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A GIS-based approach to delineating the areas of a lake that are suitable for cage fish culture

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Abstract

We present a GIS-based approach to the delineation of areas that have different levels of suitability for use as tilapia cage culture sites the Kenyan part of Lake Victoria, Africa. The study area was 4,100 km^2. The method uses high-resolution bathymetric data, newly collected water quality data from all major fishing grounds and cage culture sites, and existing spatial information from previous studies. The parameters considered are water depth, water temperature, levels of dissolved oxygen, chlorophyll-*a* concentrations, distances to the lake shoreline and proximity to other constraints on cage culture development. The results indicated that the area most suitable for fish cages comprised about 362 km^2, or approximately 9% of the total area; the remaining 91% (i.e. 3,737 km^2) was found to be unsuitable for tilapia cage culture. We conclude that the successful implementation of this approach would need stakeholder involvement in the validation and

approval of potential sites, and in the incorporation of lake zoning into spatial planning policy and the regulations that support sustainable use while minimising resource use conflicts. The results of this study have broader applicability to the whole of Lake Victoria, other African Great Lakes, and any lakes in the world where tilapia cage culture already occurs or may occur in the future.

Keywords: Lacustrine; cage culture; wild fisheries; spatial planning; management; sustainability.

1 INTRODUCTION

Lake Victoria lies within the borders of Kenya, Uganda, and Tanzania, with each country controlling 6%, 45% and 49% of its surface, respectively. The whole lake covers an area of 59,947 km^2 and has an average depth of 40 m, a maximum depth of 80 m, and a shoreline of 7,142 km (Hamilton, 2018). It hosts one of the largest freshwater fisheries in the world, providing a significant source of protein in East Africa and exporting fish to the European Union, United States, China and Japan (Sitoki et al., 2010; FAO, 2016).

The area around Lake Victoria is also characterised by a rapidly growing population (United Nations Population Division, 1995; CIESIN, 2017). This increased from 4.6 million people in 1932 to 42.4 million people in 2010, and is expected to rise to about 76.5 million people by 2030 (Bremner et al., 2013). This rapid growth in population has been associated with higher levels of poverty, with lake shore residents becoming the poorest and most food insecure of any communities within the Lake Victoria Basin (LVB) (Abila, 2003). This problem has been exacerbated by recurrent droughts, crop failures, and environmental degradation, all of which have reduced levels of food production (Abila, 2003).

Although the LVB is rich in natural resources such as minerals, forests, wetlands and wildlife, the fishery is the primary source of income and food security for tens of millions of people that live around its shoreline (Ochumba & Kibaara, 1989; Lung'ayia et al., 2001; Verschuren et al., 2002; Hecky et al., 2010; Sitoki et al., 2010; Kundu et al., 2017; Sitoki et al., 2012). In 2014, the value of this fishery was estimated to be about USD 650 million per year (Weston, 2015). However, its productivity is now being affected by a decline in the natural fish stocks of the lake, probably as a result of overfishing and illegal or unregulated fishing activities (Njiru et al., 2018b). So, while the demand for fish protein has increased due to population growth (Aura et al., 2019), there are now too many fishers chasing too few fish for capture fisheries, alone, to support the local economy (Njiru et al., 2018a).

The African Union Policy Framework and Reform Strategy for Fisheries and Aquaculture calls for lakes and reservoirs to be used to their full potential to generate wealth, deliver social benefits and contribute to food security through market-led sustainable development strategies (FAO, 2016). With wild stocks dwindling, commercial interests are now focusing on the possible development of a lacustrine aquaculture industry to help to supplement capture production in lakes such as Lake Victoria, Lake Tanganyika, Lake Kariba, and Lake Kivu (Beveridge & Phillips, 1993; Berg et al., 1996; Aura et al., 2018a). Initial results suggest that this could be a viable economic venture (Aura et al., 2018a) and aid agencies within Kenya are now supporting cage culture activities that are targeted explicitly at Lake Victoria (MSINGI, 2018).

Cage aquaculture has the potential to increase fish yield in Lake Victoria without damaging wild stocks (Lwama, 1991; Kashindye et al., 2015); it can also overcome some of the conventional constraints associated with more traditional systems, such as pond culture (Aura et al., 2018a). While it is standard practice in the marine waters of developed countries and the emerging economies of South East Asia (Garcia de Souza et al., 2013), it is a relatively nascent industry on Lake Victoria and across the wider African Great Lakes (AGLs). Using cage aquaculture to meet future demands for fish protein from a rapidly growing population will require the rapid expansion of this industry. To do this effectively, sustainable management and utilisation of lake resources will be essential.

Within the Kenyan part of Lake Victoria, there are currently about 60 cage culture firms operating 4357 (mostly floating) fish cages (Hamilton et al., 2020) most of which are rearing Nile tilapia (Aura et al., 2018a). Many of these cages are located within 200 m of the shoreline, which provides fish farmers with ease of access and potential for close supervision, and shelters these installations from potentially damaging winds and currents (Njiru et al., 2018b). However, if cages are sited in shallow areas that act as nursery and breeding grounds for wild fish, they can pose a threat to natural fish populations. While some of these regions are demarcated as breeding zones and are, thus, protected from fishing (Njiru et al., 2018b), they are not protected from cage farm developments. Cage fish farming can also result in conflicts with other uses of the water resource, such as fishing, recreation, transport, water abstractions, cultural practices and hydro-power generation (Aura et al., 2018a).

The rapid expansion of cage culture by the private sector in the Kenyan part of Lake Victoria currently lacks a robust and enforceable regulatory framework. Although the East African Community have published guidelines on the development, operation and licensing of cage aquaculture, these have yet to be incorporated into the management of cage fish farming in Kenyan waters. The guidelines provide useful step-by-step processes for establishing cage farms, including obtaining an establishment and operating license, selecting the site, and adhering to basic fish farm management practices and requirements (LVFO, 2018). However, they do not provide a robust procedure for minimising any conflicts in resource use.

Any regulatory framework for the sustainable development of cage culture systems needs to be able to protect the environment, support (or at least not harm) the wild fishery and maximise fish yields. This requires a detailed assessment of any proposed site in terms of its potential suitability for development (EL-Sayed, 2006; Aura et al., 2016). Indeed, an ability to make a robust, evidence based, decision on site suitability is likely to be key to the successful and sustainable development of cage culture systems across Kenya (Venturoti et al., 2016; Aura et al., 2018a).

Several studies have developed site suitability mapping for a range of aquatic farming activities using methods such as multi-criteria evaluation (e.g., Malczewski, 1999; Buitrago et al., 2005; Radiarta et al., 2008; Aura et al., 2016, 2017) and habitat suitability indices (e.g., Cho et al., 2012). However, most of these have focused on marine systems, with very few having been developed in relation to artisanal fisheries and inland aquaculture systems – especially in developing nations such as Africa (Aguilar-Manjarrez & Nath, 1998). So, there is little existing information on which to base a method for zoning freshwater lakes to support multiple uses that can be understood easily by local fishers. This study aimed to fill that gap in knowledge by developing standardised criteria for mapping the Kenyan part of Lake Victoria in terms its potential suitability for cage fish culture. Suitability was based on water quality, the protection of fish breeding zones and the avoidance of constraints on development, such as water hyacinth hotspots.

The current rise in cage culture investments and the haphazard installation of cages, could spell doom for the lake ecosystem unless development is controlled more effectively. This study takes a first step towards providing the evidence base that is needed to support sustainable development in the Kenyan part of Lake Victoria by addressing the following research questions:

i. Where is development constrained by physical factors that affect cage culture development?
ii. What is the level of suitability of the remaining areas for cage installations?
iii. How large is the area that could be designated for other lake based activities to reduce potential conflicts with other uses of the resource?

1.1 Study Area

The Kenyan part of Lake Victoria, which this study is focused on, comprises an area of 4,100 km^2 that has an average depth of between 6 m and 8 m, and a maximum depth of 70 m (Odada et al., 2004). In this part of the lake, cage culture has been identified as a new socioeconomic frontier that has good prospects for generating income while helping to conserve declining wild fish stocks. Using satellite and drone technologies, this part of the lake was found to contain 4,357 fish cages, covering 62,132 m^2, in 2019 (Hamilton et al., 2020). The local preference is for cages with dimensions of 2 m x 2 m x 2 m, a stoking rate of 2000 fingerlings per cage and a one cage per farmer concept. This cage size is preferred due to ease of assembling, feeding, monitoring and managing the systems. Larger cages are expensive to make, and difficult to secure and launch on the site.

In 2015, the capture fishery landed 118,145 tons of fish with an estimated value of about USD 94.4 million (Aura et al., 2020). In recent years, the rapidly increasing cage culture industry in this area has already been producing about 2,522 tons of fish per cycle with an estimated value of USD 8.83 million (Aura et al., 2018a). This suggests that cage culture is now an emerging and viable economic investment that could support the development of a “Blue Economy” in Kenya.

While an increase in adoption of cage culture would provide local communities with prospects of better income and greater food security, the sustainable use of this new technology within the lake remains uncertain.

2 MATERIALS AND METHODS

Figure 1 shows a schematic representation of the process used for delineating areas that are potentially suitable for cage fish culture within the Kenyan part of Lake Victoria. In outline, the process involved combining information on the physical constraints on cage development with the water quality preferences of caged tilapia to produce a cage farm suitability map. Existing cage fish farms were then assessed to determine the number that were located within each zone.

In general, the field calculator function in QGIS was used to estimate the area (in km^2) of each region of interest. Microsoft Excel 2016 was for data entry and cleaning, and SPSS version 21 (SPSS Inc., Chicago, IL, USA) and R version 3.5.0 (R Core team, 2014) were used for statistical analyses. The field data collected were compared using the Kruskal-Wallis one-way ANOVA to examine the spatial variations between the data from the control stations and the data collected around the fish cages. The significance level was set at an alpha of 0.05.

2.1 Maps of physical constraints on cage farm locations

The potential development of cage fish farms is affected by a number of physical constraints on their location and development. These include fish breeding grounds, water hyacinth and floating island hotspots, water depth and areas that are too close to the shore. Areas with water hyacinth and moving islands, for example, are unsuitable because they have been found to destroy cage culture installations (Aura et al., 2018a). Although water hyacinth keeps moving around, depending on the direction and strength of winds and water currents, there are specific ‘hotspot’ areas where it persists for long periods of time, minimising the space available for cage culture installations during its period of occurrence (Opande et al., 2004; Ongore et al., 2018). Furthermore, areas that are infested with heavy mats of the weed tend to have poor water quality, which prevents the development of cages in these areas (Villamagna and Murphy, 2009). In addition, the decomposition of the large amounts of organic matter that are produced by these mats of water hyacinth leads to an increase in biological oxygen demand and a decrease in dissolved oxygen (DO) levels (Balirwa et al., 2009; Taabu-Munyaho et al., 2016) which threaten the survival of the fish.

Digital maps of areas that are designated as fish breeding grounds were available from the study conducted by Aura et al. (2018b), and those designated as water hyacinth and moving island hotspots were available from that of Ongore et al. (2018). Maps of distance to shoreline were also created for the current study. Distance from the cage culture location to the shoreline is important because it affects access to the cage culture sites for the supply of goods and services (e.g. feed, equipment, fuel) and to the route to market for any fish produced (Ross et al., 2011). In addition, cages need to be placed where they can be monitored in terms of their welfare and security.

Water depth also affects the potential location of fish cages because it determines the extent to which wind velocity and fetch help to increase water circulation, this providing better DO exchange and more efficient removal of wastes (Bascom, 1964; Beveridge, 2004; Perez et al., 2005). To provide maps of site specific depth information, a 100 m resolution bathymetric model was created from more than 4 million data points that had been collected from recent hydrographic surveys. Points that did not have Global Positioning System (GPS) locations were digitised manually by fitting admiralty maps to the lake shoreline using their graticule (Beveridge, 2004). Point data were converted to raster data using the process of simple kriging (Anyah and Semazzi, 2009), using a WGS 84 EPSG 4326 projection. All of the constraint data for cage culture development were converted from polygon to raster format, where necessary, and transformed into thematic images for analysis.

2.2 Maps of water quality data

Information on selected water quality parameters were collected from the sampling sites shown in Figure 2 at quarterly intervals in the dry (July – October) and wet (March – June) seasons between October 2016 to October 2018. The sites were chosen to provide comprehensive coverage of all known fishing grounds (n = 29) and nearby cage culture sites, including near- and off-shore areas in the vicinity. The sampling sites were classified according to their position the lake as littoral near-shore [Lit], near cages [Nea], off-shore [Off], and fishing grounds [Fsg]. The choice of sampling sites was informed by indigenous knowledge provided by resource users and information from experienced cage farmers to ensure that they spanned the main factors that affect cage farm locations and wild fisheries. All sampling sites were geo-referenced using a Garmin GPS.

At each sampling site, depth profiled (one measurement at the surface and another below 1.0 m) *in situ* measurements were taken in concurrence with the maximum depth of existing cages (i.e. < 2.0 m from the surface). Data on water temperature and DO concentration were recorded using a Yellow Springs Instruments (Model: YSI 650). Water transparency was measured using a standard Secchi disk, maximum depth was determined using a sonar depth finder with a floating transducer, and chlorophyll-*a* concentrations were determined using *ex-situ* methods of analysis adapted from Wetzel and Likens (1991) and APHA (2005).

The water quality data collected generated values for discrete locations across the study area. These were interpolated to provide water quality map layers for temperature, DO, Secchi depth transparency and chlorophyll*a* concentrations.

2.3 Assessment of suitability

The level of suitability of different areas of the lake for cage fish culture were assessed on the basis of the key biophysical conditions and constraints shown in Table 1. These were chosen in terms of their likely effect on the growth and survival of caged tilapia (Dias et al., 2012; Aura et al., 2016) and criteria provided by the stakeholder community (e.g. ease of access). Using the ranges in values shown in Table 2, each part of the Kenyan part of Lake Victoria was assigned to one of the following classes in terms of their suitability for the location of cage fish farms: 'Most suitable', 'Suitable', 'Less suitable' and 'Unsuitable'.

2.4 Suitability mapping

The development of the delineation process followed the methods described by Perez et al. (2005) and Aura et al. (2016, 2017), with modifications to account for local conditions. Separate thematic maps of constraints on development, distance from the shoreline, water depth, and various aspects of water quality were created within a geographic information system (GIS). These were then combined to generate suitability criteria. This involved using a simple Multi-Criteria Evaluation (MCE) approach to aggregate the thematic maps into a map that showed the spatial distribution of different levels of suitability for the siting of fish cages. First, a binary value, $C_{(x,y)} = 0$ (constrained) or $C_{(x,y)} = 1$ (potentially suitable), was assigned to each location based on whether or not the location was constrained. Then a suitability function ($S_{(x, y)}$) was calculated for each remaining location (x,y) across the area of study. Finally, level of suitability scores were calculated for the potentially suitable areas as the weighted geometric mean of all factors (Longdill et al., 2008), modified by their factor suitability range (*FSR*) (Vincenzi et al., 2006), as shown in Equation 1.

$$S_{(x, y)} = \prod_{i=1}^{n} FSR_{(x,y,i)} \qquad \text{(Equation 1)}$$

where:

- *x,y is the spatial location of each point*
- *$FSR_{(x, y)}$ is the factor suitability value at location x,y*
- *i = is an index corresponding to each input parameter*

This process converted the original data into standardised cage culture suitability scores (Vincenzi et al., 2006) on a four point scale of most suitable (score 4), suitable (score 3), less suitable (score 2), unsuitable (score 1) and constrained (score 0). The GIS software Quantum GIS Desktop Version 2.18.11 (QGIS Development Team, 2009) and ESRI^{TM} ArcMap were used to generate thematic maps of suitability zones from these data (Batabyal & Chakraborty, 2015).

3 RESULTS

3.1 Overview of biophysical parameters recorded at sampling sites

The biophysical data collected from the field sampling sites were used to create the water quality maps. The ranges in values for each parameter recorded are described below; there were no significant seasonal ($p > 0.05$) or water column variations within the data collected. Sampling sites that were close to the fish cages showed significant variations ($p < 0.05$) in chlorophyll-*a* concentrations compared to those from the littoral, off-shore and fishing ground sites (Table 3). The highest chlorophyll-*a* concentration occurred in Anyanga (12.56 ± 17 μg L^{-1}), while the lowest was in the littoral zone at Ogal (2.29 ± 0.00 μg L^{-1}). The highest water temperature (27.19 ± 1.22 ^{o}C) was recorded off-shore at Ogal, while the fishing grounds in Mulukoba and Anyanga had the lowest temperatures, both 25.90 ± 0.01 °C. There was no significant variation ($p > 0.05$; $F = 2.78$) among temperatures near the cage sites. Ogal and Anyanga recorded a gradual increase in temperature from the littoral region towards the off-shore zones, whereas the opposite was observed in both Nyadiwa and Naya. The highest levels of DO occurred in all of the fishing grounds that were sampled. All DO levels were greater than 4.0 mg L^{-1} except in the Nyandiwa littoral zone which recorded 3.64 ± 0.56 mg L^{-1}. There were no significant variations ($p > 0.05$) in DO levels between littoral sites, cage sites, and off-shores zones. The DO levels at the cage sampling sites were significantly lower ($p < 0.05$; 5.64) than at the fishing ground sites, but were not significantly different ($p > 0.05$) from the littoral sites. The highest Secchi depths occurred in Ramba near the cages (3.20 ± 0.17 m) and in the off-shore zones (3.00 ± 0 m). The lowest water transparency among the sampling sites was recorded at Ogal. There was no clear longitudinal trend in Secchi depths and no significant variations across the sampling sites ($p > 0.05$; $F =0.38$; $\alpha_1 = 0.05$; $\alpha_2 = 0.025$). Generally, the water depth at the sampling sites was highest at Ramba, particularly at the fishing ground site (41.80 ± 0 m). The lowest depths were at Naya and Ogal (< 8.0 m). There was no clear trend in maximum depth with significant variations ($p < 0.05$; $F = 38.57$) among the sampled sites.

3.2 Potential suitability of areas for cage culture

Figure 4 shows the areas of the Kenyan part of Lake Victoria that are potentially suitable, or totally unsuitable, for fish cage culture. The less suitable sites occurred near the constraints on development, which included water hyacinth and moving island hotspots, fish breeding grounds, and along the entire nearshore area around Kisumu Bay (Figure 4). Sites that were classified as 'most suitable' and 'suitable' for cage culture were found to be located in the inner lake at water depths of between 4.0 m and 10.0 m, and along the lake shore areas north of Bukoma, Uyawi, Utajo, Sindo, and Rasira beaches.

The 'most suitable' areas for cage fish culture consisted of 191 km^2 or 4.7% of the study area, with 'suitable' areas covering a further 171.1 km^2 (4.2%). Thus, the total area of the lakescape that is potentially suitable for cage culture was found to be about 362.4 km^2, or 8.8%, of the study area. The area deemed to be 'unsuitable' for cage culture covered 3,737.50 km^2, or 91.16%, of the study area. This comprised of 2,753 km^2 of less suitable areas and 984.5 km^2 of completely unsuitable areas. Fairly inaccessible areas for cage fish farming due to the constraints on use imposed by water hyacinth, demarcated fish breeding grounds and moving islands covered about 459 km^2.

3.3 Sensitivity of individual levels of suitability to biophysical factors

The level of dominance of the biophysical determinants in terms of their impact on the outcome of the suitability mapping is shown in Table 4. Depth was the best indicator of the most suitable area (61.0% of the potential area), followed by temperature (52.0%), DO (51.6%), chlorophyll-*a* concentration (48.7%), distance to land (15.2%) and distance to constraint (14.5%). About 54% of existing fish cages were found to be located within the constrained (unsuitable) areas, with the majority being around Anyanga, Sika, Uwayi, Asat, Dunga, Chuowe, Homalime, Nyandiwa, Rasira, Sori, and Tangache beaches (Figure 3).

4 DISCUSSION

This study developed a lakescape approach for assessing areas that may be suitable for the development of cage fish culture in the Kenyan part of Lake Victoria. The total area that is potentially suitable for cage culture was found to be about 362 km^2 (9%). It is suggested that this information could be used to designate the part of the lake that could be used safely for cage culture if combined with the use of best management practices, such as compliance with recommended carrying capacities to minimise disease and fish kills. Without proper regulation, cage fish farming presents environmental and food safety challenges arising from feeds, chemicals, veterinary medicines, waste products, fish escapes, and diseases that are all potential contaminants of the natural environment.

More than 54% of existing cage culture establishments are sited within ‘less suitable’ or ‘constrained’ areas (i.e. fish breeding grounds; water hyacinth and moving island hotspots). This probably explains the incidental water hyacinth or moving islands invasion of some of these installations, such as those reported from Dunga beach in Kisumu Bay (Ombwa, V., pers. comm.). Most of this part of the lakescape (about 3,737 km^2; 91%) could be prioritised for wild fisheries and other lake use activities. These include water hyacinth control and alternative use, protection of fish breeding grounds and the development of tourism potential associated with moving islands.

The biophysical parameters that influenced the suitability classification of the sites can also affect the ecological status of the lake, including species composition and abundance of the aquatic organisms. However, the pattern of change in physical and chemical parameters across the Kenyan part of Lake Victoria is highly variable and, therefore, unpredictable across the delineated sites. This may be due to the shallow mean depth and landscape context of the Kenyan part of the lake. The lake is strongly influenced by extremely variable mixing characteristics that are driven by seasonal/diurnal changes in wind patterdraticns and shear (Okely et al., 2010), runoff from agricultural land, inputs of industrial effluent and the nature of its inflows, in addition to natural processes.

Lack of significant variations in water temperature suggests an even effect on lake biogeochemical processes. In contrast, the relatively high chlorophyll *a* in Anyanga near the areas with cages compared to other sites, such as fishing grounds, indicated a marked increase in chlorophyll *a* concentrations at the cage culture sites. This can be attributed to the cumulative effect of eutrophication processes associated with cultured fish and food wastes (Garcia de Souza et al., 2013). Low DO levels at the cage culture sampling sites were probably attributable to increased DO consumption by the cultured fish and the decomposition of their organic waste (Longgen et al., 2009). The aforementioned could have been the reason for higher DO levels in fishing grounds than in the cage culture sampling sites and could be considered as one of the main constraints on cage culture in the longer term. The high water transparency levels at Ramba are associated with the relatively high mean depths at this site and its location around the Rusinga Channel (outside Nyanza Gulf), which is open to the effects of wind induced mixing. This suggests that, here, any potential influence of the cage culture on turbidity is negated by the effects of higher levels of circulation and dilution.

Based on the delineation approach, the order of importance of the biophysical parameters affecting cage culture potential were as follows: depth > temperature > DO > chlorophyll-*a* > distance to land > distance to constraint (Table 4). This indicates that depth could be ranked as the most important variable to consider variable in the determination of cage culture site suitability compared to other factors such as distance from land. The nature of the bay (i.e. sheltered or open), and proximity to land based activities are also likely to influence levels of water quality and mixing at the sampling sites (Aura et al., 2018b). Significant effects of bathymetry are mediated, principally, through water depth, wind velocity and fetch, all of which help to increase water circulation for better DO exchange and create high water currents for the better removal of wastes (Bascom, 1964; Beveridge, 2004; Perez et al., 2005). The existence of cages in the less suitable or unsuitable areas of water depths (< 4.0 m) could be the reason for the fish kills that have been reported at cage sites such as Anyanga and Nyenye Got in Siaya county (Njiru et al., 2018b).

This initial, desk based approach to the delineation of areas that are suitable for cage culture has been shown to have the potential to support the suitable development of these systems whilst minimising conflict with other uses of this water resource. However, future development requires the incorporation of new data, for example transportation routes, water abstraction points and carrying capacity, and validation of the outputs through stakeholder engagement activities.

5 CONCLUSIONS AND RECOMMENDATIONS

The current study proposes a potential method for the delineation of areas that are suitable for cage fish culture. This is based on biophysical factors and spatial interpolations. The order of suitability, based on biophysical parameter preferences, from most suitable to the less suitable was depth > temperature > DO > chlorophyll *a* > distance to land > distance to constraint. Depth is the most important factor, because locating cages in shallow waters is likely to exacerbate problems associated with eutrophication, and with increased DO consumption by the cultured fish and the decomposition of their organic waste. Low DO levels at cage culture sites is important because it is likely to be a precursor to fish kills, which have an enormous impact on the local economy. As a result of our study, we recommend the fast-tracking of regulations to control the location of new cage culture establishments, the relocation of existing cages to 'suitable' and 'most suitable' areas, and the implementation of best management practices to minimise resource use conflicts. The proposed approach could be incorporated into future lacustrine spatial planning policies and regulations once navigation routes and abstractions points have been mapped and included. Future studies could consider inclusion of hydrography, wave height and carrying capacity data for further refinement of the approach.

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Figure legends

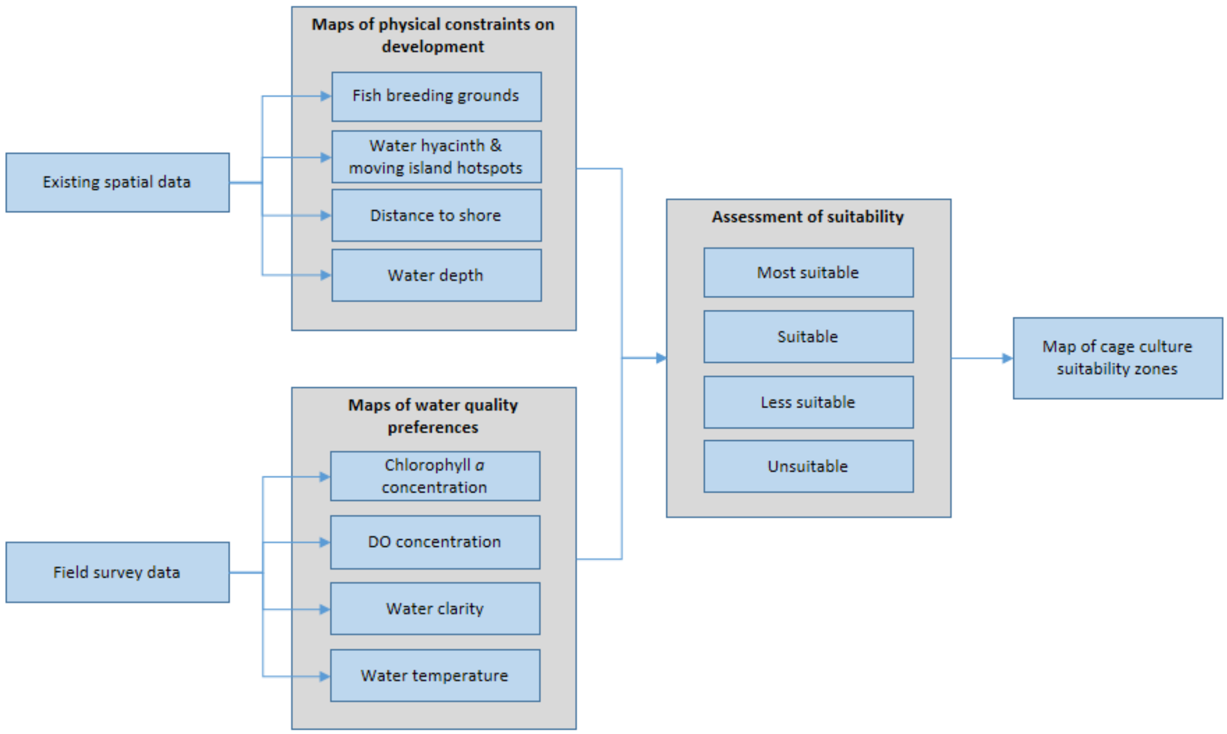
FIGURE 1 Schematic representation of the process for determining suitable areas for potential cage fish culture within Lake Victoria, Kenya.

FIGURE 2 Lake Victoria, Kenya, showing current cage culture sites and fishing grounds that were sampled for water quality. The sites were categorised as Lit = Littoral zone; Nea = Near cages; Off = Off-shore, Fsg = Fishing grounds. Samples were collected quarterly between October 2016 and October 2018.

FIGURE 3 Maps showing (a) fish breeding sites (potential areas for protection), and (b) water hyacinth hotspots of Lake Victoria, Kenya (Adapted and modified from Ongore et al., 2018 and Aura et al., 2018b)

FIGURE 4 Map of Lake Victoria, Kenya, showing potential suitability for cage fish culture.

Figures



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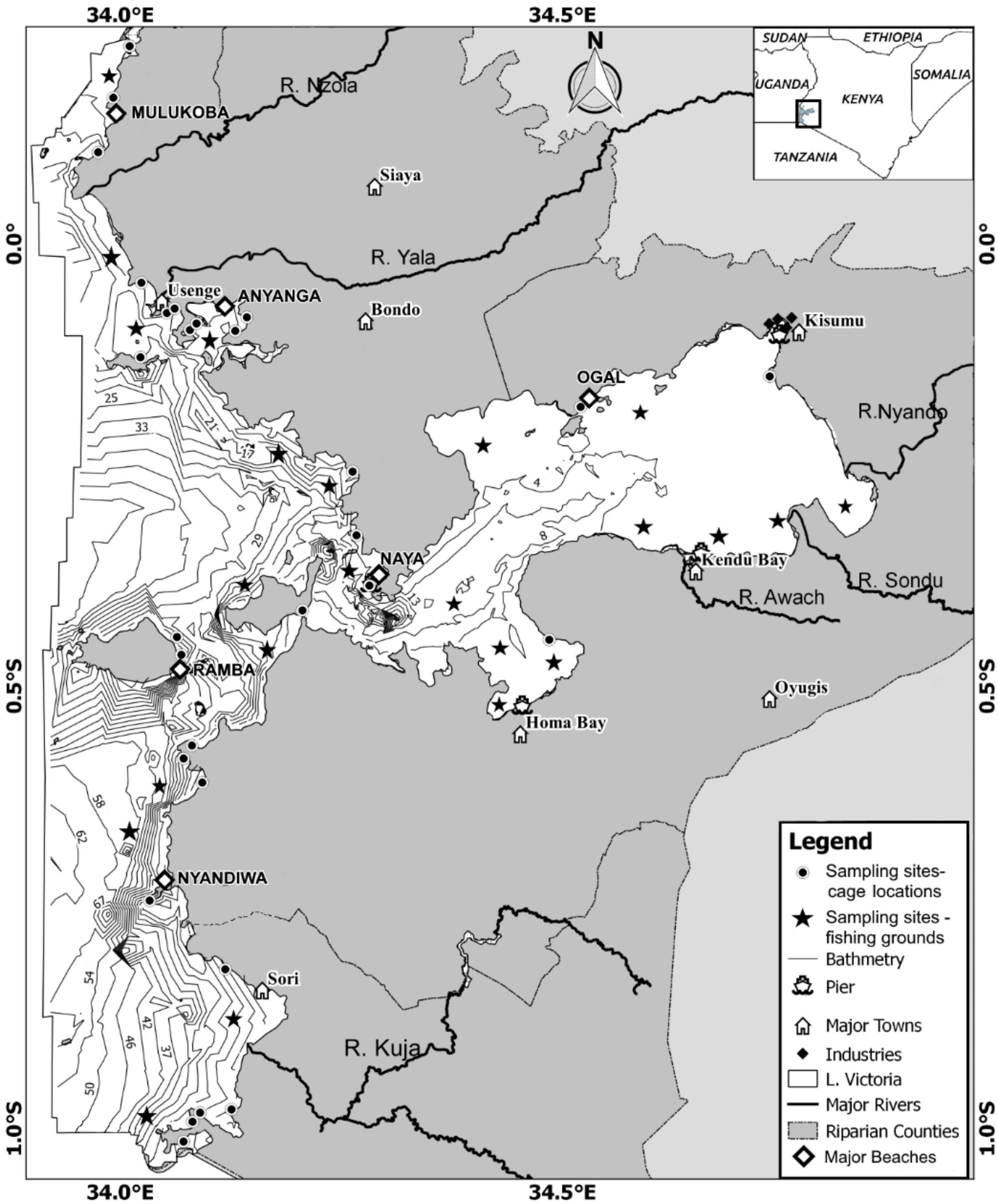

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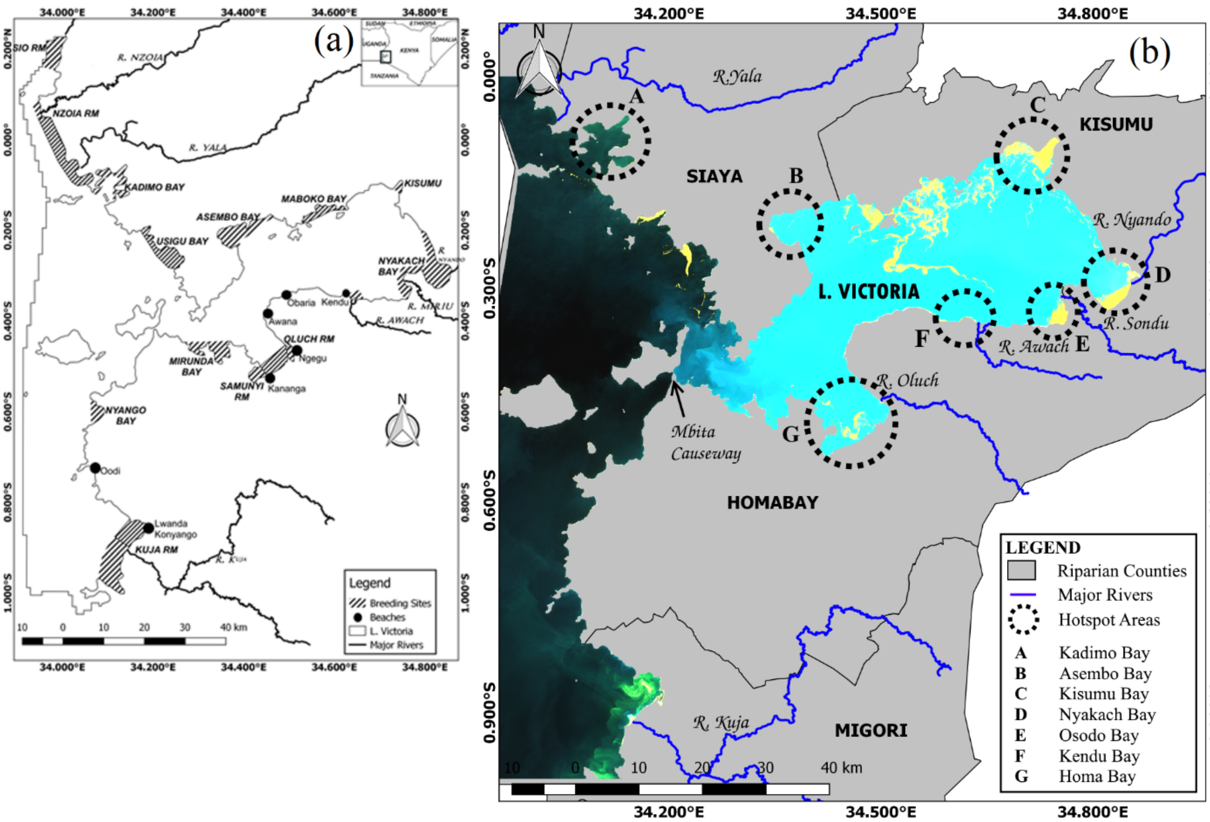

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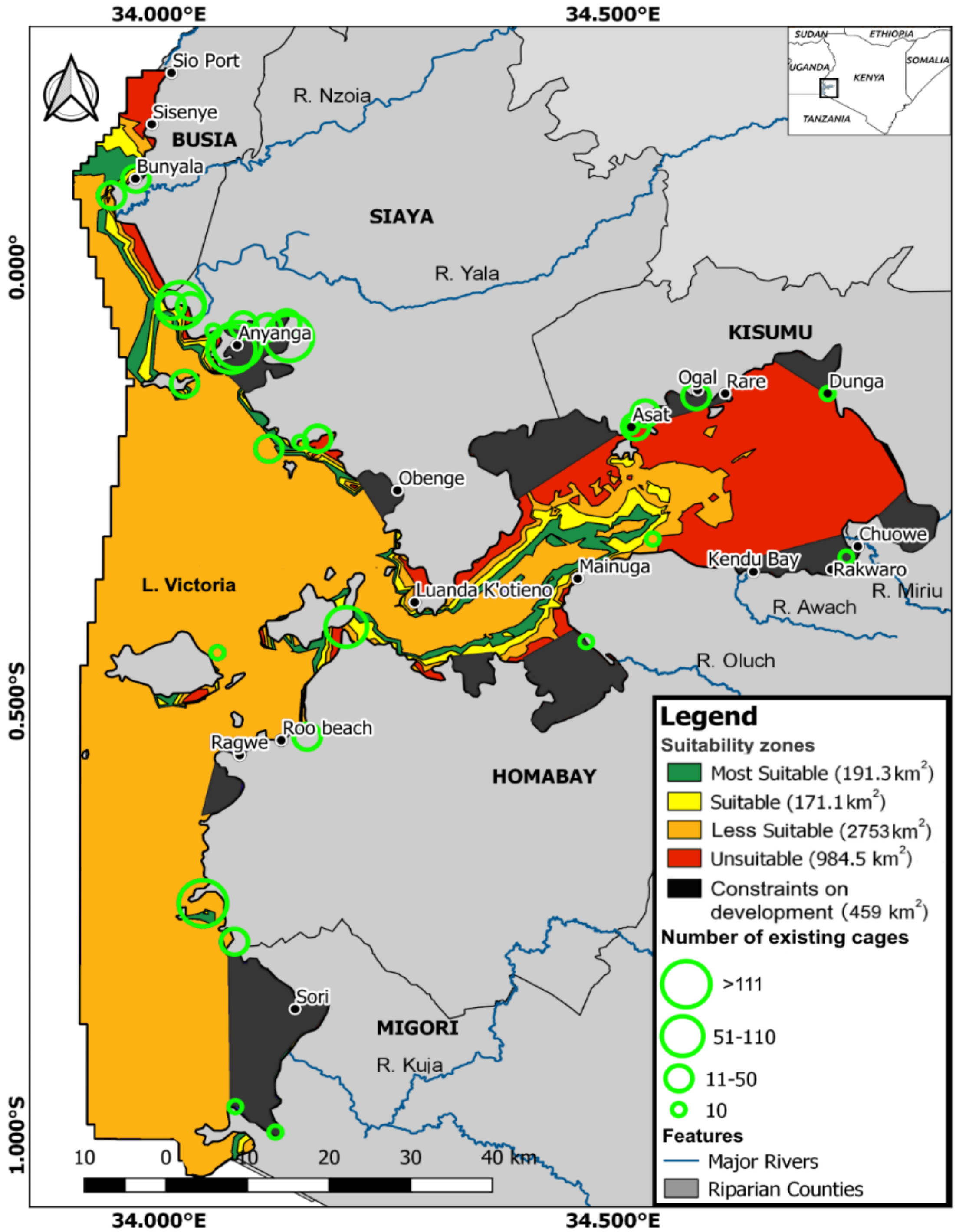

FIGURE 4 Map of Lake Victoria, Kenya, showing potential suitability for cage fish culture.

Tables

TABLE 1 Justification of the selected biophysical variables used in the cage culture site suitability classification.

Variable	Justification	References
Chlorophyll-*a* (μg L^{-1})	Indicator of primary production	OECD (1982) Bhatnagar & Devi (2013), Aura et al. (2016)
Temperature (ºC)	Water temperature affects fish metabolism, oxygen consumption, ammonia and carbon dioxide production rates, Feed Conversion Ratio (FCR) and fish growth rate.	Muir (2000), Pillay & Kutty (2005)
Dissolved oxygen (DO, mg L^{-1})	DO influences growth, survival, behavior and physiology of fish	Muir et al. (2000)
Secchi depth (m)	Composite measure of water transparency or visibility; affected by suspended and dissolved solids, sunlight and salinity.	Beveridge (2004)
Depth (m)	Greater depth facilitates water exchange and avoids oxygen depletion, accumulation of uneaten food, fecal material and debris, disease infection and buildup of noxious gases such as hydrogen sulphide and methane from decomposition of wastes; depths greater than 20 m should be avoided for small cages as they tend to have high waves that can stress the fish.	Beveridge (2004), Perez et al. (2005)
Distance to fish breeding grounds (km)	Distances to fish breeding have been included to help safeguard wild fish populations.	Ongore et al. (2018)
Distance to water hyacinth/moving islands (km)	Distances based on hotspots taking wind patterns and water currents into account; interference from water hyacinth or moving islands can destroy cage installations.	Ongore et al. (2018)
Distance to land (km)	Access to the sites for supply of goods and services (e.g. feed, equipment, fuel) and route to the markets for fish produced.	Ross et al. (2011)

TABLE 2 Suitability ratings for cage culture sites in a lacustrine ecosystem (Adapted from OECD, 1982; Bhatnagar & Devi, 2013).

Indicator	**Most suitable**	**Suitable**	**Less suitable**	**Unsuitable**
Chlorophyll-*a* (μg L^{-1})	7.5 - 4.5	<4.5 - 1.5	<1.5 - 0.5	>7.5 & <0.5
Temperature (ºC)	30 - 28	<28 - 26	<26 - 24	>30 & <24
Dissolved oxygen (DO, mg L^{-1})	≥5	<5 - 3	<3 - 1	<1
Secchi depth (m)	>0.7	0.7 - >0.5	0.5 - >0.3	≤0.3
Depth (m)	<10 - 8	<8 - 6	<6 - 4	≤4 or ≥10
Distance to breeding grounds/water hyacinth (km)	>0.5	0.5 - >0.4	0.4 - >0.2	≤0.2
Distance to land (km)	> 0.4	0.4 - >0.3	0.3 - >0.2	≤0.2

TABLE 3 Average water quality values (± StDev) for major beaches with cage culture sites compared to those for fishing grounds at similar locations. To provide representative coverage, site selection was based on intensity of cage culture practice, fishing intensity and county administrative coverage (Wu et al., 1996; Kashindye et al., 2015). Sites were categorised as Lit = Littoral zone; Nea = Near cages; Off = Off-shore; Fsg = Fishing ground and sampled quarterly between October 2016 and October 2018.

Station	Site	Chlorophyll*a* (μg L^{-1})	Temperature (°C)	DO (mg L^{-1})	Secchi depth (m)	Depth (m)
Ogal	Lit	2.29 ± 0.00	26.36 ± 0.16	5.03 ± 0.87	0.35 ± 0.00	2.67 ± 0.29
	Nea	4.58 ± 0.30	26.85 ± 0.80	5.35 ± 1.11	0.48 ± 0.03	3.93 ± 0.12
	Off	6.76 ± 1.11	27.19 ± 1.22	5.43 ± 1.01	0.50 ± 0.00	3.83 ± 0.58
	Fsg	6.53 ± 0.10	26.23 ± 0.31	7.81 ± 0.63	0.30 ± 0.00	6.70 ± 0.00
Ramba	Lit	7.20 ± 0.40	26.00 ± 0.19	5.52 ± 0.17	2.23 ± 0.40	2.23 ± 0.40
	Nea	11.56 ± 1.31	26.45 ± 0.51	4.61 ± 0.76	3.20 ± 0.17	29.67 ± 0.58
	Off	7.50 ± 0.71	26.14 ± 0.58	4.99 ± 1.02	3.00 ± 0.00	28.00 ± 0.00
	Fsg	5.47 ± 28	26.44 ± 0.33	8.18 ± 1.54	1.65 ± 0.00	41.80 ± 0.00
Nyandiwa	Lit	4.47 ± 0.17	26.55 ± 0.29	5.02 ± 0.72	1.42 ± 0.84	4.25 ± 0.00
	Nea	8.94 ± 0.22	26.36 ± 0.30	4.76 ± 0.87	1.90 ± 0.00	8.00 ± 0.00
	Off	5.61 ± 1.10	26.31 ± 0.28	4.85 ± 0.69	1.90 ± 0.00	9.50 ± 0.00
	Fsg	8.58 ± 0.74	26.24 ± 0.13	6.45 ± 1.08	0.40 ± 0.00	34.00 ± 0.00
Anyanga	Lit	5.26 ± 0.29	26.03 ± 0.07	3.64 ± 0.56	1.43 ± 0.21	1.67 ± 0.29
	Nea	12.56 ± 17	26.16 ± 0.31	4.48 ± 1.24	1.40 ± 0.00	4.17 ± 0.29
	Off	4.47 ± 0.00	26.28 ± 0.42	5.50 ± 1.57	1.13 ± 0.06	5.00 ± 0.00
	Fsg	5.50 ± 0.09	25.90 ± 0.00	6.69 ± 0.00	1.25 ± 0.00	4.70 ± 0.00
Mulukoba	Lit	4.47 ± 0.69	26.56 ± 0.25	5.78 ± 0.62	1.30 ± 0.17	2.77 ± 0.00
	Nea	8.94 ± 0.87	26.50 ± 0.69	7.09 ± 0.52	1.10 ± 0.10	6.00 ± 0.87
	Off	5.61 ± 0.17	26.52 ± 0.50	6.68 ± 0.43	1.10 ± 0.00	7.87 ± 0.32
	Fsg	6.22 ± 0.41	25.90 ± 0.00	6.69 ± 0.00	1.25 ± 0.00	4.70 ± 0.00
Naya	Lit	5.38 ± 0.43	26.37 ± 0.05	6.29 ± 0.25	1.25 ± 0.09	2.17 ± 0.76
	Nea	12.14 ± 0.31	26.30 ± 0.24	6.44 ± 0.40	1.30 ± 0.10	4.33 ± 0.29
	Off	8.31 ± 0.57	26.15 ± 0.26	6.40 ± 0.49	1.20 ± 0.00	5.00 ± 0.00
	Fsg	7.78 ± 0.62	26.82 ± 0.49	8.51 ± 1.61	0.90 ±0.00	7.40 ± 0.00

TABLE 4 Surface area of Lake Victoria, Kenya, in each cage culture suitability class as determined by the criteria shown in Table 3. Values are expressed as a percentage of total potential area (about 4,100 km^2).

Parameter	Most suitable	Suitable	Less suitable	Unsuitable
Chlorophyll-*a (*µ*g* L^{-1}*)*	48.7	32.0	10.0	9.3
Temperature (ºC)	52	33	8	7
Dissolved oxygen (DO, mg L^{-1})	51.6	36.3	10.7	1.4
Secchi depth (m)	40.4	34.6	11.2	13.8
Depth (m)	61.0	30.1	5.7	3.2
Distance to breeding grounds/water hyacinth (km)	14.5	18.9	37.5	29.1
Distance to land (km)	15.2	22.8	29.4	32.6