Cage Aquaculture in Lake Volta, Ghana. Guidelines for a sustainable future

CSIR Water Research Institute
(Accra, Ghana)

Institute of Aquaculture (Stirling, UK).

A book based on the outcomes of

Planning for Improved and Sustainable cage Aquaculture in Lake Volta, Ghana

A collaborative research project funded by

The Leverhulme Trust

and

The Royal Society

ISBN: 978-1-908063-40-3

http://www.aqua.stir.ac.uk/GISAP/Ghana

COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH · GHANA · CSIR

WATER RESEARCH INSTITUTE

Quality Research for Sustainable Development

UNIVERSITY of STIRLING

THE ROYAL SOCIETY

The Leverhulme Trust

Planning for Improved and Sustainable cage Aquaculture in Lake Volta, Ghana

The Lake Volta Project

a collaboration leading to optimised

use of sites and zones and management of their impacts

Ruby Asmah, Anthony Karikari,

Lynne Falconer, Trevor Telfer, Lindsay Ross

http://www.aqua.stir.ac.uk/GISAP/Ghana

Cite as: Asmah, R., Karikari, A., Falconer, L., Telfer, T.C. and Ross, L.G. Cage aquaculture in Lake Volta, Ghana: Guidelines for a sustainable future. CSIR Water Research Institute, Ghana and University of Stirling, Stirling UK. 112 pp

Foreword

This book describes the approach, work undertaken and key outcomes of a three-year project which commenced in December 2012. The project was based on collaboration between the Institute of Aquaculture, University of Stirling, UK, and the CSIR Water Research Institute, Accra, Ghana. It was funded by the Leverhulme Foundation through a Royal Society Africa Grant.

Our key objective was to build capacity in environmental monitoring and assessment in partner organisations and, from the work carried out, to formulate a plan for improved and sustainable cage aquaculture on Lake Volta, so contributing to the developing industry and assuring regional food security.

Specifically, the project aimed to:

- Build a spatial database to model cage system site suitability in Lake Volta
- Determine the quantities of waste being discharged into the Lake based on production practices
- Determine the mode of aquaculture waste (uneaten food, faeces and other metabolites) dispersal in the Lake
- Develop predictive models of the effects of cage culture on the lake and its effect on other uses (drinking water, irrigation etc.)
- Build skills in environmental monitoring and impact assessments
- Develop guidelines for sustained cage aquaculture in the lake

The work presented here was carried out by the core team and by our students. We do not attempt to depict all of the research undertaken during and after the project, rather, we aim to show the scope and key outputs which address our principal objectives.

A digital version of this book is available at http://www.aqua.stir.ac.uk/GISAP/Ghana

The Core Project Team:

Dr Ruby Asmah (Ghana PI)
CSIR WRI, Accra, Ghana.

Mr Anthony Y Karikari
CSIR WRI, Accra, Ghana.

Professor Lindsay G Ross (UK PI)
Institute of Aquaculture, Stirling, UK

Professor Trevor C Telfer (UK Co-PI)
Institute of Aquaculture, Stirling, UK

Dr Lynne Falconer (draft editor)
Institute of Aquaculture, Stirling, UK

Contents

Overview

Background

Ghana is a country rich in natural resources, with minerals, forests and agricultural land, as well as oil and gas reserves, in abundance. Despite this, malnutrition is a major issue and there is a need to focus on food and nutrition security in addition to the economy. Fish are an excellent food source, providing high quality protein, essential vitamins and minerals, thus helping alleviate hunger and malnutrition. Although fish account for 60% of the national dietary protein in Ghana, fish production (mainly from capture fisheries) only contributes 420,000 metric tonnes which is less than half of national requirements. As a result, imports, valued at over US$200 million, are required to meet the annual fish production deficit of 460,000 tonnes (Ministry of Food and Agriculture Fisheries Commission, 2012.).

With declining fish stocks and a growing population the deficit continues to increase. Thus, in 2012, the Government of Ghana launched the Ghana National Aquaculture Development Plan (GNADP). The GNADP outlines plans to increase aquaculture production from 10,200 tons in 2010 to 100,000 tons by the end of 2016, increasing both the market share and value of Ghanaian farmed fish (Ministry of Food and Agriculture Fisheries Commission. 2012). This would contribute to local and regional food and nutrition security, be beneficial for the economy and provide a vital livelihood for many people. However, the production targets and timescale are very ambitious and it is vital that any development is sustainable.

The geography of Ghana offers a range of features that could be utilised for aquaculture. Rivers, reservoirs, lakes and estuaries, in addition to irrigation sites, offer potential areas for culture and the coastline stretches more than 500km, providing opportunities for mariculture. Arguably, the most promising location for immediate development is Lake Volta, one of the largest man-made reservoirs in the world (Figure 1).

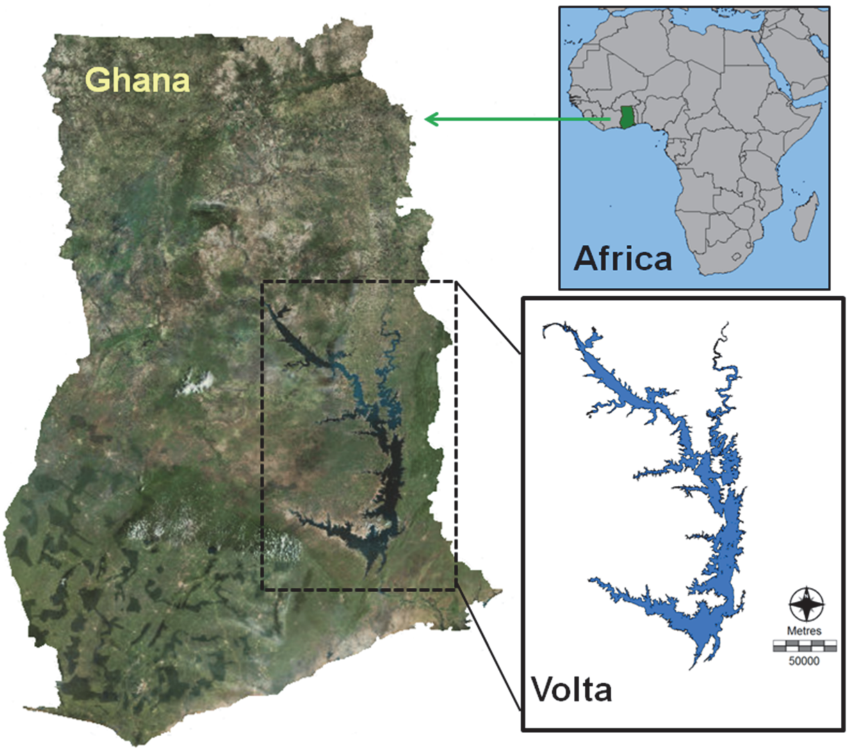

Figure 1: Lake Volta, Ghana.

Lake Volta is a multi-use environment with many different stakeholders and activities. In addition to hydropower generation, the lake is used for transport, a potable water supply, a fishing industry and cage aquaculture (Figure 2); which is a relatively new activity for the lake. The first cage farm was established in 2000 and other farms followed (Kassam, 2014). Due to the size of the lake and the favourable conditions for culture, there remains potential to increase the number of farms. However, it is important that development is carefully planned and managed and unregulated development must be prevented.

Figure 2: Cages on Lake Volta

As one of many activities on the lake, aquaculture must share the space and resources, consider the needs of other users and mitigate against negative impacts. The ecosystem approach to aquaculture (EAA) is a "*strategic approach to development and management of the sector aiming to integrate aquaculture within the wider ecosystem such that it promotes sustainability of interlinked social-ecological systems*" (Soto et al. 2008). To ensure sustainable aquaculture development, the EAA should be at the centre of planning and management of the sector.

One of the major components of the EAA is carrying capacity (Ross et al., 2013); 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. This concept is of fundamental importance for ecosystem-based management. However it is a complex issue that considers more than just environmental factors. In terms of aquaculture, carrying capacity helps set the upper limits of production based on environmental limits and social acceptability and is key to sustainable development.

Four categories of carrying capacity are considered important for aquaculture; physical, production, ecological and social (Ross et al., 2013):

- **Physical carrying capacity**, which may also be referred to as site identification, is the suitability for a development within the environment given the physical factors and farming system.
- **Production carrying capacity** estimates the maximum production, normally at farm scale.
- **Ecological carrying capacity** is the amount of production that can be supported without leading to significant changes to the ecosystem.
- **Social carrying capacity** is the level of aquaculture production that can be developed without adverse social impacts.

The importance of each category will vary depending on the species, system and region. Assessment of physical carrying capacity is usually the first stage as this determines if aquaculture can physically be located at a site or not (Figure 3). However, it is important to acknowledge that the categories inter-link and they are not entirely separate. The sequence of carrying capacity categories and the potential end-point of the decision process may also vary (Figure 4).

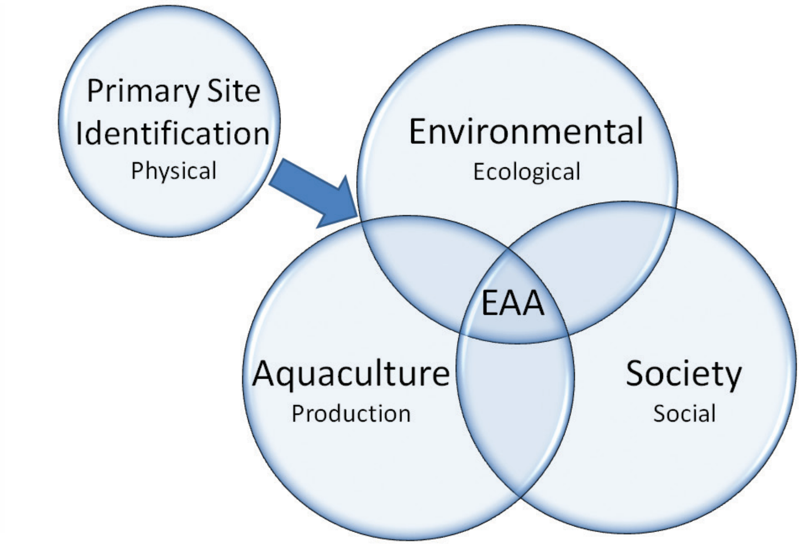

Figure 3: The interaction of the different categories of site identification and carrying capacity to arrive at an ecosystem approach to aquaculture. After primary site identification the process can pass on to any or all of the three other areas (Ross et al., 2013).

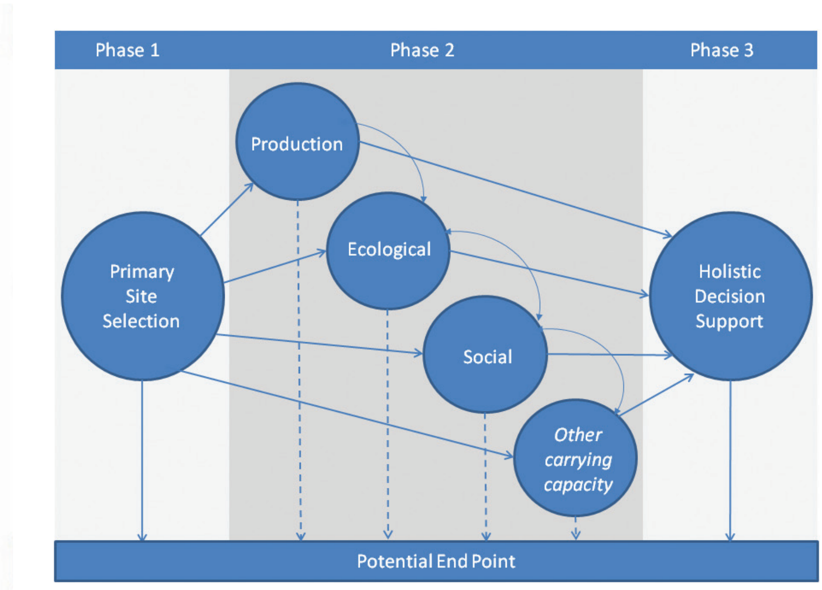

Figure 4: Schematic approach to the relationships and possible sequencing of the different carrying capacity categories, showing the range of end-points in the decision process. The order of priority in the second phase can be case specific (Ross et al., 2013).

Sustained long term development of cage aquaculture in Lake Volta will require estimation of carrying capacity. This involves monitoring existing conditions and using models to predict alternative and future scenarios. However, monitoring and modelling requires knowledge of the necessary tools and methodologies in as well as an appreciation and understanding of the lake environment, aquaculture systems and wider issues.

Project aims and objectives

This book provides an overview of the project "Planning for improved and sustainable cage aquaculture in Lake Volta, Ghana". The project was funded by a Leverhulme Trust/Royal Society Africa Grant and ran for three years from December 2012. It was a collaboration between the Institute of Aquaculture, University of Stirling, UK and the Council for Scientific and Industrial Research Water Research Institute (CSIR WRI), Accra, Ghana.

The principal aim of the project was to build capacity in environmental monitoring and assessment and to formulate a plan for improved and sustainable cage aquaculture on the Lake Volta, so contributing to the developing industry and assuring regional food security.

Approach

A decision support framework for aquaculture planning and management was developed, encompassing site selection, zoning and carrying capacity assessment for Lake Volta (Figure 5). The approach is flexible and can be adapted and applied for other species, systems and areas.

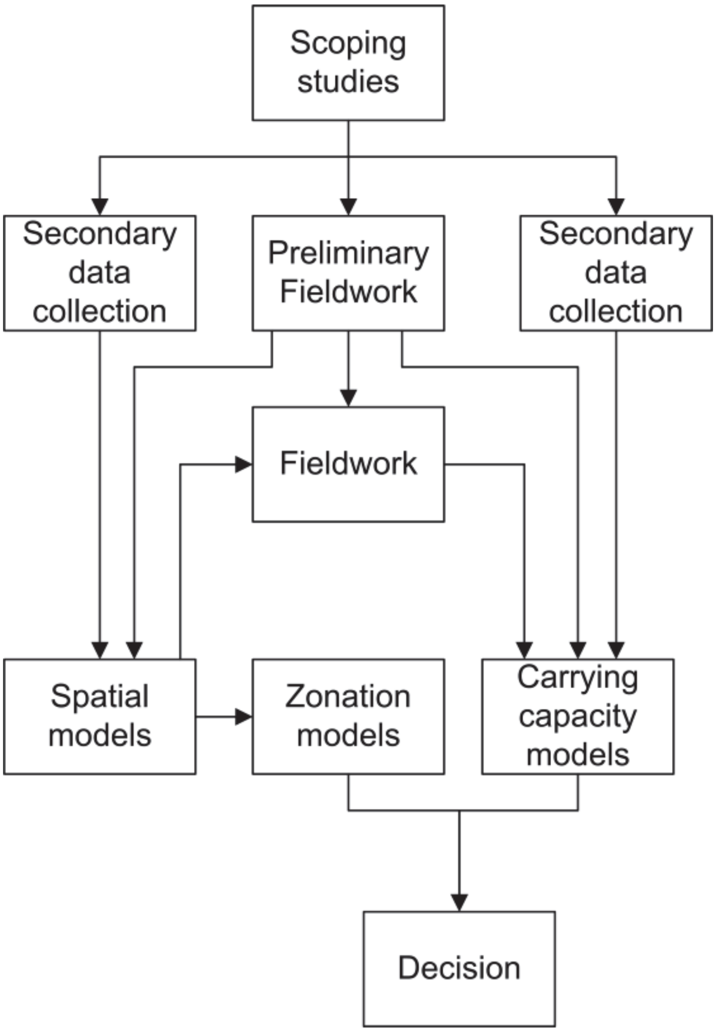

Figure 5: Project decision support framework

The first phase of the project involved scoping studies to collect background information, identify data gaps and define project scope and boundaries. Most farms on the lake stock tilapia species. The native Nile tilapia (*Oreochromis niloticus*) is the dominant species due to suitable conditions, relative ease of culture and a large market demand. These factors make tilapia cage culture an attractive prospect for increasing fish production. Thus, the project focused on tilapia production in Lake Volta.

The fieldwork campaign can be divided into two parts; farmer survey and environmental samples. Farmer surveys were conducted to obtain more information on the farms including the cage design, management styles, production data and the inputs into the systems. Environmental samples were collected at sites in the lake that were selected to represent different environmental conditions and farming practices. The data from both the farmer survey and environmental sampling were analysed and some data were also used in model development.

Models were developed to assess different categories of carrying capacity (Figure 6). Large-scale spatial models were developed using Geographic Information Systems (GIS) and remote sensing tools to assess the suitability of Lake Volta for cage culture. The spatial models considered the physical carrying capacity of the lake as well as some socio-economic factors and could be used for site selection and zoning. The spreadsheet based models assessed the ecological and production carrying capacity in important aquaculture areas.

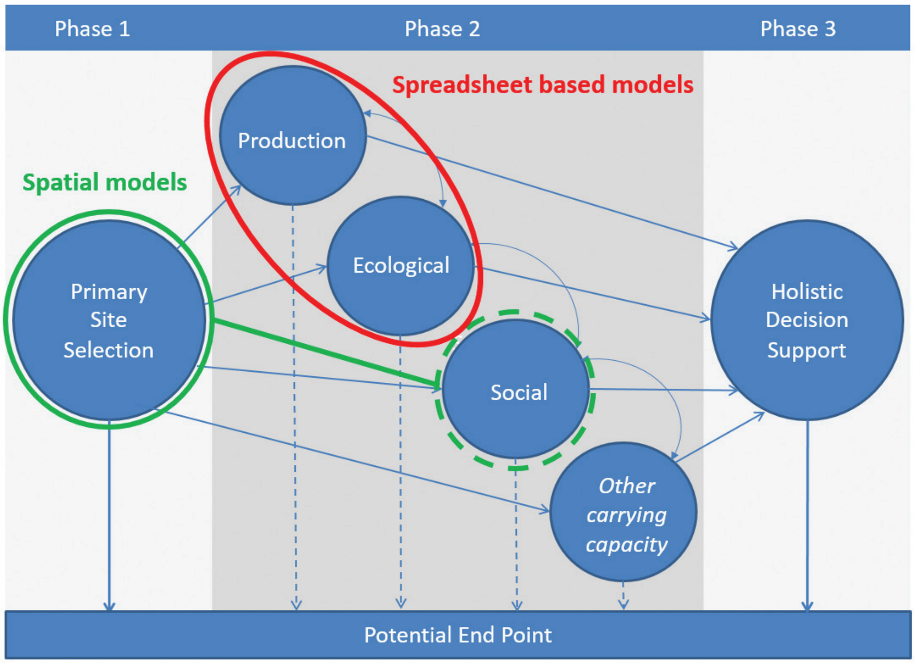

Figure 6: The spatial models focused on primary site selection (physical carrying capacity) but also considered some of the social issues which define production (social carrying capacity). The spreadsheet based models evaluated production and ecological carrying capacity.

The main aim of the project was to build capacity, so in addition to fieldwork, monitoring and modelling, the project team ran three workshops with key stakeholders in Ghana. The workshops were used for training, knowledge exchange, dissemination of results and project evaluation.

Summary

- Although fish are a major part of the diet in Ghana, there is a production deficit and shortfall is met by imports from other countries.

- The Government of Ghana has developed a national plan (GNADP) aimed at increasing aquaculture production.

- There is potential to increase production in Lake Volta but development must be sustainable.

- Three year project funded by a Leverhulme/Royal Society Africa grant ran with the principal aim of building capacity in environmental monitoring and assessment and formulating a plan for improved and sustainable cage aquaculture on the Volta Lake.

- A survey was used to obtain information about existing farms, management styles, production data and markets.

- Environmental samples were collected over two years at sites in the lake that were selected to represent different environmental conditions and farming practices.

- Spatial models were developed to assess physical carrying capacity with some consideration of social carrying capacity

- Zonation models were developed to help decision makers identify suitable zones for aquaculture development.

- Spreadsheet based models were developed to assess ecological and production carrying capacities.

- The project team held workshops in Ghana to help build capacity for environmental monitoring and assessment.

- This book is an overview of the project; summarising the approaches and results to produce general guidance for improved and sustainable cage aquaculture in Lake Volta.

Fish farm surveys

Cite as:

Karikari, A.Y.and Asmah, R. 2016. Fish farm surveys. In:Asmah, R., Karikari, A., Falconer, L., Telfer, T.C. and Ross, L.G. Cage aquaculture in Lake Volta, Ghana: Guidelines for a sustainable future. CSIR Water Research Institute, Ghana and University of Stirling, Stirling UK.112 pp.

Introduction

In order to identify monitoring sites and develop site selection and carrying capacity models it is first important to understand the farming practices of existing cage sites in Volta. This step is of vital importance as it provides background information and data which is necessary for both monitoring and modelling. Thus, in 2013, during the early stages of the project, a farmer survey was carried out by members of the project team (Figure 7). Twenty-three farmers were interviewed using structured questionnaires, which were administered to the farmers individually. The farms were randomly selected and included large, medium and small scale farmers, mainly in the Asuogyaman district in the south east of the lake (Figure 8), where most cage aquaculture is presently located.

Figure 7. Interviewing a farmer for the farmer survey

General information

All of the surveyed farms had been operating for less than ten years at the time of the survey (2013) with several farms established since 2011/2012. Thus, many of the cage aquaculture operations in Volta are still in their infancy. Most of the cages are constructed with local materials using a galvanised pipe frame and hardwood for the main structure of the cage, plastic or metal barrels for flotation, nylon mesh netting and concrete blocks and ropes for mooring (Figure 9).

Two of the larger farms use circular cages, however these require greater capital costs compared to the smaller square cages. In 2008 a circular cage (16 m in diameter) cost GH¢ 45000 (US$22500) whereas the cost of square cages (5x5, 6x6, 7x7) constructed between 2008 and 2012 ranged from GH¢ 1500 to 6460 (US$750 - 3230). Consequently, most farms use the cheaper, smaller, square cages. The number of cages on a farm increases or decreases over time depending on demand; at the time of the survey the number of cages ranged from 5 to 300 (Table 1).

Most farms were operated and managed by a hired farm manager or supervisor, resident in the local community, rather than the farm owner. Notably, only one farm out of the 23 was owned by a woman. In total, 674 workers were employed by the 23 farms across a range of roles; accounting clerks, administrative personnel, fingerling producers, pond and hatchery workers, drivers, storekeepers, security, net menders, graders and maintenance staff. This highlights the importance aquaculture can have on the local community, providing a valuable source of income and employment to many people.

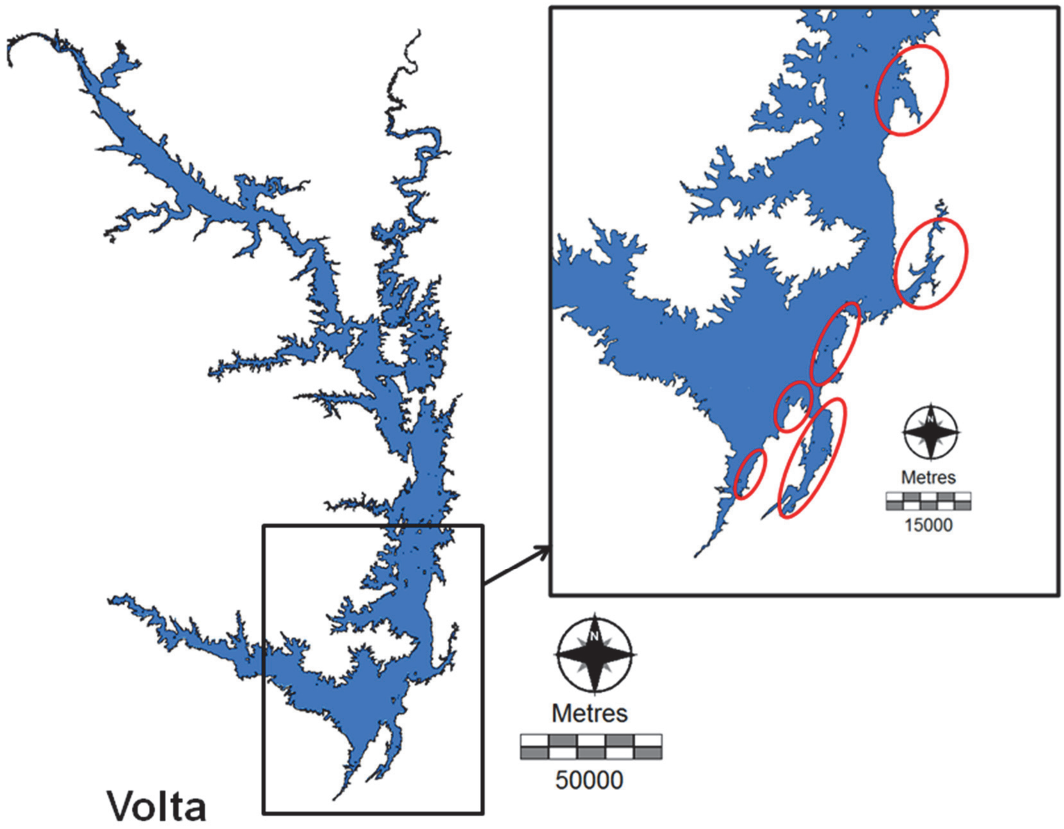

Figure 8: Locations of the surveyed farms in Lake Volta.
The red circles show the approximate location of one or more farms.

Figure 9: Typical small to medium scale cages used in Lake Volta

Table 1: General farm information from the 2013 survey

Farm	Year established	Type of cages	Total no. cages	No. workers
1	2008	Circular*	80	60
2	2008	4x4 / 5x5	168	37
3	2009	3x4 / 3x3 / 5x5 / 6x6	249	55
4	2012	4x4	100	8
5	2012	6x6	30	8
6	2012	6x6	40	8
7	2009	3x3 / 6x6	18	4
8	2006	3x3 / 6x6	> 200	315
9	2010	Circular	5	7
10	2010	6x6	120**	15
11	2011	5x5	80	50
12	2011	5x5	300	38
13	2011	5x5 / 6x6	24	5
14	2010	5x5	9	7
15	2010	5x5 / 6x6	18	10
16	2008	5x5 /5x8	10	5
17	2008	5x5	12	4
18	2011	5x5 / 6x6	18	5
19	2012	3x3 / 5x5 / 6x6	12	9
20	2011	3x3 / 5x5	17	5
21	2011	7x7 / 8x 8	22	7
22	2005	5x5	21	4
23	2010	5x5	246***	8

* 16m diameter **68 stocked *** 30 stocked

Production

All of the farms stocked *Oreochromis niloticus* from hatchery seed and most farms use the improved "Akosombo strain" for broodstock. This strain was developed through a joint collaboration between WorldFish and the CSIR WRI and grows up to 30% faster than non-improved wild fish. However farmers reported delays and availability issues with the supply of "Akosombo" fingerlings from the Aquaculture Research and Development Centre (ARDEC) of the CSIR WRI, which meant that although they prefer those fingerlings, they often had to go elsewhere.

Fry are nursed from one to three months, depending on the farmer, usually in 3 x 3 x 3m cages and then transferred to grow-out cages. Fingerling size ranged from 2 to 5g, this is well below the recommended weight of 15g (Beveridge, 2004) which may be due to lack of availability or farmer/market preference. Stocking density varied depending on cage size (Table 2).

Table 2: Average stocking density for the different cage sizes

Cage size	Average stocking density (fingerlings per cage)
4x4x4 m	5000 to 6000
5x5x4m or 5x5x5m	5000 to 10000
6x6x4 m or 6x6x6 m or 7x7x7m	10000 to 15000
Circular cages (16m diameter)	500000

The farms use imported commercially complete feed (extruded pelletized floating tilapia feed) as well as local feeds and farmers either feed to satiation or per biomass of fish. The food conversion ratio (FCR - amount of feed required to produce 1kg of fish) ranged from 1.6 to 2.4; which is within the typical range for similar systems throughout Africa.

The cages can be operated all year round, with fish stocked throughout the year. Farms choose when to harvest based on maximum profit (Figure 9). Large scale farms tend to harvest weekly or twice weekly, whereas small and medium scale farms harvest less frequently from one month to six month intervals.

Figure 9: Fish harvested from cages

Ice blocks are used during harvesting to preserve the freshness of the fish, but other inputs such as pesticides and chemicals are not commonly used by farmers. Total annual production varies depending on the scale of the farm, with small-scale farms producing between1 - 50 metric tonnes and some of the larger farms producing over 5000 metric tonnes (Table 3).

Table 3: Categories of fish farms and production activities.

Size of Farm* Operation	Strain of Tilapia Produced	Type of Feed used	Stocking density (fish/m^3)	Mean annual production (tonnes)
Small scale (< 50 tonnes/yr)	Akosombo strain	Extruded pelletized feed	23 – 50	1 – 50
Medium Scale (50 – 100 tonnes/yr)	Akosombo strain	Extruded pelletized feed	28 – 96	50 – 84
Large Scale (≥ 100 tonnes/yr)	Akosombo strain	Extruded pelletized feed	41 - 80	165 - 5150

*Based on Ghana EPA farm scale definition

Marketing

Tilapia is a popular food fish in Ghana, increasing demand for the product. There are several routes to market, but most farmers prefer to sell to wholesalers with whom they have a good relationship as they usually pay in cash at the farm gate. Approximately 75% of the surveyed farms sell at the farm gate, with a further 13% selling at both the farm gate and local market. Larger farms have stopped selling at the farm gate; instead they have sale points in nearby towns and cities for ease of access to products by their clients.

Figure 10: Fish grading after harvest

Fish are graded prior to selling (Figure 10) as they are sold per kg and price depends on the size (Table 4). At the time of the survey, price was largely uniform across all fish farms, mainly determined by the larger farms. Cheaper imports from other countries can impact the price, and although imports from China are illegal it still occurs as Ghanaian production is not enough to meet the demand.

Table 4: Average prices of tilapia per kg in the study area during the 2013 survey

Sizes	Size range (g)	Price/ kg (GH¢)	Price/ kg (US$)*
3	700 – 1000	7.90	3.95
2	500 – 700	7.20	3.60
1	300 – 500	6.50	3.25
Regular	200 - 300	6.00	3.00
Economy	150 – 200	5.00	2.50
School boys	< 150	4.00	2.00

* 1US$ = 2.0 GH¢ in 2013

Technical assistance

Technical assistance to farmers and operators is provided by the Fisheries Directorate, ARDEC of CSIR WRI, NGO's, feed suppliers and the fish farm companies. Farmers received assistance on feeding, stocking and water quality, provided through workshops and on-farm training with experts. However, although technical assistance and training is available, farmers noted it is not regular and half said they did not receive any assistance.

Constraints

To understand the constraints facing aquaculture development in Lake Volta, farmers were asked about the problems they had encountered or were aware of. The constraints could be classified into groups; technical, social, production, institutional, economic/environmental and other (Table 5). However, it is important to note that both the groupings and the constraints are not always independent and many are also interconnected.

Table 5: Constraints to aquaculture production on Lake Volta identified by farmers

Technical	Social
• Lack of trained and qualified managers • Inadequate facilities • Post-harvest loss	• Poaching and stealing • Interference by community
Production	**Institutional**
• High feed costs • Insufficient availability of fingerlings • Irregular starter feed supply	• Lack of adequate skilled personnel • Bureaucracy • Logistical problems with shipping
Economic / environmental	**Other**
• Lack of credit • Water quality • White spot disease	• Storm damage to cages • Net destruction by wild predatory fish

Concerns

In addition to constraints, farmers were also asked about concerns they had regarding cage culture in Lake Volta. Unlike constraints, concerns are not necessarily barriers to production. Nevertheless, they may affect production, community acceptance and the sustainability of the sector.

Some farmers expressed concern over high stocking densities potentially leading to nutrient pollution. However, other farmers did not consider this an issue and believed the large size of the lake and wind action would mean that any nutrients would be dispersed quickly. Most farmers did not think their activities would impact water quality, although localised impacts have been observed during the dry season (December to April). Large scale farms monitored water and sediment quality, but small scale farms had little or no environmental awareness. This is a reflection of the regulatory requirements where large farms are required to submit environmental impact statements and management plans, but small farms (below 50 tonnes per annum) are only required to register their farm activities with the Ghana EPA, providing information of type of production system, sources and types of inputs used.

There is conflict between indigenous fishermen and cage farmers. The indigenous fishermen believe their catches are greater near cages as there are escapees in addition to wild fish attracted by waste feed. However, farmers do not want fishermen near their cages, and this is often a source of friction, particularly where fish farm boundaries are not properly defined.

Local people have also expressed concern over the siting of cages, notably in areas where the location of cages makes navigation of the waterways, a public space, difficult or impossible. This can create tension between local communities, especially fishermen and boat users who have a right to access and use of the lake.

Summary

- Twenty-three farmers were surveyed using a structured questionnaire to obtain knowledge and understanding of the existing cage sites and farming practices in Volta.
- The farmers were randomly selected, mainly from the Asuogyaman district in the south east of the lake where most cage aquaculture is presently located.
- Most cages are square/rectangular and made of locally sourced materials, however two of the larger farms use circular cages.
- All farms stocked *O. niloticus,* with a preference for the "Akosombo strain".
- The farms use imported commercially complete feed (extruded pelletized floating tilapia feed) as well as local feeds. FCR ranged from 1.6 to 2.4.
- Cages can be operated all year round, with fish stocked throughout the year. Farms choose when to harvest based on maximum profit.
- Fish are graded before selling and price is mainly dictated by the larger farms.
- Although technical assistance and training is available, farmers noted it is not regular and many said they did not receive any assistance.
- Farmers identified a number of technical, social, production, economic/environmental and institutional constraints (lack of training, water quality, inadequate facilities etc.).

Water and sediment quality

Cite as:

Karikari, A.Y. and Asmah, R. 2016. Water and sediment quality. In:Asmah, R., Karikari, A., Falconer, L., Telfer, T.C. and Ross, L.G. Cage aquaculture in Lake Volta, Ghana: Guidelines for a sustainable future. CSIR Water Research Institute, Ghana and University of Stirling, Stirling UK.112 pp.

Introduction

Aquaculture in freshwater is rapidly developing in Ghana, in Lake Volta. The increasing number of cage farms in the Lake is of concern since several studies suggest wastes generated from cage aquaculture can negatively impact water and sediment quality (Beveridge, 2004). These impacts are a result of wastes from fish faeces, uneaten food, and bacterial biomass. The faeces and the food wastes have higher contents of carbon, nitrogen and phosphorus than the natural sediments (Morrisey et al., 2000). This causes the lakebed beneath these farming systems to have elevated levels of organic matter and nutrients. The intensive fish culture in cages can lead to the eutrophication of water bodies and to the emergence of deleterious effects on the water quality, such as the blooms of toxic cyanobacteria that are harmful for wildlife and humans. Since the exchange time of freshwater systems is normally longer than that in marine environments, the environmental effects of wastes produced by freshwater cage fish culture can be stronger and longer lasting than those of marine cage farming (Beveridge *et al.,* 1997). This aspect of the work looked at the effects cage fish farm may be having on the water and sediment quality of the Lake.

Data collection

Bi-monthly hydrological data, water and sediment samples were collected over a two-year period to characterise the Lake environment. The three sites were selected to represent different environmental conditions, farming practices and size of operation. They are all located in the south east of the lake, in areas that are currently used for aquaculture. Ten to seventeen monitoring stations were selected per site (Figure 11).

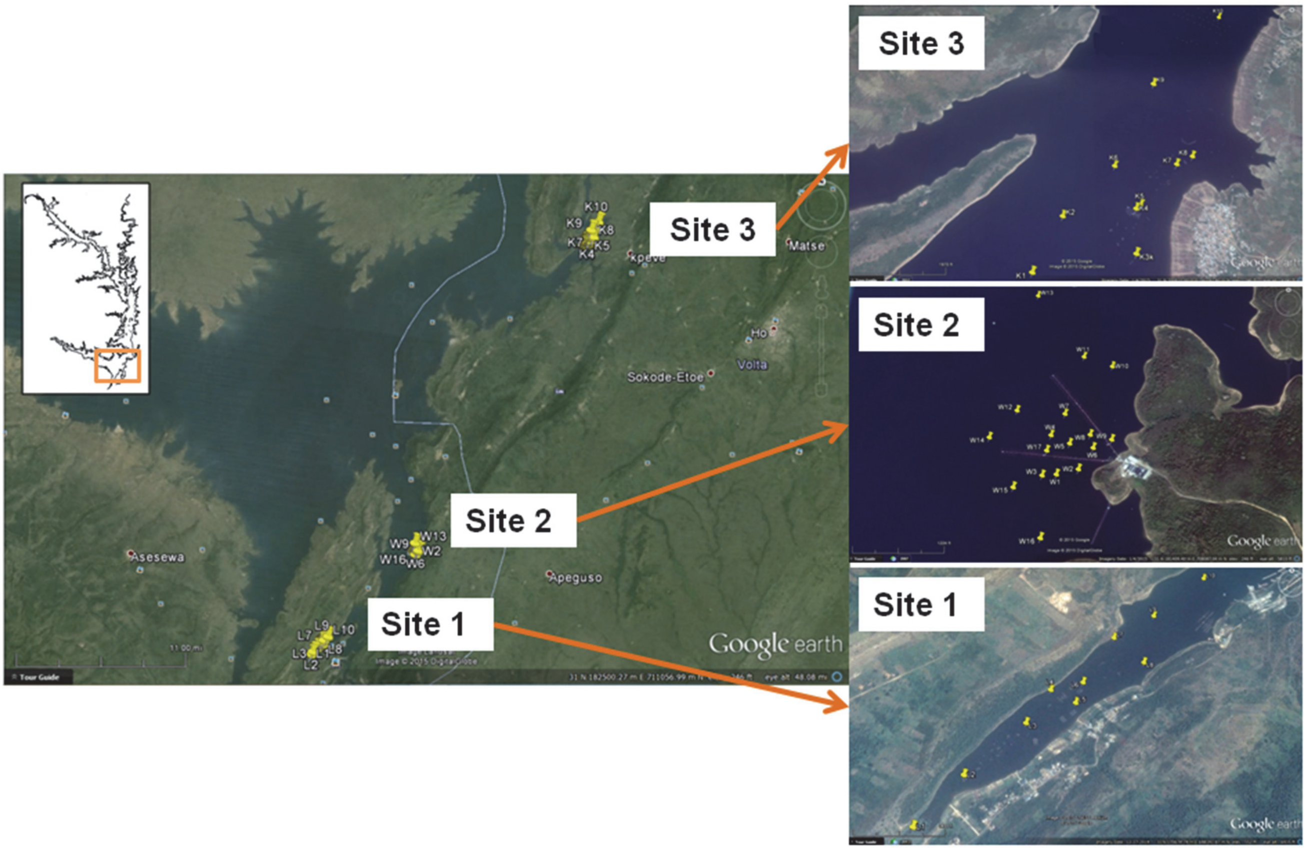

Figure 11:The study sites showing the sampling stations.

Hydrographic Surveys

Figure 12: Drogues deployed in Lake Volta

Surveys were conducted to collect current and depth data in areas adjacent to the key study areas. Current velocity and direction was collected using drogues (Figure 12) and a Valeport™ Model 002 current meter (Valeport Ltd, Totnes, UK). The measurements were taken at 1m, 5m and 10m depths. Water depths were measured using an echo sounder.

Water quality monitoring

Water samples were collected with a 5 litre Van Dorn sampler from 1m below the surface and 1m above the bottom of the lake (Figure 13).

Figure 13: Collecting water samples with a Van Dorn water sampler

Measured parameters:

- pH
- Temperature
- Dissolved Oxygen (DO)
- Chemical Oxygen Demand (COD)
- NO_3-N
- NH_4-N
- PO_4-P
- SS
- H_2S
- Turbidity

Dissolved Oxygen, pH, temperature and turbidity were measured *insitu* using WagtechMaji-meter (Wag-WE 51,000, UK).The analytical methods used in the analyses of the water and sediment samples are summarised in Table 6.

Sediment monitoring and assessment

Bottom sediment samples were collected using an Ekman grab with dimensions; 20 x 20 cm (Figure 14).

Macroinvertebrate assessments of the monitoring station were made from composite sediment samples collected from the sites. Three grab samples were collected per station.

Figure 14: Sediment sampling

Measured parameters:

- Particle size
- Organic matter
- Organic carbon
- Total nitrogen
- Total phosphorus
- Selected trace metals
- Macro-invertebrates

Table 6: Analytical methods used

Parameter	Method
pH	WagtechMaji-meter, Wag-WE 51000, UK
Conductivity	WagtechMaji-meter, Wag-WE 51000, UK
Temperature	WagtechMaji-meter, Wag-WE 51000, UK
DO	YSI meter, model 13J100771, USA
Turbidity	HACH 2100P Turbidimeter
Transparency	Secchi disc
Chlorophyll-a	Extraction with acetone
NO_3-N	Hydrazine reduction
NO_2-N	Diazotization
NH_4-N	Direct Nesslerization
PO_4-P	Stannous chloride
COD	Closed tube method
Metals (Fe, Zn, Cu, Mn, Cd, Pb, Se)	Atomic Absorption Spectroscopy
Total Nitrogen (TN)	Kjeldahl method
Organic Carbon (OC)	Walkley Black method
Total Phosphorus (TP)	Ascorbic acid method
Total Organic Matter (TOM)	Ignition Method

Lake water quality classification

The Water Quality Index is an effective way of describing water quality for an intended use. It has the capability to combine measurements of several water quality variables in such a way as to produce a single score that is representative of quality impairments or suitability of use (Dunnette, 1979). For the sake of comparison, two methods were selected to compute the water quality status of Volta Lake and to determine its suitability for fish farming. The first was the CCME WQI (Canadian Council of Ministers of the Environment, 2001) which has been used to compute the WQI for tilapia cage farming and the second was the adapted Ghana water quality index which is based on Solway to calculate the WQI for other intended ecosystem use.

The water quality parameters used in classification of the sites for their suitability for aquaculture are presented Table 7.

Table 7: Optimum ranges of variables for culture of Tilapia

Variables	Optimum ranges for tilapia culture
Temperature (°C)	> 22 and < 38
pH	>6.5 and <9.0
DO (mg/L)	6.5 and < 9.0
Total hardness (mg/L)	>20 and < 350
Nitrate (mg/L)	< 10.0 /L
Ammonium-nitrogen (mg/L)	< 5.0
Alkalinity (mg/L)	>54 and < 200
Dissolved reactive phosphate (mg/L)	<1.5
TDS (mg/L)	< 300
Sulphate (mg/L)	< 500
Nitrite-Nitrogen (mg/L)	< 0.10
Unionized ammonia	<0.01

Hydrology of Lake Volta

Water currents are used to model the dispersion of particulate waste from fish farms. Currents determine the distance and direction that wastes from cages would spread and eventually be deposited. The hydrographic current flows at farm site 2 are given in Figures 15and 16. The mean current velocities in August 2014 was0.105 ms^{-1} at 1m depth and 0.057 ms^{-1} at 10 m depth, suggesting a good dispersion capacity. The scatter plots (Figure 15) showed similar direction of water movement (North-East) irrespective of depth. Additional measurements taken in March 2015, showed slower movement of the water with average velocities of 0.037$ms^{-1}$and 0.036ms^{-1}at 1 m and 10 m respectively; suggesting that the current velocities are not consistent all year round. The residual flow, however, remained in the same direction - north east (Figure16).

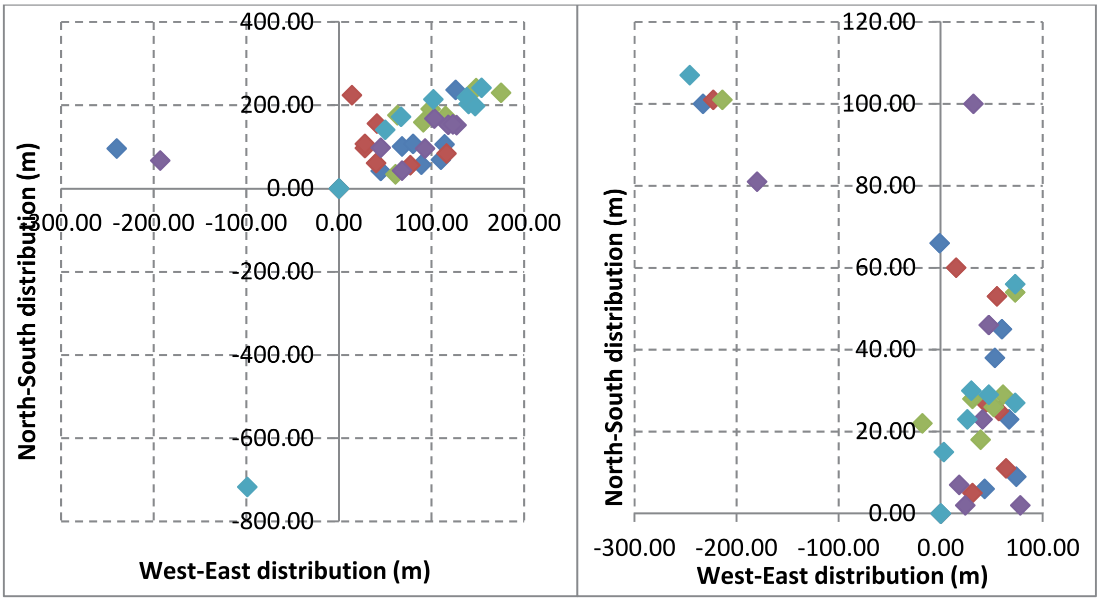

Figure 15: Scatter plot of currents at 1 m and 10 m depth at Farm Site 2.

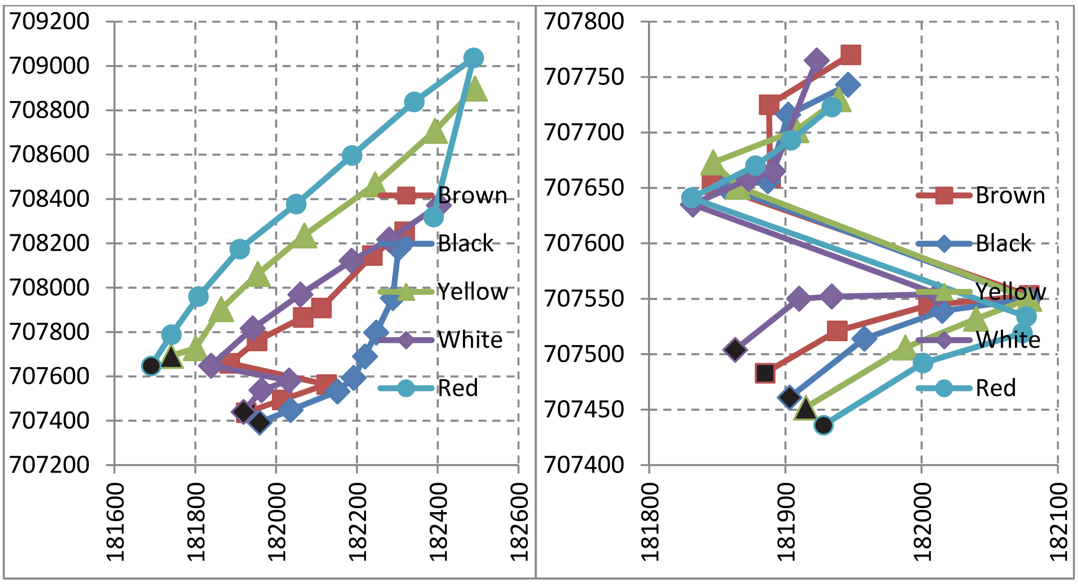

Figure 16: Track plot showing residual currents at Farm Site 2

Water quality

Results of the water quality analyses suggested that the sampled sites unpolluted and suitable for tilapia culture. The pH values were observed to range from 6.3 to 8.7 at all the sites. Hydrogen sulphide was not detected in the water over the monitoring period. The water temperature of the lake reflected ambient weather conditions (26.6–30.9°C) and showed minimal variation between farmed and control sites. The conductivity of the water was typical of fresh water bodies with values of 54.6 to 133.4 µS/cm. Transparency at all the farm sites ranged from 1.37 to 3.28 m with site 2 recording the highest transparency. Transparency at the control sites were slightly higher with values ranging from 1.4 to 3.8 m (Figure18). The total hardness and alkalinity values were, however, slightly lower than the recommended range of 50 – 250 mg/l for fish culture. These parameters are important for excellent fish growth.

Dissolved oxygen (DO) is one of the most important parameters for aquatic life. Levels in the sites studied in the Lake ranged from 4.58 to 9.33 mg/l and these were all above the critical farm value of 3.7 mg/l (Abo and Yokohama 2007) (Figure 18). DO concentrations at the control sites were marginally higher than those at the farm sites. Depth profiles of DO at the study sites showed that the water was well oxygenated to depths of 15 to 25 m, depending on the depth of water, beyond which the levels dropped sharply to anaerobic conditions. Dissolved inorganic nutrients (NO_2-N, NO_3-N, NH_4-N and PO_4-P) were not significantly different ($p>0.05$) between the farms and the control sites. Surface water NO_2-N concentrations ranged from 0.001 to 0.020 mg/L, NO_3-N levels ranged from 0.001 to 0.250 mg/L. Ammonium-nitrogen levels varied from 0.001 to 0.419 mg/L and PO_4-P concentration in the water fluctuated from 0.001 to 0.275 mg/L.

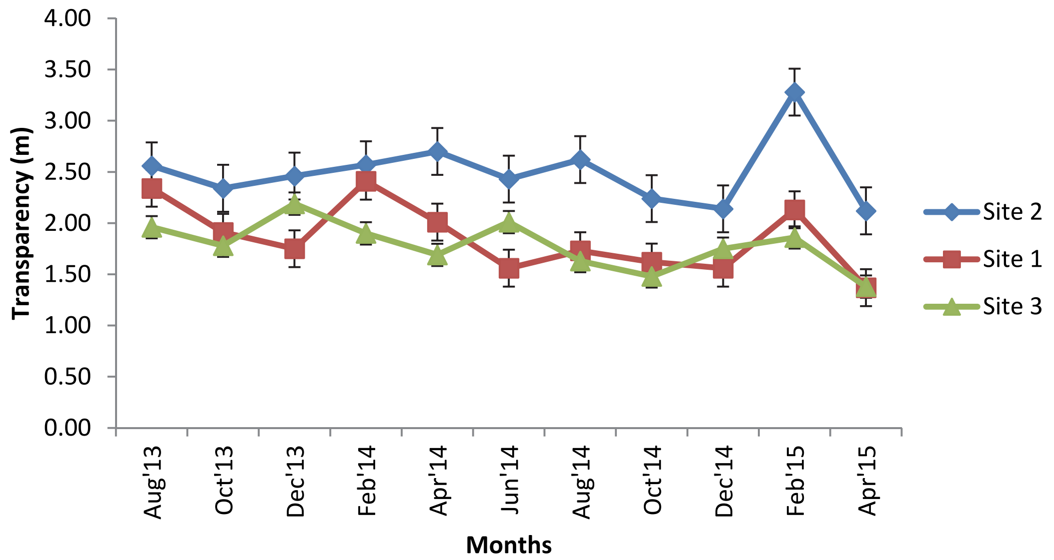

Figure 17: Transparency levels at the farm sites

Chlorophyll-a levels ranged from 1.19 to 12.53 µg/L at all sites (Figure 19). Total phosphate (TP) concentrations in the water were normally below 200 µg/L except for seasonal spring peaks which can exceed 600 µg/L(Figure19). There were no significant differences between the farm sites and the control sites in TP and chlorophyll-a concentrations ($p>0.05$). Phosphorus has been reported as a vital nutrient determining eutrophication status of reservoirs (Marinho and Huszar, 2002).

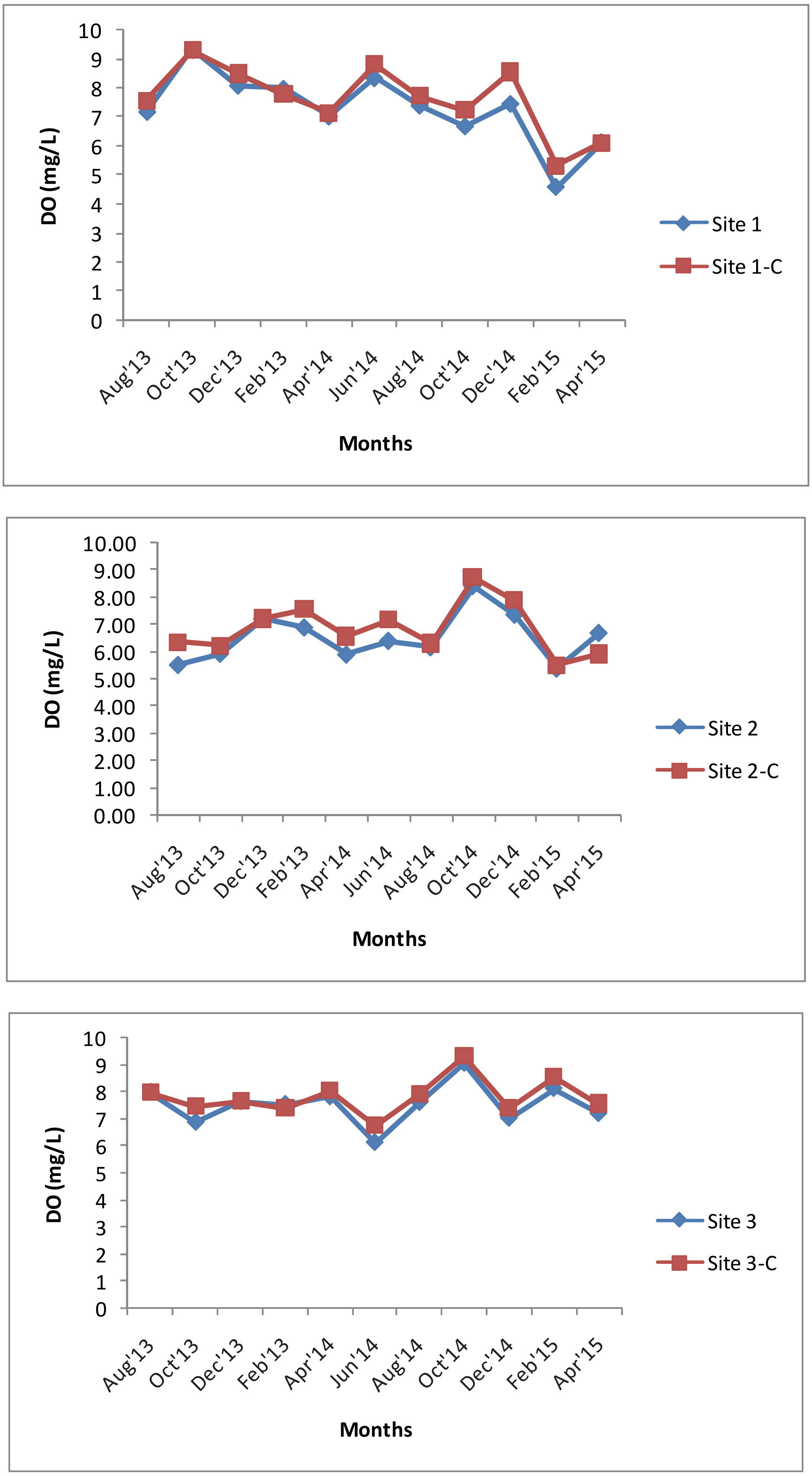

Figure 18: Temporal variation of mean DO in surface waters at farms and control sites.

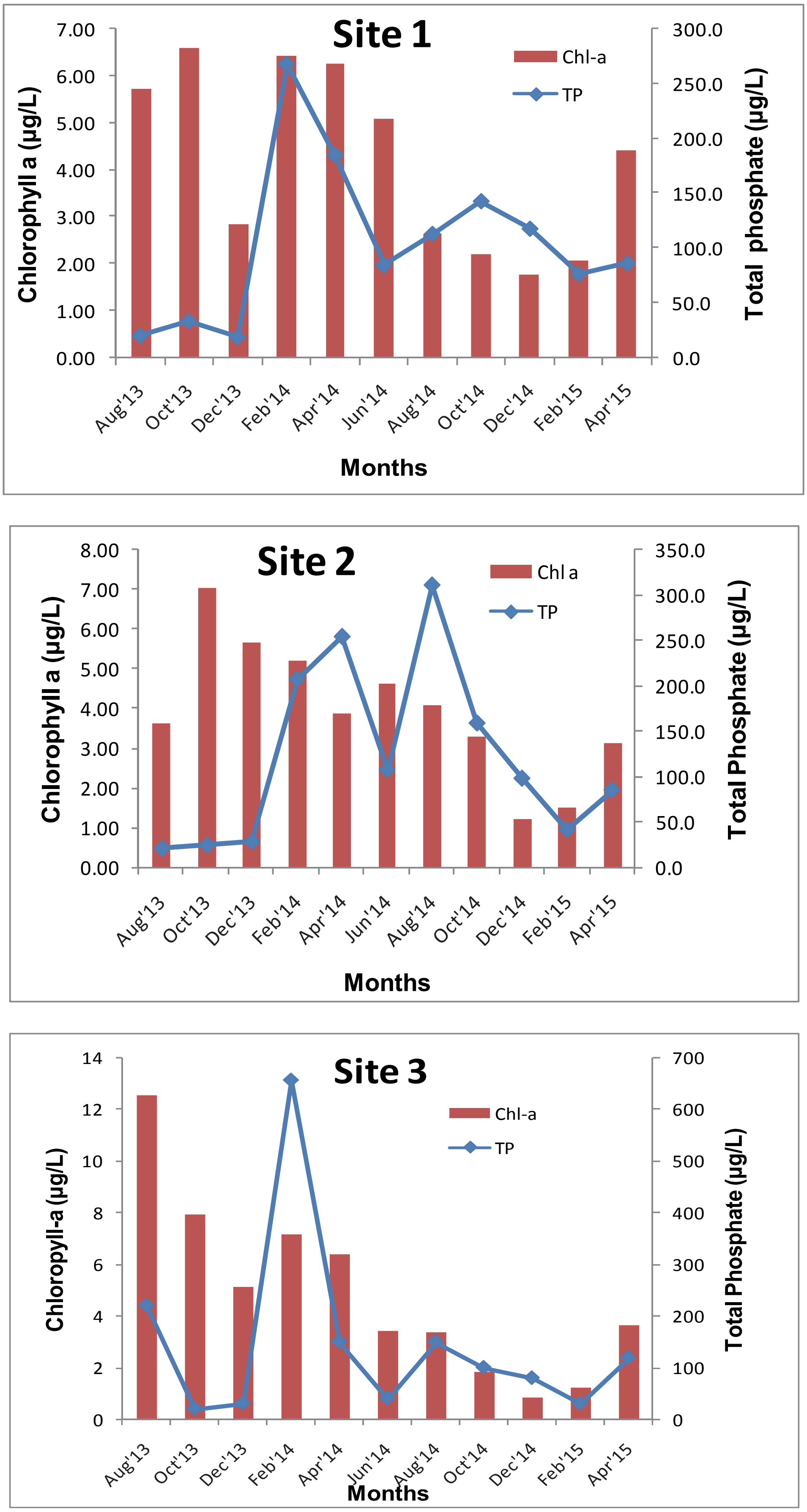

Figure 19: Levels of Chlorophyll-a and total phosphate of surface waters in the farm sites.

Metal concentrations in the water column at both the surface and the bottom were generally low. Lead, Cu, Cd and Se were not detected in the Lake water (Table 8). However, Zn, Fe and Mn levels detected in the water column were within the permissible limits for freshwaters recommended by USEPA (1986).

Table 8: Metal levels in Lake Volta water

Metal	Site 1	Site 2	Site 3
Pb (mg/L)	ND	ND	ND
Zn (mg/L)	0.003 ± 0.007	0.010 ± 0.028	0.007 ± 0.020
Cu (mg/L)	ND	ND	ND
Cd (mg/L)	ND	ND	ND
Fe (mg/L)	0.11 ± 0.132	0.144 ± 0.272	0.066 ± 0.068
Mn (mg/L)	0.042 ± 0.041	0.075 ± 0.155	0.019 ± 0.097
Se (mg/L)	ND	ND	ND

ND= not detected

Canadian and Ghana Water Quality Indices (CCME-GWQI)

The CCME water quality model results for the Farm sites are shown in Figure 20, while that of GWQI is presented in Figure 21. The CCME water quality model results for all the Farm sites confirmed that the water quality was good and does not differ much from the natural or desired levels. The water quality index for the wet and dry seasons ranged between a score of 90 and 94 ("Good" water quality) which is very conducive for tilapia production. The seasonal changes did not affect the water quality. For ecosystem use, the adapted GWQI showed good water quality (Class I) for most of the monthly assessment both for the farm and the control areas (not shown). However, the studied areas indicated class II (range 72.36 – 77.16), which is classed as "Fairly Good" water, suggesting that only few uses of the water have been impaired (Figures 26 and 27). Overall, water quality at the sample sites was acceptable for any intended uses such as for water supply, irrigation, recreation and cage culture or tilapia production.

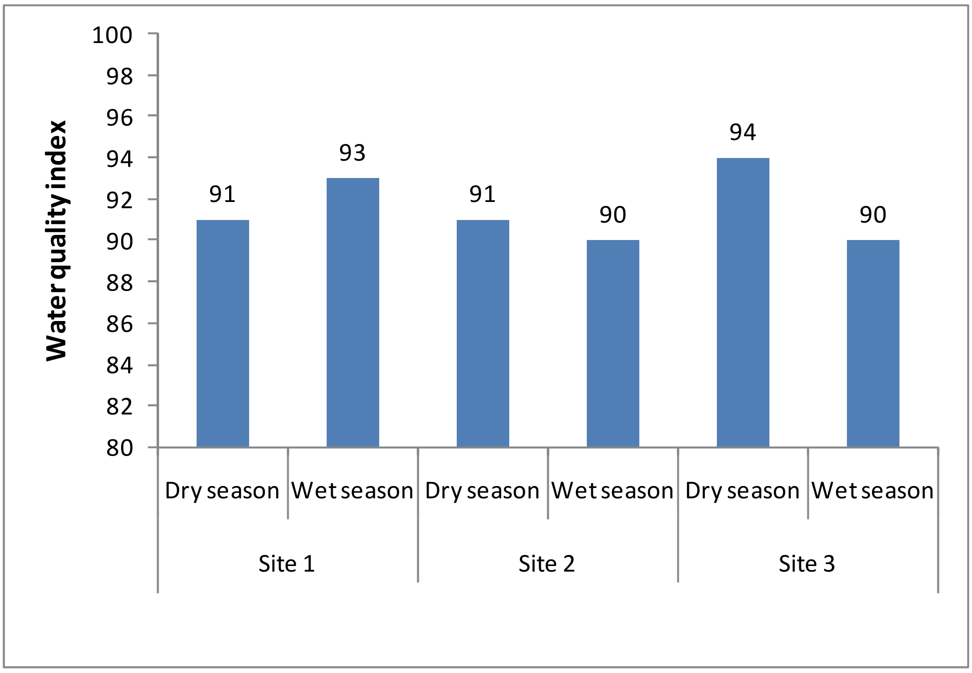

Figure 20: CCME water quality index of tilapia cage farms at different seasons (wet and dry) on the Lake Volta.

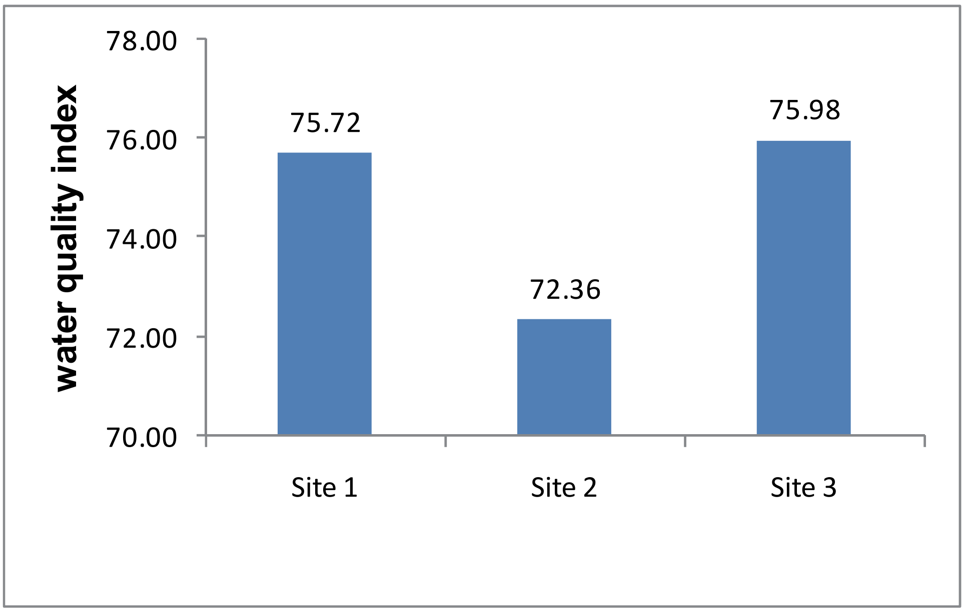

Figure 21: Average GWQI water quality index for the farm sites

Sediment quality

Sediments at the monitoring sites were largely sandy clay loam, comprising on average 52.8 to 58.3 % sand, 19.2 to 22.1 % silt, and 21.9 to 25.0 % clay (Table 9). The type of sediments at sites 2 and 3were very similar and showed no significant variation in composition. Sediments at Site 1had slightly lower contents of sand when compared to Sites 2 and 3. Average compositions of sediments at the monitoring stations of the three sites are presented in Figures22, 23 and 24.A comparison of sediment types at the monitoring stations for each of the site showed minimal variations ($p > 0.05$) between the farmed and control areas at sites 2 (Figure23) and site 3 (Figure 24). Variations were, however, observed in sediment composition at Site 1. The monitoring stations closest to the fish cages (Figure 22) had higher contents of silt and clay, and these varied significantly ($p<0.001$) from the reference sites and some of the monitoring stations. These results suggest that fish farming activities at site 1 may be having localized effect on sediment composition of its immediate environment.

Table 9: Mean percentage sediment composition and ranges at the sites

Sediment Type	Site 1	Site 2	Site 3	level of significance
Gravel	0.03	0.06	0.08	>0.05
	0.00 – 1.91	0.00 – 3.00	0.00 – 7.60	
Sand	52.8	58.2	58.3	<0.001
	31.5 – 65.5	28.8 – 76.7	32.0 – 81.2	
Silt	22.1	19.2	19.6	<0.001
	16.5 – 30.3	9.4 – 30.6	3.8 – 31.2	
Clay	25.0	21.9	22.0	<0.001
	17.7 – 40.7	13.0 – 59.4	12.6 – 49.8	

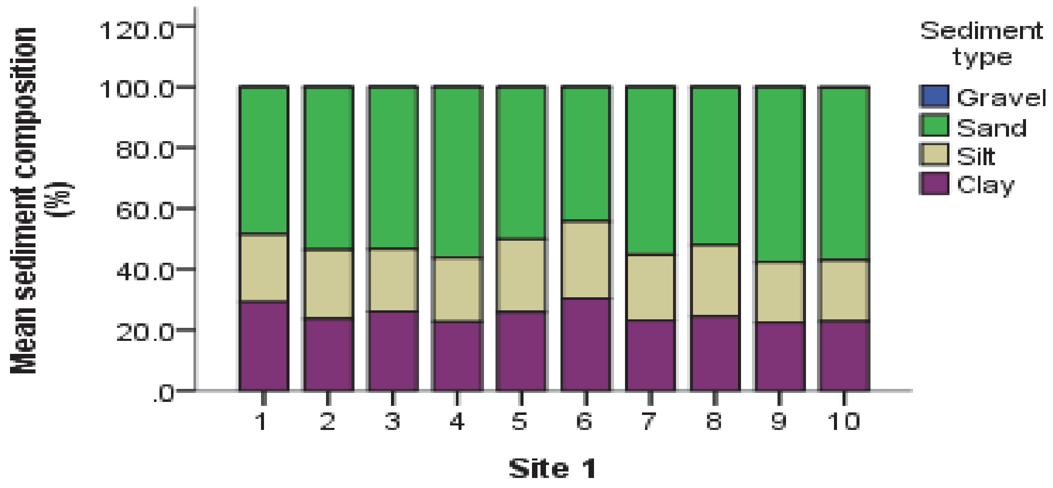

Figure 22: Mean sediment composition at monitoring stations in Site 1 (n = 108). Station numbers on horizontal axis

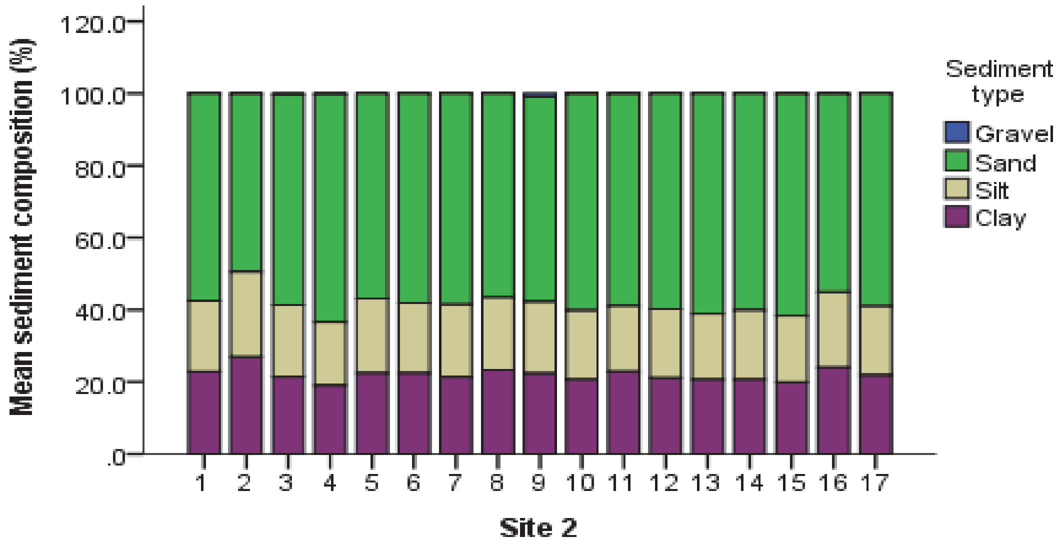

Figure 23: Mean sediment composition at Site 2 (n = 110). Station numbers on horizontal axis

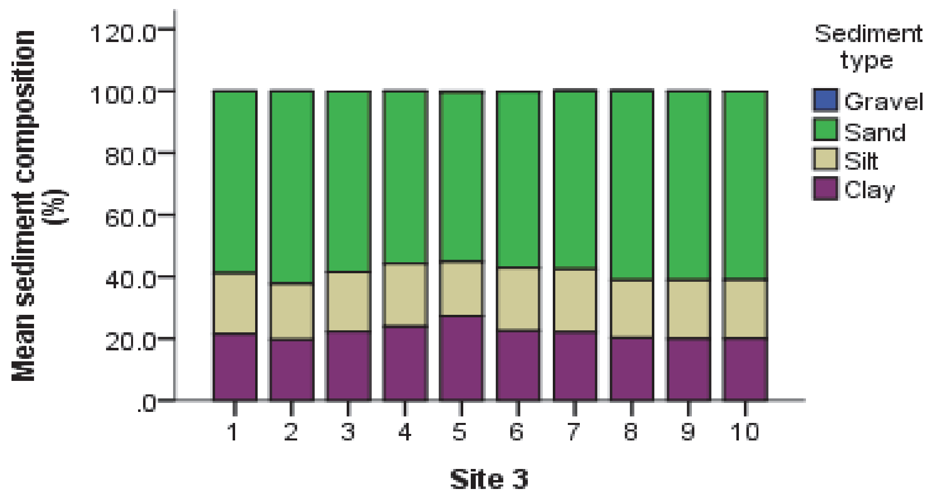

Figure 24: Average sediment composition at Site 3 (n = 110). Station numbers on horizontal axis

The pH of the sediments was quite acidic with values ranging from 4.81to 5.22 (Table 10). The moisture contents were quite high ranging from 47 % to 69%. Strong correlations existed between sediment composition and the moisture content; direct proportionality was observed between the moisture content and the quantity of sand in the sediment.

TOM, TN, OC and TP represent the long-term, average burial rate of organic material in sediments (USEPA 2002) and their levels are often used as indicator of sediment enrichment by organic waste. Accumulation of organic material in a Lake, particularly in the zones with poor current flow, can cause major changes in the constituents of the sediment. It is estimated that for a zone to be considered uncontaminated, the content of organic matter in the sediment must range from 0.5 to 5 %, whereas sediments with more than 15 % organic matter are typical in contaminated zones (Méndez, 2002). US EPA (2002) recommending assessment categories for TOC in sediments, proposed mean TOC at farm sites to range from 2.07 – 4.60%. The overall average concentrations of TOC at the three monitoring Sites were within this recommended range, but the range of values obtained from the study as presented in Table 10suggest there were occasions when these threshold values were grossly exceeded. For low impact, TOC should be less than 1 %; for intermediate impact, TOC should range 1 to 3 %; and for high impact the TOC in sediments should be greater than 3%. However, these thresholds are still under evaluation.

Table 10: Quality of sediments at farm and control sites

		pH [Farm]	%Org. C [Farm]	%Org. M [Farm]	%TN [Farm]	C/N
Site 1	Farm	**5.16** (4.0 – 7.1)	**2.01** (0.01 – 5.44)	**3.50** (0.14 – 9.60)	**0.18** (0.01 – 0.47)	11.2
	Control	**5.09** (4.7 – 5.96)	**2.48** (0.74 – 5.4)	**4.27** (0.79 – 9.4)	**0.21** (0.01 – 0.47)	11.8
Site 2	Farm	**5.16** (3.9 – 7.2)	**3.98** (0.98 – 8.3)	**6.87** (1.15 – 15.2)	**0.34** (0.06 – 1.45)	11.7
	Control	**5.11** (4.35 – 6.4)	**4.38** (3.3 – 8.3)	**7.53** (5.68 – 9.7)	**0.38** (0.28 – 0.72)	11.5
Site 3	Farm	**4.80** (3.9 – 5.6)	**3.95** (1.15 – 6.94)	**7.0** 1.98 – 11.9)	**0.35** 0.10 – 0.60)	11.3
	Control	**4.66** (4.0 – 5.23)	**3.85** (1.57 – 6.5)	**6.84** (2.7 – 8.84)	**0.34** (0.13 – 0.56)	11.3

Macro-invertebrates

Macro-invertebrates were present in sediments at all the three sites. The diversities and numbers per unit area were varied. Site 1 had the highest diversity of macro-invertebrate with a total of 25 species from 10 families (Figure 25); this was followed by Site 3 with 18 species from 12 families (Figure 29), with Site 2 having the least number and diversity of macroinvertebrates(Figures27). The number of species per unit area for sites 1, 2 and 3 are also presented Figures 26, 28 and 30 respectively. Macro-invertebrates in sediments are influenced by factors such as sediments grain size, and organic matter of less than 2mm, water depth and temperature (Donohue & Irvine 2003) and that could account for the variations observed; Site 2 was the deepest of the three sites monitored. When tested, correlations between the species diversity and OM, TN and TOC were low and insignificant; correlation coefficient values for sites 3 for example were 0.19, 0.17 and 0.15 respectively. Graçaet al (2004) has, however, indicated that the relative importance of factors affecting the diversity of aquatic macroinvertebrates differs among studies, and attributed it to considerable inter-habitat and inter-climatic variation. The dominance of Chironomidae and Chaoboridae in the Lake are consistent with finding of Amakye (2001).

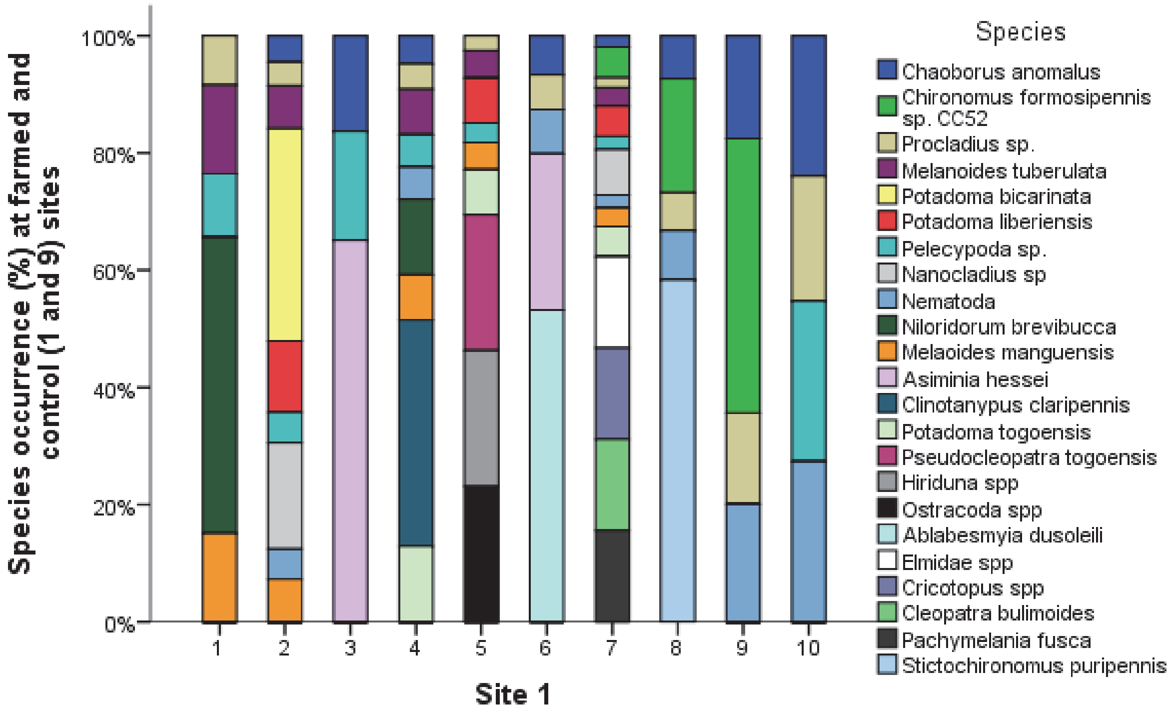

Figure 25: Macroinvertebrate composition at site 1

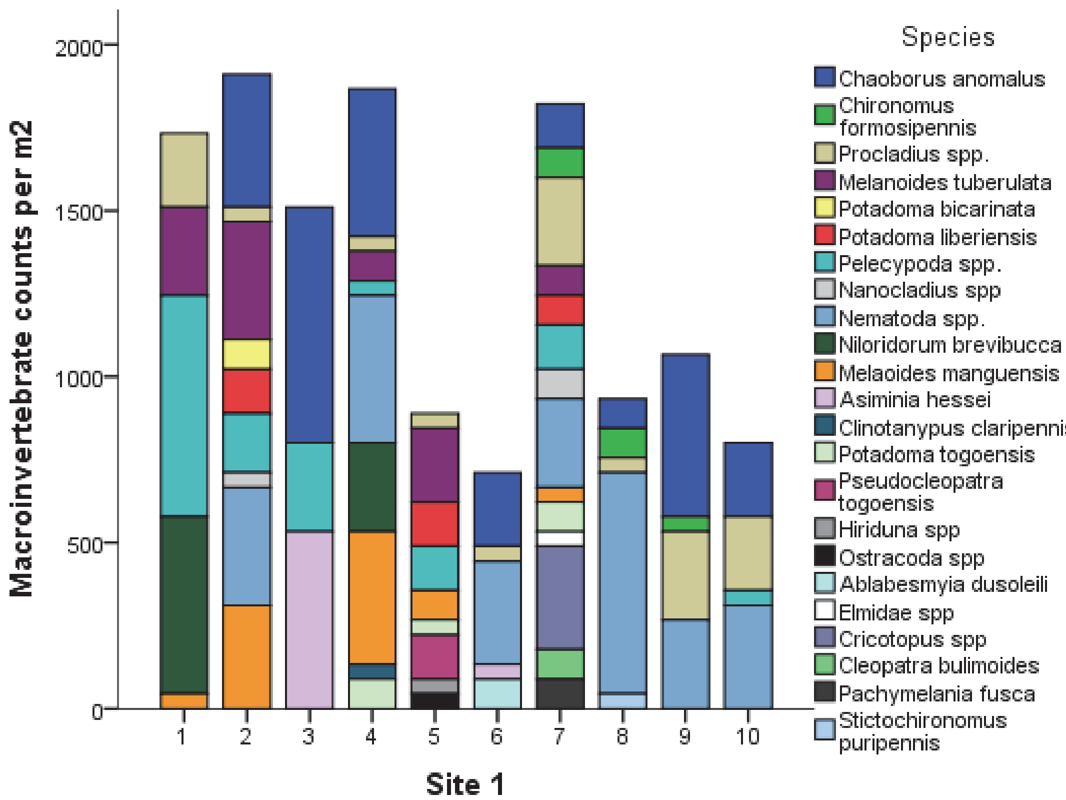

Figure 26: Macroinvertebrate densities at sampling stations at site 1

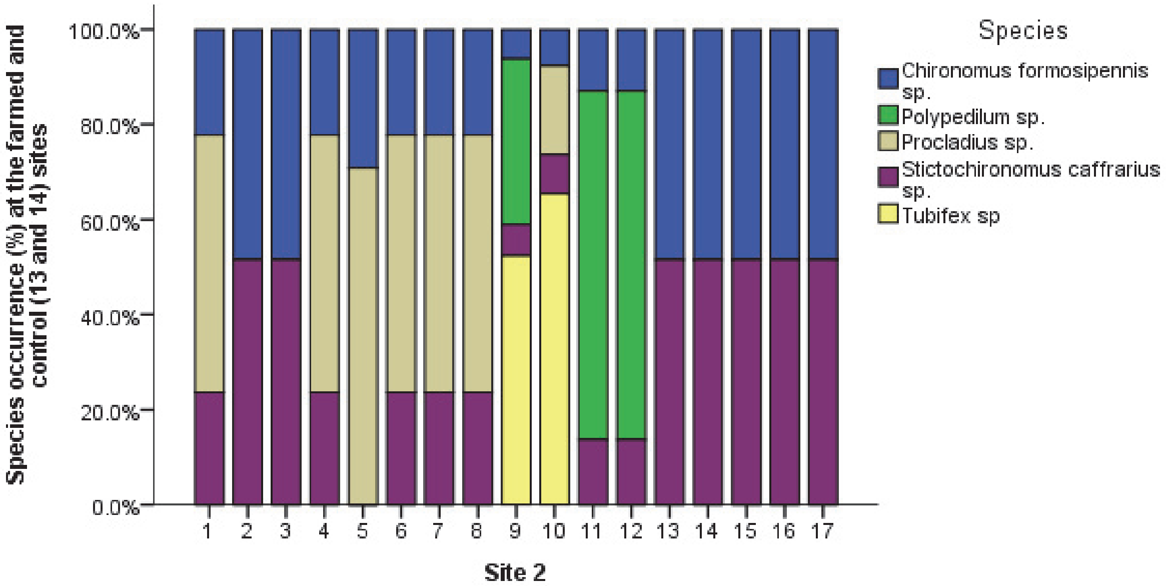

Figure 27: Macroinvertebrate composition at site 2. Station numbers on horizontal axis

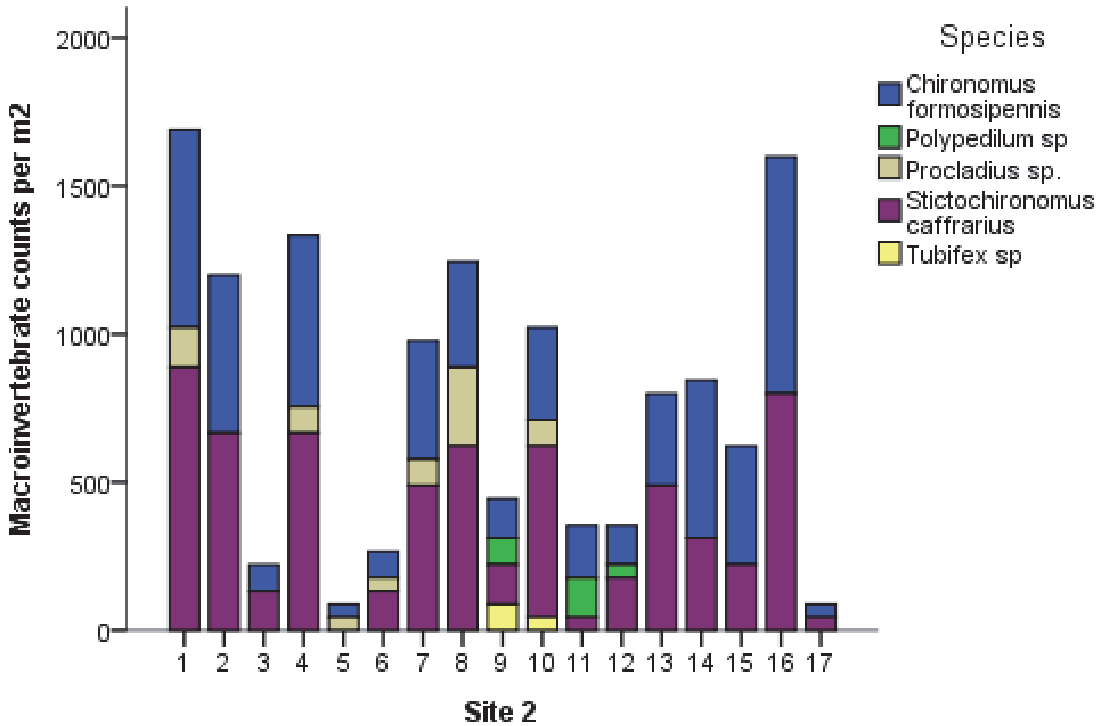

Figure 28: Macroinvertebrate densities at sampling stations at site 2. Station numbers on horizontal axis

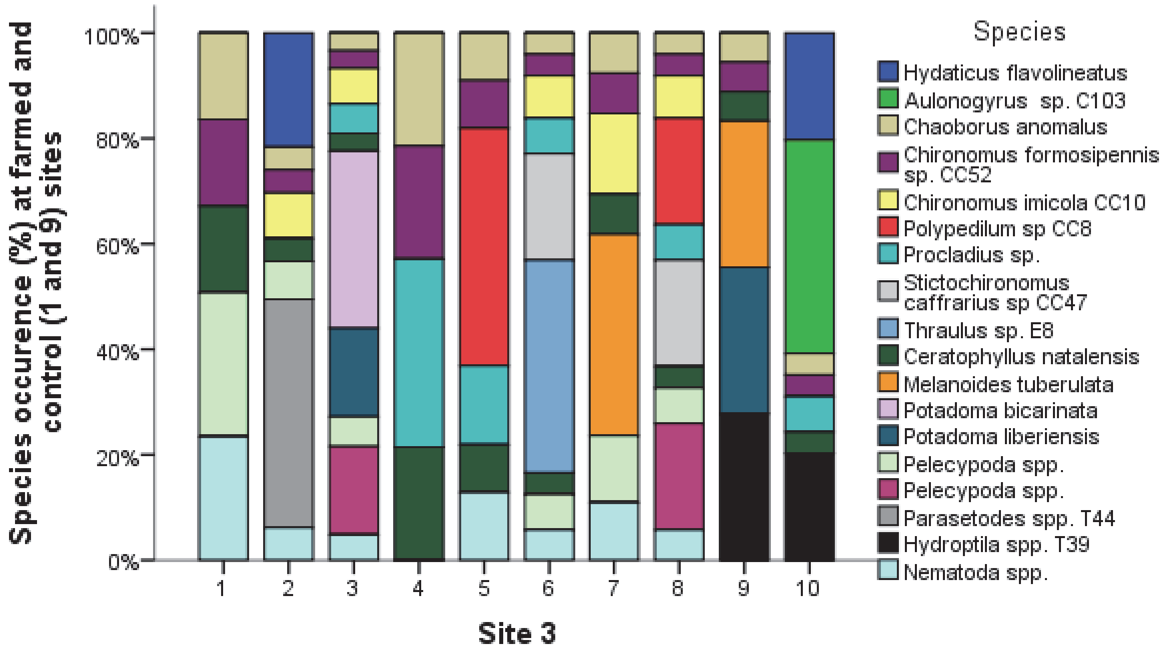

Figure 29:Macroinvertebrate species in the sediments at Site 3. Station numbers on horizontal axis

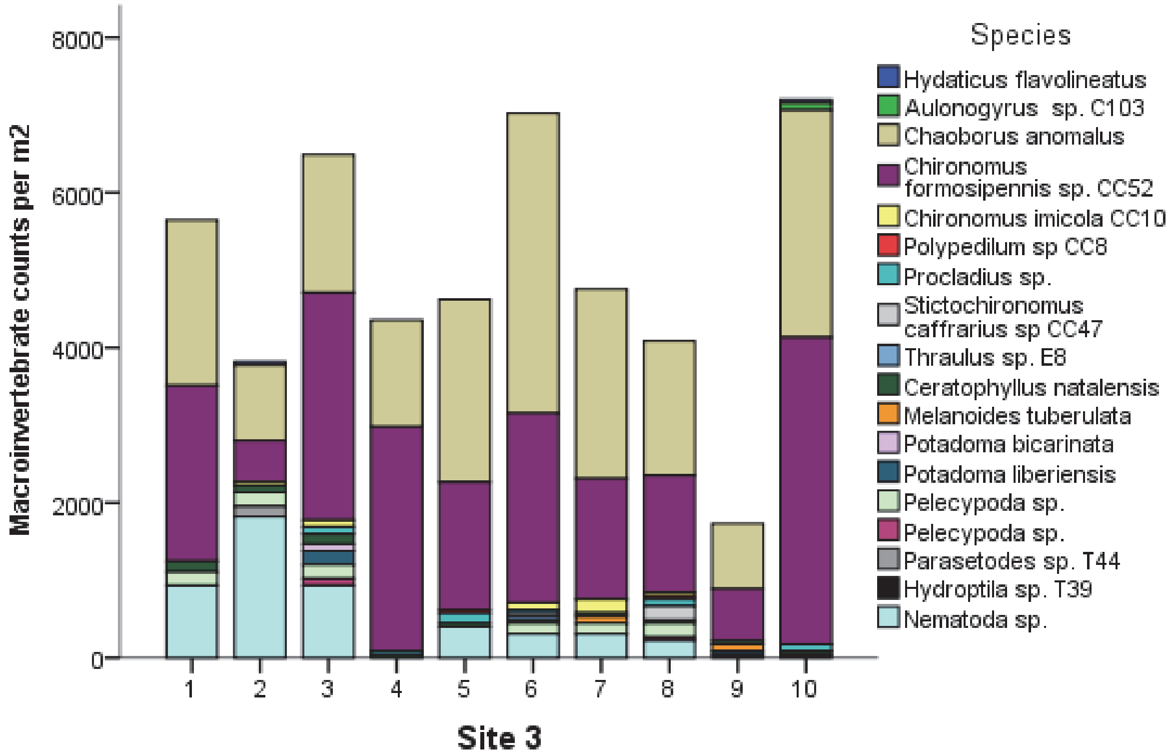

Figure 30: Macroinvertebrate densities in the sediments at Site 3. Station numbers on horizontal axis

Summary

- Physico-chemical water quality parameters including dissolved inorganic nutrients and chlorophyll-a varied temporally and showed no significant difference ($p>0.05$) between the fish farm sites and the control sites.

- High levels of total phosphates recorded seasonally at the study sites which would require further site-specific investigation.

- The low impact of cage culture on the lake environment could be attributed to the dispersion of wastes by water currents, consumption of waste by large aggregates of wild fish species around the cages and also by dilution.

- The water quality indices (CCMEQI and GWQI) indicated that water at the study sites was of good or fair quality and suitable for tilapia production and other ecosystem uses such as irrigation, recreation and water supply.

- Data collected in wider studies by CSIR-WRI show that sites in the north of the lake are likely to be of lower quality for aquaculture.

- Heavy metal concentrations in both the water column and the sediment were low and within range of tolerable levels for the Lake ecosystem.

- Sediment analysis revealed that the sediment texture at all monitoring sites were sandy clay loam.

- TOC, TOM and TN content in the sediments were moderately low indicating low or no organic enrichment.

- No immediate impact of cage aquaculture on macroinvertebrate communities in the Lake sediment was observed.

Spatial Models for Lake Volta

Cite as:

Ross, L.G, Falconer, L., Telfer, T.C., Xia, F., Al-Wahaibi, M. and Al-Shihi, J. 2016.Spatial models for Lake Volta. In:Asmah, R., Karikari, A., Falconer, L., Telfer, T.C. and Ross, L.G. Cage aquaculture in Lake Volta, Ghana: Guidelines for a sustainable future. CSIR Water Research Institute, Ghana and University of Stirling, Stirling UK.112 pp.

Introduction

Spatial models were developed using Geographical Information Systems (GIS) and remote sensing tools to assess the broad-scale physical carrying capacity of Lake Volta. Physical carrying capacity is the suitability of the environment for a particular system and species (e.g. cage culture of tilapia in Lake Volta) (Ross *et al*., 2013). The models also included some consideration of social carrying capacity with the addition of a market access sub-model. The spatial models can be used to identify potential sites for aquaculture and be used as a foundation for zoning models.

The models passed through several iterations over the lifespan of the project (Al-Shihi, 2013; Xia, 2014; Al-Wahaibi, 2015), being refined as more data became available. The final results are presented here.

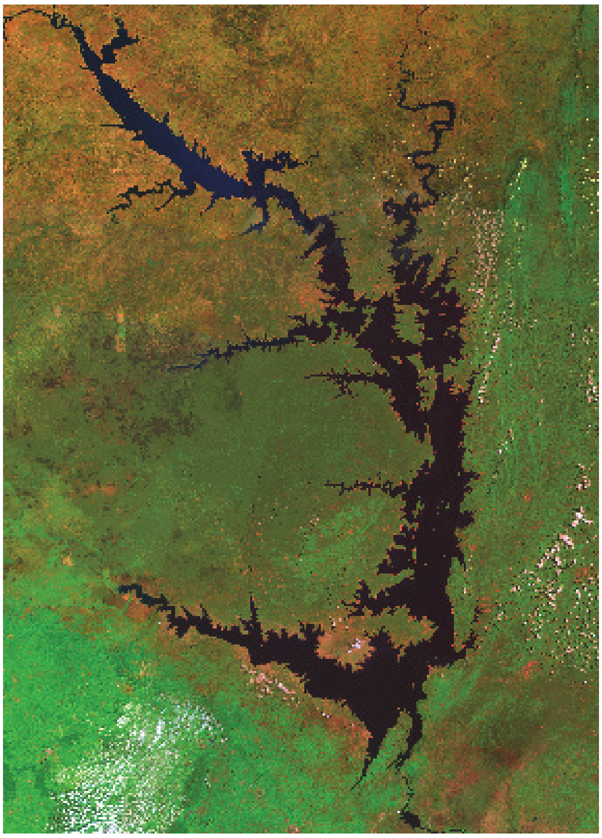

Figure 31: True colour composite Landsat 8 satellite imagery

Study area

Lake Volta lies between longitude 1° 30° W and 0° 20° E and latitude 6° 15´ N and 9° 10´ N in the West of Ghana (Figure 31). The study area for the spatial models covered the main body of the lake from the main river inflow locations to the Akosombo Dam, with a total surface area of almost 6000km^2 (Figure 34). It would be difficult, costly and time consuming to survey the entire lake for aquaculture site selection. Large-scale spatial models can be used to identify the most suitable locations for aquaculture sites, thus prioritising areas for more detailed fieldwork, monitoring and modelling.

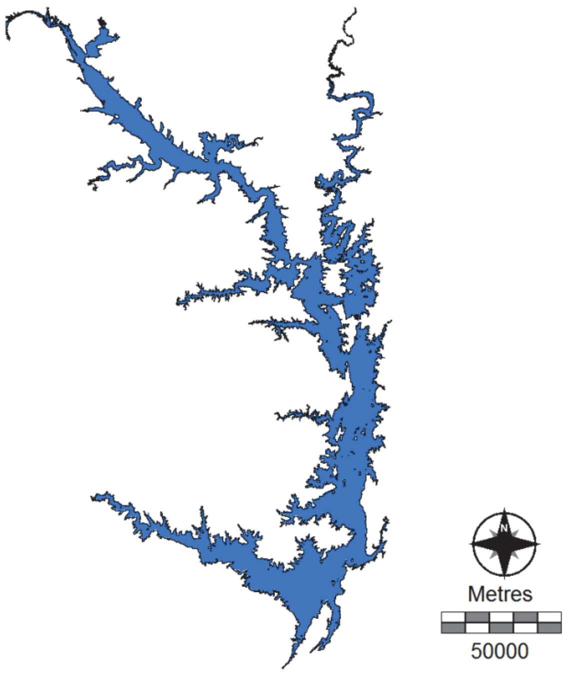

Figure 32: Study area for the spatial models

Methodology

The spatial models were developed using GIS and remote sensing tools. GIS software included IDRISI Selva [Clarks Labs, Massachusetts, USA], QGIS [QGIS Development Team, Open Source Geospatial Foundation Project] and ArcGIS 10 [Esri, California, USA].The study area (Figure 34) covers the main body of the lake and extends from the main river inflows in the north to the Akosombo Dam in the south. Baseline imagery was derived from Landsat 7 and 8 sources .All data layers were georeferenced using the UTM reference system and had a spatial resolution of 15m.Four cage sizes were modelled (Table 11); small square cages (5x 5x 5m), medium square cages (7x 7x 6m), Large circular cages (15m diameter, 6m net depth) and extra-large square cages (30m diameter, 8m net depth).Circular cages, 16m in diameter, are currently the largest cages used on the lake but extra-large cages could be installed in the future if there are suitable conditions and production is within the carrying capacity of the environment.

Table 11: Shape and dimensions of the modelled cages

Cage type	Shape	Dimensions
Small cages	Square	5 x 5 x 5m
Medium cages	Square	7 x 7 x 6m
Large cages	Circular	15m diameter 6m net depth
Extra-large cages	Circular	30m diameter 8m net depth

The overall spatial model (Figure 33) has a constraint layer and three sub-models; Bathymetry, Hydrography and Market and Access. The constraint layer is a Boolean layer which identifies “suitable” locations where aquaculture can be developed and “not suitable” areas where aquaculture must not be developed (e.g. too shallow for cages to be installed there). Physical factors (wave height and bathymetry) which could potentially limit cage installation were used in the constraint layer. The three sub-models were reclassified to a common 5 point scale based on suitability for aquaculture. Thus, in addition to the constraint (“not suitable”) there were another five categories; “Very unsuitable”, “unsuitable”, “moderately suitable”, “suitable” and “extremely suitable” (Table 12).

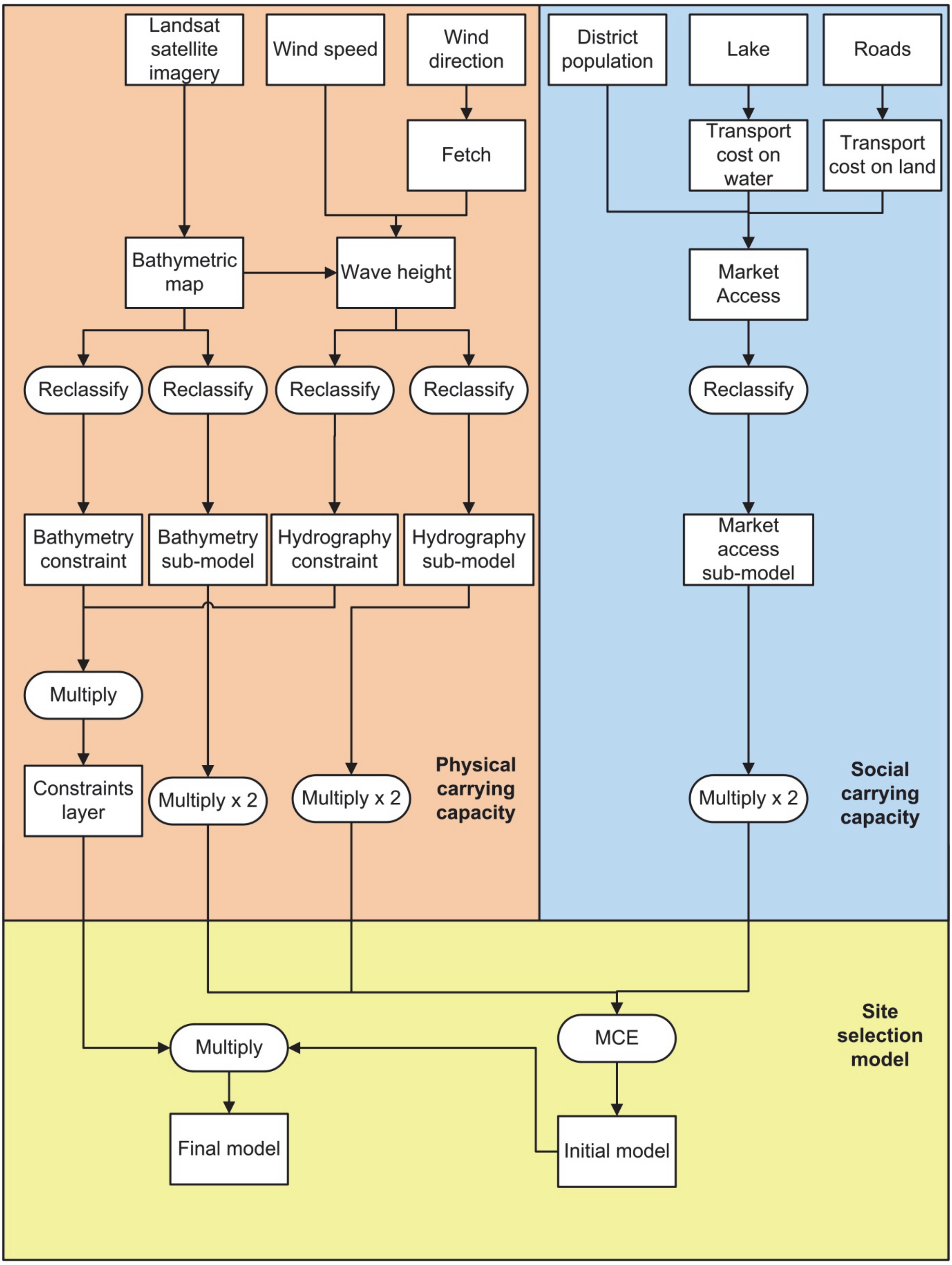

Figure 33: The conceptual model showing the overall framework and the different components of the site selection model.

Table 12: Reclassification scheme for the sub-models

Score	Suitability Category	Bathymetry/waves	Market/access
0	Not suitable	Cages cannot be located these locations.	n/a
1	Very unsuitable	Cages/nets would be damaged in these areas and/or it would be too expensive or difficult to install cages in this location.	The most costly areas with regard to market for siting cages.
2	Unsuitable	There is a high risk that cages/nets will be damaged in these areas and/or it could be too expensive or difficult to install cages.	Higher cost per tonne fish per kilometre per person.
3	Moderately suitable	There is a slight risk cages/nets may be damaged and/or the location may be more costly to develop	Average cost per tonne fish per kilometre per person.
4	Suitable	Suitable for cage installations	Lower cost per tonne fish per kilometre per person.
5	Extremely suitable	The optimal area for siting cages	The least costly areas with regard to market for siting cages

After reclassification, the sub-models were multiplied by two to preserve sensitivity and then combined using a weighted linear multi-criteria evaluation (MCE) to obtain the final outputs. This approach multiplies the factors (in this case sub-models) by a previously assigned weight to determine the trade-off between the different factors and constraints are then applied to remove excluded (constraint) areas from the final output(Eastman, 2012). Two different weight combinations were used; one for farms that would mainly

be producing fish for subsistence or local markets and another for farms that would be producing fish for the commercial market throughout Ghana.

Bathymetry sub-model

Bathymetry is a critical factor for cage site selection as it determines where cages can be located. If a site is too shallow for a particular cage type the cage and nets may be damaged, there may be poor waste dispersal and the health and welfare of the fish will be affected (Beveridge, 2004). As depth increases, the costs and engineering requirements for moorings and cages become more complex (Beveridge, 2004). Cages must therefore be located in areas that are neither too shallow nor too deep. Suitable depth ranges will depend on the type and sizes of cages.

No bathymetric datasets were available for Lake Volta so a new bathymetric map was developed from Landsat 8 satellite data and partially verified using bathymetric data collected from the lake (Xia, 2014). Satellite data was collected in March 2014 which is near the start of the rainy season so the bathymetry around this period would be the shallowest of the year. Water depth was calculated using Equation 1 (Jupp, 1988). To avoid damage to cages from seasonal water depth change, the lowest water depth in Lake Volta was then calculated by subtracting 2m water depth (Crétaux et al., 2011).

$$\text{Depth} = \frac{1}{-2K_\lambda} * \ln\left(\frac{R_\lambda}{A_\lambda}\right) \qquad \text{Equation 1}$$

Where:

K_λ=coefficient of attenuation
R_λ=reflectance in Band 3
A_λ=surface reflectance

The resulting bathymetric map (Figure 34) is based on a number of assumptions and thus should be considered indicative depth rather than actual depth, however the calculated depths showed good correlation with a bathymetric survey of a small section of the lake. The bathymetric map was reclassified in terms of suitability for the four different cages (Table 13). Beveridge (2004) suggests that nets should be at least 4 to 5m above the sediment, however Lake Volta is a man-made reservoir and there are submerged trees, buildings and other obstacles on the lake floor which could damage cages and nets. To account for this, an optimal safety depth was calculated for each cage using Equation 2.

$$D_{min} = \left(D_c + \left(\frac{D_c}{2}\right)\right) \times 2 \qquad \text{Equation 2}$$

Where:

D_{min} = optimal minimum water depth (safety depth)
D_c = Cage depth

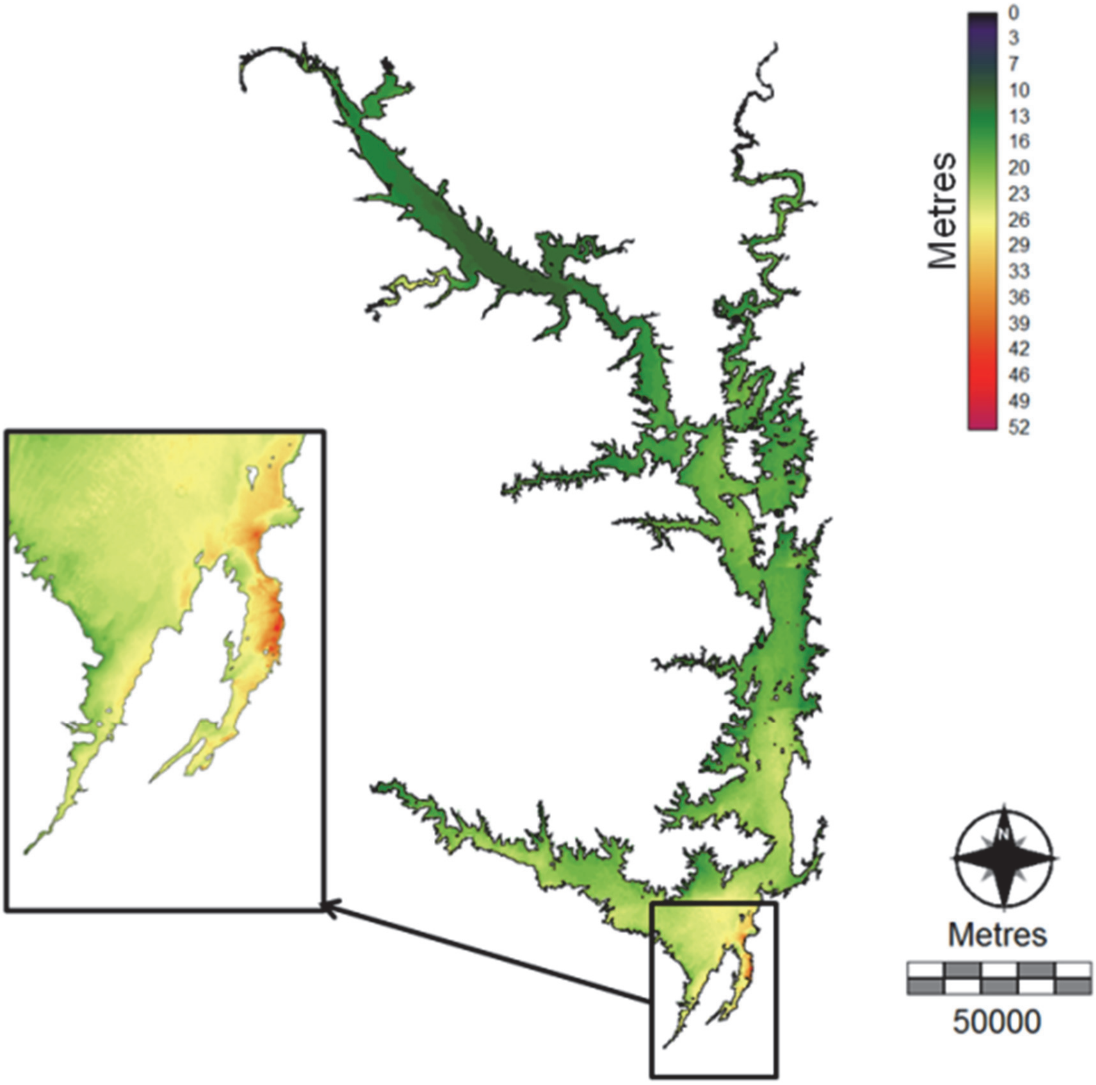

Figure 34: Bathymetry of Lake Volta derived from satellite imagery.

Table 13: Reclassification values for bathymetry (in metres)

Class	Small cages	Medium cages	Large cages	Extra large cages
Not suitable	< 11 > 45	< 14 > 50	< 14 > 50	<20 > 55
Highly unsuitable	11 - 12 40 - 45	14 - 15 45 - 50	14 - 15 45 - 50	20 - 21 50 - 55
Unsuitable	12 - 13 35 - 40	15 - 16 40 - 45	15 - 16 40 - 45	21 - 22 45 - 50
Moderate	13 - 14 30 - 35	16 - 17 35 - 40	16 - 17 35 - 40	22 - 23 40 - 45
Suitable	14 - 15 25 - 30	17 - 18 30 - 35	17 - 18 30 - 35	23 - 24 35 - 40
Highly suitable	15 - 25	18 - 30	18 - 30	24 - 35

Hydrography sub-model

Wave height is one of the most important parameters with regard to cage aquaculture and was highlighted by farmers during fieldwork as a constraint to development Figure 35). Cages can be damaged or stressed by waves, thus potentially affecting the welfare of the stock and/or leading to escapes. Waves can also create an unsafe working environment for farmers so it is important to ensure cages are located in suitable areas for the safety of the farmer and the business.

Figure 35: Waves at Kpeve

Current velocity is another important parameter for cage site selection. Cages must be sited in areas where there is sufficient current to allow waste dispersal, oxygen replenishment and good water exchange. However, if currents are too strong they can damage cages and stress the fish. Thus currents should be considered during site selection. Collecting current data across large areas such as Lake Volta is a difficult and laborious task. At present, there is insufficient current data available for Lake Volta to include in the model. However, when/if the data becomes available the model can be updated. Conversely, the broad-scale spatial models can be used to identify potential areas which could be suitable for aquaculture and then more detailed fieldwork and data collection of relevant parameters can occur at a pre-identified area saving time and money.

Wave height was calculated (Xia, 2014) using equations (Equation 3) developed by the US Army Corps of Engineers (1984, 2002). This approach involves the use of data on wind direction and speed, fetch and water depth and has been used previously in other aquaculture site selection studies (Scott, 2004; Falconer et al., 2013). The calculated wave heights are based on the worst case scenario rather than normal conditions (Table 14). Although such events would be rare, if they did occur they could have serious consequences for cages if they were located in unsuitable areas. The resulting wave height layer (Figure 36), and thus the hydrography sub-model, was reclassified based on expert opinion and experience in the field (Table 14).

$$Wave\ height = \frac{Ua^2 \cdot TANH\left(0.530 \times \left(\frac{9.8D}{Ua}\right)^{0.75}\right) \cdot TANH\left\{\frac{0.00565\left(\frac{9.8F}{Ua^2}\right)^{0.5}}{TANH\left[0.530\left(\frac{9.8D}{Ua^2}\right)^{0.75}\right]}\right\}}{9.8} \quad \text{Equation 3}$$

Where:

> Ua is wind speed (ms^{-1})
> F = fetch (m)
> D = water depth (m)

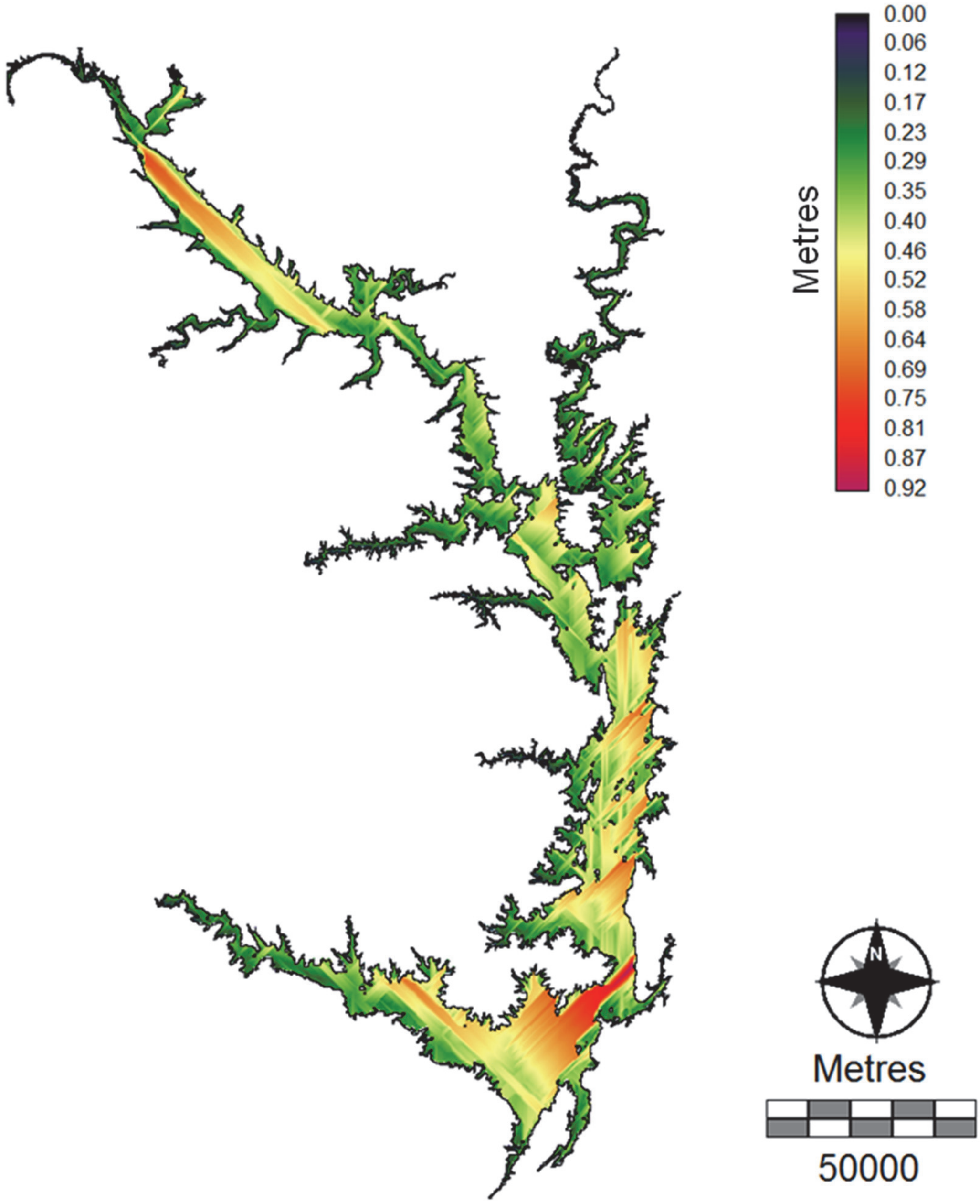

Figure 36: Maximum significant wave height in Lake Volta (metres)

Table 14: Reclassification values for wave height (metres)

	Small cages	Medium cages	Large cages	Extra large cages
Not suitable	>0.6	>0.7	>1.0	>1.0
Highly unsuitable	0.5 - 0.6	0.6 - 0.7	0.9-1.0	0.9-1.0
Unsuitable	0.4 - 0.5	0.5 - 0.6	0.8-0.9	0.8-0.9
Moderate	0.3 - 0.4	0.4 - 0.5	0.6-0.8	0.6-0.8
Suitable	0.2 - 0.3	0.3 - 0.4	0.3-0.6	0.3-0.6
Highly suitable	<0.2	<0.3	<0.3	<0.3

Market Access sub-model

Cost effective transportation links are essential for a successful aquaculture business (Figures 37 and 38). Access to sites for supply of goods and services is of vital importance and transportation costs will be reflected in the price of the fish and whether or not a farm is economically viable. Furthermore, the demand for fish will be higher in areas with more people, potentially providing a more lucrative market opportunity for farmers. Transportation cost and population were both considered in the market access sub-model (Al- Wahaibi, 2015).

Figure 37: Transporting feed to a fish farm

Roads were classified into three categories based on the product cost of transportation. The average transportation cost per tonne of product for a "cheap" road is is Ghȼ 0.90 per km to the market centres, for one tonne of product on an expensive road the cost is Ghȼ 1.43per kilometre, and for a medium road the cost is Ghȼ 1.25 per tonne-kilometre (Taiwo and Kumi, 2013). The cost of transportation across Lake Volta is

Figure 38: Access road to a fish farm

1.755 Ghȼ per kilometre, using 2015diesel prices and based on a 14m long canoe carrying 3 tonnes of produce.

The cost of product transportation was then calculated for each of the 170 districts. Each cost district map was divided by the population in the district to product 170 layers representing the cost of transportation from each district per person. The 170 layers were added together to form on single layer representing product transportation cost per km per person (Figure 39) which was then reclassified based on expert opinion and experience in the field (Table 15).

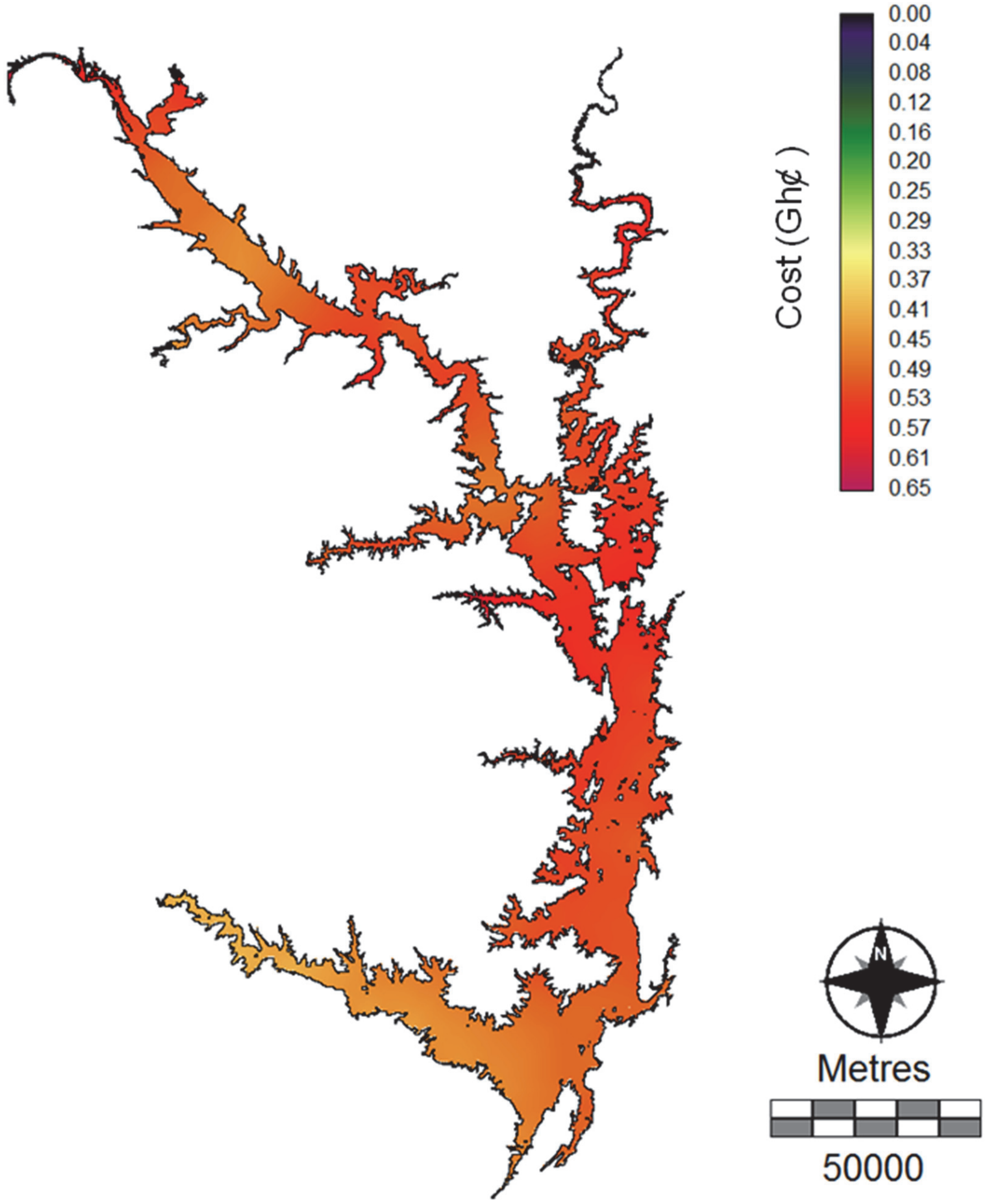

Figure 41: Product transportation cost per kilometre per person over Volta Lake, Ghana

Table 15: Reclassified cost of product transportation

Class	Ghȼ per tonne fish per kilometre per person.
Highly unsuitable	>0.59
Unsuitable	0.54-0.59
Moderate	0.49-0.54
Suitable	0.44-0.49
Highly suitable	<0.44

Constraint layer

Constraints are areas that are "not suitable" for cage aquaculture under any circumstances. Constraint layers were reclassified from the bathymetry and hydrography sub-models using the values shown in Tables 16 and 17 (Figure 40). All four cage sizes had a bathymetric constraint, but only the small and medium cages had a hydrographic constraint as there were no modelled waves above 1m (which would limit siting of medium and large cages).

Table 16: Constraint values for bathymetry

	Small cages	Medium cages	Large cages	Extra large cages
Suitable	11 - 45	14 - 50	14 - 50	20 - 55
Not suitable	<11	<14	<14	<20
	>45	>50	>50	>55

Table 17: Constraint values for hydrography

	Small cages	Medium cages	Large cages	Extra large cages
Suitable	0 - 0.6	0-0.7	0-1.0	0 - 1.0
Not suitable	>0.6	>0.7	n/a	n/a

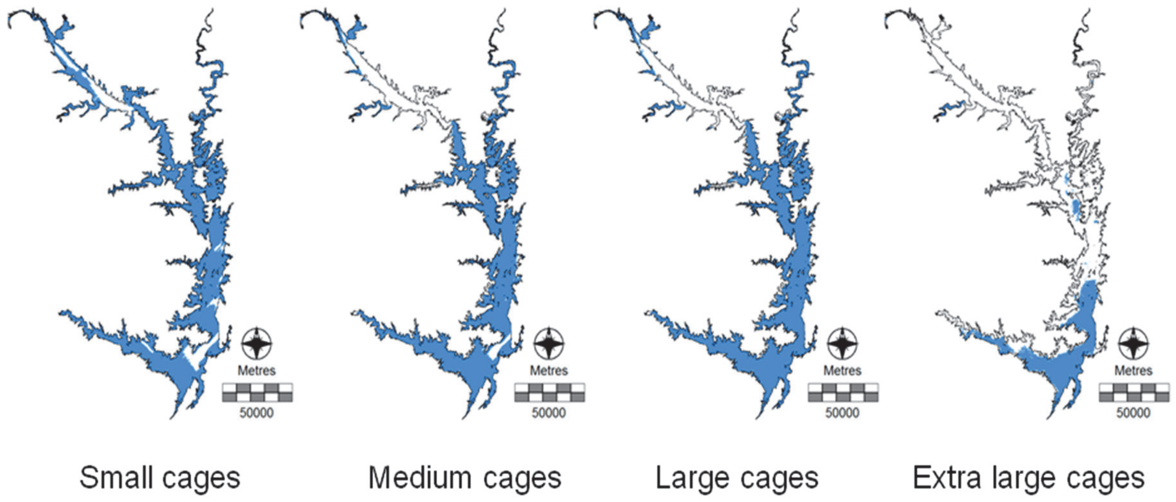

Figure 42: The constraint layers for each cage type

Local Market Model

Aquaculture is a vital contributor to food and nutrition security in local communities near the lake; consequently it is important to assess the suitability of the lake for smaller scale farms which focus on producing fish for subsistence and the local market. Such farms do not require frequent access to national transportation links and markets, thus the market access sub-model is less important than other sub-models. This is reflected in the weights assigned to the local market model (Table 18). The small and medium cages were modelled using the local market model. These cages use locally sourced materials so are cheap to construct and easy to maintain so would be suitable for small-scale production.

Table 18: Weights for the local model

Sub-model	Weights
Bathymetry	0.425
Wave height	0.425
Market access	0.15

Commercial Market model

The national demand for fish continues to increase as the population grows. Aquaculture producers can help meet the demand by focusing on the commercial market throughout Ghana rather than just local communities (Figure 41). The three sub-models are equally weighted in the commercial market model (Table 19). All four cage sizes were modelled using the commercial market model.

Figure 41: Sales outlet of a commercial farm

Table 19: Weights for the commercial models

Sub-model	Weights
Bathymetry	0.333
Wave height	0.333
Market access	0.333

Final site selection models

Each sub-model was multiplied by two prior to the MCE to preserve sensitivity (Figure 33 - conceptual model). This resulted in a new 10 point scale for all of the model outputs which is still related to the original suitability categories. Table 20 provides guidance on interpreting the model results. Six site selection models were developed; two for the local market model and four for the commercial market model (Table 21)

Table 20: Description of the 10 point suitability scale

Score	Suitability Category	Descriptor
0	Constrained area	Conflicting uses or other factors prevent any use for aquaculture
1-2	Extremely unsuitable	Low scores on all factors mitigate against any aquaculture development
3-4	Unsuitable	Low scores on most factors mitigate against aquaculture development
5-6	Moderately suitable	Low scores on more than one factor
7-8	Suitable	High scores on most factors
9-10	Extremely suitable	Scores very highly on all factors considered

Table 21: Models developed for each cage size

Cage size	Local Market Model	Commercial market model
Small cages	X	X
Medium cages	X	X
Large cages		X
Extra-large cages		X

Suitability of Lake Volta for aquaculture using small cages for local markets

Most of the lake is suitable or extremely suitable for small cages modelled using the local market scenario (Figure 42). In the north-west some areas are too shallow, while in the south there are areas with a high risk of waves. Extremely suitable areas are found in sheltered locations around the edge of the lake, particularly in the west and in the north east.

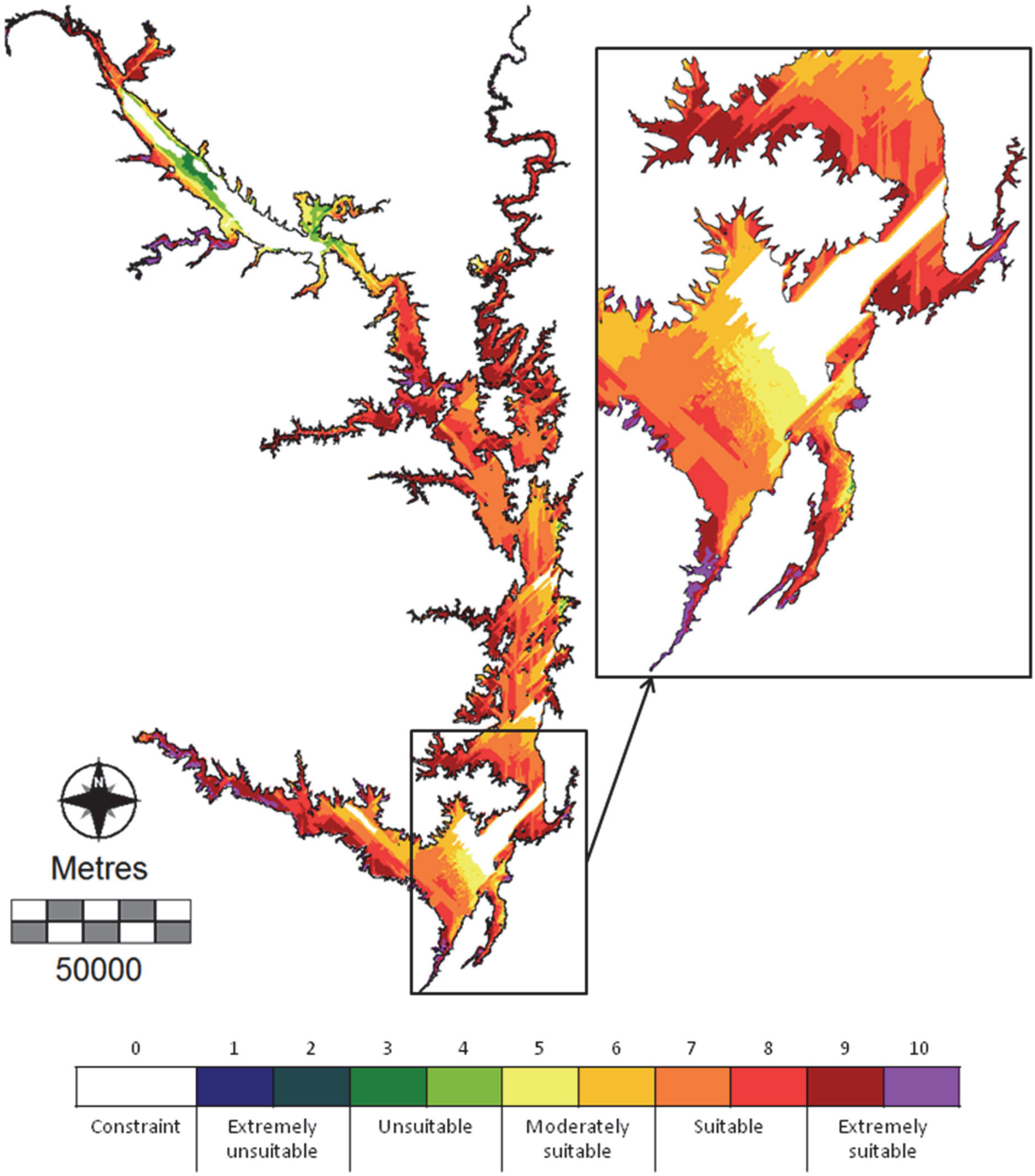

Figure 42: Suitability of Lake Volta for aquaculture using small cages for local markets

Suitability of Lake Volta for aquaculture using small cages for commercial markets

Most of the extremely suitable areas for small cages modelled using the commercial market scenario are found in sheltered locations in the south west of the lake (Figure 43). These areas have very good transport links, enabling access to markets throughout Ghana and a better price margin on their product.

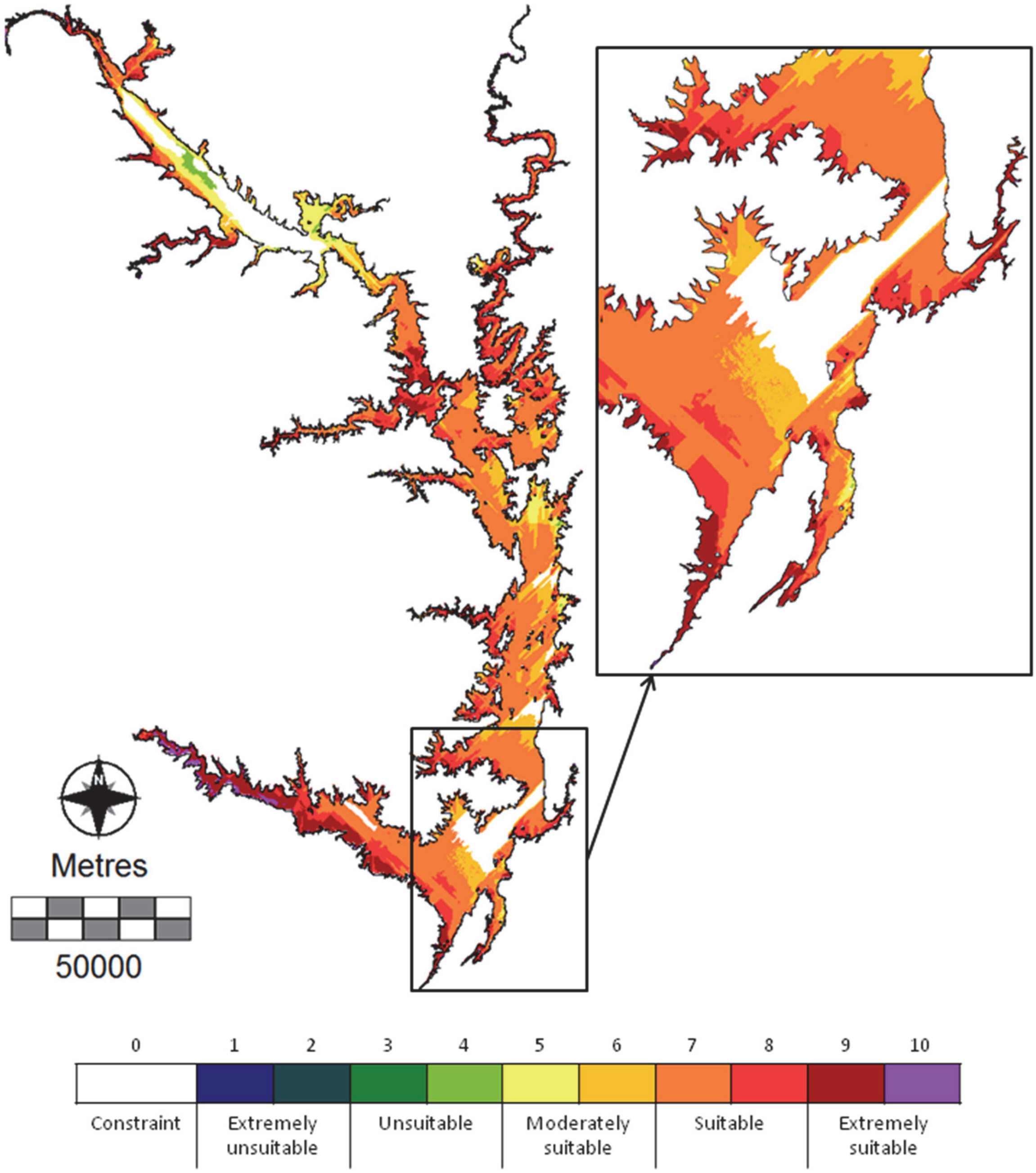

Figure 43: Suitability of Lake Volta for aquaculture using small cages for commercial markets

Suitability of Lake Volta for aquaculture using medium cages for local markets

There are many suitable and extremely suitable areas for medium cages modelled using the local market scenario (Figure 44). Areas near the eastern edge of the lake have lower scores as they are more exposed to higher waves due to the prevailing winds. Most of the highest scores are found in the south west due to the strong transport links and the optimal physical environment.

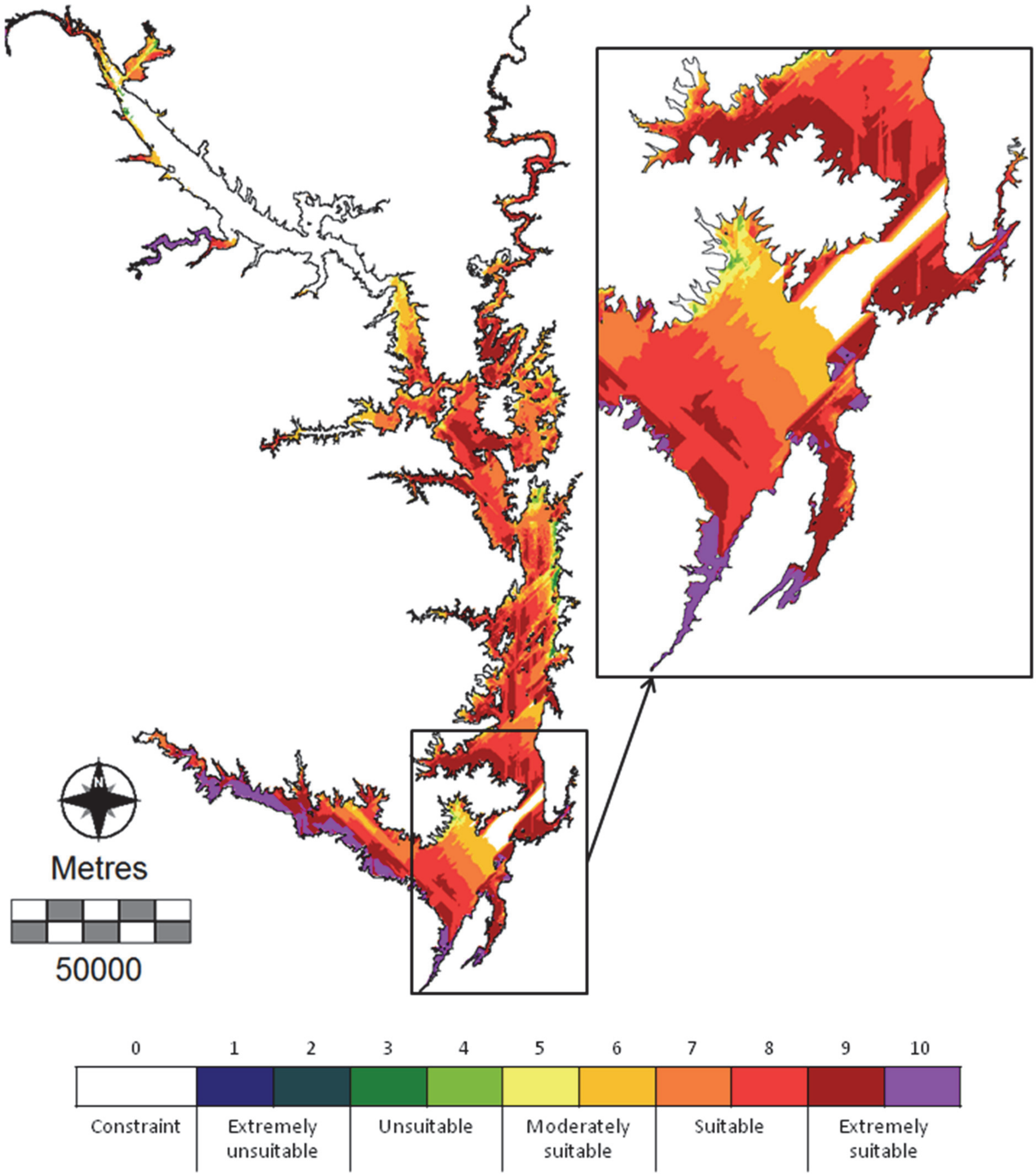

Figure 44: Suitability of Lake Volta for aquaculture using medium cages for local markets

Suitability of Lake Volta for aquaculture using medium cages for commercial markets

For medium cages modelled using the commercial market scenario, the highest scoring areas are found in the south and south west of the lake (Figure 45). These areas are more sheltered and have the most suitable market access in addition to optimal depth. Areas further north are generally less suitable as they have less suitable market access.

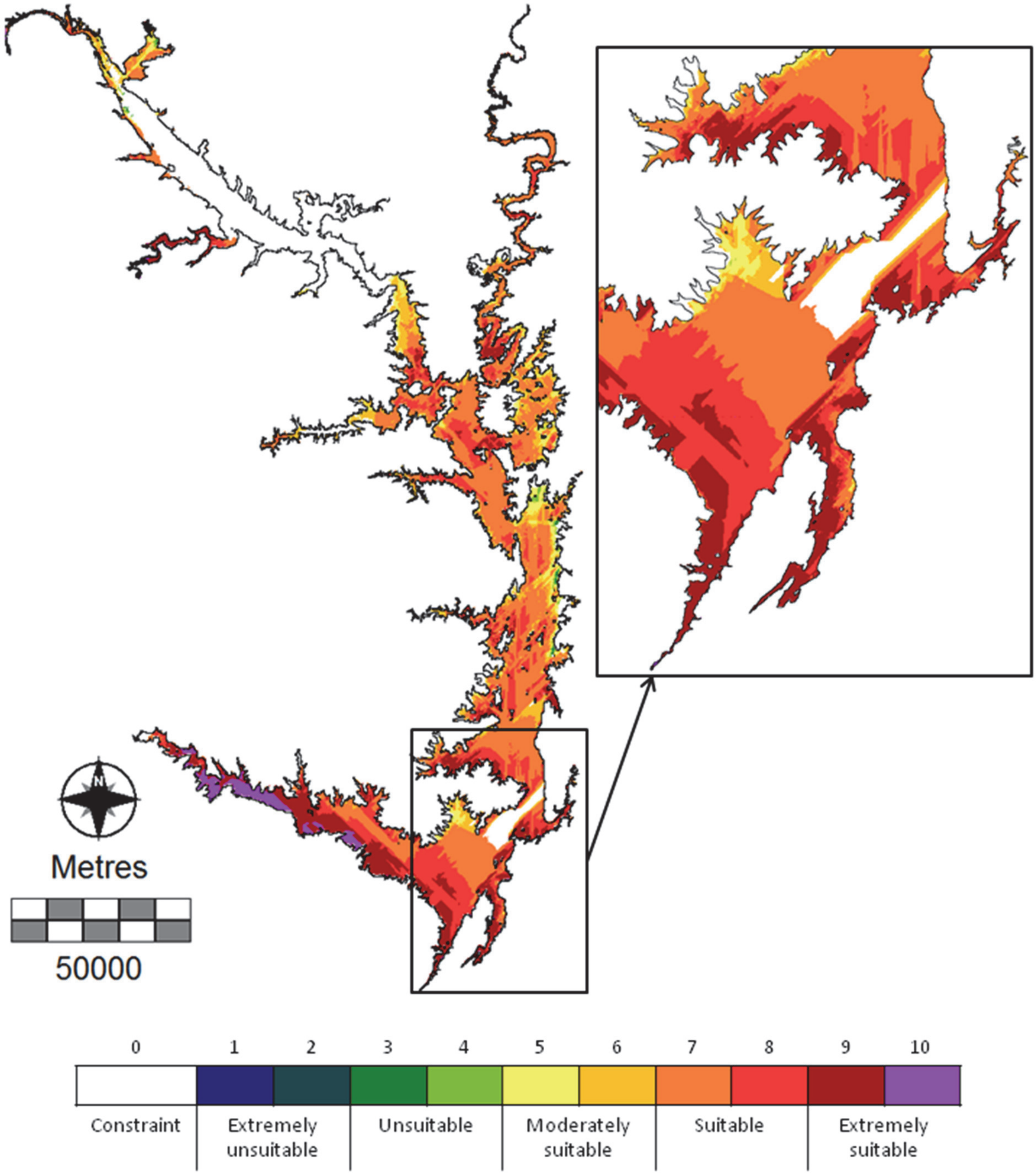

Figure 45: Suitability of Lake Volta for aquaculture using medium cages for commercial markets

Suitability of Lake Volta for aquaculture using large cages

Shallower depths in the north east of the lake are the main constraint for large cages, most of the extremely suitable locations are found in the south of the lake (Figure 46); similar cages are already used in this area by several farms.

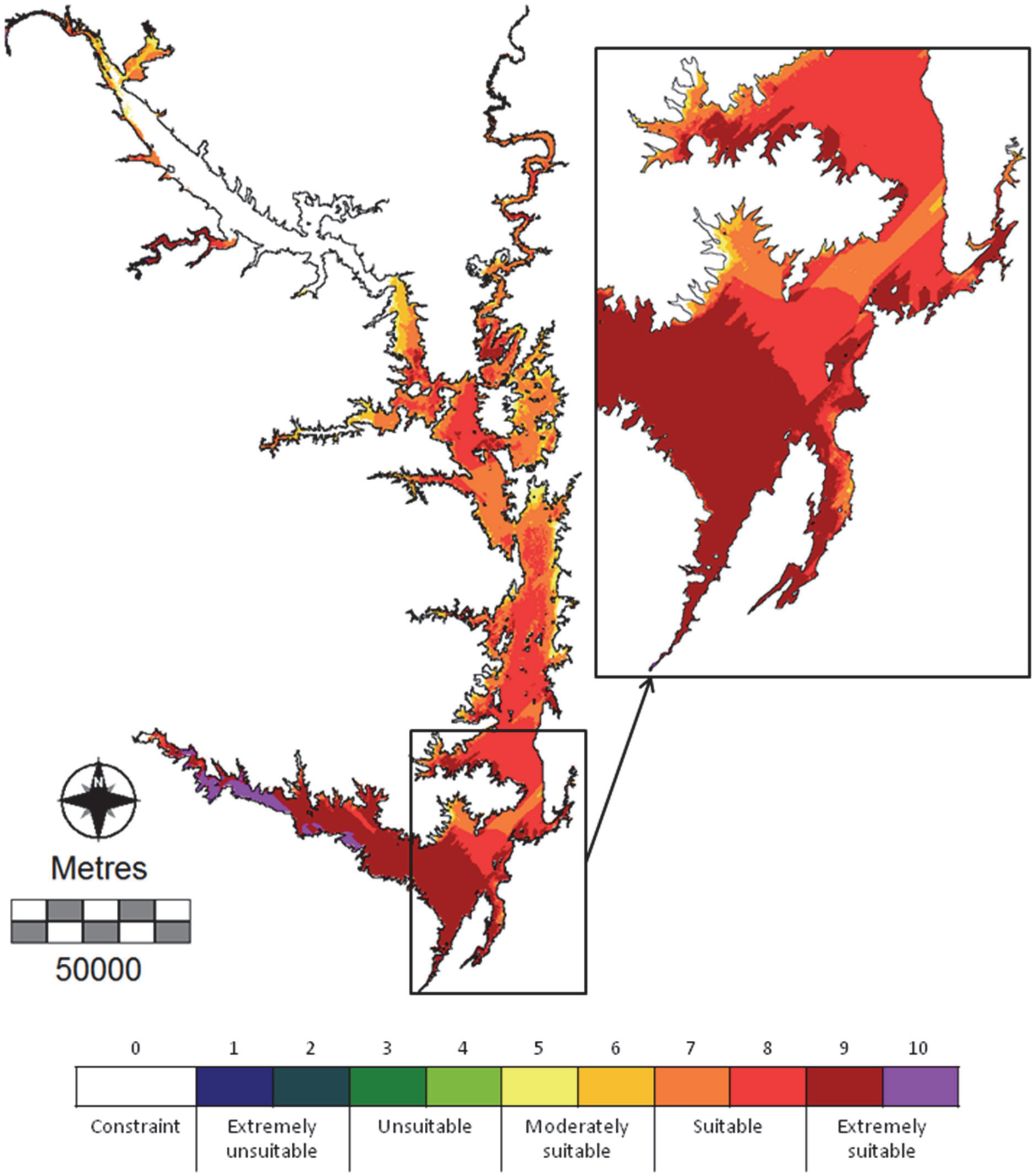

Figure 46: Suitability of Lake Volta for aquaculture using large cages for commercial markets

Suitability of Lake Volta for aquaculture using extra-large cages

Almost all of the suitable/extremely suitable areas for extra-large cages are found in the south of the lake (Figure 47). Most of the northern section of the lake is too shallow for the required net safety depth, thus restricting potential for development.

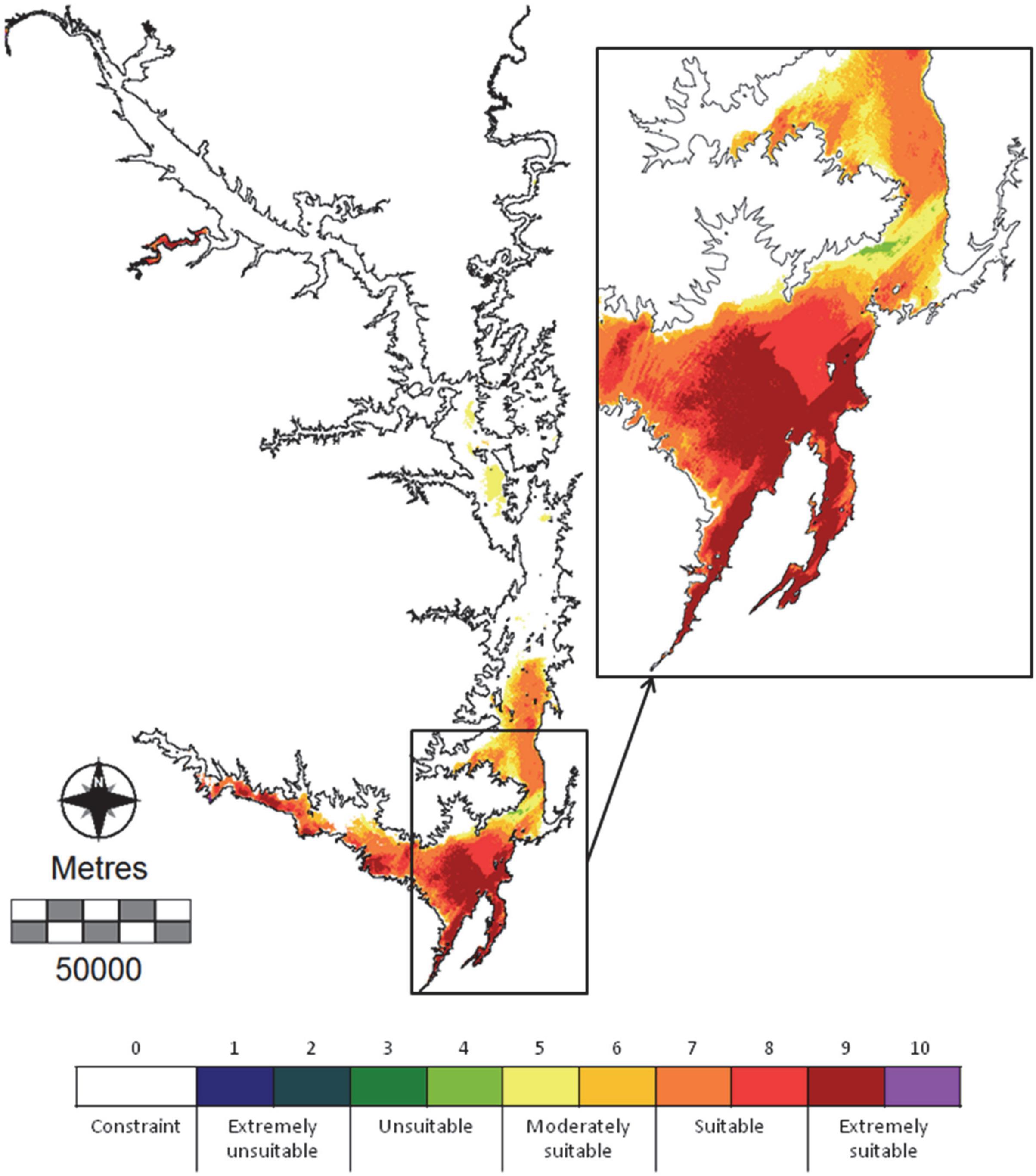

Figure 47: Suitability of Lake Volta for aquaculture using extra large cages for commercial markets

Aquaculture site selection

The models have shown that, with regard to physical carrying capacity and some consideration of social carrying capacity, there are many suitable and extremely suitable areas for aquaculture in Lake Volta. Overall, suitability varies depending on cage size and the modelled market, but the south east section of the lake, where most aquaculture is presently located, is one of the most suitable locations for any type of cage.

In addition to the model results shown in Figures 42 to 47, quantitative analysis is provided in Table 22 and Figure 49. Presently, the small and medium size cages are commonly used for production in Lake Volta (Figure 48). The models indicate there are many suitable and extremely suitable areas throughout the lake for medium cages, notably there are more extremely suitable areas for the local market scenario than the commercial market scenario. Most of these "extra" extremely suitable areas are in the north of the lake and are more costly in terms of commercial market hence a lower suitability score for that model.

Extra-large cages are not currently used on the lake, however if there are no spatial conflicts with other users, there may be potential to install them, subject to ecological and production carrying capacity. As would be expected, there are far fewer suitable/extremely suitable locations for extra-large cages than any other cage type for the commercial market scenario due to the depth constraints. However the south of the lake could be used if other conditions were met.

Figure 48: Small square cages on Lake Volta

Table 22: Areas (km²) of the lake covered by each suitability category for the different models

	Small		Medium		Large	Extra large
Score	**Local**	**Commercial**	**Local**	**Commercial**	**Commercial**	**Commercial**
0	596	596	1206	1206	1122	4275
1	-	-	-	-	-	-
2	-	-	<1	-	-	-
3	42	<1	16	6	-	<1
4	129	44	40	19	<1	6
5	249	321	160	249	157	208
6	629	595	665	556	445	255
7	1519	2569	1172	2148	1529	550
8	1278	955	1363	926	1378	275
9	1280	745	980	663	1141	326
10	175	71	295	124	124	1

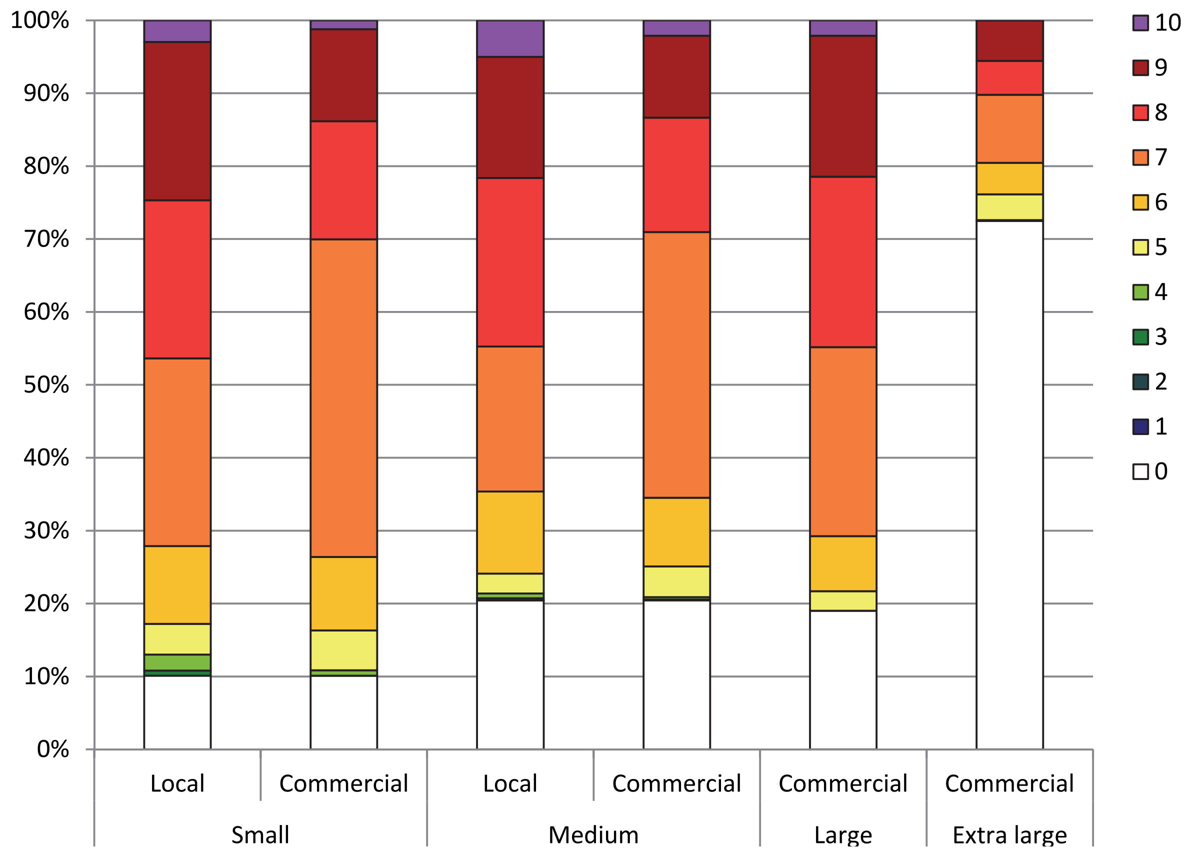

Figure 49: Areas (%) of the lake covered by each suitability category for the different models

The model framework is flexible and adaptable so can be updated and revised should more, or improved, data become available. The bathymetric layer in particular could be improved as it is based on remote sensing data rather than survey data. Nevertheless, at present this is the best available information hence its use in the model.

The models developed in the project provide guidance on the broad-scale suitability of Lake Volta for cage aquaculture. They allow preliminary site identification of potential areas for production, subject to more detailed fieldwork and analysis. This is extremely useful for a large area such as Lake Volta which would be difficult to survey in its entirety. Such a survey, if possible at all, would be wasteful as it would include areas that are not suitable for culture in the first place.

Summary

- Spatial models were developed using GIS and remote sensing tools for aquaculture site selection in Lake Volta.
- The models provide guidance on the broad-scale suitability of Lake Volta for cage aquaculture
- Four sizes of cage were modelled: small square cages (5x 5x 5m), medium square cages (7x 7x 6m), large circular cages (15m diameter, 6m net depth) and extra-large square cages (30m diameter, 8m net depth).
- Spatial model comprises of three sub-models (bathymetry, hydrography and market access) and a constraint layer (bathymetry and hydrography).
- Bathymetry sub-model considers water depth and the implications for cage site selection.
- Hydrography sub-model focuses on wave height and can be used to identify sheltered and exposed areas.
- Market-access sub-model calculates transportation cost with regard to population.
- Two market scenarios were modelled: local market model using the small and medium cages, and commercial market model using all cage sizes.
- The models have shown that, with regard to physical carrying capacity and some consideration of social carrying capacity, there are many suitable and extremely suitable areas for aquaculture in Lake Volta.
- The south east section of the lake, where most aquaculture is presently located, is one of the most suitable locations for any type of cage.

Zonation guidelines for Lake Volta aquaculture

Cite as:

Ross, L.G, Falconer, L. 2016. Zonation guidelines for Lake Volta aquaculture. In:Asmah, R., Karikari, A., Falconer, L., Telfer, T.C. and Ross, L.G. Cage aquaculture in Lake Volta, Ghana: Guidelines for a sustainable future. CSIR Water Research Institute, Ghana and University of Stirling, Stirling UK.112 pp.

Introduction

Throughout the world, competition for space is a major issue. Conflict, cumulative impacts and resource degradation can all result from mismanaged multi-use areas. In contrast, well-managed areas can share space and resources, while at the same time, maximise productivity and community benefits through appropriate planning mechanisms. One such tool is zoning, where an area is zoned for multiple purposes (Fig 50); an aquaculture zone is an area that is suitable for culture and has been allocated for development.

Figure 50: Hypothetical example of a simple zoning scheme for a coastal area

Effective zoning will consider the needs of the farm as well as the environmental, economic and social impacts of siting a farm in a particular location. Poorly zoned areas will be assigned without full consideration of the suitability of the zoned area for the chosen activity. Thus it is imperative, particularly for an industry such as aquaculture that is fundamentally linked to the environment, that zonation is not arbitrarily decided and instead is based on more objective, scientific analysis.

Aquaculture Zonation models

Site selection models are an ideal starting point for aquaculture zonation as they provide information on the suitability of an area for culture. Spatial models developed using GIS can be used to produce zonation models; the qualitative and quantitative results provide information on the suitability of the area for aquaculture, and thus can be used to assign zones. The site selection models were reclassified to a three tier zoning scheme (Table 23). Constrained areas remain as they are not suitable for culture under any circumstances. The worst areas for zones are locations classed extremely unsuitable or unsuitable by the suitability modes. Moderately suitable areas are considered marginal for zoning; they could be used but would require remedial input and investment to install cages. Locations identified as suitable or extremely suitable for the installation of cages are the most preferred areas for zones.

Table 23: Reclassification scheme to classify zoned areas from the suitability models

Score	Suitability Category	Descriptor	Proposed zoning
0	Constrained area	Conflicting uses or other factors prevent any use for aquaculture	Areas where no aquaculture can be considered in any circumstances
1-2	Extremely unsuitable	Low scores on all factors mitigate against any aquaculture development	Worst zones where required remedial inputs would be excessive or would not be able to offset problems installing cages
3-4	Unsuitable	Low scores on most factors mitigate against aquaculture development	
5-6	Moderately suitable	Low scores on more than one factor	Marginal. Could be considered but would require remedial input and investment to install cages
7-8	Suitable	High scores on most factors	Most preferred zones requiring almost no remedial inputs to install cages
9-10	Extremely suitable	Scores very highly on all factors considered	

The model results show areas that could be zoned for aquaculture based on suitability for cage installation, rather than actual aquaculture zones. To define specific aquaculture zones, further assessment of carrying capacity at a more local scale would be required as well as consideration of other lake users and other relevant factors. Nevertheless, these large-scale zonation models can be considered one of the first steps in developing a complete zonation plan for Lake Volta.

Aquaculture zonation local market scenario

The results of the zonation models for the local market scenario using small and medium cages (Figure 51) indicate there are many areas that could be zoned for aquaculture based on the physical carrying capacity and the ability to install cages. Both cages would be susceptible to high winds and minimum/maximum depth constraints which is included in the model and shown in the results.

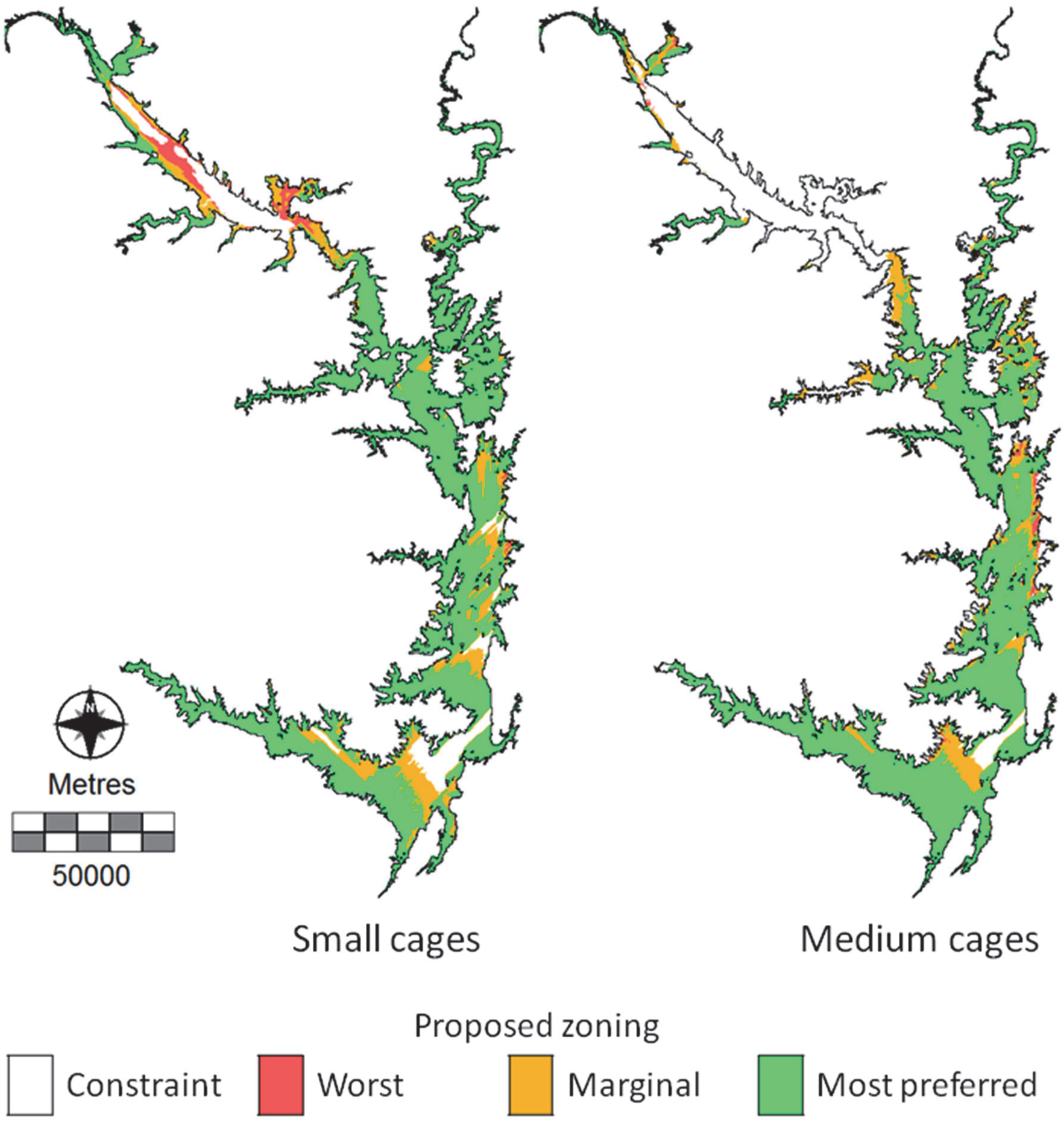

Figure 51: Results of the zonation models for the local market scenario using the small and medium cages

Aquaculture zonation commercial market scenario

The suitability of the lake for the installation of aquaculture cages varies depending on the size of the cages. This is reflected in the results from the zonation models developed for the commercial market scenariousing all four cage sizes: small, medium, large and extra large (Figure 52).

Much of the main body of the lake could potentially be zoned for cage aquaculture using small, medium and large cages. The optimal zoning areas using extra-large cages are mainly limited to the southern half of the lake where the water is deeper.

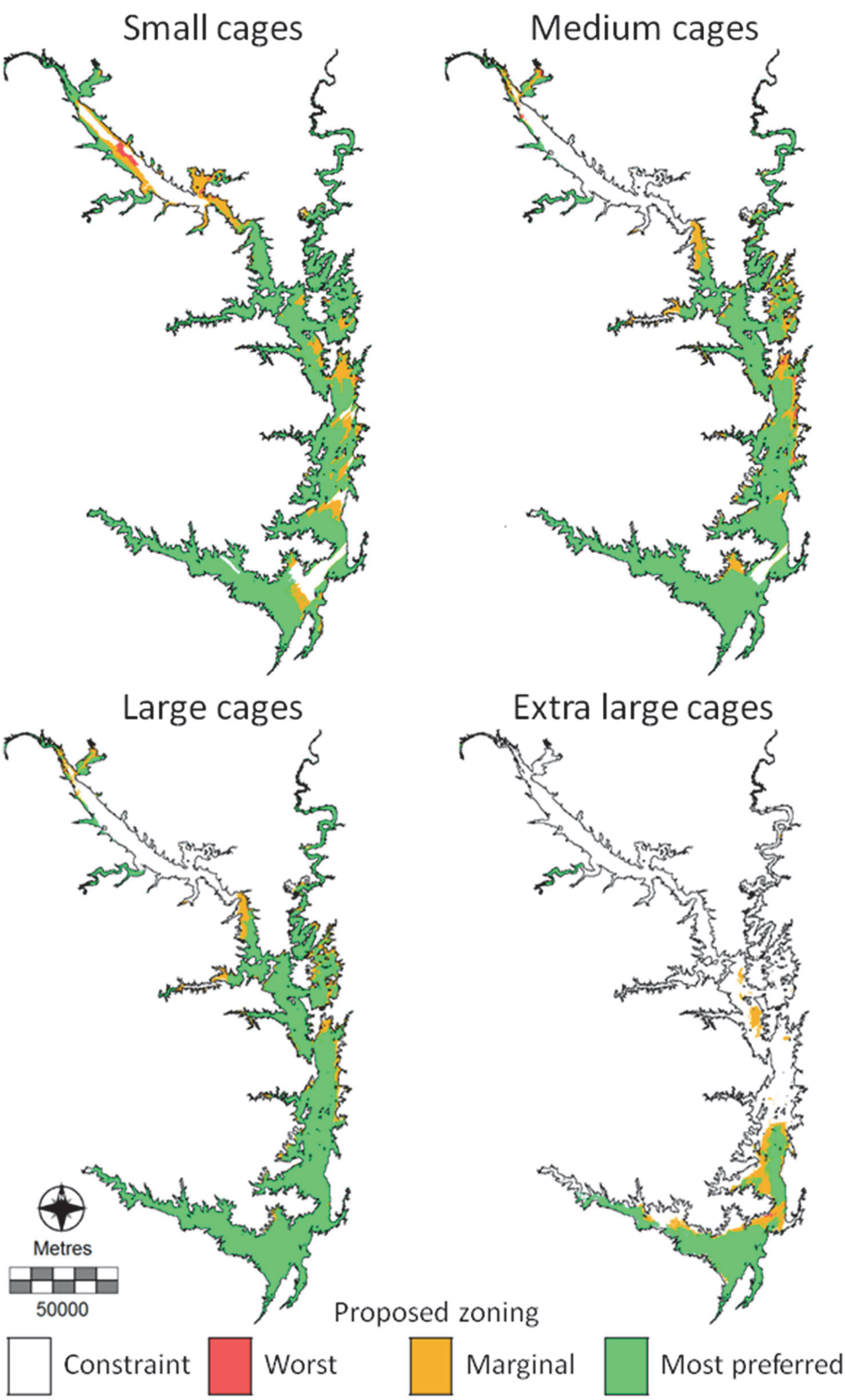

Figure 52: Results of the zonation models for the commercial market scenario using all four cage sizes.

Aquaculture zonation in Lake Volta

The results (Figures 51, 52& 53) suggest that a general aquaculture zone may not be sufficient for aquaculture in Lake Volta and instead it may be necessary to zone different areas for different purposes (e.g. a zone for small or medium cages for local markets, another zone for larger cages with a more commercial market focus). This is something decision makers can consider as the zonation plans progress and will also depend on the production carrying capacity of an area, view of stakeholders, other activities and broader plans for development of the aquaculture sector.

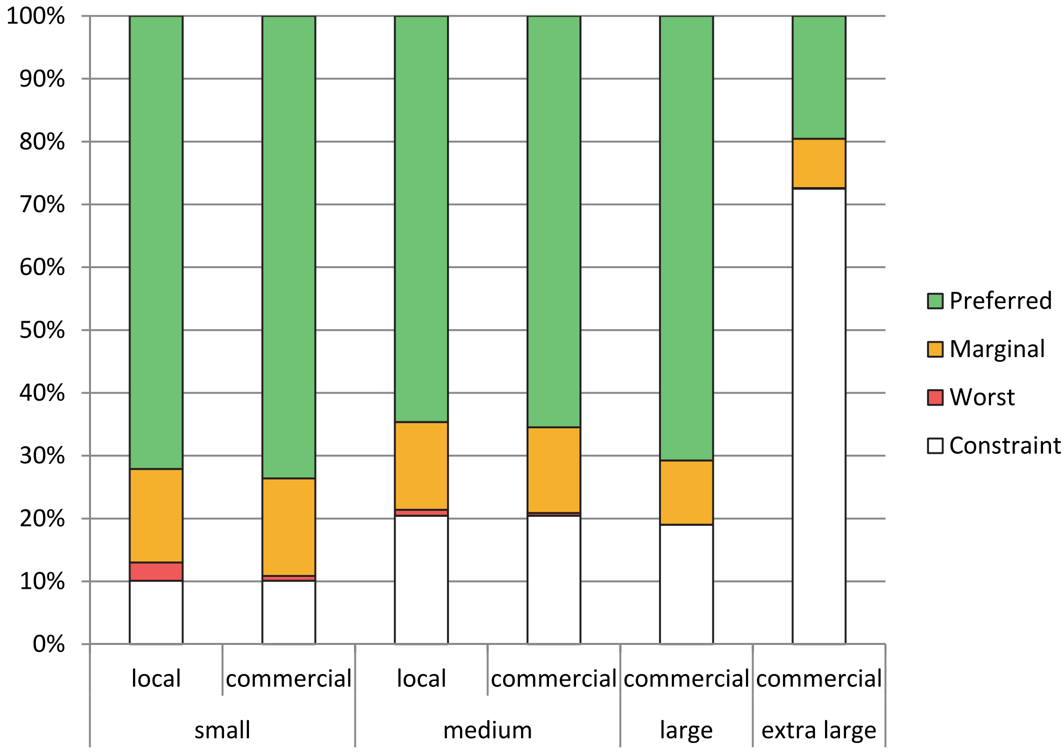

Figure 53: Areas (%) covered by each zone for the zonation models

Table 24: Areas (km²) covered by each zone for the zonation models

Proposed zoning	Cages and market scenarios					
	Small		Medium		Large	Extra-large
	Local	Commercial	Local	Commercial	Commercial	Commercial
Constraint	596	596	1206	1206	1122	4275
Worst	171	44	55	25	0	6
Marginal	878	916	825	805	602	464
Preferred	4252	4340	3810	3861	4172	1152

Summary

- Zonation facilitates development and integration of an activity in a multi-use area, maximising production and reducing conflict over shared space and resources.

- Effective zoning will consider the needs of the farm as well as the environmental, economic and social impacts of siting a farm in a particular location.

- Site selection models are an ideal starting point for aquaculture zonation as they provide information on the suitability of an area for culture.

- The site selection models were reclassified to a three tier zoning scheme which represented zoning preference: worst, marginal and most preferred.

- The results show areas that could be zoned rather than actual aquaculture zones. More detailed assessment of local carrying capacity and consideration of socio-economic issues and needs of other stakeholders and lake users would be required before establishing zones on the lake.

- General aquaculture zone(s) may not be sufficient for Lake Volta and instead it may be necessary to zone different areas for different purposes (e.g. cage sizes, market)

- The models can be considered one of the first steps in developing a complete zonation plan for Lake Volta.

- Further work is needed to establish a multi-user zonation plan which takes into account all relevant stakeholders and activities.

Production and ecological carrying capacity models for Lake Volta

Cite as:

Ekpeki, A. and Telfer, T.C. 2016.Production and ecological carrying capacity models for Lake Volta. In:Asmah, R., Karikari, A., Falconer, L., Telfer, T.C. and Ross, L.G. Cage aquaculture in Lake Volta, Ghana: Guidelines for a sustainable future. CSIR Water Research Institute, Ghana and University of Stirling, Stirling UK.112 pp.

Introduction

The spatial and zoning models considered physical carrying capacity, and to some extent social carrying capacity, across the entire lake. Further work is needed to establish production and ecological carrying capacity and this needs to be at a more local scale.

Ecological and production carrying capacity were calculated for some of the main cage aquaculture locations in Lake Volta. Spreadsheet-based models were developed (Ekpeki, 2015) based on water column assimilation of soluble nutrient wastes (phosphorus - a limiting nutrient in freshwater) and sedimentary assimilation of particulate nutrient wastes (organic carbon).

Study areas

Three sites, previously identified as suitable areas for cage culture (Figure 54, 55), were modelled using data collected during the field work campaign. Each study area had a defined boundary with other bodies, usually a narrowing or shallowing which affects water flow and can be clearly seen in the satellite imagery. This creates boundary conditions and flows which are critical in estimating the water exchange residence time and flushing rates of the water body. The sites are Aquaculture Management Areas, not zones (Table 25).

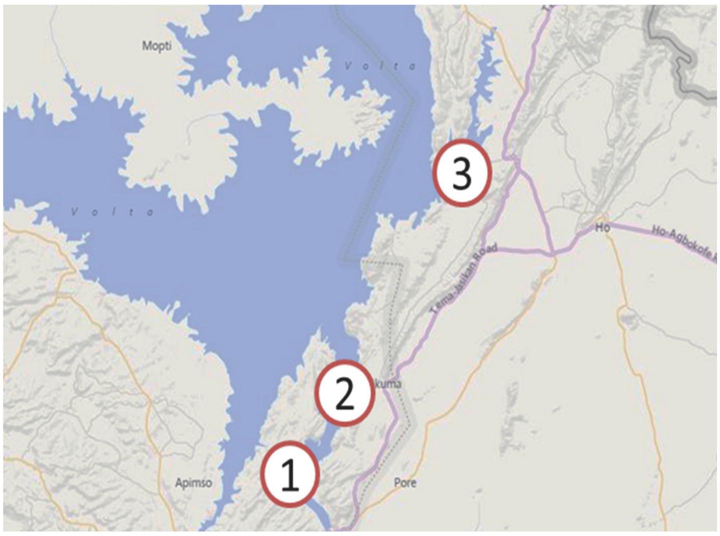

Figure 54: Locations of the three sites

Table 25: Site information for each study area

Site	Area(km^2)	Mean depth(m)	Water volume (m^3)
1 (Near Akosombo)	6	25	1.5×10^8
2 (Near Asikuma)	66	30	23×10^8
3 (Kpeve)	13	20	2.6×10^8

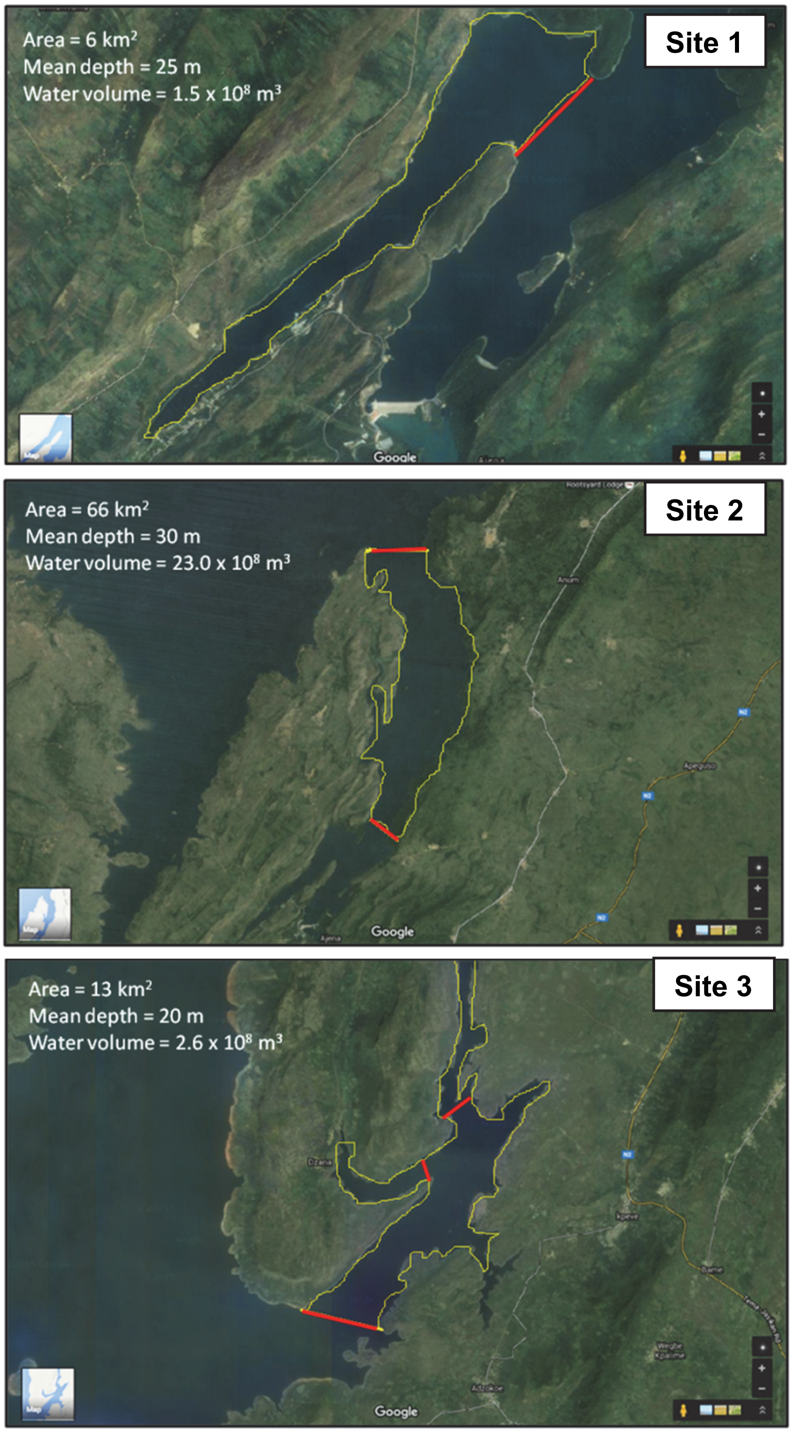

Figure 55: Three study areasin Lake Volta

Mass Balance models

Phosphorus loading into the environment (P_{env}) from fish cages was calculated using a simple mass balance equation (Equation 4). A mass balance model is used to account for a substance, in this case phosphorus, entering and leaving a system (fish cage). Production data was provided by the farms at Site 1 and Site 2 for 2013/2014 (Table 26).

The results of the mass balance models are shown in Table 27 and show that Phosphorus outputs into the environment (P_{env}) were 29.74 kg T yr^{-1} at Site 1 and 19.97 kg T yr^{-1} at site 2. No production data was available for Site 3. However, assuming the FCR is similar to Site 1 due to their common feeding patterns, regimes and management techniques, then the total environmental phosphorus would be approximately 29.74 kg T yr^{-1}, the same as Site 1.

$$P_{env} = (P_{feed} * FCR) - P_{fish} \quad \text{Equation 4}$$

Table 26: Production data for Site 1 and 2 provided by the farms

	Annual feed (kg)	Annual production (kg)	Overall FCR
Site 1	357,800	150,000	2.4
Site 2	3,912,000	2,304,000	1.7

Table 27: Results of the mass balance models for Phosphorus

	Site 1	Site 2	Units
FCR	2.4	1.7	
% of P in feed	1.41	1.41	%
Total P in feed	14.1	14.1	kg^{-T}
P_{feed}	33.84	23.97	kg^{-} fish
% of P in fish	0.41	0.4	%
P_{fish}	4.1	4	kg^{-T} fish
P_{env}	29.74	19.97	kg^{-T} prod

Dillon-Rigler Model

The Dillon-Rigler (1974) model (Equation 5) is used to predict the increase in phosphorus concentration in a lake due to cage farming. The equation was calibrated according to Beveridge (2004) and rearranged to estimate the "allowable" fish production in relation to pre-determined change in phosphorus (Equation 5). "Allowable" annual fish production was then calculated using Equation 7.

$$[P] = \frac{L(1-R)}{\bar{z}\rho} \quad \text{Equation 5}$$

Where:

[P] is potential additional phosphorus
L: P loading from the fish cages
R: P losses to the sediment
z : the mean depth
ρ: the flushing rate

$$L = \frac{\Delta[P]\bar{z}\rho}{(1-R)} \text{ Equation 6}$$

$$Fishproduction = \frac{L \times lakesurfacearea(m^2)}{Ploadpertonnefishprod\ (kg)} \quad \text{Equation 7}$$

The model inputs and results are shown in Table 28. Values for area loading were obtained based on changes in measured phosphate levels prior to exploitation (set at 20mg m^{-3}) and after culture had been established (determined by present measured values). The resulting phosphorus loading values were 1610.54 g $m^{-2}yr^{-1}$ for Site 1, 1242.25 g $m^{-2}yr^{-1}$ for Site 2 and 1271.43 g $m^{-2}yr^{-1}$ for Site 3. These were used to calculate current carrying capacity (Equation X) for each of the three sites; 318 T for Site 1, 4085.9T for site 2 and 565.75T for Site 3.

Table 28: Dillon-Rigler model inputs and results

	Site 1	Site 2	Site 3	Units
Mean Depth (z)	25	35	20	m
Surface Area (A)	5.894	65.684	13.278	km^2
Volume (V)	$1.474*10^8$	$2.299*10^9$	$2.656*10^8$	m^3
Outflow (Q)	1400	8830.5	1632	m^3s^{-1}
Flushing rate (ρ)	299.83	121.22	193.937352	yr^{-1}
Residence Time (T)	0.0033	0.0082	0.0052	yr
P_f ([P] with culture)	120	151	170	mg m^3
P_i([P] prior to exploit)	20	20	20	mg m^{-3}
x (% TP lost to sed.)	50	50	50	%
R (Sed. Coefficient)	0.0691	0.1052	0.0848	
R_{fish}	0.53	0.55	0.54	
Δ[P]	100	131	150	mg m^{-3}
TP loading yr-1 (L_{fish})	1610.54	1242.25	1271.43	g $m^{-2}yr^{-1}$
Present CC	318.11	4085.91	565.75	T yr^{-1}

OECD model

The total annual loading obtained from the Dillon and Rigler model was used in the OECD model (OECD, 1982), calibrated by Johansson and Nordvarg (2002) (Equation 8), to calculate total phosphorus concentration at each of the three sites. The model inputs and outputs are shown in Table 29. The calculated total phosphorus values from the OECD model were 126.7 mg m^{-3} for Site 1, 163.3 mg m^{-3} for Site 2 and 179.1 mg m^{-3} for Site 3.

$$\Delta TP = a\left(\frac{\Delta TPin}{(1+\sqrt{T})}\right)^{b} \qquad \text{Equation 8}$$

Where:

ΔTP is phosphorus concentration in the lake

T is the retention time

ΔTP_{in} is the phosphorus content in inflow calculated from the annual total phosphorus load divided by the inflow

a and b are empirical constants from the OECD (1982) dataset

After phosphorus levels had been determined, they were used to estimate chlorophyll through a regression equation. Beveridge (2004) recommends the Walmsley and Thornton (1984) equation (Equation 9) for tropical water bodies like Lake Volta.

$$[Chl] = 0.416[P]^{0.675} r = 0.84; \quad n = 16 \qquad \text{Equation 9}$$

Table 29: OECD model inputs and results

	Site 1	Site 2	Site 3	Units
Mean depth (z)	25	35	20	m
Surface Area (A)	5.9	65.684	13.278	km^2
Mean Flow rate (v)	0.04	0.087	0.051	$m\ s^{-1}$
Length of Outlet (L_o)	1400	2900	1600	m
Area of outlet (A_o)	35000	101500	32000	m^2
Outflow (Q)	1400	8830.5	1632	m^3s^{-1}
Volume (V)	$1.47*10^8$	$2.299*10^9$	$2.656*10^8$	m^3
Residence Time [T]	0.0033	0.0082	0.0052	yr
Annual P_{env}	1610539.28	1242245.69	1271431.31	$kg\ yr^{-1}$
A	1.55	1.55	1.55	
B	0.82	0.82	0.82	
TP in inflow (P_{in})	214.8569715	292.804555	327.7943353	$mg\ m^{-3}$
Total [P]	126.703892	163.318721	179.1442555	$mg\ m^{-3}$

The results of the OECD model were compared to measured values (Figure 56). The modelled results were approximately 25% higher than measured phosphorus. Due to a lack of data, constants used in the models were obtained from the OECD combined data set but the relationship between total phosphorus, chlorophyll and Secchi disk depth may vary regionally. Additional fieldwork would be needed to further calibrate the model for Lake Volta.

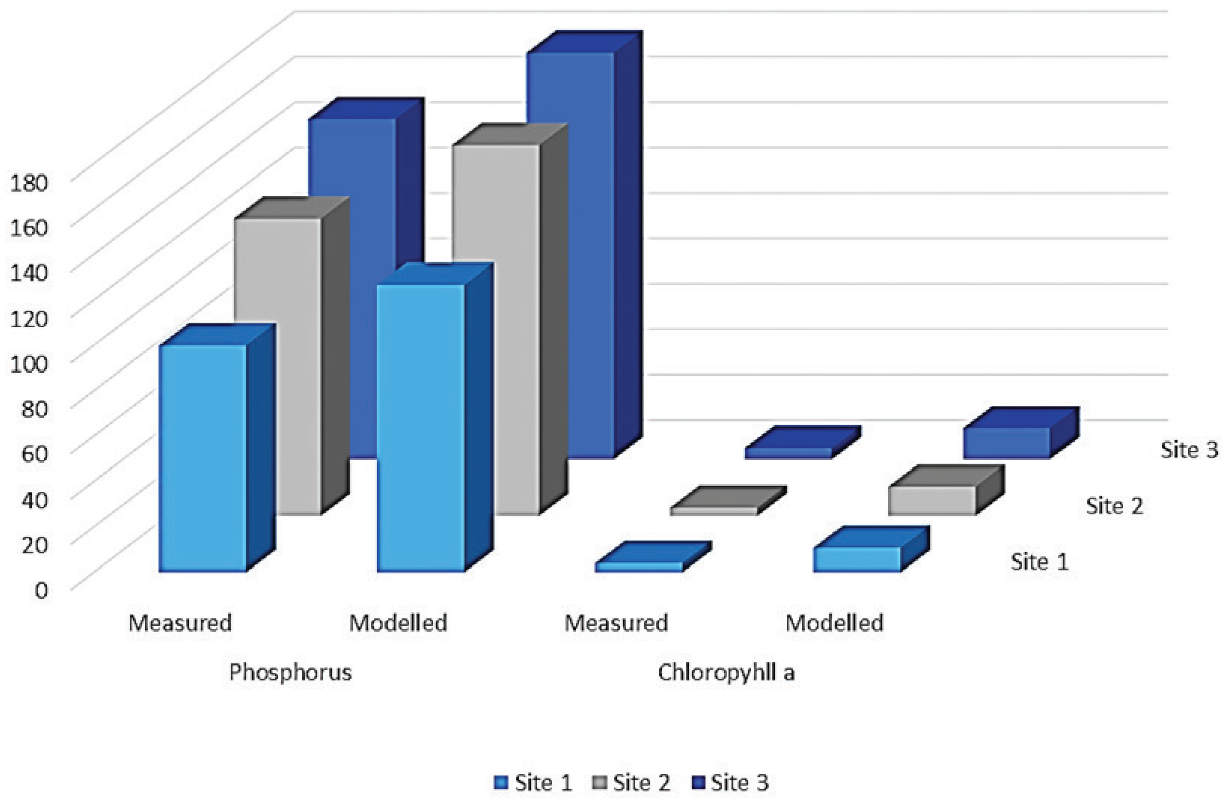

Figure 56: Comparison of measured and modelled levels of total phosphorus using the OECD model and corresponding Chlorophyll a values.

Measured chlorophyll values were lower than expected given the measured phosphorus values. The Chlorophyll values indicate that sites are mesotrophic, whereas the measured phosphorus and models indicate a eutrophic state. A regular programme of monitoring would need to be established to refine and update the models.

Allowable increase in carrying capacity

To calculate allowable carrying capacity, Carlson's Trophic State Index (Table 30) was used to determine the change from one tropic state to another. Using the modelled results for current total phosphorus levels, allowable phosphorus levels were set at the next level of the index (192mg m^{-3}) and then the Dillon-Rigler model was used to calculate the allowable increase in Phosphorus load and carrying capacity (Table 31). Based on the model results, Sites 1, 2 and 3 have an allowable carrying capacity increase of 229 T yr^{-1}, 1278.8 T yr^{-1} and 82.9 T yr^{-1} respectively. This is the allowable increase on top of current production levels that would not cause trophic change within the system.

Table 30: Carlson's Trophic State Index (TSI) (Carlson, 1977)

TSI	Secchi disk (m)	Surface P (mg m^{-3})	Surface Chl (mg m^{-3})
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.125	384	427
100	0.062	768	1183

Table 31: Allowable increase in phosphorus load and carrying capacities

	Allowable ΔP load (g m^{-2} yr^{-1})	Allowable ΔCC (T yr^{-1})
Site 1	1159.59	229.0
Site 2	388.79	1278.8
Site 3	186.48	82.9

CAPOT model

The Cage Aquaculture Particulate Output Transport (CAPOT) model is an excel spreadsheet based model that was developed at the University of Stirling to estimate the amount and distribution of solid waste materials entering the environment from fish cages (Figure 56). The CAPOT model uses production data (present or future), hydrographic data and the spatial layout of the cages as well as other empirically derived measures and assumptions.

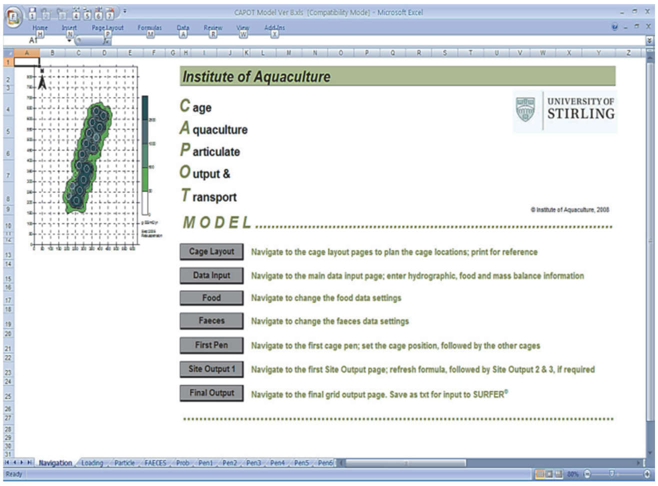

Figure 56: The CAPOT Model

CAPOT was used to calculate the carbon output into the environment and subsequent dispersal of solid waste at farms at Site 1 and Site 2. The results were imported in to Surfer Version 12 [Golden Software, Colorado, USA] to generate contour plots (Figures 57 and 58). The results show that carbon waste above 100 gC m^{-2} yr^{-1} spread up to approximately 20m from the cages at Site 1 (Figure 57) and carbon waste above 1000 gC m^{-2} yr^{-1} spread up to approximately 40m from the cages at Site 2 (Figure 58).

The area into which a carbon load greater than that which leads to negative redox and oxygen depletion can be calculated and the SOD estimated based on empirically calibrated data (Telfer and Robinson, 2006). The value for significant footprint for SOD was extrapolated from one used for salmon cages in Ireland by Telfer and Robinson (2003). As mean water temperature is three times higher in Ghana than Ireland, the significant level was set at 1080g C m^{-2} yr^{-1} at which the Carbon footprint impacts SOD and SOD was set at the 594mg O_2 m^2 hr^{-1}.

The results (Table 32) show the footprint at Site 2, and consequently the SOD, is 3 times greater than Site 1. However this is a much faster flowing area, which can support a greater production tonnage. A follow on assessment could use these values to calculate a water based DO demand to derive an ecological carrying capacity based on sustainable oxygen levels.

Table 32: Carbon footprint at Sites 1 and 2.

	Total area of all waste (m^2)	Reduced sediment footprint (m^2) >3 gC m^{-2} d^{-1}	SOD from RS footprint (kg O_2 d^{-1})
Site 1	980,100	28,833	411
Site 2	1,593,000	93,546	1,334

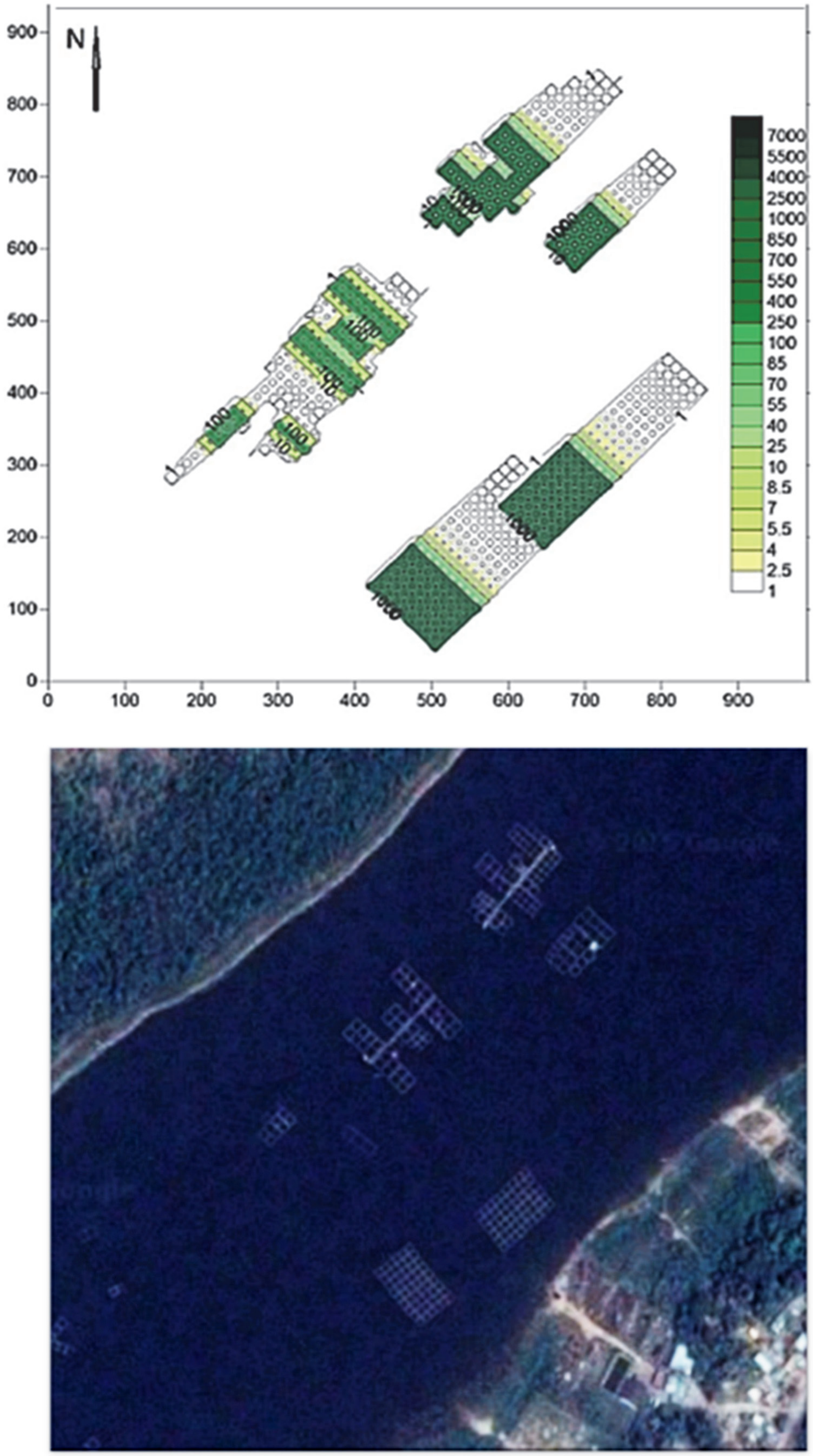

Figure 57: Modelled organic carbon distribution footprint at Site 1 using current speed/direction from drogues. *Units are in gC m^{-2} $yr^{-1.}$ Axes are in metres.*

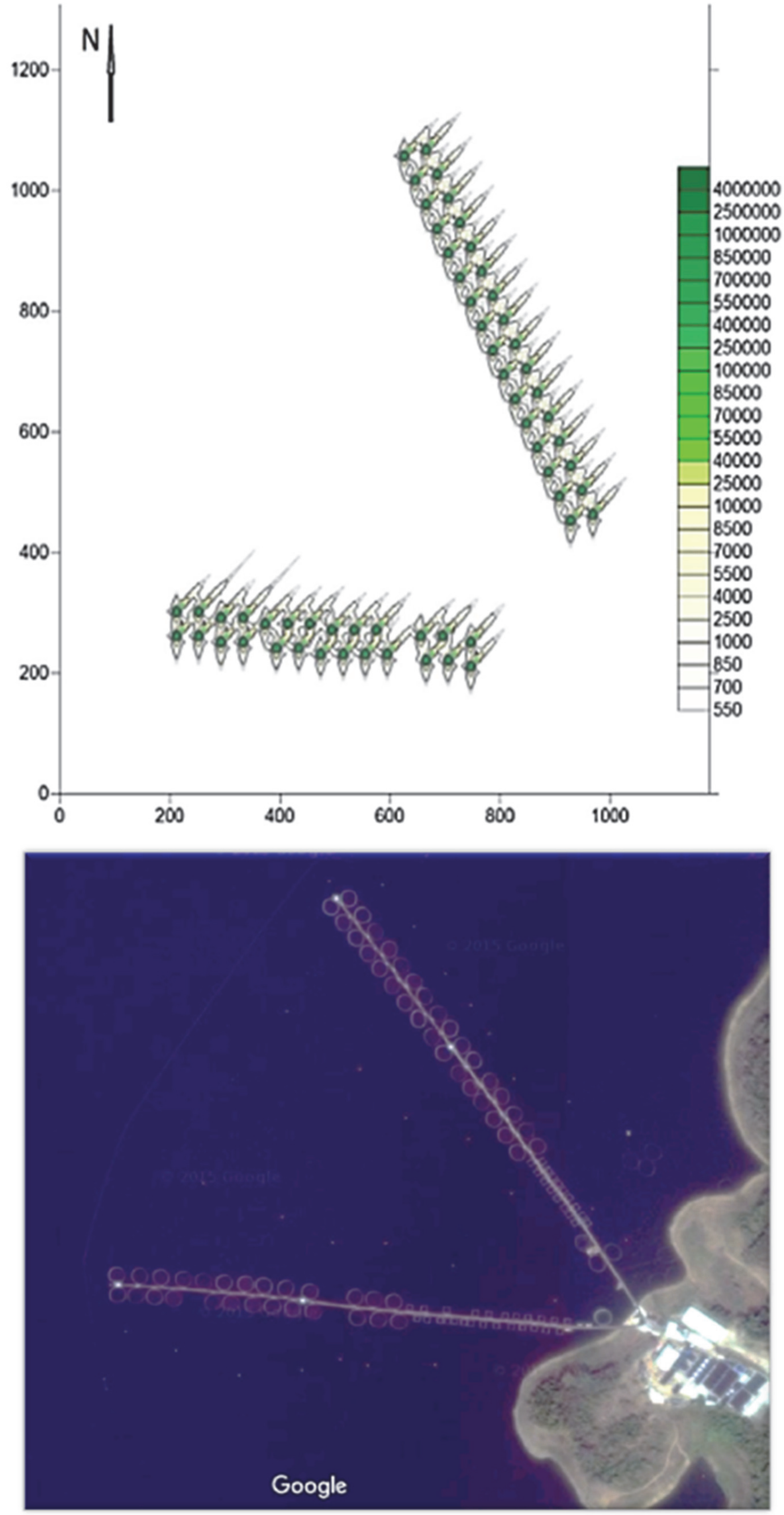

Figure 58: Modelled organic carbon distribution footprint at Site 2 using current speed/direction from drogues. *Units are in gC m^{-2} yr^{-1}. Axes are in metres.*

Summary

- Spreadsheet based models developed using the Dillon-Rigler (1974) and OECD (1982) models were used to calculate environmental phosphorus loading and carrying capacity.

- Three sites previously identified as suitable areas for cage culture were modelled using data collected during the field work campaign

- A waste dispersion model was used to estimate the spread of waste from the farm sites.

- The models calculated that Sites 1, 2 and 3 have an allowable carrying capacity increase of 229 T yr^{-1}, 1278.8 T yr^{-1} and 82.9 T yr^{-1} respectively. This is the allowable increase on top of current production levels that would not cause trophic change within the system.

- Site 2 had a footprint, and consequently SOD, more than 3 times greater than Site 1. However this is a faster flowing areas which can support a greater production tonnage.

Capacity Building

Cite as:

Asmah, R., Karikari, A., Telfer, T.C. and Ross, L.G.2016. Spatial models for Lake Volta. In:Asmah, R., Karikari, A., Falconer, L., Telfer, T.C. and Ross, L.G. Cage aquaculture in Lake Volta, Ghana: Guidelines for a sustainable future. CSIR Water Research Institute Ghana and University of Stirling, Stirling UK.112 pp.

Introduction

One of the main aims of the project was to build capacity in environmental monitoring and assessment. Capacity building is more than just training individuals; it involves human resource development, organizational development and institutional and legal framework development. All of this takes time, so this project focused on human resource development; providing access to information, knowledge and training thereby giving individuals the understanding and skills needed to perform effectively. The expectation is that once stakeholders are engaged, institutional and legal framework development will gradually follow.

A series of capacity building workshops were held in Accra, Ghana with invited key stakeholders (Figure 59); Workshop 1 "*Environmental Management for Sustainable Cage Aquaculture*", Workshop 2 "*Advanced Environmental modelling for Cage Aquaculture*" and Workshop 3 "*Mapping zonation, carrying capacity and development*". The first two workshops focused on training, through presentations and practical exercises, while the final workshop was used to disseminate the results and outcomes of the project. The workshops were also used for project evaluation to ensure the needs of stakeholders and industry were being met and the approaches and methods used were examined.

Figure 59:The project team and workshop participants in Ghana

Workshop 1: "Environmental Management for Sustainable Cage Aquaculture"

The first workshop "Environmental Management for Sustainable Cage Aquaculture" was held in February 2013. This workshop served as an introduction to the project and also included several days training on environmental monitoring and assessment, carrying capacity and site selection (Table 33). Over thirty participants were in attendance from several key organisations; including the Environmental Protection Agency, Water Resources Commission, Ghana Aquaculture Association, Fisheries Commission, the African Regional office of the Food and Agriculture Organisation (FAO) as well as universities and research institutions.

The workshop lasted four days and included a series of presentations. The first day and a half focused on environmental impact assessment, environmental monitoring and risk assessment. This included presentations on survey techniques and data analysis as well as environmental modelling.

Figure 60: Workshop participants working on GIS-based site selection case studies

Subsequent sessions covered spatial modelling, specifically site selection for aquaculture. In addition to presentations, the workshop included practical sessions where relevant software was introduced and participants worked through exercises and real world case studies (Figure 60). Instructions and tuition was provided as the participants followed the step-by-step exercises.

Figure 61: Certificate awarded to a participant

The final day also included a presentation which introduced the project and discussed the aims, objectives and overall impact of the work. Breakout groups were organised in the afternoon to facilitate discussion amongst the stakeholders and project team about the workshop and the project. At the end of the workshop certificates were awarded to each participant (Figure 61).

Table 33: Programme for Workshop 1: “Environmental Management for Sustainable Cage Aquaculture”

Date	Time		Presenter
Tues 26/02/13			
	9:00am – 9:15am	Registration of participants	
	9:15am – 9:30am	Opening of workshop: Dr Ampofo	Director, WRI
	9:30am – 11: 10am	Importance of EIA in aquaculture	Prof.Trevor Telfer
	11:10am – 11:30am	Coffee break	
	11:30am – 1:10pm	EU guidelines to compiling EIS for aquaculture	Prof.Trevor Telfer
	1:10pm – 2:10pm	Lunch	
	2:10pm – 4:00pm	Environmental Monitoring – Surveys and data analysis	Prof.Trevor Telfer
Wed 27/02/13			
	9:30am – 11: 10am	Environmental Monitoring – Modelling dispersion of cage effluent	Prof.Trevor Telfer
	11:10am – 11:30am	Coffee break	
	11:30am – 1:10pm	Risk Assessment	Prof. Trevor Telfer
	1:10pm – 2:10pm	Lunch	
	2:10pm – 4:00pm	1_EAA, Carrying Capacity and Site Selection	Prof. Lindsay Ross
	3:00 – 4:00	2_Introduction to GIS	Prof. Lindsay Ross
Thurs 28/02/13			
	9:30am – 11: 10am	3_Examples of using GIS for decision support in aquaculture	Prof. Lindsay Ross
	11:10am – 11:30am	Coffee break	
	11:30am – 12:15	Installing the IDRISI system & databases Introduction to the software	Prof. Lindsay Ross & All Participants
	12:15- 1:10pm	4_Case study 1: Small scale marine cage farming.	Prof. Lindsay Ross & All Participants
	1:10pm – 2:10pm	Lunch Break	Prof. Lindsay Ross
	2:10pm – 4:00pm	5_Case study 1: continued.....Small scale marine cage farming.	Prof. Lindsay Ross & All Participants
Fri 01/03/13			
	9:30am – 11:00am	5_Case study 2: Modelling pond aquaculture potential in Ghana	Profs. Lindsay Ross, Trevor Telfer& All Participants
	11:00am – 11:20am	Coffee break	
	11.20 – 12:00	Presentation on Lake Volta Sustainable cage aquaculture project	Dr. Ruby Asmah Mr. Anthony Karikari
	12:00 – 1:30pm	Breakout groups & discussions	All
	1:30pm – 2:30pm	Lunch	
	2:30pm – 3:00pm	Closing session	WRI staff

Workshop 2: “Advanced Environmental Modelling for Cage Aquaculture”

The second workshop "Advanced Environmental Modelling for Cage Aquaculture" was held in March 2014. This workshop focused on environmental modelling and covered the ecosystem approach to aquaculture, carrying capacity and environmental modelling for decision support (Table 34). The workshop was attended by thirty participants from thirteen institutions; including the Environmental Protection Agency, Water Resources Commission, Fisheries Commission, Ghana Aquaculture Association, the African Regional office of FAO, Volta River Authority and the Ministry of Environment Science and Technology and Innovation in addition to universities and research institutions.

On the first day, there were a series of presentations covering the carrying capacity concept and modelling approaches used for assessment. One of the key presentations focused on models for that would be used for Lake Volta. In the afternoon there was a group task (“checklist approach to site selection, zoning and carrying capacity”) where participants were asked their opinion factors used for cage site selection. This provided information for model development (Figure 62).

Figure 62: Group discussions during the workshop

The second day covered spatial models for site selection and zoning. This included a demonstration of case studies as well as the theory behind developing site selection models. The results from the preliminary database development and spatial models were developed and feedback was recieved from stakeholders.

On the final day, the project team presented the initial results from the fieldwork, water quality and sediment quality analysis. Participants provided feedback and gave comments on the work. Round table discussions also provided an excellent opportunity for knowledge exchange and collaboration, building on existing networks and establishing new connections for the next phase of the project.

Table 34: Programme for Workshop 2: “Advanced Environmental Modelling for Cage Aquaculture”

Date	Time		Presenter
Monday 03/03/14			
	9:00am – 9:30am	Registration of participants	
	9:30am – 9:45am	Opening of workshop	WRI Director
	9:45am – 11:00am	Carrying Capacity Background and Theory	Prof. Trevor Telfer
	11:00am – 11:30am	Coffee break	
	11:30am – 12.30pm	Approaches to modelling	Prof. Trevor Telfer
	12.30pm – 1.00pm	Lake Volta models	Prof. Trevor Telfer
	1:00pm – 2:00pm	Lunch	
	2:00pm – 3:00pm	Group Task: Checklist approach to site selection, zoning and carrying capacity	All Participants
Tuesday 04/03/14			
	9.30am – 10.00am	Spatial tools for site selection and zoning	Prof. Lindsay Ross
	10:00am – 10.45am	Case study on implementation of tilapia cage culture in a large Mexican reservoir	Prof. Lindsay Ross
	10:45am – 11:15am	Coffee break	
	11:15am – 12.00pm	Preliminary spatial database and models for optimising cage locations in Lake Volta	Prof. Lindsay Ross
	12:00pm – 1:00pm	Project background	Dr. Ruby Asmah
	1:00pm – 2:00pm	Lunch	
	2:00pm – 3:00pm	Group Task: Checklist approach to site selection, zoning and carrying capacity - revisited	All Participants
Wednesday 05/03/14			
	9:30am – 10:00am	Preliminary project results – Water quality	Mr. Anthony Karikari
	10:00am – 11:00am	Preliminary results - sediment quality	Dr. Ruby Asmah
	11:00am – 11:30am	Coffee break	

11:30am – 12:30pm	Round Table Discussions	All Participants
12:30am – 12:45	Discussion summary	Prof. Lindsay Ross
12:30pm – 1:00pm	Workshop evaluation	All Participants
1:00pm – 2:00pm	Lunch	
2:00pm	Closure of workshop	Dr. Ruby Asmah

Workshop 3: “Mapping Zonation Carrying Capacity and Development”

During the third, and final, workshop "Mapping Zonation, Carrying Capacity and Development" held in November 2015, the research team presented the outcomes from the project (Table 35). This was a useful opportunity to disseminate results to relevant stakeholders from multiple agencies. The latter half of the workshop involved group discussion and project evaluation. The participants were divided into groups and asked to discuss seven key questions;

1. How do you think the work done and principles demonstrated can be best used in Ghana?
2. What are the major missing factors and conflicts?
3. Are there any modelling approaches currently used in Ghana?
4. Are they used for environmental regulation or assessment?
5. How best could Ghana implement the use of zones
6. How could Ghana implement use of Aquaculture Management Areas?
7. Are there any other major topics related to cage aquaculture that need to be addressed?

The team received positive feedback regarding the project. Stakeholders were eager that the work continued and some suggested the project could be used as a foundation for a national review of guidelines. Stakeholders were not aware of any modelling approaches currently used in Ghana and said if they are used then they are not well known or used for environmental regulation and assessment.

Social aspects, which were not within the scope of the project, were highlighted as the most important missing factor. This included water use by communities, traditional groups and fishing rights. Security was also a concern, echoing similar fears of poaching and vandalism from farmers interviewed earlier in the project.

There were many suggestions regarding how Ghana could best implement the use of zones. There was a demand for a clear, comprehensive framework for zoning in the lake with support from all relevant agencies. Committees could be established to manage zones and zoning must be included in polices and enforced by regulators. Stakeholders also acknowledged the need for further data collection and continuous monitoring if zoning is to be effective.

Group discussions during the workshop

The final question asked stakeholders if there were any other major topics regarding cage aquaculture that should be addressed. A recurring theme was the need for better guidelines and further improved technical training of farmers, which could be promoted by zone committees. Stakeholders suggested the need to consider chemical use within the water, measuring and monitoring residues. Furthermore, there was interest in establishing production limits and stocking densities for farms/areas. This would involve assessment of carrying capacity using the techniques and modelling approaches in this study. Finally, there were also concerns over climate change and the implications that would have on the lake and cage culture.

Table 35: Programme for workshop 3: "Mapping Zonation Carrying Capacity and Development"

Time		Presenter
9:00am – 9:30am	Registration of participants	
9:30am – 10:00am	Opening of workshop	WRI Director
10:00am – 10:25am	Introduction to the Lake Volta project	Dr. Ruby Asmah
10:25am – 10:50 am	Our science objectives	Prof Lindsay Ross
10:50am – 11:20 am	Coffee break	
11:20am – 12:00pm	Field approaches and data analysis	Anthony Karikari

		& Dr Ruby Asmah
12:00am – 12:25pm	Spatial models for Lake Volta	Prof Lindsay Ross
12:25pm – 12.50 pm	Environmental models for Lake Volta	Prof Trevor Telfer
1:00pm – 2:00pm	Lunch	
2:00pm – 2:30pm	Zonation guidelines for Lake Volta aquaculture	Project partners
2:30pm – 3:15pm	Round table discussion	All Participants
3:15pm – 3:45pm	Closure of the workshop	All Participants
3:45pm – 4:00pm	Coffee Break/Departure	All Participants

Project evaluation

At the end of the terminal workshop participants were asked to complete a questionnaire which served as an evaluation of both the workshop and the project since the workshop focused on the project outcomes. The questionnaire contained eight statements (right) and the participants were asked whether they agreed or disagreed with each statement. There were 20 responses, which have been collated in Table 36.

There were no responses that disagreed with the statements and only one neutral response for three statements. Most of the responses strongly agreed suggesting there was high satisfaction with the work presented in the workshop showing the approaches and results used in the whole project.

A further four questions (right) were asked to elicit additional comments and observations from the participants and to give the opportunity for more expansive responses. The results are collated and summarised in Table 37.

1. The duration of the workshop was about right.
2. The location and facilities for the workshop was good.
3. The organisation of the workshop was good.
4. The content of the workshop broadly met your expectations.
5. The content of the presentations were interesting.
6. The standard of the presentations was good.
7. The focus of the workshop was helpful to me in my current post.
8. The focus of the workshop should be helpful to Ghana in the future.

----

9. Features of the workshop you found problematic?
10. What aspects of the programme did you find most useful?
11. What topics you would like to see in a future workshop in relation to the Lake Volta project
12. Do you have any further comments?

Table 36: Responses to the project evaluation questionnaire

Question	Strongly agree	Agree	+/-	Disagree	Strongly disagree
Duration was right	11	9	0	0	0
Location & Facilities	12	8	0	0	0
Organisation good	16	4	0	0	0
Content met expectations	13	6	1	0	0
Content was interesting	15	4	1	0	0
Standard of presentations	15	5	0	0	0
Focus helpful in my present post	13	6	1	0	0
Focus helpful to Ghana in future	17	3	0	0	0

Table 37. Additional comments and observations from terminal workshop participants.

Were there any features of the workshop you found problematic?	• None (x9) • Did not understand the modelling/data (x3) • Modelled distance between proposed sites • Depth reclassification • No plan for sustained data collection • No emphasis on constraints or bottlenecks
What aspects of the programme did you find most useful?	• Very clear presentations & data (x4) • Spatial modelling (x4) • Ecological modelling (x3) • Data analysis showing no adverse effects of aquaculture • Bathymetry work • Zonation models (x6) • Carrying capacity studies (x5) • Group discussion • Water quality monitoring (x3) • Findings very useful in moving forward on Lake Volta
What topics you would like to see in any future workshop in relation to the Lake Volta project?	• Shared outputs taken up by those government agencies managing permits • Impact of climate change (x2) • Water chemistry and nutrient levels (x2) • Reports on further progress • How to relocate cages if not well situated • How to mitigate conflicts between users (x2) • How to implement models practically • More on carrying capacity and production • Work on trace metals

	• Hydro generation • More on zonation and AMA's (x2) • Fish /biodiversity conservation areas • More on trophic status of the lake • Effect of aquaculture on other ecosystem services
Any other comments?	• Follow-up studies would be useful (x2) • Cover whole lake • Excellent presentations • Well organised • Involve the media next time • Great - excellent educational workshop (x3) • Work on chemical residues would be useful • Model for the Keta lagoon • Use simpler language

N.B. not all respondents answered every question

Summary

- Three annual workshops were held over the lifespan of the project in Accra, Ghana with invited key stakeholders (Figure 63).

- The workshops served multiple purposes; dissemination, evaluation, training and network building. All of which builds capacity in the area of environmental monitoring and assessment.

- The first workshop " Environmental Management for Sustainable Cage Aquaculture" introduced the project and also included several days training on environmental monitoring and assessment, carrying capacity and site selection

- The second workshop "Advanced Environmental Modelling for Cage Aquaculture" involved presentation of initial project results and a training on modelling techniques that could be used to assess carrying capacity in Lake Volta.

- During the third and final workshop "Mapping Zonation Carrying Capacity and Development" the project team presented the main results of the project.

- Over 30 key stakeholders attended each workshop which led to knowledge exchange and collaboration, strengthening existing networks and establishing new connections for the next phase of the project.

- Feedback from the workshops and the final project evaluation was very positive.

Figure 63: Project team and some of the workshop participants

Conclusions and future recommendations

Project activities undertaken

- Survey of fish farms on Lake Volta
- Bathymetry & hydrological model of the Lake
- Field sampling of water and sediments at selected sites
- Laboratory Analyses of samples and interpretation of data
- Spatial decision Support Modelling
- Capacity building for environmental impact assessment

Science outcomes

- Introduced new approaches and methods in environmental monitoring and assessment
- Defined possible area of interactions between aquaculture and the environment and potential impacts on biota
- Enhanced understanding of cage aquaculture and its potential impacts on the lake
- Identified optimal sites and potential areas that could be zoned for cage aquaculture development based on physical suitability with further, more local level assessment being needed to establish specific aquaculture zones.
- Estimated quantities of waste discharges from fish cages to the lake
- Estimated local carrying capacity for aquaculture

Training and Capacity Building

A. Three training workshops with personnel from key agencies, including:
- Environmental Protection agency (EPA)
- Volta River Authority (VRA)
- Water Resources Commission (WRC)
- Ministry of Food and Agriculture (MOFA)
- Fisheries Commission
- Ghana Water Company (GWCL)
- CSIR Water Research Institute (CSIRWRI)
- Irrigation Development Authority (IDA)
- Aquaculture Farmers

B. Higher degree training:

- Karikari, A. 2016. Assessment of impact of cage aquaculture on Lake Volta, Ghana. PhD. Kwame Nkrumah University of Science and Technology. Kumasi, Ghana.

- Michelle Naa Kordei Clottey. 2015. Effects of microbial loads on the physiological condition and fecundity of some selected fishes in the Volta Lake (stratum II). MPhil. University of Ghana. Accra, Ghana.
- Miriam Yayara Ameworkor. 2015. Impacts of fish cage culture on water quality and selected commercially important fish stocks in Volta Lake (Stratum II). MPhil. University of Ghana. Accra, Ghana.
- Lily Osei Konadu. 2016.. Monitoring bacterial loads in Lake Volta fish farm sediments. MSc. Kwame Nkrumah University of Science and Technology. Kumasi, Ghana.
- Al-Shihi, J. 2013. Construction of a spatial database of aqua-farms in Ghana and identification of locations for future developments of the sector. MSc. Institute of Aquaculture, University of Stirling.
- Fan Xia. 2014. Construction of a spatial database for Lake Volta, Ghana, and identification of locations for future developments of the sector. MSc. Institute of Aquaculture, University of Stirling.
- Al-Wahaibi, M. 2015. Spatial modelling of Infrastructure, Population, Markets for aquaculture development in Volta Lake. MSc. Institute of Aquaculture, University of Stirling.
- Ekpeki, A. 2015. Development of carrying capacity estimates for zonation of cage aquaculture in Lake Volta, Ghana. MSc. Institute of Aquaculture, University of Stirling.

Impact and Legacy of the project

The workshops, training and experience imparted during the project have raised awareness in key agencies of the use of simple and more complex modelling, based on field work and data collection, to support and enhance decision making in aquaculture. It is anticipated that the site selection, zonation and carrying capacity models will be of immediate use in managing the enormous body of water in Lake Volta as well as stimulating research and regulatory activity to refine processes. The spatial models suggest that there is considerable scope for development of optimally located new sites based on the modelled parameters. These sites would of course require assessment of carrying capacity as well as consideration of social capacity in terms of interactions with communities and competing activities. Such studies are best carried out at a more local, site-specific scale. If environmentally benign expansion can be made, this could provide high quality fish for Ghana as well as for export within and outside of the region.

Acknowledgements

This work was supported by a Royal Society (London) Africa grant funded by the Leverhulme Trust.

The research team are grateful to the following technicians of the Environmental Chemistry Sanitation and Engineering Division, the Environmental Biology and Health Division of the CSIR Water Research Institute and technicians of the CSIR Soil Research Institute, Accra Office:

Mr. Daniel Amoah, Mr. Victor Mantey, Mr.Serapis Appiah, Mr Emmanuel Ofori, Mr Godwin Amegbe, Ms Lindah Nuamah, Mr Gabriel Appiah and Mr. Emmanuel Akuffu for assisting with field data collection and analyses of samples in the laboratories.

We are also grateful to the Director of the CSIR Water Research Institute for his support.

References

Abo, K., and Yokayama, H. 2007. Assimilative capacity of fish farm environments as determined by the benthic oxygen uptake rate: Studies using a numerical model. *Bulletin of Fisheries Research Agency*, 19: 79–87.

Al-Shihi, J. 2013.Construction of a spatial database of aqua-farms in Ghana and identification of locations for future developments of the sector. MSc. Institute of Aquaculture, University of Stirling. 35pp.

Al-Wahaibi, M. 2015.Spatial modelling of Infrastructure, Population, Markets for aquaculture development in Volta Lake. MSc. Institute of Aquaculture, University of Stirling.

Amakye, J.S. 2001.Some observations on macro-invertebrate benthos of Lake Volta at Yeji area (Stratum VII) thirty years after impoundment. West African Journal of Applied Ecology, 2: 91-102.

Azevedo P.A., Podemski C.L., Hesslein R.H., Kasian S.E.M., Findlay D.L. & Bureau D.P. 2011 Estimation of waste outputs by a rainbow trout cage farm using a nutritional approach and monitoring of water quality. *Aquaculture* 311, 175–186.

Beveridge, M.C.M, Phillips, M.J, & Macintosh, D.J. 1997. Aquaculture and the environment: the supply of and demand for environmental goods and services by Asian aquaculture and the implications for sustainability. Aquaculture research 28 (10), 797-807

Beveridge, M.C.M. 2004.Cage Aquaculture. Third edition. Blackwell Publishing, Oxford, UK. 380pp.

Canadian Council of Ministers of the Environment. 2001. Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, Technical Report. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg.

Carlson, R.E. 1977. A trophic state index for lakes. *Limnology an Oceanography*, 22: 361 - 369.

Crétaux, J.F., Jelinski, W., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M. &Maisongrande, P. 2011. SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research*, 47(9): 1497-1507.

Degefu, F., Mengistu, S. and Schagerl, M., 2011. Influence of fish cage farming on water quality and plankton in fish ponds: A case study in the Rift Valley and North Shoa reservoirs, Ethiopia. *Aquaculture*, vol. 316, pp. 129- 135

Dillon, P.J. and Rigler, F.H. 1974. The phosphorus-chlorophyll relationship in lakes. *Limnology and Oceanography*, 19: 767-773.

Donohue, I. and Irvine, K. 2003. Effects of sediment particle size composition on survivorship of benthic invertebrates from Lake Tanganyika, Africa. ArchivfürHydrobiologie, 157(1): 131-144.

Dunnette, D.A. 1979. A geographically variable water quality index used in Oregon.*Journal of Water Pollution Control Federation* 51 (1), 53-61.

Eastman, J.R. 2012.IDRSI Selva Manual. Clark Labs, Massachusetts USA. 324pp.

Ekpeki, A. 2015. Development of carrying capacity estimates for zonation of cage aquaculture in Lake Volta, Ghana. MSc. Institute of Aquaculture, University of Stirling.

Falconer, L., Hunter, D.C., Scott, P.C., Telfer, T.C. and Ross, L.G. 2013.Using physical environmental parameters and cage engineering design within GIS-based site suitability models for marine aquaculture. AquacultureEnvironmentInteractions, 4: 223-237.

Graça, M. A. S., P. Pinto, R. Cortes, N. Coimbra, S. Oliveira, M. Morais, M. J. Carvalho & J. Malo. 2004. Factors affectingmacroinvertebrate richness and diversity in Portuguese streams: a two-scale analysis.International Review of Hydrobiology., 89: 151–164.

Johansson, T. and Lennart, N. 2002. Empirical mass balance models calibrated for freshwater fish farm emissions. *Aquaculture*, 212: 191-211.

Jupp, D.L.B. 1988. Background and extensions to depth of penetration (DOP) mapping in shallow coastal waters. *Proceedings of the Symposium on Remote Sensing of the Coastal Zone, Queensland*, SIV2.1-IV2.29.

Karikari, A. 2016. Assessment of impact of cage aquaculture on Lake Volta, Ghana. PhD. Kwame Nkrumah University of Science and Technology. Kumasi, Ghana.

Kassam, L. 2014. Aquaculture and food security, poverty alleviation and nutrition in Ghana: case study prepared for the Aquaculture for Food Security, Poverty Alleviation and Nutrition project. WorldFish, Penang, Malaysia. Project Report: 2014-48.

Marinho, M.M. and Huszar,V.L.M. 2002. Nutrient availability and physical conditions as controlling factors of phytoplankton composition and biomass in a tropical reservoir (Southeastern Brazil). *Archiv fur Hydrobiologie*, 153(3):443-468.

Méndez, N. 2002. Annelid assemblages in soft bottoms subjected to human impact in the Urías estuary (Sinaloa, Mexico). *ActaOceanológica*. 25: 139-147.

Ministry of Food and Agriculture Fisheries Commission. 2012. Ghana National Aquaculture Development Plan (GNADP). 92pp.

Morrisey, D. J., Gibbs, M. M., Pickmere, S. E. and Cole, R. G. 2000.Predicting impacts and recovery of marine farm sites in Stewart Island, New Zealand, from the Findlay-Watling model.Aquaculture. 185: 257-271.

OECD. 1982.Eutrophication of Waters.Monitoring assessment and control.Final Report. OECD Cooperative Programme on Monitoring of Inland Waters (Eutrophication Control), Environment Directorate, OECD, Paris, 154 p

Pawar, V., Matsuda, O. and Fujisaki, N. 2002.Relationship between feed input and sediment quality of the fish cage farms. *FisheriesScience 68*: 894–903.

Pawar, V., Matsuda, O., Yamamoto, T., Hashimoto, T. and Rajendran N. 2001. Spatial and temporal variations of sediment quality in and around fish cage farms: A case study of aquaculture in the Seto Inland Sea, Japan. *Fisheries Science 67*: 619–627.

Ross, L.G., Telfer, T.C., Falconer, L., Soto, D. & Aguilar-Manjarrez, J. (eds). 2013. Site selection and carrying capacities for inland and coastal aquaculture. FAO/Institute of Aquaculture, University of Stirling, Expert Workshop, 6–8 December 2010. Stirling, U.K. No. 21. FAO,Rome. 282pp.

Schenone, N.F., Vackova, L. and Cirelli, A.F. 2011. Fish-farming water quality and environmental concerns in Argentina: a regional approach. *Aquaculture International*, vol. 19: 855-863.

Scott PC 2003 GIS and remote sensing-based models for development of aquaculture and fisheries in the coastal zone: a case study in Baia de Sepetiba, Brazil. PhD thesis, University of Stirling, Stirling.

Soto, D.; Aguilar-Manjarrez, J.; Hishamunda, N. (eds). 2007 Building an ecosystem approach to aquaculture.FAO/Universitat de les IllesBalears Expert Workshop.7–11 May 2007, Palma de Mallorca, Spain.FAO Fisheries and Aquaculture Proceedings.No. 14. Rome, FAO. 2008. 221p.

Stewart, A.R.J. and Grant J. 2002. Desegregations rates of extruded salmon feed pellets: influence of physical and biological variables. *Aquaculture Research 33*: 799-810.

Taiwo, A. and Kumi, F. 2013. An appraisal of road condition effect on rural transportation in Sekyere Central District of the Ashanti Region of Ghana.Hournal of Transportation Technologies, 3(4): 266-271.

Telfer, T. and Robinson, K. 2003.Environmental quality and carrying capacity for aquaculture in Mulroy Bay County Donegal. Environmental Services, Institute of Aquaculture, University of Stirling. 103pp.

U.S. Environmental Protection Agency (EPA). 2002. Mid-Atlantic Integrated Assessment (MAIA) Estuaries 1997-98: Summary Report, EPA/620/R02/003, pp. 115.

United States Environmental Protection Agency (USEPA) 1986. Quality criteria for water.EPA 440/5-86-001. May 1986. Office of water regulations and standards. Washington DC, USA.

US Army Corps of Engineers.1984. Shore protection manual, Vol 1, 2, 3, 4th edn. US Army Engineer Waterways Experiment Station Coastal Engineering Research Center, Vicksburg, MI

US Army Corps of Engineers.2002 Coastal engineering manual. Engineer manual 110-2-1100. US Army Corps of Engineers, Washington, DC

Walmsley, R.D. and Thornton, J.A. 1984. Evaluation of OECD-type phosphorus eutrophication models for predicting the trophic status of Southern African man-made lakes. South African Journal of Science, 80: 257-259.

Xia, F. 2014. Construction of a spatial database for Lake Volta, Ghana, and identification of locations for future developments of the sector. MSc. Institute of Aquaculture, University of Stirling.