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Waterbody scale assessment using spatial models to identify suitable locations for cage aquaculture in large lake systems: A case study in Volta Lake, Ghana

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Abstract

Large lakes throughout the world offer development opportunities for cage aquaculture. However, due to their vast area, identifying the most suitable locations can be a challenge. This is also complicated as lake systems are often multi-use environments, so a strategic approach to managing the resource is required. This study uses geographic information systems (GIS) to develop a broad-scale approach that identifies potential areas that may be suitable for cage aquaculture development. Volta Lake, one the world's largest man-made lakes, is used as a case study. The overall GIS model combines four sub-models, bathymetry, hydrography, water quality and access, and a constraints layer, to identify the most suitable locations for tilapia production. Three different cage sizes are modelled: small, medium and large. The model outputs suggest that approximately 102 km^2 (1.7%), 406 km^2 (6.9%) and 407 km^2 (6.9%) of Volta Lake can be categorized as highly suitable for development of small, medium and large cages respectively. A further 634 km^2 (10.8%), 1264 km^2 (21.4%) and 1055 km^2 (17.9%) can be categorized as suitable for the same. The results can be used by stakeholders and decision makers to identify specific areas where aquaculture development for cage farming of tilapia could be prioritized.

KEYWORDS
cage aquaculture, geographic information system, large lakes, reservoirs, site selection, sustainable development

1 | INTRODUCTION

As the global population continues to grow, one of the main challenges facing individuals, communities and nations is the need for healthy and nutritious food, while managing natural resources and minimizing impact on ecosystems and biodiversity (Godfray et al., 2010). In 2015, the United Nations (UN) Member States adopted the Sustainable Development Goals (SDGs), a series of targets that should be achieved by 2030. Many of the SDGs are related to food production and consumption, including No poverty (SDG1), Zero Hunger (SDG2), Good Health and Well-Being (SDG3) and Responsible Consumption and Production (SDG12) (UN, 2015). Therefore, food production sectors and associated stakeholders play an important role in meeting these targets. To achieve these

SDGs, there is a need to identify opportunities to increase food production sustainably and develop strategic plans to maximize benefits and minimize negative impacts.

Aquaculture is an important food production sector, and if planned and managed appropriately, it can provide safe and nutritious food as well as socio-economic benefits for local and national communities (Soto et al., 2008). Freshwater cage aquaculture in large lake and reservoir systems is recognized as a way of increasing fish production that would contribute to food security and help achieve the SDGs if carefully planned and managed (Cowx & Ogutu-Owhayo, 2019). A key part of this is identifying the most suitable locations for development of aquaculture. Lakes are used for many different purposes (Reynaud & Lanzanova, 2017), and there are often areas that will not be available for development. Constraints, including physical barriers, legislative restrictions or other resource users, will limit opportunities to establish cage aquaculture sites. Furthermore, even if areas are available for development, they may not be suitable. An aquaculture site must fulfil certain biological, environmental and socio-economic criteria if a farm is to be established (Ross et al., 2013). Identification of suitable areas for production is a prerequisite of sustainable development.

For large lakes, the size of the waterbody, which can extend across hundreds or thousands of km^2, presents a challenge for identifying suitable areas for aquaculture development. Conditions can vary considerably throughout a lake system, but it is costly and time-consuming to perform detailed fieldwork and environmental sampling. Planners and aquaculture producers require more cost-effective solutions to identify priority areas where they should target resources and focus their attention. Geographic information systems (GIS) can be used to combine multifactorial data to produce an output that helps decision makers identify potential locations that are likely to be suitable for aquaculture based on defined criteria (Falconer et al., 2020). Stakeholders can then focus on these areas for more detailed analysis through data collection and modelling to establish whether these locations are suitable for aquaculture or not. The use of GIS and spatial modelling for aquaculture planning and management has been used in many studies (Aguilar-Manjarrez & Ross, 1995; Falconer et al., 2013; Longdill et al., 2008; Pérez et al., 2005; Ross et al., 2011; Salam et al., 2003). However, to date, there have been far fewer applications of spatial modelling for freshwater cages compared with other aquaculture production systems (Falconer et al., 2020).

Large lakes throughout the world would benefit from more strategic planning of freshwater cage culture and a GIS-based approach to help identify suitable areas for production can facilitate this. In Africa, cage aquaculture is growing rapidly in natural and man-made lakes (Musinguzi et al., 2019), in many cases prompted by a decline in capture fisheries (Cowx & Ogutu-Owhayo, 2019; Temesgen et al., 2019). Volta Lake in Ghana, West Africa, is one of the world's largest man-made lakes, and although primarily created for hydroelectric power generation, aquaculture has become an important economic activity (Amenyogbe et al., 2018). A key objective of the Ghana National Aquaculture Development Plan is to increase output from aquaculture to make up for the short fall in domestic supply from capture fisheries (Fisheries Commission, 2012). Concerns have been raised about the potential impacts of increased cage tilapia production on the ecology of the lake and its other uses (Ameworwor et al., 2019; Asmah et al., 2014). Furthermore, Rurangwa et al., (2015) reported 1200 cages were recently abandoned by producers. There are a number of factors behind cage abandonment, but the main factor was found to be fish mortality, thought to be a result of low oxygen levels, poor water quality and disease outbreaks (Mantey et al., 2020). Inadequate site selection considerations may have contributed to these problems. The process of siting cages in Volta Lake lacks a formal structure and needs strategic guidance to maximize potential sustainable production. If cage aquaculture is planned appropriately, Volta Lake, and other large lakes worldwide, can play an important role in increasing fish production and contribute to achieving the SDGs.

The aim of this study was to develop a GIS-based approach to identify suitable areas for tilapia cages in Volta Lake that can be prioritized for more detailed assessments to support site selection and sustainable development of aquaculture. Though Volta Lake is the focus of the study, the approach and findings are relevant to other large lake systems in Africa and globally. The work demonstrates the usefulness of broad-scale GIS assessment as a cost-efficient planning tool for aquaculture in great lakes.

2 | MATERIALS AND METHODS

2.1 | Study area

Volta Lake lies between longitudes 1°30′W and 0°20′E and latitudes 6°15′N and 9°10′N (Figure 1). It is one of the largest man-made lakes in the world and at the maximum level has a volume of 149 km^3, a surface area of about 8500 km^2, mean depth of 19 m and a length of 500 km. It is dendritic in shape and forms part of the Volta Basin which has a catchment area of approximately 394,000 km^2 shared by six countries namely Mali, Benin, Togo, Burkina Faso, Ivory Coast and Ghana. The lake has been divided into eight strata to facilitate fisheries stock assessment and management (Béné, 2007; Vanderpuye, 1982) (Figure 1). These strata have been used extensively for biological, limnological and economic studies of the lake. Here, they are used as a basis for hydrographic and water quality monitoring.

The climate type of the basin is tropical continental or savannah, with a single rainy season in the northern section which spans July to September, and two rainy seasons in the southern part of the lake with peaks in June/July and September/October. These are followed by a prolonged dry season. The annual rainfall ranges between 1000 and 1150 mm. Inflows to the lake are largely influenced by discharges from the major tributaries which are all influenced by climatic conditions in northern Ghana.

Besides fishing by the riparian communities, agriculture is the major land use activity in the basin, with a large percentage of the inhabitants being engaged in extensive cultivation of crops and livestock rearing. Cage fish farming sites are presently concentrated in stratum II.

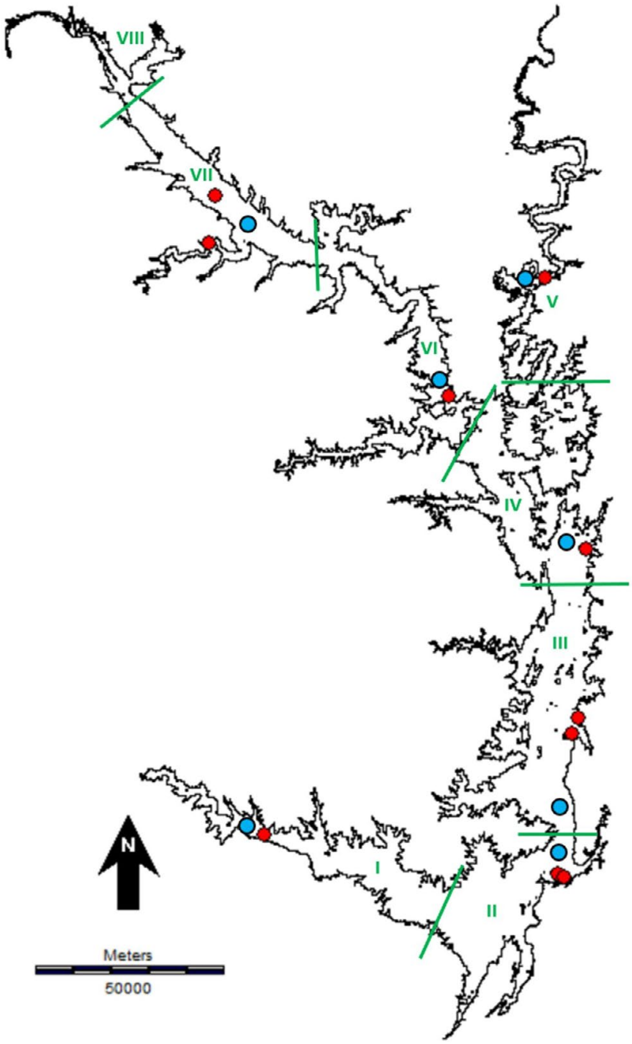

FIGURE 1 Volta Lake, Ghana, showing the water quality (red) and current (blue) sampling locations. The lake strata are shown (green). Stratum I = Afram arm; II = lower main body of the Lake; III = middle main body; IV = upper main body; V = Oti river arm; VI = lower Volta riverine body; VII = middle Volta riverine body; and VIII = Upper Volta riverine body (Vanderpuye, 1982)

2.2 | Model development

The spatial model was developed using the GIS software TERRSET [Clark Labs]. ArcGIS Version 10.1 [ESRI] was used for some data processing. Data layers used within the model were identified following discussions with experts and stakeholders, as well as consultation of literature and other studies. Data were obtained from primary and secondary data sources and satellite imagery. Baseline satellite imagery of the lake was developed from a mosaic of six Landsat 8 Operational Land Imager and thermal infrared sensor obtained from the USGS website for scenes Path 193, Row 054 (24 January 2014); Path 193, Row 055 (8 January 2014); Path 193, Row 056 (23 December 2013); Path 194, Row 054 (18 February 2014); Path 194, Row 055 and Path 194, Row 056 (22 March 2014). All data were reprojected to UTM 31 N as this is the GPS system used in the field surveys and were pansharpened using data band 8 to a spatial resolution of 15 m. The data were used to derive bathymetry and composite images provided clear boundaries of land and water bodies.

The classification of suitable areas for cage aquaculture zones on Volta Lake was based on a constraints layer (areas that are unavailable for aquaculture) and four sub-models: bathymetry, hydrography, water quality and access. In each sub-model, the data layers were reclassified to the same scoring system where 1 is considered highly unsuitable and 5 is highly suitable. Similar studies have used other scoring systems, such as a 1–4 scoring system developed for southwestern Bangladesh (Salam et al., 2003); 1–8 scoring system used in Tenerife, Canary Islands (Pérez et al., 2005) and a 1 to 15 scoring system used in the State of Sinaloa, Mexico (Aguilar-Manjarrez & Ross, 1995). For the present study, a 1–5 scoring system, as used by Ross et al., (2011) for a similar site selection study in Mexico, was selected as it allowed sensitivity but was not too complex to implement (Table 1). Scores were assigned to data in the layers based on values from the literature and/or expert opinion.

Producers operate a range of cages of different sizes and net depths in differing numbers and configurations. Site suitability is based on the cage sizes and configuration rather than on size of the operation. Consequently, three cage sizes representative of systems which are, and could potentially be, used in Volta Lake, were selected for the model: small cages (5 × 5 m, net depth of 4 m plus 2 m for net hang); medium cages (15 × 15 m, depth of 5 m plus 2.5 m for net hang) and large cages (circular cages of

TABLE 1 Rationale for scoring of parameters

Score	Suitability category	Descriptor
0	Excluded area	Conflicting uses or other factors prevent any use for aquaculture
1	Highly unsuitable	Low scores on all factors – mitigate against any aquaculture development
2	Unsuitable	Low scores on most factors – mitigate against aquaculture development
3	Moderately suitable	Low scores on more than one factor
4	Suitable	High scores on most factors
5	Very suitable	Scores very highly on all factors considered

30 m diameter, depth of 6 m plus 3 m for net hang). These dimensions were based on cage sizes presently used by fish farmers on the lake (Karikari, 2016) and allows decision makers to assess the suitability of the lake for three different scales of aquaculture. The small cages were considered suitable for subsistence or local market farming, while the medium and large cages are more suitable for commercial operations seeking to sell to the national and international market. Relevant data layers were reclassified for each of the three cage types.

Figure 2 shows the overall structure of the model. The submodels were based on best available data and constructed following discussions with aquaculture experts. The layers within the submodels are combined using weighted linear Multi-Criteria Evaluation (MCE) (Eastman, 2016). An MCE is a decision support function which

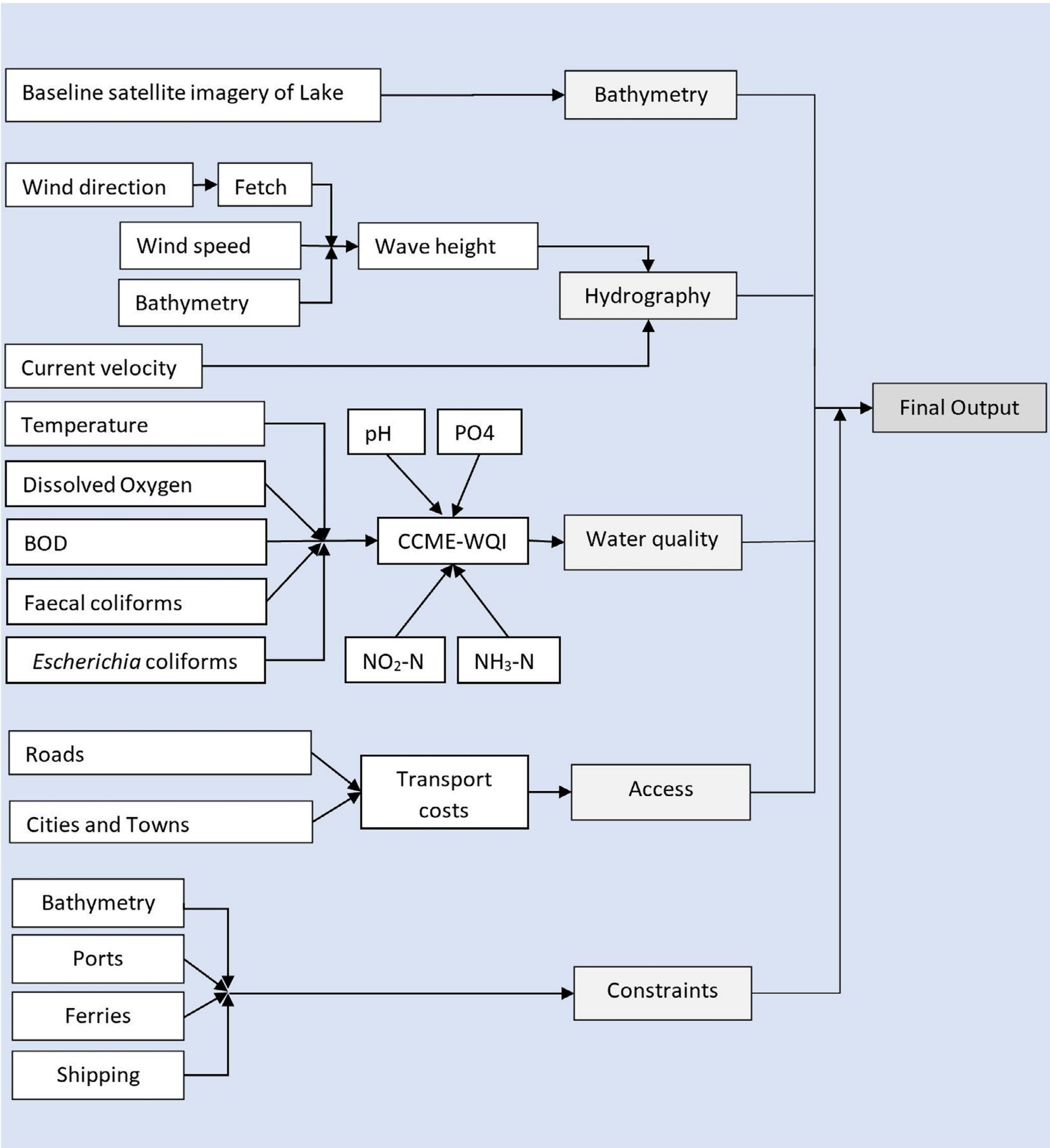

FIGURE 2 Overall model structure for cage aquaculture site selection and zoning of Volta Lake

TABLE 2 Water depth (in metres) reclassification for three different cage sizes

Cage size	Classification 1 Highly unsuitable	2 Unsuitable	3 Moderately suitable	4 Suitable	5 Highly suitable
Small (5 × 5 × 4 m)	0 to <8 >33	8 to <9 28 to <33	9 to <10 23 to <28	10 to <11 >18 to <23	11–18
Medium (15 × 15 × 5 m)	0 to <9 >40	9 to <11 3 5 -<40	11 to <12 3 0 -<35	12 to <14 >25 to <30	14–23
Large (30 m diameter × 6 m depth)	0 to <11 >51	11 to <13 43 to <51	13 to <15 35 to <43	15 to <18 27 to <35	18–27

combines a weighted set of criteria to achieve a single composite outcome focussed on a specific objective. Some sub-models had multiple outputs depending on the three cage types. The final output was produced by adding each of the four sub-models together and then multiplying by the Boolean constraints layer. All values above 18 were classed as 'highly suitable', and all values between 17 and 18 were classed as 'suitable' for development of aquaculture in each of the cage size categories.

2.2.1 | Constraints

Certain areas of the lake surface will be unavailable for cage aquaculture due to conflicts with other major activities and environmental factors. The shallowest bathymetry up to 10 m was reclassified as a constraint. The 3 km mandatory buffer zone from Akosombo dam was also classified as a constraint. Landing stages and riparian market centres were identified from Roche (2014), and a 2 km buffer zone was delineated around such centres to avoid conflict with movements as well as potential negative environmental interactions. Similarly, a 3 km buffer zone was delineated around major ports. A 1 km buffer zone was delineated around existing and planned ferry routes. As the lake is a significant transport corridor, existing and planned major shipping lanes were identified from Roche (2014) for which a 1 km buffer zone was delineated.

2.2.2 | Bathymetry Sub-model

The bathymetry sub-model comprised of a water depth layer. Cages must be situated in locations where there is sufficient depth below the net to allow for water exchange and waste dispersal (Beveridge, 2004). For lakes and reservoirs such as Volta where water level fluctuates, it is important to evaluate potential changes in depth to avoid locating cages in areas that may not be suitable throughout the culture cycle (Ross et al., 2011). As there is no comprehensive depth map for Volta Lake, bathymetric data were generated using an empirical approach based on Landsat 8 images. Light passing through water becomes attenuated, so shallow areas appear bright whereas deep areas appear dark in an image (Gholamalifard et al., 2013; Lyzenga, 1981). As Landsat 8 imagery contains real values reflected from objects in the environment, it is possible to approximate water depth from differential reflectance in the bands. Band 3 (Green, wavelength from 0.525 to 0.600 μm) has the highest penetration in water and was used to calculate water depth, while band 6 (Short Wavelength Infrared) was used to define the water body outline because of its clear reflection from the water surface and minimal atmospheric interference. Approximate water depth was calculated as described by Landmap Geoknowledge (2005) and depends on the empirical tuning noted by Jerlov (1976), Lyzenga (1981) and Jupp (1988). Depth in metres is approximated by:

$$\text{Depth (m)} = 1/-2K\lambda * \ln(R\lambda/A\lambda) \tag{1}$$

where: K_λ = coefficient of attenuation; R_λ = reflectance in Band 3; A_λ = surface reflectance.

Annual fluctuation in water level in Volta Lake can be up to 10 m due to seasonal rainfall and draw-down for electricity generation. The satellite data were collected in March 2014 which are near the start of the rainy season, so the bathymetry at this time would be the shallowest of the year, thus allowing modelling of the worst-case scenario as this would be the limiting factor for siting a cage. A number of assumptions were made in the calculation, so the depths can only be indicative of the range found in the lake. However, the calculated depths correlated well with the results of a bathymetric survey of a small section of the lake in Stratum I and with spot measurements taken throughout the lake strata during fieldwork. The final bathymetric layer (Figure S1) was reclassified based on specifications of small and medium rectangular cages and large circular cages (Table 2).

2.2.3 | Hydrography sub-model

The hydrography sub-model was developed from two key parameters: current velocity and wave height.

Current velocity is an important factor in cage aquaculture as higher current velocity allows good water exchange through fish cages which removes waste from feeding in addition to replenishing oxygen in water (Beveridge, 2004). However, if currents are too strong they can damage cages, reduce net volume and stress fish (Yamazaki et al., 2019). Wave height is also an important consideration for cage aquaculture as high waves can stress or damage cage infrastructure, create unsafe working environments and poor welfare conditions for the fish (Falconer et al., 2013).

Current velocities were measured quarterly between June 2015 and March 2016 inclusive. Ten 40 × 40 cm drogues, 5 set at 1 m and 5 set at 5 m depths, were deployed at locations within each stratum on the Lake to determine the current velocities (Figure 1). The initial time of deployment and the GPS coordinates of the location at initial deployment were recorded using a Garmin GPS76, and this was repeated at 30-min intervals for 10 h. The current velocities at the two depths were calculated from the field data and digitized in ESRI ARC GIS version 10.1 to create choropleth raster files depicting current velocities in each stratum.

Current velocity in the lake varied spatially and seasonally and an aggregate of the annual data is shown in Figure S2. An overall, current velocity layer was developed by combining the surface (1 m) and midwater (5 m) velocities in an MCE with weightings of 0.3 and 0.7 respectively. This layer was reclassified to develop a current velocity suitability layer (Figure S3) using the criteria in Table 3.

Maximum significant wave height was calculated using the approach developed by the US Army Corps of Engineers (1984), which has also been used by Scott (2004) and Falconer et al., (2013) in aquaculture site selection studies This approach uses data on wind direction and speed, fetch and water depth and is suitable for water depths less than 90 m, such as in Volta Lake. Wind data were collected from 4 weather stations around the lake: Akuse (Near lower dam); Ho (East of the Lake); Kete Krachi (North of the lake) and Koforidua (South west of Volta Lake). The monthly wind speeds (from 1986 to 2013) of the 8 principal wind directions (North, Northeast, East, Southeast, South, and Southwest, West, Northwest respectively) were converted into an incident angle (e.g. 45 represents northeast, 360 represents true north, etc.) following the approach used by Falconer et al., (2013). The TerrSet dispersal module was used to simulate wind constantly blowing across the water surface to create a maximum potential fetch layer for each direction, so considering the worst-case scenario. The resulting 8 wave height layers were then combined using a maximum overlay function within TerrSet so that each pixel in the final wave height layer (Figure S4) had the maximum value of the corresponding positions in the input layers (Eastman, 2016).

Different cage sizes and construction materials have different tolerances to waves which must be considered when selecting sites and cages for aquaculture. Most studies on wave exposure have focussed on cages in exposed areas where the wave height is often over 2 m and the system design criteria and tolerances are well defined (Huang et al., 2008; Ma et al., 2009; Pérez et al., 2003). However, as the maximum wave heights predicted in Volta Lake were <1 m (Figure S4), and cage tolerances less defined, wave height classifications were based on expert opinion and experience of cage suitability at different wave heights (Table 4).

The final reclassified current speed and wave height layers were combined in an MCE to create the Hydrography sub-model. Both layers were considered to be of equal importance so were given equal weights.

2.2.4 | Water Quality Sub-model

Good water quality is essential for production, health and welfare of farmed fish and parameters must be within the tolerance ranges for the selected species (Beveridge, 2004), in this case, tilapia. The parameters measured are important environmental parameters for tilapia production and provide a good quality indicator for aquaculture suitability in a given area. Water quality data were obtained from field sampling of the lake between March 2015 and February 2016. Monthly samples were collected using a Van Dorn water sampler from each of the eight strata (Figure 1) between March and November 2015. Three monitoring sites were randomly selected in each stratum. Water samples were collected from 1 m below the surface into pre-cleaned 1 L Nalgene sample bottles. Water samples for microbial quality assessment were collected in 500 ml pre-cleaned sterilized glass bottles. All the samples were preserved on ice and transported to the Environmental Chemistry and Microbiology laboratories of the Water Research Institute in Accra for analyses.

TABLE 3 Current velocity reclassification (in cm/s) for all sizes cages

Classification				
1 Highly unsuitable	2 Unsuitable	3 Moderately suitable	4 Suitable	5 Highly suitable
<1	1 to <2	2 to <3	3 to <5	5+

TABLE 4 Wave height reclassification (in metres) for three different sizes cages

	Classification				
Cage size	1 Highly unsuitable	2 Unsuitable	3 Moderately suitable	4 Suitable	5 Highly suitable
Small (5x5x4 m)	1.0 to >0.7	0.7 to >0.5	0.5 to >0.35	0.35 to >0.2	0.2–0.0
Medium (15x15x5 m)	1.0 to >0.8	0.8 to >0.6	0.6 to >0.4	0.4 to >0.2	0.2–0.0
Large (30 m diameter x 6 m depth)	1.0 to >0.9	0.9 to >0.8	0.8 to >0.6	0.6 to >0.3	0.3–0

The water quality parameters measured were temperature, pH, dissolved oxygen, turbidity, conductivity, total phosphate, nitrate-nitrogen and ammonium-nitrogen, biochemical oxygen demand, faecal coliform and *Escherichia* coliform. Temperature, pH, dissolved oxygen, turbidity and conductivity were measured in-situ with a YSI EXO 2 Sonde. Total phosphorus was determined using the persulphate digestion method. Nitrate-nitrogen and ammonium-nitrogen were determined using the hydrazine reduction and direct Nesslerization methods respectively. All the analyses were according to procedures described in Standard Methods for the Analyses of water and waste water (APHA-AWWA-WEF, 2005).

Suitability classification of the lake water quality for tilapia aquaculture was determined using a modified version of the Canadian Council of Ministers of Environment (CCME) Water Quality Index (CCME-WQI) (Equation 2), which is a tool for simplifying the reporting of water quality data (CCME, 2001). The CCME-WQI objectively compares measured water quality values to guidelines for a given activity (in this case criteria for production of tilapia; see Table 5) to produce a score ranging from 0, representing worst quality, to 100, representing the best quality for the given activity.

TABLE 5 Optimum range of key water quality parameters for tilapia culture used in calculating the CCME Water quality classification index (compiled from various sources: see supplementary material)

Variables	Optimum ranges for tilapia culture
Temperature (°C)	>22 and <38
pH	>6.5 to <9.0
DO (mg/L)	5.0–9.5
Total hardness (mg/L)	>20 and <350
Nitrate (mg/L)	<10.0/L
Ammonium-nitrogen (mg/L)	<5.0
Unionized ammonia (mg/L)	<0.01
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
Faecal coliform (counts/100 ml)	0–249

The CCME-WQI is generated by Equation 2:

$$100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \quad (2)$$

where F_1 (Scope) represents the percentage of variables that do not meet their objectives at least once during the time period under consideration, relative to the total number of variables measured; F_2 (Frequency) represents the percentage of individual tests that do not meet objectives; F_3 (Amplitude) represents the amount by which failed test values do not meet their objectives. Computation of F_1, F_2 and F_3 are available in detail in (CCME, 2001). The index scores were reclassified based on the protocol in Table 6. The criteria or test values are those defined as within optimal ranges for tilapia culture (Beveridge & McAndrew, 2000).

Some variations in concentrations of selected water quality parameters were observed during monitoring. Consequently, a CCME-WQI was calculated to reflect conditions in the four seasons in northern Ghana; the dry season (January – March) pre-rainy season (April to June), rainy season (July – September) and post-rainy season (October – December). The four seasonal water quality suitability models (Figure S5) were combined using an MCE with equal weighting to generate an overall combined water quality suitability sub-model.

2.2.5 | Access Sub-model

Physical access to sites is a key factor in the success of a cage site. Two major factors were considered: population size and transportation costs taking into account distance over roads of differing quality.

Transportation cost from or to a fish farm influences fish price and is affected by good road access and the road type. Access to farm sites for supply of goods and services from cities and small towns is also very important (Ross et al., 2011), as this will bring in labour, feed, equipment, spares and fuel to the site and will also allow access to the fish markets. Similarly, the distance to small towns and

TABLE 6 CCME-WQI Index of categorization and Water quality suitability classification

Rank	Score	Interpretation	Classification
Excellent	95–100	Water quality is intact. Conditions are very close to natural or desired levels	5
Good	80–94.9	Water quality is intact, and only minor threat is observed. Conditions rarely differ from the natural or desired levels	4
Fair	65.0–79.9	Water quality is intact, but occasionally deteriorated. Conditions sometimes deviate from the natural or desired levels	3
Marginal	45.0–64.9	Water quality is frequently endangered or deteriorated. Conditions often deviate from the natural or desirable levels	2
Poor	0–44.9	Water quality is almost always deteriorated; conditions usually deviate from natural or desirable levels	1

TABLE 7 Seasonal variation in CCME-WQI water quality index Volta Lake

Stratum	Water quality index (%) Dry season (Jan–March)	Pre-rainy season (April–June)	Rainy season (July–Sept)	Post-rainy season (Oct–Dec)
I	77.4	82.8	82.8	62.2
II	77.4	94.1	90.3	67.4
III	75.7	86.5	84.6	66.5
IV	79.2	84.6	81.0	65.0
V	77.4	77.9	57.8	40.9
VI	84.6	90.25	65.6	48.0
VII & VIII	66.6	68.89	61.7	51.0

cities is important as generally, the closer farms are to such areas, the higher the demand for products and lower travel costs in terms of time and money.

Population data were obtained from the Ghana Statistical Service population and housing census for 2010 (GSS, 2012) and were used to develop a layer representing population levels in 170 districts. The size of population per unit area can be used to approximate the size of markets (Sato et al., 2012). The Ghanaian road map, which identifies 23 road types, was reclassified based on road condition to three categories based on the likely relative cost of transportation: 1 = 'expensive', 2 = 'medium', 3 = 'inexpensive'; footpaths and bridleways were ignored.

The access sub-model was developed using the TerrSet COST process, based on transportation cost along roads and over water starting from the 170 districts, and also the populations in each district. According to Taiwo and Kumi (2013), the average transportation cost for a 'good quality' road is Gh¢ 0.90 per tonne-kilometre to the market centres, Gh¢ 1.25 per tonne-kilometre for 'medium quality' roads and Gh¢ 1.43per tonne-kilometre for 'poor quality' roads. Gulbrandsen (2012) noted that the motorized canoe is the traditional fishing boat in Ghana. They are normally 14 m long, can carry 3 tonnes of produce and have a maximum speed of 14.8 km/h, consuming 8 litres of diesel per hour or 0.54 L/km. Thus, at 5.413 Gh¢/L (Global Fuel Prices, 2020), the cost of transportation over water for Volta Lake is presently 2.923 Gh¢ per kilometre.

Road and lake cost layers were combined to form a single cost layer from which the cost of product transportation from any lake location to any district centre was calculated. Each district cost map was divided by the head of population in the district to produce the cost of transportation from each district per person. This layer was then reclassified using the values in Table 7 to produce two access sub-models: small cages and medium/large cages. Farmers operating small cages were assumed to have limited access to capital to invest for transportation and other equipment, so proximity to potential local markets would be more important. Medium and large cage operators are more likely to deal with larger national or export markets, so proximity to roads or railways would be much more advantageous.

3 | RESULTS

3.1 | Constraints

The constraints layer indicates areas that would not be available for aquaculture development (Figure 3). All parts of the lake have areas where constraints prevent development of cage aquaculture. The major constraints are the transport routes located throughout the entirety of Volta Lake. The North West of the lake has a large area, in strata VII and VIII, that would be unavailable for aquaculture due to concentration of transportation routes.

3.2 | Bathymetry sub-model

Highly suitable and suitable areas of Volta Lake available for cage aquaculture based on water depth are mostly located in the southern and central parts of the lake (Figure 4). Highly suitable areas for the small cages are in the margins of the lake, although much of the area is classed as suitable with major exceptions being the deeper parts of the southern section. Almost all of the lake has either highly suitable or suitable depths for medium cages with low scores in the shallow northwest and in the deepest parts of the southern basin. Much of the southern basin and central section of the lake has highly suitable depths for larger cages.

3.3 | Hydrography sub-model

The results of the hydrography sub-model suggest there are a greater number of suitable locations for small and large cages than medium size cages (Figure 5). Suitable locations for small cages are found in the north, west and mid-sections of the lake. While for the large cages, suitable locations are found in the mid-sections and south of the lake. This is a reflection of the water exchange in these areas as the higher volume of fish in the larger cages require consistently faster water flows, which are found in wider areas in the mid and south areas due to wind effects on the water surface, and being nearer the outflow of the lake in the south.

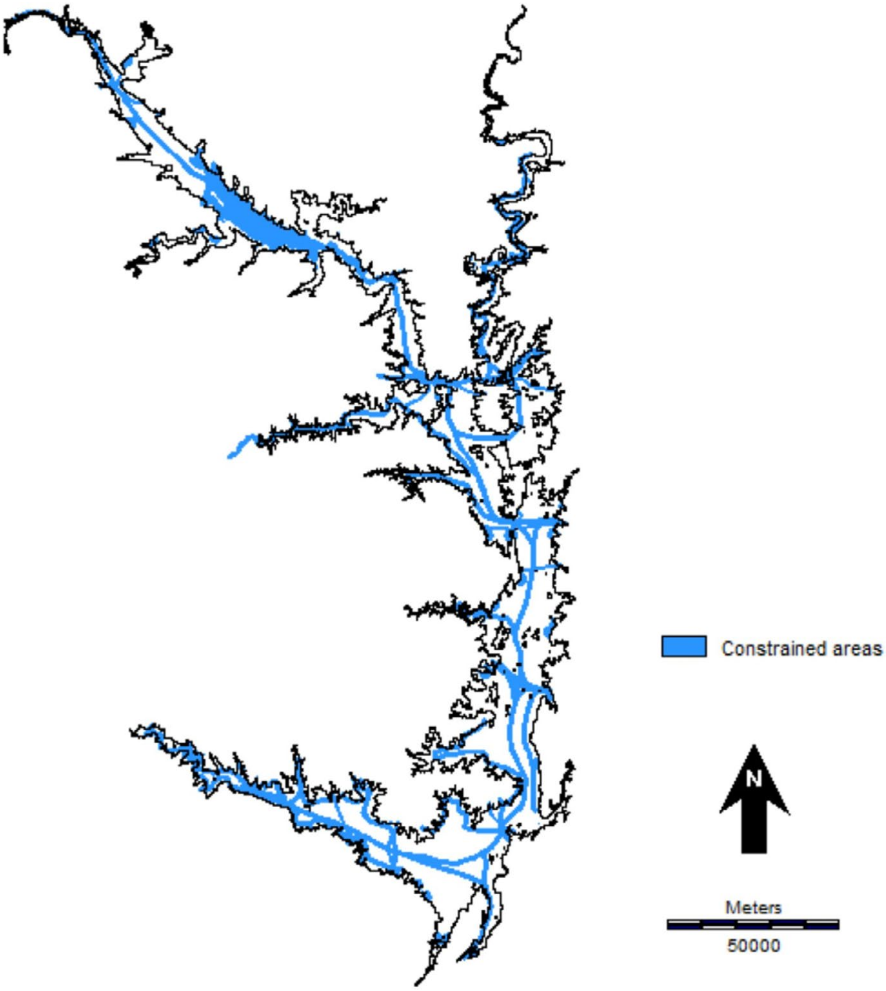

FIGURE 3 Constraint layer for Volta Lake

3.4 | Water quality sub-model

Based on the CCME-WQI, water quality in the different strata, as for the hydrography, varied seasonally and spatially (Table 8). The reclassified suitability of the lake water quality ranged from suitable to moderately suitable for cage aquaculture in the southern parts and unsuitable in the northern section (Figure 6). The most southerly and central sections of the lake had the overall highest water quality, whereas the Afram arm (stratum I) and the northerly sections were least suitable. Overall, 54.2% of the lake area was classed as moderately suitable, the remainder being unsuitable (low for cage aquaculture) (Figure 6).

3.5 | Access sub-model

The sub-model outcome (Figure 7) indicates that for transport costs, the highly suitable and suitable areas for small cages are located around the edge of Volta Lake where small scale fish farmers would have easy access to facilities and to markets. Over 90% of the lake area is highly suitable or suitable for larger scale commercial scenarios with only small areas in the centre and northwest of the lake being unsuitable. In comparing these two scenarios, there are greater opportunities for medium and large cages as highly commercial aquaculture will deploy better cage technology, management systems, transport facilities and have better ability to serve more distant markets. Although the products from small cage farms are less easily moved over large distances, they are nevertheless important as they are traded locally and consumed by local families around villages.

3.6 | Final model outputs

The most suitable areas for cage aquaculture vary depending upon cage size and technology level (Figure 8). When constraints are applied, much of the northern Black Volta (strata VII and VIII) and Oti (stratum V) arms of the lake are unsuitable, whereas substantial suitable areas for cage aquaculture are located in the main body of the lake. A greater proportion of the lake is classed as suitable or highly suitable for medium and large cages in comparison to small cages (Table 9). The most suitable areas for small cages are near the lake shores, medium sized cages can occupy more of the lake area while large cages can take advantage of much of the lake surface scoring highly especially in the south. This is illustrated well in the southern parts of the lake (see expanded images) where there is a considerable area that is highly suitable for large cages, a more limited area for medium and small cages.

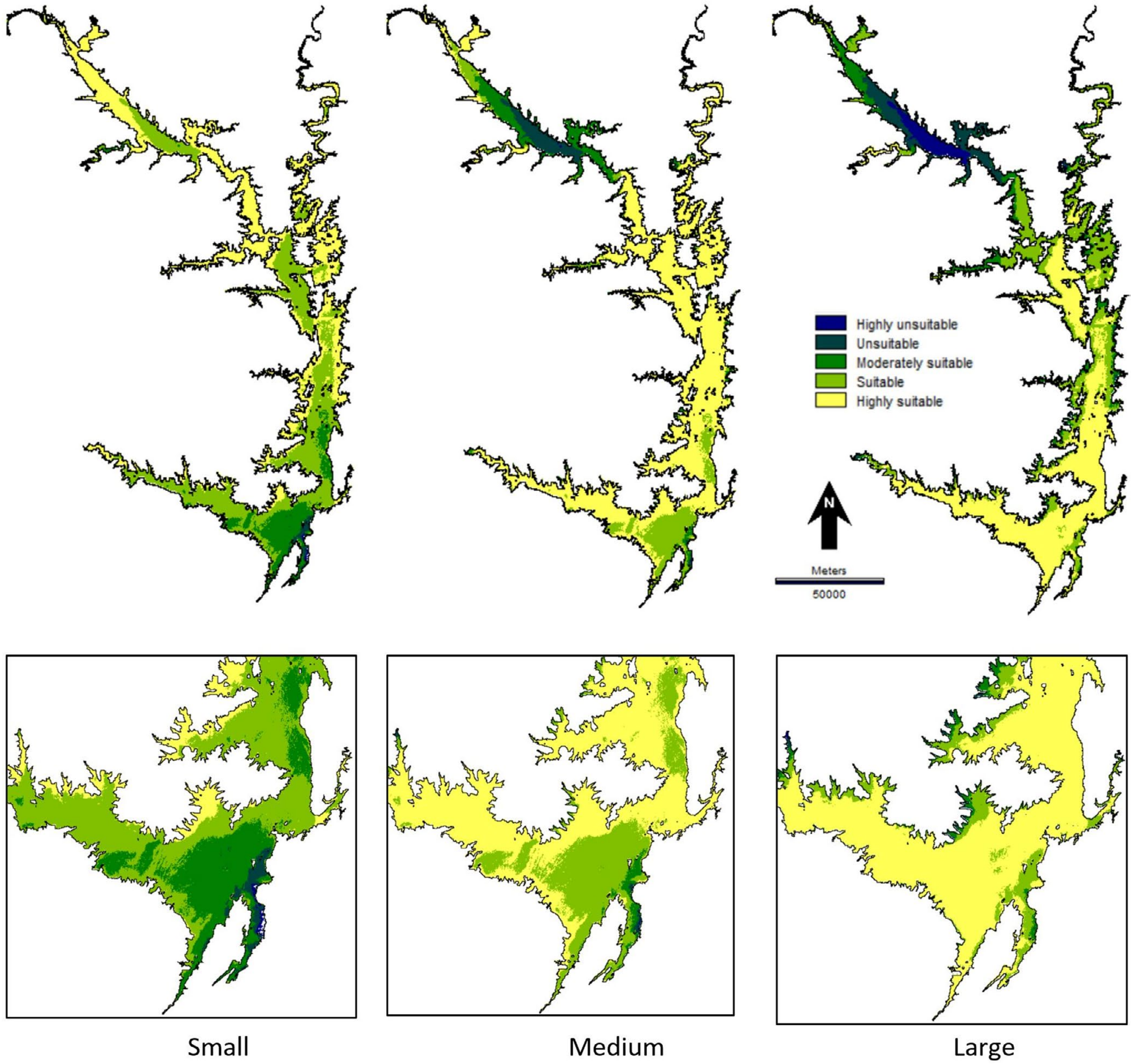

FIGURE 4 Bathymetry suitability sub-model for small, medium and large cages in Volta Lake (above) and in enlarged southern parts of the lake (below)

4 | DISCUSSION

The study used GIS to outline potential suitable locations for cage aquaculture in Volta Lake. The modelling approach used data from a range of sources to assess whether areas throughout the lake met the specified requirements for cage culture of tilapia. This is a similar method to other aquaculture studies that have used GIS for site suitability assessment and site selection studies (Aguilar-Manjarrez & Ross, 1995; Falconer et al., 2013; Longdill et al., 2008; Pérez et al., 2005; Ross et al., 2011; Salam et al., 2003). Similar to Ross et al., (2011) and Falconer et al., (2013), several different cage sizes were modelled to support decision makers in identifying the most suitable areas for a range of cage systems. Differences in suitable areas were apparent in the sub-models and in the final model output, highlighting the importance of modelling multiple cage dimensions when evaluating suitability of large lakes for aquaculture. The depth layer gives a good approximation of depth based on remote sensing data; however, there are substantial areas of the lake with submerged trees which are an impediment to cage installation. As no specific data were available, these areas were not included as constraints but would need to be taken into account when installing cages.

Availability and quality of data is a major constraint for any spatial assessment (Falconer et al., 2020). Although Volta Lake has been studied previously for different purposes, it is still a data scarce location and there is a lack of high-resolution lake-wide data sets that capture the spatio-temporal heterogeneity of parameters of importance

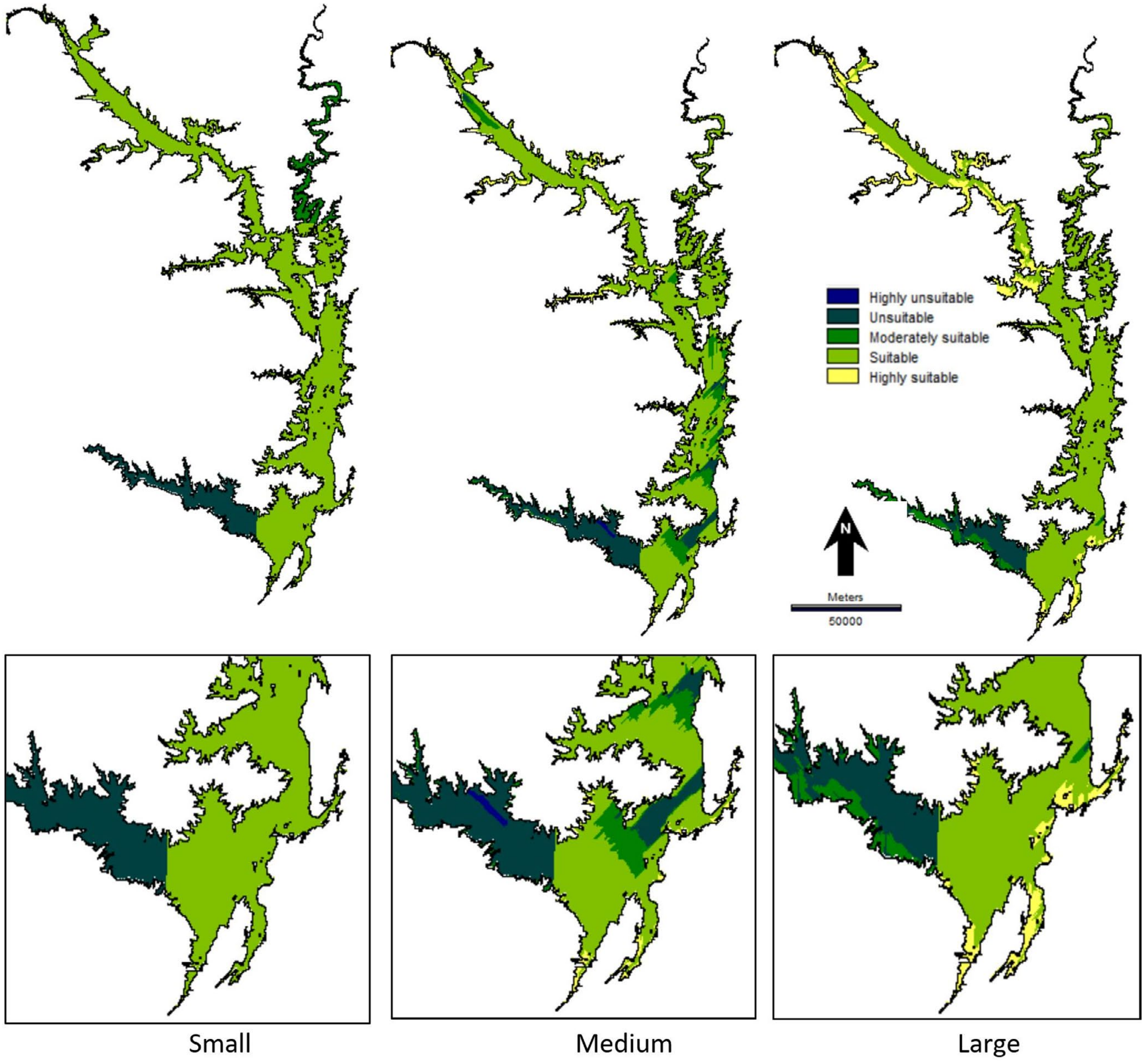

FIGURE 5 Hydrography suitability sub-model for small, medium and large cages Volta Lake (above) and in enlarged southern parts of the lake (below)

to aquaculture. This study has used data from a number of different sources, but there are still limitations. For hydrography and water quality measurements, sample stations were used to characterize the stratum of lake and it is recognized that variations in the area will not be captured. Selection of station location was based on previous experience and knowledge of conditions in the lake. Additional sample sites and more frequent sampling would improve the underlying data and, in turn, would improve the spatial models, but the results nevertheless provide a general overview of the lake conditions. This then allows future effort to be targeted on the highest scoring areas as these areas are most likely to be suitable for aquaculture.

The model outputs identify the most suitable locations based on the input criteria and are used to identify areas for more detailed analysis and fieldwork. The number of cages or biomass of fish that can or should be established within the lake depends on other factors including regulations and carrying capacity (Ross et al., 2013). For large, complex, lake systems such as Volta that have many branches and varying hydrological conditions, local scale assessment is particularly important. With more location specific data, models such as Dillon and Rigler (1975) and OECD (1982) can be used to calculate production and ecological carrying capacity and determine the level of fish production that could take place at individual sites. Furthermore, land use in the surrounding catchment and nutrient loading into the lake will also influence local carrying capacity and production potential (Milne et al., 2015; Paterson et al., 2006). Further research is required to develop improved modelling

TABLE 8 The access and market classification and weight for small and medium & large cages

Factor	Classification 1 Highly unsuitable	2 Unsuitable	3 Moderately suitable	4 Suitable	5 Highly suitable	Weight
Small cages						
Road (km)	50–12	12–9	9–6	6–3	3–0	0.186
Small town (km)	50–40	40–30	30–15	15–5	5–0	0.300
Urbanization (km)	50–40	40–30	30–15	15–5	5–0	0.070
Population (>100 people/km^2)	30–20	20–15	15–10	10–5	5–0	0.484
Medium and Large cages						
Road (km)	50–12	12–9	9–6	6–3	3–0	0.324
Small town (km)	50–40	40–30	30–20	20–10	10–0	0.072
Urbanization (km)	100–90	90–85	85–80	80–50	50–0	0.152
Population (>500 people/km^2)	90–75	75–60	60–40	40–20	20–0	0.452

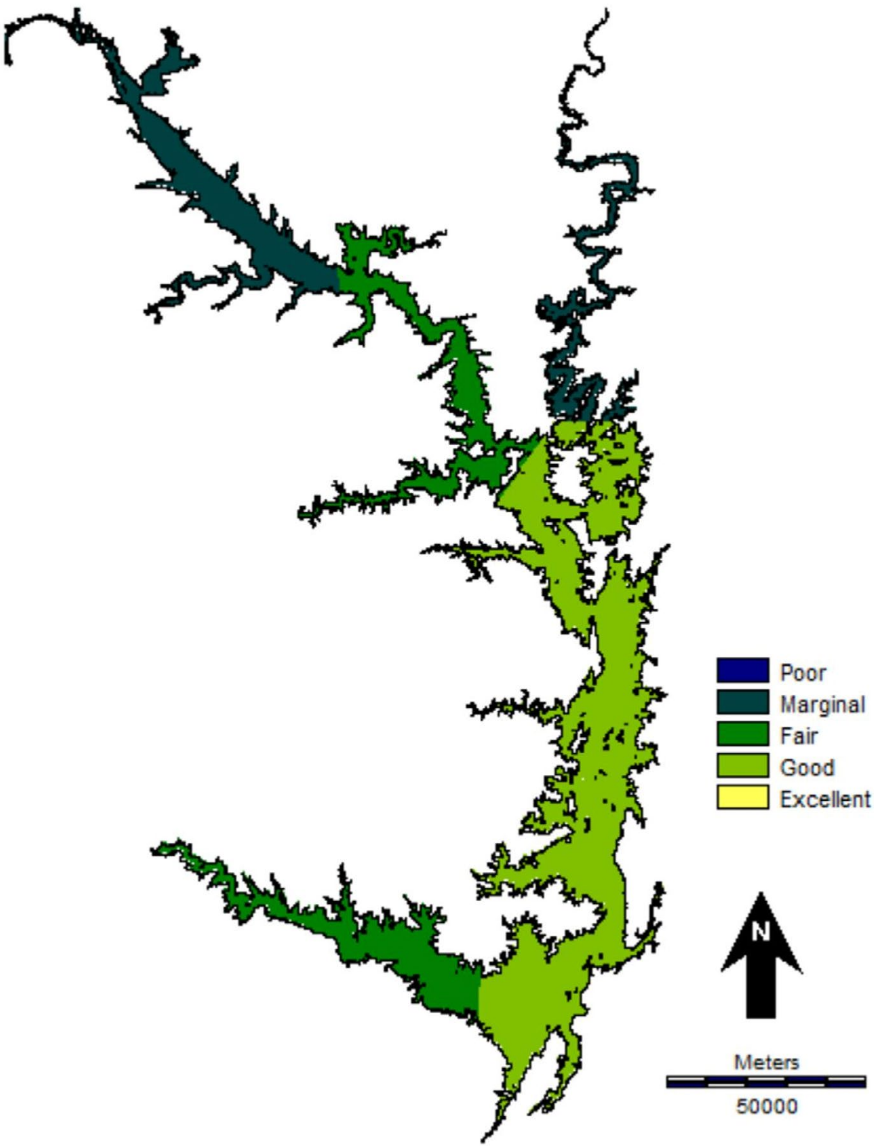

FIGURE 6 Water quality suitability sub-model for Volta Lake

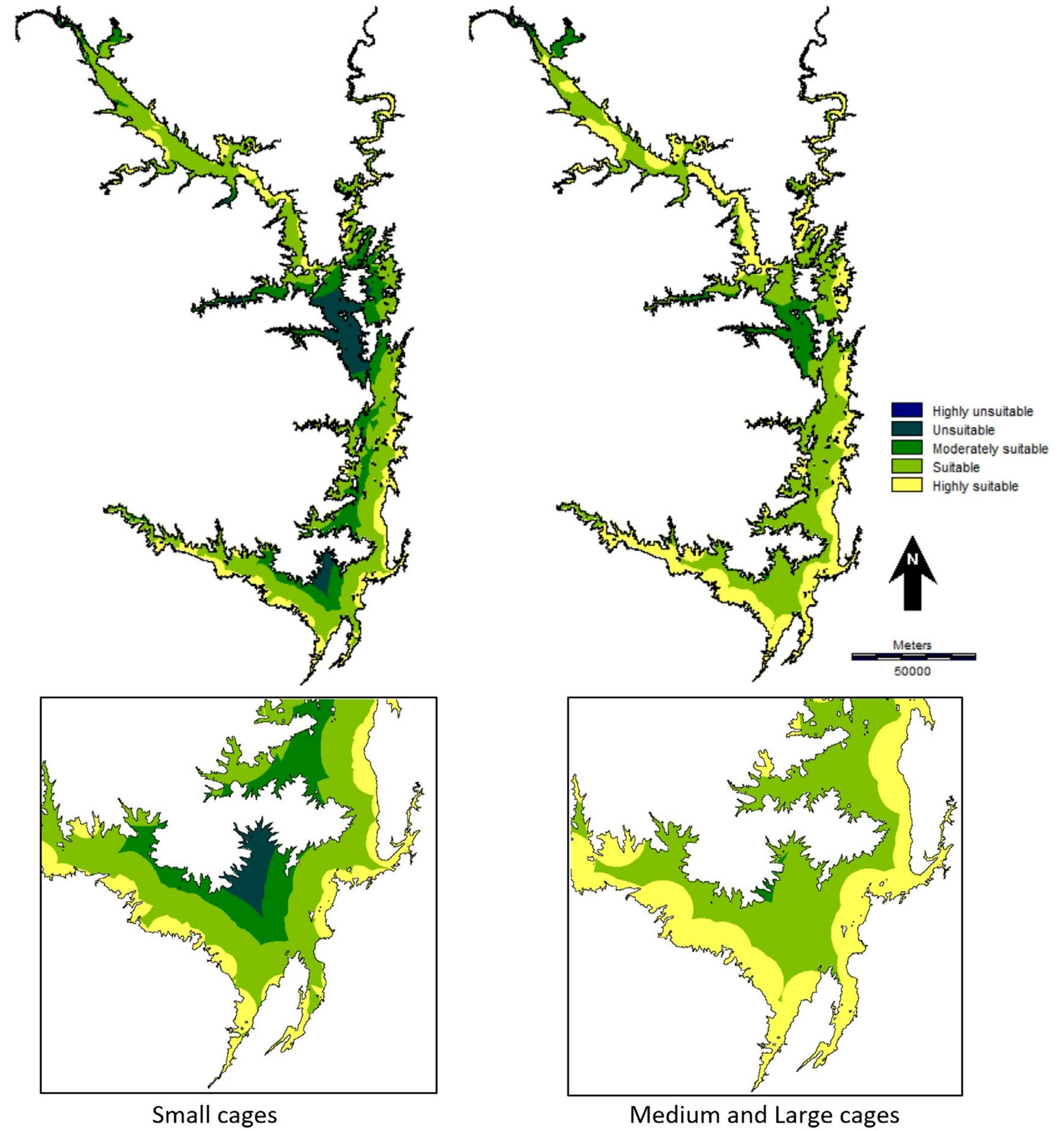

FIGURE 7 Access sub-model for two different farm size scenarios in Volta Lake (above) and in the southern parts of the lake (below)

approaches to assess carrying capacity of the suitable areas in large lake systems and the aquaculture and environmental interactions.

The outputs of the suitability model presented here can be used to help planners and regulators identify areas within Volta Lake that should be investigated with the aim of establishing an aquaculture zone. Aquaculture zones are areas that are assigned for aquaculture development, where aquaculture is prioritized over other activities (Aguilar-Manjarrez et al., 2017). Many aquaculture zoning studies focus on marine systems, where zoning can play an important role in the marine spatial planning process (Sanchez-Jerez et al., 2016), but similar approaches can also be utilized for large lakes. Regulatory authorities, government bodies or coordinating organizations can develop and implement zones, but these should also be supported by relevant policies and legislation to ensure aquaculture is planned and managed appropriately. Not all areas designated as suitable will necessarily be incorporated into aquaculture

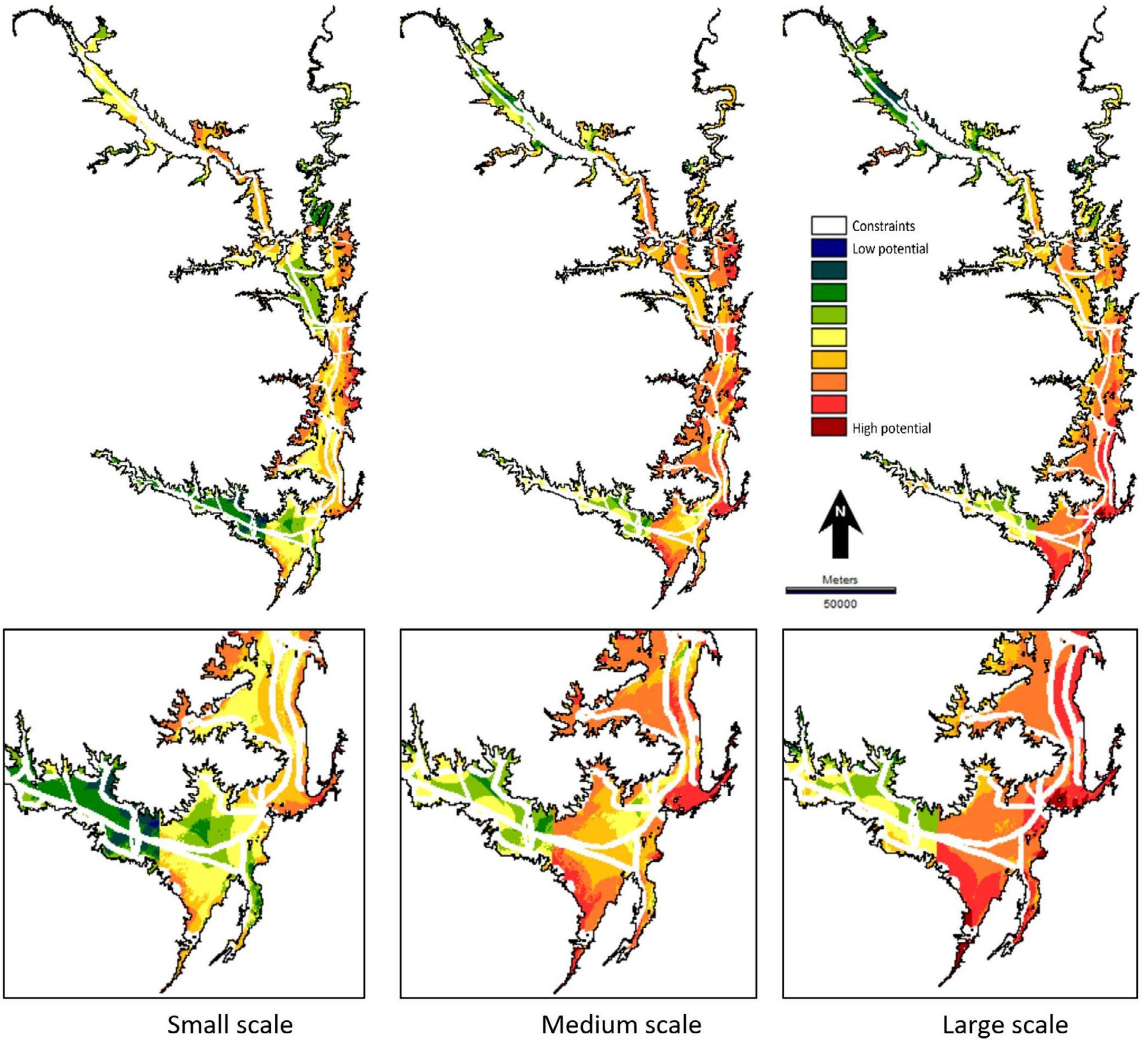

FIGURE 8 Overall model outcomes for cage aquaculture in Volta Lake (above) showing enlarged southern parts of the lake (below)

TABLE 9 Suitability metrics for cage fish farming in Volta Lake

	Small		Medium		Large	
Category	Area (km^2)	% of lake area	Area (km^2)	% of lake area	Area (km^2)	% of lake area
Highly suitable	102	1.7	406	6.9	407	6.9
Suitable	634	10.8	1264	21.4	1055	17.9
Total	736	12.5	1670	28.3	1461	24.8

zones. This is especially important if aquaculture is to contribute to meeting the SDGs as shared resources such as freshwater lake systems are often under pressure from many different user groups and a coordinated approach to optimize use of lake resources for all activities is necessary. The outcome of this study has significant potential to contribute to implementation of the newly instituted Ghana Government 'Aquaculture for food and jobs' policy (MOFAD, 2019), by facilitating site selection, zonation and commencement of aquaculture business in the lake region. The model outcomes can also be used to inform policy development, which would act as a guide to levels of investment required to address different aquaculture strategies.

5 | CONCLUSIONS

The great lakes of the world, and the growing number of very large reservoirs such as Volta Lake, provide a range of ecosystem services including hydropower, transportation routes, water for domestic and agricultural purposes as well as fish from principally artisanal fisheries. They are also prime sites for production of fish in floating cages, which can contribute to national economies and to international food security. Any expansion of the cage aquaculture industry must be contained within the lakes' capacity to assimilate wastes without compromising the supply of ecosystem services or the access and benefit rights of riparian communities. A first step in sustainable development of aquaculture is to identify potential suitable locations. Broad-scale, lake-wide, assessment using GIS modelling is a cost-effective approach that allows resources to be targeted in the most appropriate locations to support sustainable management of cage aquaculture in Lake Volta, Ghana, and elsewhere. The approach developed for three cage sizes can provide objective support for decision-making, minimizing conflict with other water users. In addition, based on transportation cost and population distribution, we have shown the spatial distribution of the important effect of market access to suitability for aquaculture development. This combination of sub-models can be used together with more local scale models of environmental carrying capacity and environmental quality to determine prospective sustainable yield from aquaculture in the large water bodies of the world, and as a starting point for development of aquaculture management zones.

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CONFLICT OF INTEREST

The authors affirm that there are no sources of conflict of interest pertaining to this work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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