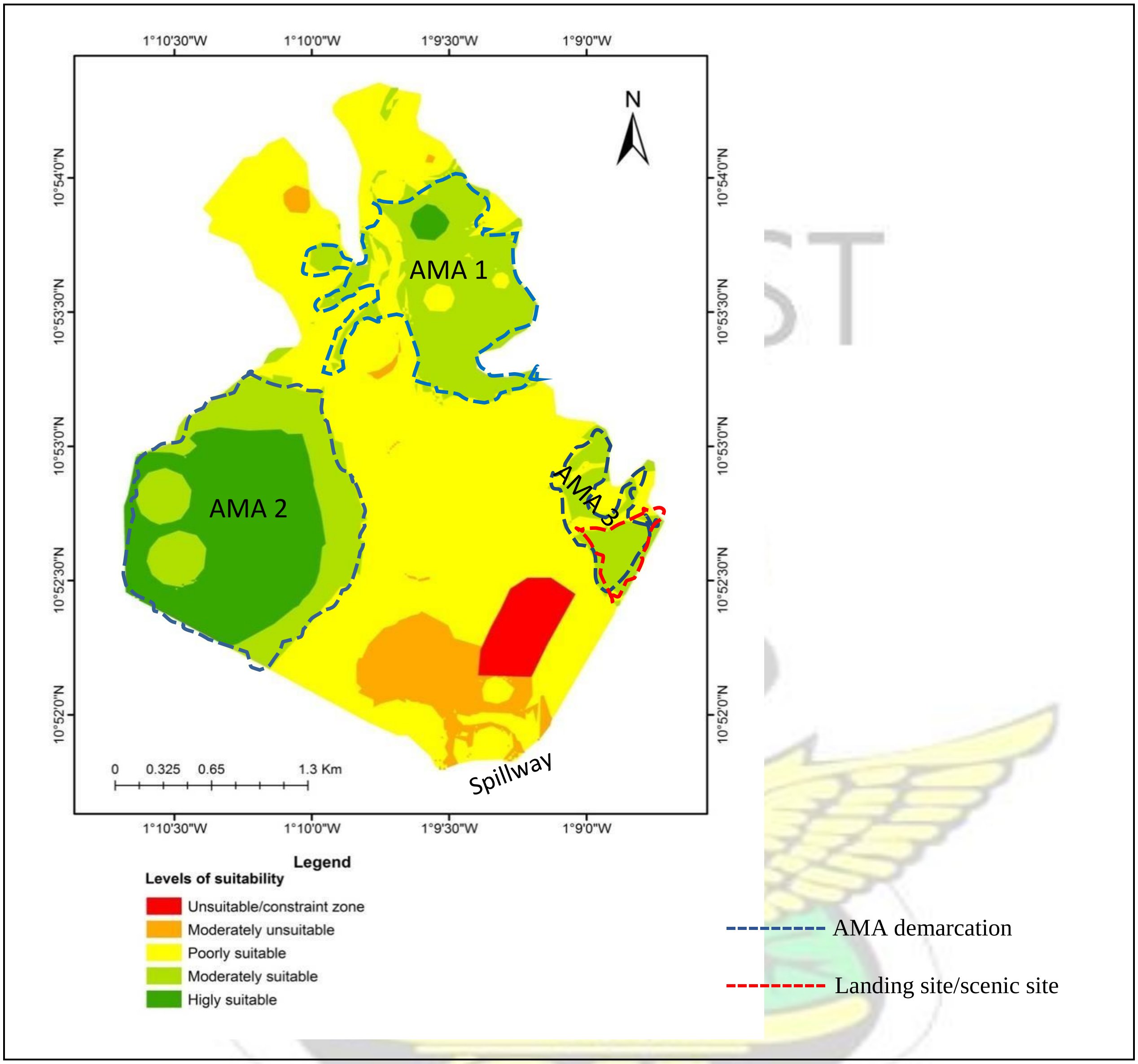


Figure 4.4.3 Aquaculture management area map generated for aquaculture development in Tono reservoir in the Upper East Region, Ghana

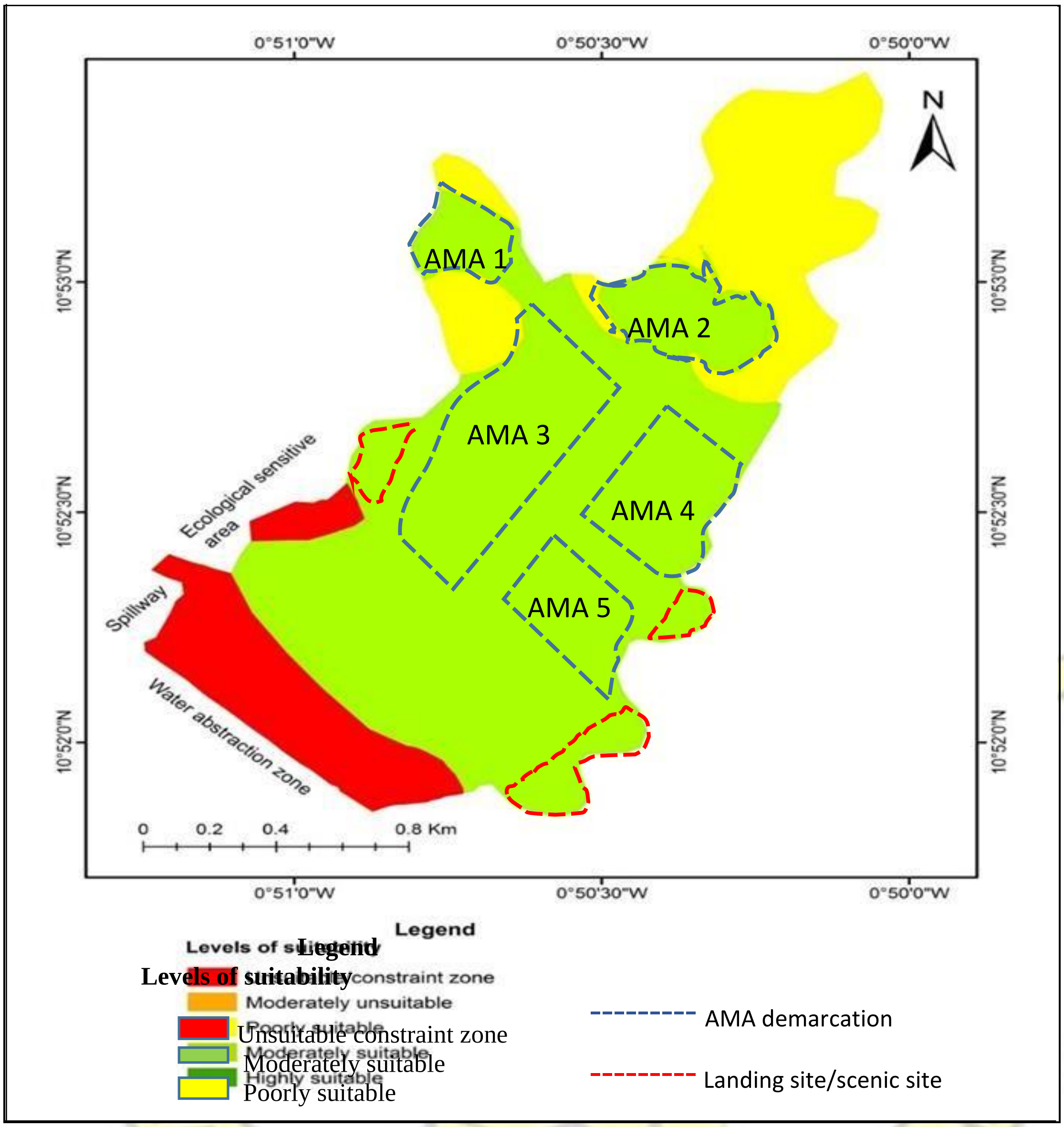


Figure 4.4.4 Aquaculture management area map generated for aquaculture development in Vea reservoir in the Upper East Region, Ghana

Allocation of production targets based on the aquaculture carrying capacity and trophic status indicates that the amount of fish feed loading that could be allowed within each AMAs should be different (Tables 4.4.5 and 4.4.6). Although, the Vea reservoir had more AMAs, the maximum fish production from its AMAs was 9, 835 kg compared to 107, 910 kg for Tono reservoir (Tables 4.4.5 and 4.4.6). The results indicated that, reservoirs with more social-infrastructural consideration could have less AMAs which leads to lower potential for fish production apart from the size of the reservoir being a limiting factor.

Table 4.4.5 Aquaculture management areas and production plan for Tono reservoir

Tono	% allocation*	Projected cage vl.m^{-3}	Feed load/d/kg	Max. pdtn. (kg)
AMA 1	0.3	215.82	116.54	32373.00
AMA 2	0.65	467.61	252.51	70141.50
AMA 3	0.05	35.97	19.42	5395.50
Total		719.4	388.48	107,910.00

*65%, 30% and 5% of production target allocation within suitable zones from suitable zones. vl.: volume, FCR: 1.5, Develop with 1 km between cluster and 10m between cages as buffer zone as recommended by the Ghana National Aquaculture Code of Practice and guidelines, and Fishery Regulation Act.2010, (L.I. 1968).

Table 4.4.6 Aquaculture management areas and production plan developed for Vea reservoir

	% allocation*	Projected cage vl.m^{-3}	Feed load/d/kg	Max. pdtn. (kg)
AMA 1	0.04	2.622	1.42	393.30
AMA 2	0.06	3.933	2.12	589.95
AMA 3	0.5	32.775	17.70	4916.25
AMA 4	0.3	19.665	10.62	2949.75
AMA 5	0.1	6.555	3.54	983.25
Total		65.55	35.40	9,832.50

*4%, 6%, 50%, 30% and 10% of production target allocation within suitable zones.
vl.: volume, FCR: 1.5, Develop with 1 km between clusters and 10m between cages as buffer zone as recommended by the Ghana National Aquaculture Code of Practice and guidelines, and Fishery Regulation Act. 2010, (L.I. 1968).

4.4.4 Discussion

4.4.4.1 Trophic status and aquaculture management areas

The trophic status of a water body is determined by the integration of several ecological change indicators to obtain trophic indices. Variation in methods of estimation of trophic status for lakes and reservoirs makes it difficult for objective comparison (Sass *et al.*, 2007). This is because fish productivity in reservoirs is considered to be dependent on morphometric, edaphic and climatic factors with emphasis on nutrient availability and primary productivity; thus, oligotrophy is seen as trophic status that needs to be corrected (Pavluk and Bij de Vaate, 2017).

Carlson's trophic state index (TSI), TRIX index, trophic diatom indices, benthic trophic state index, oligochaete trophic index, trophic level index (TLI) are commonly used for trophic state indices. The latter index, TLI is seen as more robust and reliable as it involves more nutrients that affects eutrophication. The TLI integrates the important limiting nutrients in water, namely phosphorus and nitrogen (nitrite-nitrogen, nitrate-nitrogen, ammonium-nitrogen), in addition to those that are conventionally used (transparency: Secchi disc depth and chlorophyll-a) for assessment of eutrophication status in lakes and reservoirs, with other sophisticated ones conducted using various water quality models (Agbeko *et al.*, 2019). Other studies suggest the use of nitrite-nitrogen based TSI as nitrites are easily converted to nitrate through nitrification, decreases the fluorescence and affects photosynthesis; thus, analogous to Carlson's index (APHA, 1998). Another study reiterates that no single assessment variable could determine the true trophic status of the aquatic ecosystem (El-Serehy *et al.*, 2017).

The higher the number of indicators used for the estimation of trophic index, the better (Lee and Liu, 2018). Thus, this could have enhanced the efficiency of the trophic level index (TLI) obtained for both reservoirs as four major indictors were used: transparency (SDD), chlorophylla, total phosphates, and total nitrogen as TLI; compared to less indictors used in the Carlson trophic state (TSI). Inference from the estimated trophic levels based on single indicator or parameter such as chlorophyll-a or transparency (SDD) in the Tono reservoir indicated that the reservoir was meso-trophic. However, further analysis involving the nutrients indicate Tono reservoir was super eutrophic (TLI: 5.23) and thus, very high in nutrient enrichment. This study showed that the use of the TLI could provide a more comprehensive way of assessing the physical, chemical and biological status of reservoirs and lakes.

Observed ecological changes (trophic levels) that may occur within a given aquatic habitat helps in futuristic management options that should be deployed (El-Serehy *et al.*, 2017). Eutrophication could be minimized through nutrient control, bio-manipulation, regulations, public awareness, environmental education and changes in social and cultural perspectives of lakes and reservoirs (Kolding and Van Zwieten, 2006). In this study, the Tono and Vea reservoirs have varying degrees of eutrophication (from very high to high) which could be bio-manipulated for cage culture by using filter-feeding planktivorous fish such as tilapia. With compensatory high dissolved oxygen concentration (>5 mg l^{-1}) as observed in Tono and Vea reservoirs, cage culture of tilapia in these trophic waters could be beneficial for fish growth, with or without intensive fish feeding. However, the threshold for added enrichment from fish feed vary with the prevailing trophic state of the environment (Gupta, 2014). Thus, the estimated amount of feed loading into each reservoir could be minimized based on the estimated threshold for each AMA using supplementary feeding regimes. Therefore, extruded or floating pelletized feeds are preferred since such feeds could stay longer on the water surface for it to be consumed by the fish. This promotes better fish growth as well as minimizing rapid sinking of feed that could pollute the water. The fish culture process may cause changes in the water quality through nutrient loading from fish faeces and ammonia released into the water from fish respiration (cultural eutrophication). However, a threshold for each AMA in a given reservoir could safeguard the reservoir from further pollution from cage culture as well as allow the utilization of eutrophic reservoirs for sustainable production of fish. AMAs development processes must factor in such effects into its estimation as indicative in this study. As a result, for sustainable aquaculture development, some studies (Lim and Webster, 2006; Aguilar-Manjarrez *et al*., 2017) suggest an allocation of 1% of the carrying capacity within a suitable area as an AMA. Studies conducted on Brazilian reservoir showed that percentage allocation for three aquaculture parks in the Itaipu reservoir were 0.46%, 0.48%, 0.09% for sustainable aquaculture promotion Lim and Webster, (2006) similar to those obtained in this study for AMA allocation (<1%) for Vea and Tono reservoir in Ghana.

This study provides an integrated approach to the delineation of AMAs in inland water bodies such as reservoirs, lakes and lagoons. Thus, it is worth noting that some potential AMAs in Vea reservoir (AMAs 1 and 2) may be too small for commercial production (<500 kg per production)

However, such smaller AMAs could be allocated to small holder fish farmers. These smaller AMAs could be easy to manage and monitor, in terms of water quality changes, input and output effects on reservoirs. Good water quality depends on effective control and management of the threat of cultural eutrophication (Kolding and Van Zwieten, 2006; Pavluk and Bij de Vaate, 2017). Existing fisher-folks operating in the reservoirs could be trained to own and manage these AMAs to maintain good water quality, mitigate water-user conflicts, and enhance livelihoods and food security for the riparian communities. This study also provides some evidence (aquaculture stakeholders' inclusion approach) to minimize and avoid social objection towards cage culture development in the Tono and Vea reservoirs. Most of the reservoir areas where landing sites exist were avoided, route or fishing grounds for canoes navigation were maintained, and additional areas were created along the AMAs to avoid water-user conflicts associated with cage culture.

4.4.5 Conclusions and Recommendations

4.4.5.1 Conclusions

Aquaculture management areas (AMAs) in the Tono and Vea reservoirs could contribute approximately 117.74 metric tonnes of Nile tilapia per year. Fish production could be doubled, if a six-month production cycle is adopted per year. The three AMAs in Tono and five AMAs in Vea reservoir could be exploited to support inland aquaculture development policies of the Ghana Government. This study had shown that with the application of trophic status, carrying capacity estimation coupled with fish production factors, AMAs could be identified and developed for sustainable cage culture on reservoirs in northern Ghana. Consequently, capture fisheries could be integrated with culture-based fisheries in reservoirs in a sustainable way.

4.4.5.2 Recommendations

- The adoption of aquaculture management areas (AMAs) for the Tono and Vea reservoirs should be promoted as a pragmatic cage culture management approach for sustainable aquaculture production in these reservoirs.
- It is further recommended that, pilot cage production of fish in designated AMAs should be jointly monitored for futuristic decision making by aquaculture research scientists, regulators, and interested small-scale fish farmers in Tono and Vea reservoirs.
- A pilot fish production within potential AMAs in Tono and Vea reservoirs could be implemented to serve as a baseline to monitor nutrient loading effects on the current trophic status of the reservoirs based on the maximum production targets postulated in this study. From this premise, the upscaling of the AMA approach to other shallow reservoirs (<10 m depth) could help boost fish production in reservoirs as well as minimize social objection and water-user conflicts over shared water resources
- There is the need for further studies involving biosecurity consideration within the potential AMAs for Tono and Vea reservoirs, which was not explicitly considered for this study.

CHAPTER FIVE

5. GENERAL DISCUSSION

5.1 Water quality

The climatic, hydrological, geological, and anthropogenic factors influenced the water quality (Sharma *et al.*, 2016). The climate and hydrological changes in relation to physico-chemical properties of Tono and Vea reservoirs produced three distinctive seasonality regimes: pre-flood, flood and post-flood seasons. The post flood season was characterised by fluctuation in water level and drastic monthly changes in reservoir water quality. The post-flood season could impact reservoir fisheries and cultured tilapia growth performance. Compelling evidence exist to assume that water chemistry is an important influence on aquatic plants and animals (Batzer *et al.,* 2004, Sharma *et. al.,* 2016), their ability to adapt to inter and intra seasonal changes, and changes from riverine to lacustrine food webs of reservoir environment (van Zwieten *et al.*, 2011). The mean depth of water in reservoirs affects the quantity of water available and thus the carrying capacity for aquaculture. The quality of water in any lentic water body such as reservoirs, lakes, pools, ponds and dugouts affect the survival, growth and the health of aquatic organisms. Agriculture and aquaculture activities such as cage culture, pen culture, oyster farming and pond culture had been reported to change fresh water inputs into wetlands (Khalit *et al.,* 2017). These activities can accelerate siltation and pollution of freshwaters bodies if unregulated and managed, thereby reducing the effective space and potential for culture over time. Previous studies indicate that farming activities have contributed to the decline in the productivity of many fisheries resources (Béné, 2007). Water temperature, dissolved oxygen, pH, nutrient levels and other water quality variables are difficult to predict over a given threshold in an aquatic ecosystem (Schmittou, 2006), thus there is the need for regular water quality monitoring. Understanding the water quality is important as it ensures high productivity, minimise stress and fish health issues (Aguilar-Manjarrez *et al.*, 2017). Principally, multivariate statistical methods had been recommended for water quality assessment in recent times (Lei, 2013; Gu *et al.,* 2016; Khalit *et al.,* 2017), as a pattern recognition technique in water quality management (Jiang-Qi *et al.,* 2013). As ordination technique in multivariate statistics, the correspondence analysis (CA) performed in this study is more suitable to account for the phytoplankton phylum that demonstrates unimodal response to the underlying favourable water quality variables associated with each zone/site in the reservoirs. But principal component analysis (PCA) does not have, as it often produces linear response or relationship. The limitation of PCA for species or taxa association with spatial trends, known as the horseshoe effect in PCA could account for this, despite not proven in this study.

The Tono and Vea reservoirs have optimum water quality required to aid all year aquaculture development. Although, water quality dynamic was seasonally influenced, the seasonal impact was marginal for the pre-flood and flood season but variable for the post-flood. High water temperature during the post-flood period as observed in Tono and Vea reservoirs, is reported to alter phytoplankton (algae) abundance due to nutrient loading (Jiang *et al.*, 2013; Davis, 2016). Phytoplankton phylum, chlorophyta was dominant in the midstream zones of Tono and Vea reservoirs. Previous study indicates that the midstream zone of Vea reservoir was more productive in terms of phytoplankton abundance (Agbeko, 2012). This could be due to high dissolved oxygen, low water flow and utilization of nutrients (Sharma *et al.*, 2016), that characterised the transitional section (midstream zone) of the reservoir. Thus, selection of the midstream zones as suitable areas of high productivity for fish growth in most reservoirs and other lentic water bodies could be elucidative. In Sri Lanka (Lao), reports indicate that high productivity zones and seasons for reservoirs are exploited for culture-based fisheries (De silva *et al.* 2006). For reservoirs in the Indo-Gangetic Basin of India, large and medium-sized reservoirs are most productively managed only through stocking and regulating capture fisheries, while production from small reservoirs is easier to maximize through cage aquaculture (van Zwieten *et al.*, 2011). Thus, reservoir water quality and productivity over space and time influences the fisheries and aquaculture strategy to adopt to increase fish production.

5.2 Aquaculture suitability, zonation and carrying capacity

The most important factors for aquaculture development after water quality, could be site selection and carrying capacity (Falconer *et al*., 2013). Various GIS-based suitability models and classification tools exist (i.e., Equal interval, Fuzzy, Quantile, Boolean, and natural breaks/Jenks classifications). The application of GIS-based ILWIS software to undertake spatial multi-criteria evaluation (SMCE) involving equal interval to delineate suitable areas within Tono and Vea reservoirs provides useful specific outputs for informative decision making. Tono and Vea reservoirs were relatively shallow (<6 m of average water depth), and smaller in size and surface area (<50 km^2), but its total suitability was high (>85%) for cage aquaculture. Similar studies on sections of lake Volta (areas near Akosombo, Asikuma and Kpeve) indicated allowable change in carrying capacity were 229.0, 1278.8, 82.9 metric tonnes of fish per year, respectively (Ekpeki and Telfer, 2016). However, the number of cages that could be mounted (cage volume) in these areas in lake Volta for sustainable aquaculture was not estimated or stated.

Sustainable aquaculture can be promoted if rigorous integrated studies are applied to select and designated areas suitable for fish farming by aquaculture or fishery regulatory bodies. This could be of help to avoid would-be farm enterprise failure because site has been wrongly chosen. Spatial demarcation of areas on water surfaces and riparian zone for aquaculture could promote sustainable development of the aquaculture sector.

Selection of suitable zones for cage aquaculture could be a difficult task and costly activity. For instance, the would-be fish farmer could become more vulnerable and, in some instances, aggravated by agitation and societal objection. Nonetheless, grouping of farms could lead to spread of fish diseases under poor biosecurity (Murray and Peeler, 2015). Riparian community engagement with stakeholders and policy makers are critical to address societal interests, ecological issues with pollution and seasonality regimes for an effective workable cage aquaculture sustainability.

The reservoirs and dugouts were usually for domestic use, animal watering, irrigation, capture fisheries and seldom for aquaculture. This is because most of these reservoirs and dugouts are shallow (average depth <10 m). Selection of suitable zones to make aquaculture.

Compared to this study on Tono and Vea reservoirs, allowable carrying capacity was 71.58 and 6.52 metric tonnes per year, with an estimated cage volume of 719.40 and 65.55 cubic meters, respectively. The total area available for cage farming was 8.95 km^2 and 2.76 km^2 for Tono and Vea reservoirs, respectively. Thus, potential quantity of fish production in cages for each reservoir can be inferred from the total suitable area. Report indicates suitable zones for freshwater prawn farming in Bangladesh was successfully determined using GIS- based multicriteria evaluation (MCE) in a study conducted at Noakhali (Bangladesh) and its application for aquaculture in Nasser lake, primarily for Nile tilapia and catfish (Wagdy and Kawi, 2015).

These studies indicate that GIS-based MCE models could be dependable tools for location of suitable areas for aquaculture.

Levels of suitability may not necessarily be related to the size of the water body being considered for cage culture. Although, this study spatially modelled the entire Tono and Vea reservoirs, there were some similarities in terms of levels of suitability compared to studies on lake Volta which modelled prioritized areas of the lake (Ross *et al.*, 2016), which were bigger than the Tono and Vea reservoirs. Although, generally total suitability was higher for Tono reservoir compared to Vea reservoir, more than half of that was in poorly suitable range (51.72%, out of the total 90.77% suitability) while Vea reservoir had more of suitability levels being in moderately suitable range (68.40%, out of the total 87.90 % suitability) for Tilapia cage culture. Poorly suitable areas were included in the total suitability because with the appropriate aquaculture management intervention their level of suitability could improve for its utilized for cage culture. This was reiterated by similar studies on lake Volta (Asmah *et al.,* 2016). Explicitly, the poorly suitable areas (produced under worst case scenario) could become moderately or highly suitable during the flood seasons (August-October). Thus, poorly suitable areas could be used for grow-out culture (3 months' production cycle using juvenile tilapia stocks > 40g) when water levels are high in the reservoir to allow floating of cages. Previous studies in the marine aquaculture sector by Falconer *et al.* (2013), Baxter *et al.* (2008) and consideration for mooring effects of cage culture on the sea floor (Bekkby *et al.* 2008), indicates that GIS-based models could be reliable tools for assessment of suitable zones for floating cage culture. The adaptation and application of GIS models for aquaculture planning and development is evolving (Yulius *et al.,* 2009; Falconer *et al.*, 2013; Nayak *et al.,* 2014; Wagdy and Kawi, 2015), for inland freshwater culture. Application of GIS in aquaculture development could serve as a decision support tool for better prediction of the suitable zones for aquaculture (Kapetsky, 2002).

5.3 Trophic status and implications for aquaculture management areas (AMAs)

The trophic status of a water body may affect the availability of an aquaculture management area/s (AMA/s). Thus, sustainable aquaculture cannot be achieved without understanding the nutrient enrichment process of a water body. It can be inferred from this study that, high anthropogenic activities (farming, bush burning and sand mining) in the catchment area of the reservoir causes nutrient loading that could trigger hyper-eutrophic conditions (very high nutrient enrichment). This was evident in Tono reservoir compared to Vea reservoir which was eutrophic. Previous study conducted from 2009 - 2010 (Agbeko, 2012) and in recent reports by Abache (2014); indicates that Vea reservoir could become eutrophic, if anthropogenic activities on the reservoir remain the same. According to Jiang-Qi *et al.* (2013), adverse effects of eutrophication can lead to algal blooms which may produce cyanobacteria toxins as a potential risk for both aquatic organisms and humans who consume the fish. Other studies had reiterated similar effects of eutrophication (Karikari and Asmah, 2016). This study established that the trophic status of both reservoirs were high (eutrophic) but were within levels that could be considered for the development of aquaculture management area.

Aquaculture management areas (AMAs) can be aquaculture parks, clusters or any aquaculture area within a zone where farms share a common water body or water source and that farms may benefit from a common management system aimed at minimizing environmental, social and fish health risks (FAO and World Bank, 2015). The structure of the AMA entity will vary depending on whether parties are the same size. AMA entities should be inclusive, as appropriate, for identification of issues, and stakeholder participation is essential (FAO, 2017). Using the stated approach, this study delineated three (3) and five (5) management areas from the suitable zones on Tono and Vea reservoirs as aquaculture management areas (AMAs), respectively. Cumulatively, maximum production estimated from AMAs in Tono and Vea was 107.91 and 9.83 tonnes of fish. The differences in values obtained for aquaculture carrying capacity and AMAs estimated could be attributed to the maximum threshold deployed in the estimation in terms of percentage allocation of the carrying capacity and the current trophic status of the reservoirs.

Important steps which are key to the sustainable implementation and management of AMAs as recommended by the Food and Agriculture organisation (FAO) and the World Bank (AguilarManjarrez *et al.*, 2017) includes:

(i) delineation of management area boundaries with appropriate stakeholder consultation
(ii) establishing an area management entity involving local communities as appropriate
(iii) carrying capacity and environmental monitoring of AMAs
(iv) disease control in AMAs
(v) Best management practices

(vi) group certification

(vii) essential steps in the implementation, monitoring and evaluation of a management plan for an AMA.

This study produces compelling evidence in line with the research questions that were postulated to support the development of reservoir through sustainable aquaculture. Some published studies exist on aquaculture suitability for mari-culture: brackish or marine aquaculture (Radiarta *et al.*, 2008; Falconer *et al.*, 2013; Gentry *et al.*, 2017). And in recent times, some suitability studies were conducted on selected zones of Lake Volta (Asmah *et al.*, 2016). The approach of delineating suitable areas using GIS-based models for sustainable aquaculture development as deployed by this study provides a multi-stage process that allows different parameters that were originally measured in different units to be compared on a similar scale and logical numerical model as cited by Falconer et al. (2013). Thus, very few studies have addressed the scientific methods and techniques posited by this study based on the ecosystems approach to aquaculture (EAA) involving majority of the key steps of AMA development to attain sustainable aquaculture in reservoirs.

CHAPTER SIX

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study provides information on the application of suitable zones, trophic status and carrying capacity estimation coupled with other fish production factors for the development of aquaculture management areas (AMAs). The study has shown that, the water quality in the Tono and Vea reservoirs were positively influenced by pre-flood and flood periods on the temporal scale. However, water quality changes were spatially influenced by the cyanophyta association, conductivity, total hardness, nitrate, sulphate, turbidity, water depth and dissolved oxygen's responsiveness to the midstream zone in Tono and Vea reservoirs. Hence, these parameters could be the prime factors for water quality monitoring for aquaculture on Tono and Vea reservoirs.

For suitable areas for cage aquaculture, geographical information system (GIS)-based spatial multi criteria evaluation (SMCE) indicated aquaculture suitability of 90.77% and 87.90% for Tono and Vea reservoirs, respectively. Within these suitable areas, the volume of cages that could be mounted based on aquaculture carrying capacity (CC) estimates for Tono and Vea reservoirs were 719 and 66 cages (1x1x1 m^3 cage size), respectively. For the sustainability of these reservoirs, the allowable feed loading into these reservoirs were 388.43 kg/day for Tono and 35.40 kg/day for Vea. These thresholds could be adjusted based on the reservoirs' response to the existing high eutrophic status observed in both reservoirs.

From the potential AMAs in this study, 107.91 and 9.83 metric tons of cultured fish (Nile tilapia) per production cycle could be sustainably produced from Tono and Vea reservoirs, respectively. Small scale farms or an individual farmer could be allocated to smaller sized AMAs such as AMAs 1 and 2 within Vea reservoir whiles the large size AMAs (AMAs 3 and 4) could be divided among a group of individual farms or given to large scale farms. Although, both reservoirs are eutrophic, it could support Nile tilapia (*Oreochromis niloticus*) cage aquaculture in a sustainable way. Thus, cage fish farming on the Tono and Vea reservoirs together with other similar reservoirs such as Sankana reservoir in Upper West Region, Bontanga and Golinga reservoirs in Northern Region could be harnessed for sustainable cage culture while the smaller reservoirs (<100 hectares) could be used be used for culture based fisheries to achieve the national target of 20% local fish production.

This study currently provides potential aquaculture management areas (AMAs) on the Tono and Vea reservoirs that could support the sustainable development of aquaculture policies to increase fish production from reservoirs. This study further provides empirical information that can be used as baseline (blueprint) for the development of cage culture in reservoirs.

6.2 Recommendations

With a total of eight aquaculture management areas (AMAs), aquaculture potential on the Tono and Vea reservoirs could be harnessed through cage fish farming to contribute to the national target of 20% local fish production. The development of suitable areas into AMAs should be promoted as a pragmatic fish farming development approach for sustainable cage aquaculture in reservoirs in Northern Ghana. There should be wider or broader consultation for dissemination, decision-making and implementation of AMAs by regulators, fishery stakeholders and interested small-scale fish farmers in the Upper East Region (UER) before piloting of cages on Tono and Vea reservoirs.

This study further recommends the following;

- Regular water quality monitoring programme is required during the post-flood periods (October-December) to ensure an all-year round production of Nile tilapia on the Tono and Vea reservoirs.
- Effects of cyanobacteria (cyanophyta) association with water quality for aquaculture in Tono and Vea reservoirs was equivocal, hence there is the need for eco-toxicological studies to understand and minimise the negative impact of cyanophyta on aquaculture production.
- Tono and Vea reservoirs are shallow reservoirs (average water depth < 10 m) but it is often compensated by the existence of high dissolved oxygen levels (DO > 5 mg l^{-1}), hence it is recommended that 1x1x1 or 2x2x1 or 3x3x1 m^3 cage sizes of the low volume

high density (LVHD) cage technology should be used to maximize Nile tilapia growth and production in these reservoirs.

- To further enhance sustainable production of Nile tilapia from the AMAs on Tono and Vea reservoirs, Best management practices (BMPs) for cage culture in reservoirs should be implemented to minimise anthropogenic effects on these reservoirs.
- Pilot production (feasibility studies) within the selected AMAs on Tono and Vea reservoirs should be done. This could serve as a baseline to monitor nutrient loading and its effects on the current trophic status (eutrophic) of the reservoir based on the estimated maximum production threshold of 107.91 and 9.83 metric tonnes of fish for Tono and Vea reservoirs, respectively; as postulated in this study.
- Biosecurity, vulnerability and disaster risk management (DRM) assessment of proposed cages in the suitable zones should be done, prior to the development of aquaculture management plan for a given aquaculture management area (AMA). This could be considered for further studies.
- Up-scaling of this AMA approach to other water stress regions where shallow reservoirs (mean depth < 10 m) exist in Northern Ghana, could boost sustainable fish production in reservoirs as well as minimize social objection and water-user conflicts over shared resources.
- All reservoirs in Northern Ghana with average water depth of 5-10 metres need to be studied to ascertain their suitability for sustainable cage culture. The rest could be used for culture-based fisheries.

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APPENDICES

Appendix I Summary statistics of water quality variables (monthly mean) monitored in Tono reservoir

Month/ Year	TUR. (NTU)	W. Temp (°C)	DO	Cl-	$SO_4$2-	$PO_{4^{2-}}$	SiO_2	NO_{3^-} N	NO_2N	NH_4N	CON. (μs cm^{-1})	pH	SDD (m)	W. Depth. (m)	ALK.	T.HAR.	CHL-a (mg/m3)	PHY.BIO. (mg m^{-3})
Feb.15	84.44	26.63	6.78	0.88	16.45	0.064	12.16	0.8	0.032	5.47	670.56	7.64	0.42	3.67	44.3	70.5	1.72	115.24
Mar.15	95.44	26.1	13.4	2.98	19.14	0.033	16.01	3.02	0.04	5.43	650.5	7.42	0.45	3.55	45.2	71.46	1.29	86.43
Apr.15	147.8	26.7	9.51	2.54	28.01	0.09	24.6	4.88	0.057	1.97	660.9	7.12	0.4	3.89	44.6	70.1	1.27	85.09
May.15	327.6	26.8	9.65	1.99	25.39	0.089	26.65	11.07	1.05	7.72	1020.3	6.5	0.35	5.2	52.1	69.8	1.3	87.1
Jun.15	142	27.9	8.51	3.14	24.25	0.124	26.71	11.13	0.8	7.83	1045.8	7.15	0.38	5.5	50.1	68.1	1.41	94.47
Jul.15	290.2	28.58	7.74	2.98	5.8	0.035	4.4	6.97	0.6	4.22	1079.5	7.11	0.53	6.9	48.4	66.25	1.27	85.09
Aug.15	220	28.63	7.32	3.82	24.79	0.19	29	2.45	0.42	3.85	631	7.33	0.6	7.82	49.9	66.1	1.35	90.45
Sep.15	225	29.5	7.36	3.85	24.98	0.191	29.11	1.75	0.25	2.41	722	8.57	0.58	8.6	53.4	64.9	1.45	97.15
Oct.15	221	27.5	8.77	3.89	25.22	0.102	29.85	1.54	0.21	2.33	545	6.59	0.9	8.9	57	64.7	1.47	98.49
Nov.15	159	26.8	8.99	3.91	24.19	0.093	28.23	1.08	0.19	1.94	921	8.57	1	8.5	53	63.89	1.23	82.41
Dec.15	133	25.4	7.55	3.93	19.81	0.089	19.17	0.75	0.08	1.02	1001	7.23	0.9	6.3	50.1	63.45	1.24	83.08
Jan.16	**42.89**	**21.98**	**7.09**	**4.05**	**10.51**	**0.07**	**8.26**	**0.1**	**0.04**	**0.57**	**645.33**	**8.7**	**0.5**	**3.8**	**48.3**	**63.37**	**1.21**	**81.07**
Feb.16	40.2	28.9	7.51	4.067	10.247	0.073	8.06	0.084	0.018	0.45	665.2	7.86	0.4	3.25	45.1	63.37	1.23	82.41
Mar.16	38.9	30.5	10.81	3.01	17.28	0.069	7.045	0.089	0.05	0.25	450.7	7.47	0.4	3.22	43.2	65	1.3	87.1
Apr.16	38.5	32.6	8.9	2.85	18.54	0.061	6.09	0.012	0.008	2.15	430.9	8.2	0.45	3.45	42.5	65.78	1.74	116.58
Mean	147.1	27.63	8.66	3.192	19.64	0.092	18.36	3.05	0.256	3.17	742.65	7.56	0.55	5.50	48.5	66.45	1.37	91.48

All parameters were measured in mg L^{-1} except otherwise stated

Appendix II Summary statistics of water quality variables (monthly mean) monitored in Vea reservoir

Month/ Year	TUR. (NTU)	W. Temp (°C)	DO	Cl-	SO_4^{2-}	PO_4^{2-}	SiO_2	NO_3N	NO_2N	NH_4N	CON. (µs cm^{-1})	pH	SDD (m)	W. Depth (m)	ALK.	T.HAR.	CHL-a (mg/m3)	PHY.BIO. (mg m^{-3})
Feb.15	14.89	24.9	10.08	5.42	7.29	0.001	14.81	0.22	0.009	0.75	1132.8	8.14	0.56	2.98	63.4	80.15	0.051	3.417
Mar.15	14.17	25.81	8.05	5.21	6.33	0.001	15.49	0.34	0.011	0.74	1135.7	8.09	0.55	2.61	62.4	78.48	0.052	3.484
Apr.15	16.12	25.23	8.43	5.01	6.52	0.001	14.12	0.39	0.011	0.73	1013	7.99	0.45	2.45	60.4	75.12	0.052	3.484
May.15	114	25.08	7.1	5.37	6.99	0.002	9.15	2.04	0.012	0.75	954.01	7.95	0.51	3.63	61.9	73.45	0.054	3.618
Jun.15	158	26.4	6.98	5.42	7.01	0.003	5.26	4.28	0.031	0.8	852	7.42	0.3	3.6	55.1	69.77	0.06	4.02
Jul.15	250	27.9	7.39	5.48	6.05	0.003	4.67	4.39	0.04	0.81	922.8	6.86	0.2	4.3	56.2	60.78	0.075	5.025
Aug.15	266.8	28.49	7.69	5.87	7.52	0.004	2.99	4.41	0.04	0.85	1116	7.89	0.47	4.61	56.6	57.74	0.079	5.293
Sep.15	249.8	28.47	7.5	5.41	13.24	0.076	5.27	9.11	0.04	0.88	770.56	7.78	0.404	4.87	48.7	53.33	0.079	5.293
Oct.15	371	29.4	6.81	7.88	14.31	0.095	6.86	8.96	0.05	0.89	1205	7.49	0.4	5.43	50.5	64	0.078	5.226
Nov.15	365	29.87	6.8	6.25	14.26	0.081	8.02	1.65	0.05	0.87	1010	7.38	0.55	4.86	49.2	62.33	0.064	4.288
Dec.15	291	29.94	6.8	5.38	14.35	0.09	8.95	0.8	0.04	0.75	1102	7.51	0.45	3.55	57.7	65.66	0.059	3.953
Jan.16	**87.79**	**23.4**	**6.79**	**5.27**	**14.46**	**0.11**	**10.53**	**0.2**	**0.04**	**0.76**	**1122**	**8.3**	**0.49**	**3.41**	**59.9**	**68.42**	**0.05**	**3.35**
Feb.16	90.44	25.7	9.45	5.63	14.03	0.105	10.49	0.16	0.045	0.76	1000.5	8.15	0.4	3.2	61.6	71.56	0.052	3.484
Mar.16	45	20.5	6.8	5.86	13.86	0.102	10.3	0.172	0.032	0.73	1039	8.15	0.3	2.65	63.2	70	0.051	3.417
Apr.16	32	29	7.98	5.88	13.39	0.099	10.57	0.17	0.041	0.73	1001.8	8.17	0.35	2.69	69.3	70.22	0.053	3.551
Mean	157.7	26.67	7.64	5.69	10.64	0.052	9.17	2.49	0.033	0.79	1025.14	7.82	0.426	3.656	58.4	68.067	0.061	4.06

All parameters were measured in mg L^{-1} except otherwise stated