Received: 13 April 2019 | Revised: 21 May 2020 | Accepted: 23 February 2021

DOI: 10.1111/lre.12357

ORIGINAL ARTICLE

Lakes & Reservoirs Science, Policy and Management for Sustainable Use WILEY

A GIS-based approach for delineating suitable areas for cage fish culture in a lake

Christopher Mulanda Aura[1] | Safina Musa[2] | Chrisphine S. Nyamweya[1] | Zachary Ogari[1] | James M. Njiru[3] | Stuart E. Hamilton[4] | Linda May[5]

[1]Kenya Marine and Fisheries Research Institute, Kisumu, Kenya

[2]Kenya Marine and Fisheries Research Institute, Kegati, Kenya

[3]Kenya Marine and Fisheries Research Institute, Mombasa, Kenya

[4]Salisbury University, Salisbury, USA

[5]UK Centre for Ecology & Hydrology, Penicuik, Midlothian, UK

Correspondence
Christopher Mulanda Aura, Kenya Marine and Fisheries Research Institute, Kisumu, Kenya.
Emails: auramulanda@yahoo.com; aura.mulanda@gmail.com

Funding information
Lake Victoria Environmental Management Project Two (LVEMP II); Kenya Marine and Fisheries Research Institute (KMFRI); UKRI Natural Environment Research Council under the SUNRISE programme, Grant/Award Number: NE/R000131/1

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
cage culture, Lacustrine, management, spatial planning, sustainability, wild fisheries

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 lake covers an area of 59,947 km^2 and has an average and maximum depth of 40-m and 80-m, respectively, and a shoreline of 7,142 km (Hamilton et al., 2020). It hosts one of the largest freshwater fisheries in the world, providing a significant source of protein in East Africa and source of fish for exporting to the European Union, United States, China and Japan (FAO, 2016; Sitoki et al., 2010).

The area around Lake Victoria is characterised by a rapidly growing population (CIESIN, 2017; United Nations Population Division, 1995). It 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 population growth has been associated with higher levels of poverty, with lakeshore 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 having reduced food production levels (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 living around its shoreline (Hecky et al., 2010; Kundu et al., 2017; Lung'ayia et al., 2001; Ochumba & Kibaara, 1989; Sitoki et al., 2010, 2012; Verschuren et al., 2002). The monetary value of this fishery in 2014 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, likely because of overfishing and illegal or unregulated fishing activities (Njiru et al., 2018). Thus, while the demands for fish protein have increased because of 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., 2018).

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, however, commercial interests are now focusing on possible development of a lacustrine aquaculture industry to help to supplement capture fish production in lakes such as Lake Victoria, Lake Tanganyika, Lake Kariba, and Lake Kivu (Aura, Musa, et al., 2018; Berg et al., 1996; Beveridge & Phillips, 1993). Initial results suggest this could be a viable economic venture (Aura, Musa, et al., 2018), and aid agencies within Kenya are now supporting cage culture activities targeted explicitly at Lake Victoria (MSINGI, 2018).

Cage aquaculture has the potential to increase fish yields in Lake Victoria without damaging wild stocks (Kashindye et al., 2015; Lwama, 1991). It can also overcome some of the conventional constraints associated with more traditional systems such as pond culture (Aura, Musa, et al., 2018). 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 for a rapidly growing population will require rapid expansion of this industry. Sustainable management and utilisation of lake resources will be essential to effectively achieve this goal.

There are currently about 60 cage culture firms operating 4,357 (mostly floating) fish cages (Hamilton et al., 2020) within the Kenyan part of Lake Victoria, most of which are rearing Nile tilapia (Aura, Musa, et al., 2018). Many of these cages are located within 200 m of the shoreline, providing fish farmers with an ease of access and potential for close supervision, as well as sheltering these installations from potentially damaging winds and currents (Njiru, Aura, et al., 2018). However, if the fish cages are placed in shallow areas that act as nurseries 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, therefore being protected from fishing (Njiru, Aura, et al., 2018), 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, Musa, et al., 2018).

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 has published guidelines on the development, operation and licencing of cage aquaculture, they have yet to be incorporated into the management of cage fish farming in Kenyan waters. These guidelines provide useful step-by-step processes for establishing cage farms, including obtaining an establishment and operating licence, site selection and adherence to basic fish farm management practices and requirements (LVFO, 2018). However, they do not, however, provide a robust procedure for minimising resource use conflicts.

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

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

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

1. Where is development constrained by physical factors that affect cage culture development?
2. What is the level of suitability of the remaining areas for cage installations?
3. 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, the focus of the present study, comprises an area of 4,100 km^2 with an average depth of between 6-m and 8- m, and a maximum depth of 70-m (Odada et al., 2004). Fish cage culture has been identified as a new socioeconomic frontier with good prospects for generating income in this part of the lake, while also helping 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 × 2-m × 2-m, a stocking rate of 2,000 fingerlings per cage, and a one-cage per farmer concept. This cage size is preferred because of its ease of assembling, feeding, monitoring and managing the systems. Larger cages are expensive to make and difficult to secure and launch on the site.

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

A schematic representation of the process used for delineating areas potentially suitable for cage fish culture within the Kenyan part of Lake Victoria is provided in Figure 1. The process involves 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 located within each zone.

The field calculator function in QGIS was generally used to estimate the area (in km^2) of each region of interest. Microsoft Excel 2016 was for data entry and cleaning, and the SPSS version 21 (SPSS Inc., Chicago, IL, USA) and R version 3.5.0 (R Core team, 2014) was used for statistical analyses. The collected field data were compared with the Kruskal–Wallis One-Way ANOVA to examine the spatial variations between the data from the control sites and the data collected around the fish cages, with a significance level set at an alpha value 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, including fish breeding grounds, water hyacinth and floating island hotspots,

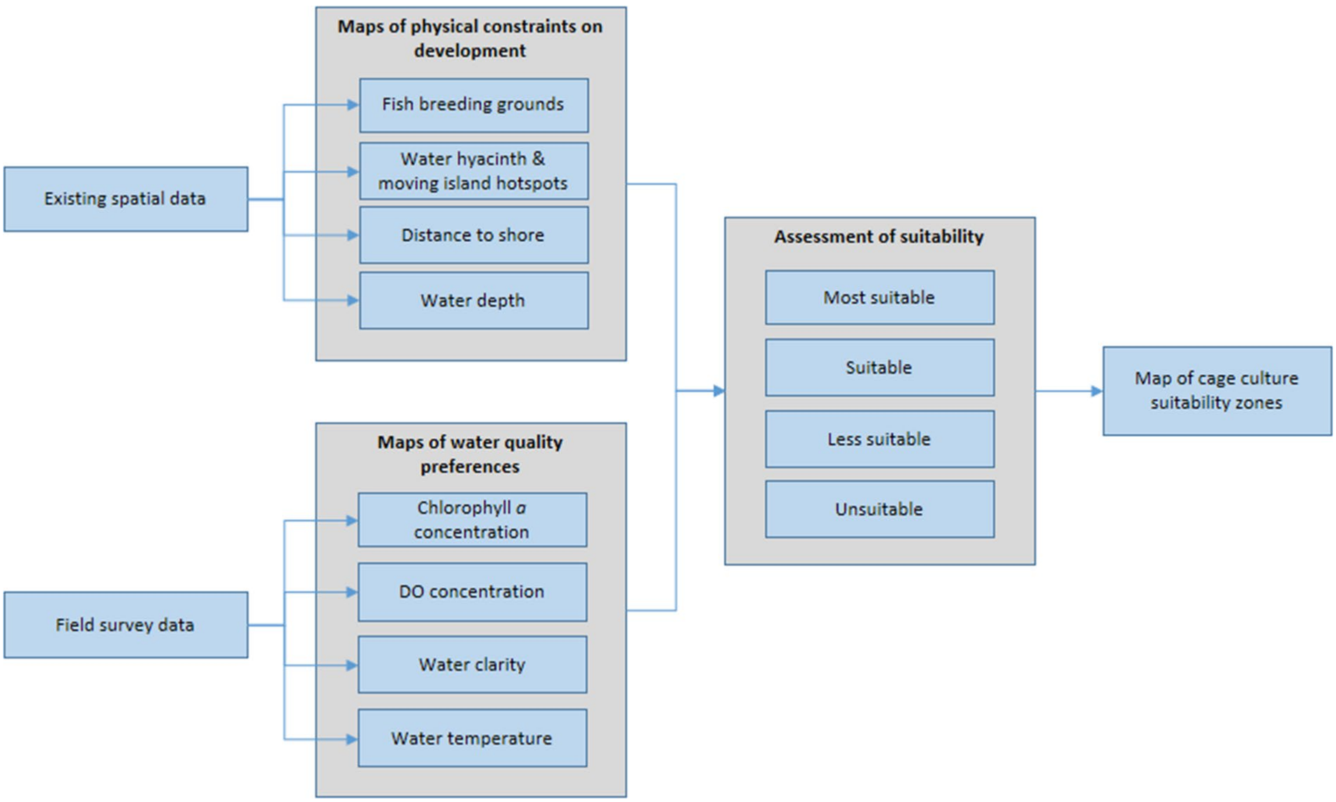

FIGURE 1 Schematic representation of the process for determining suitable areas for potential cage fish culture within Lake Victoria, Kenya.

water depth and areas located too close to the shoreline. Areas containing water hyacinth and moving islands, for example, are unsuitable because they have been found to destroy cage culture installations (Aura, Musa, et al., 2018). Although water hyacinth keep moving around as a function of 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 when it is present (Ongore et al., 2018; Opande et al., 2004). Furthermore, areas infested with heavy mats of the weed tend to exhibit poor water quality, preventing the development of cages in these areas (Villamagna & Murphy, 2009). The decomposition of the large quantities of organic matter produced by these mats of water hyacinth also leads to an increased biological oxygen demand and decreased dissolved oxygen (DO) concentrations (Balirwa et al., 2009; Taabu-Munyaho et al., 2016), threatening the survival of the fish.

Digital maps of areas designated as fish breeding grounds were available from the study of Aura, Nyamweya, et al. (2018), while those areas designated as water hyacinth and moving island hotspots were available from the study of Ongore et al. (2018). Distance to shoreline maps was also created for the present study. The distance from the cage culture location to the shoreline is important because it affects access to the cage culture sites for the supply of needed 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.

The water depth also affects the potential location of fish cages because it determines the extent to which wind velocity and fetch help increase water circulation, thereby providing better DO exchange and more efficient waste removal (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 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 & Semazzi, 2009) with 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 | Water quality maps

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

Depth-profiled (one measurement at surface; another below 1.0 m) *in situ* measurements were taken at each sampling site in concurrence with the maximum depth of existing cages (i.e., <2.0 m from the surface). Water temperature and DO concentration data were measured with a Yellow Springs Instruments metre (Model: YSI 650). Water transparency was measured with a standard Secchi disc and the maximum depth was determined with a sonar depth finder with a floating transducer, while the chlorophyll-*a* concentrations were determined with *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 subsequently interpolated to provide water quality map layers for temperature, DO concentrations, 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 was assessed on the basis of the key biophysical conditions and constraints (Table 1). These were chosen in terms of their likely effects on the growth and survival of caged tilapia (Aura et al., 2016; Dias et al., 2012), 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 a given class in terms of their suitability for locating cage fish farms, including '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), as modified 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 subsequently combined to generate suitability criteria. This involved using a simple Multi-Criteria Evaluation (MCE) approach to aggregate the thematic maps into a map illustrating the spatial distribution of different levels of suitability for siting fish cages. A binary value ($C_{(x,y)=0}$ [constrained]; $C_{(x,y)=1}$ [potentially suitable]) was first assigned to each location, based on whether or not the location was constrained. A suitability function ($S_{(x,y)}$) was then calculated for each remaining location (x,y) across the study area. Finally, the level of suitability scores was 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 follows:

$$S_{x,y} = \prod_{i=1}^{n} FSR(x, y, i) \quad (1)$$

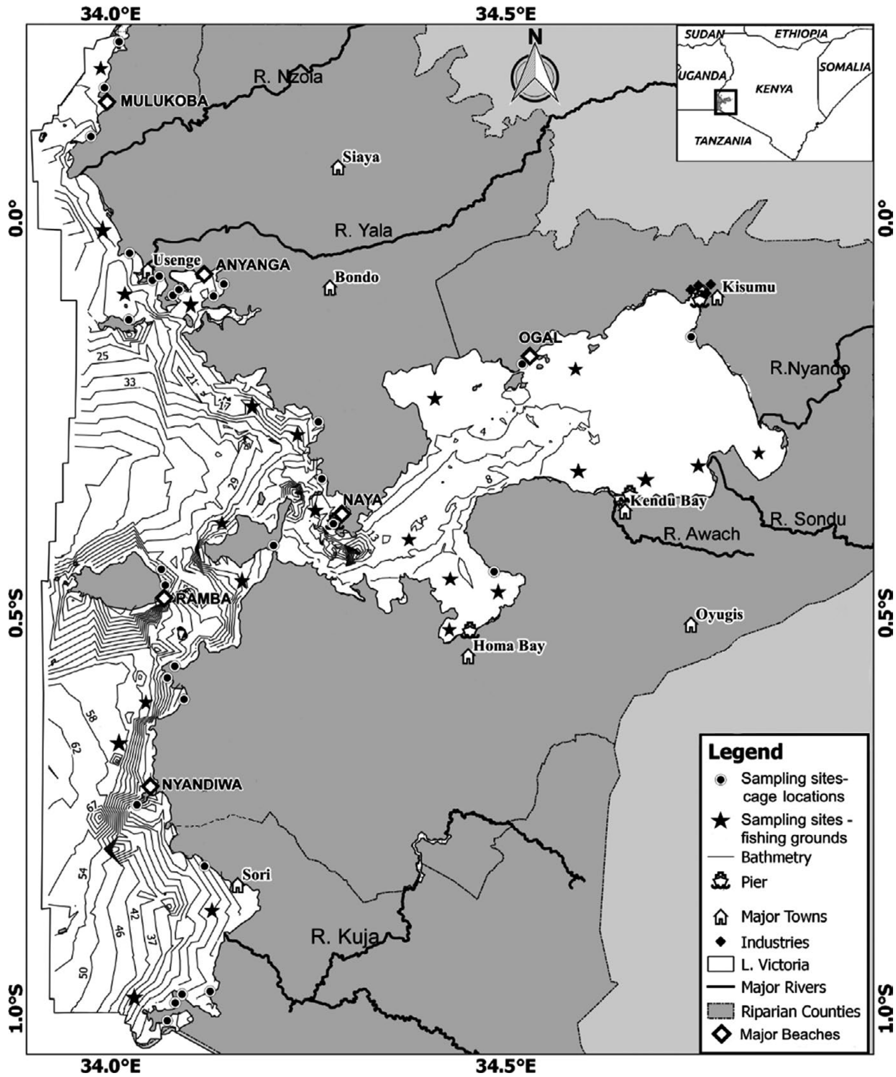

FIGURE 2 Lake Victoria, Kenya, showing current cage culture sites and fishing grounds that were sampled for water quality. The sites were categorised as Fsg, Fishing grounds; Lit, Littoral zone; Nea, Near cages; Off, Offshore. Samples were collected quarterly between October 2016 and October 2018.

where x,y = spatial location of each point; $FSR_{(x, y)}$ = factor suitability value at location x,y; and i = an index corresponding to each input parameter.

This process converted the original data into standardised cage culture suitability scores (Vincenzi et al., 2006) based 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 was used to generate thematic maps of suitability zones from these data (Batabyal & Chakraborty, 2015).

3 | RESULTS

3.1 | Overview of biophysical parameters measured at sampling sites

The biophysical data collected from the field sampling sites were used to create the water quality maps. There were no significant seasonal ($p > 0.05$) or water column variations within the collected data. Sampling sites located close to the fish cages exhibited significant variations ($p < 0.05$) in the chlorophyll-*a* concentrations, compared to those from the littoral, offshore and fishing ground sites (Table 3). The highest chlorophyll-*a* concentration was observed in Anyanga (12.56 ± 17 µg/L), while the lowest was in the littoral zone at Ogal (2.29 ± 0.00 µg/L). The highest water temperature (27.19°C ± 1.22°C) was measured offshore at Ogal, while the fishing grounds in Mulukoba and Anyanga exhibited the lowest temperatures, both being 25.90°C ± 0.01°C. There was no significant variation ($p > 0.05$; F = 2.78) among measured temperatures near the cage sites. Ogal and Anyanga exhibited a gradual increase in temperature moving from the littoral region towards the offshore zones, whereas the opposite was observed in both Nyadiwa and Naya. The highest DO concentrations were observed at all the fishing grounds that were sampled. All the DO concentrations exceeded 4.0 mg/L except in the Nyandiwa littoral zone which exhibited 3.64 ± 0.56 mg/L. There were no significant variations ($p > 0.05$) in the DO concentrations between the littoral sites, cage sites and offshores zones. They were significantly lower ($p < 0.05$; 5.64) at the cage sampling sites than at the fishing ground sites, but were not significantly different ($p > 0.05$) from the littoral sites. The highest Secchi depths

TABLE 1 Justification for selected biophysical variables used to determine cage culture site suitability classifications.

Variable	Justification	References
Chlorophyll-*a* concentration (μg/L)	Indicator of primary production	OECD (1982); Bhatnagar & Devi (2013); Aura et al. (2016)
Temperature (°C)	Water temperature affects fish metabolism, oxygen consumption, ammonia and carbon dioxide production rates, Feed Conversion Ratio (FCR) and fish growth rate.	Pillay & Kutty (2005)
Dissolved oxygen (DO) concentration (mg/L)	DO concentration influences growth, survival, behavior and physiology of fish	
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 constrains oxygen depletion, accumulation of uneaten food, fecal material and debris, disease infection and buildup of noxious gases (e.g. hydrogen sulphide; methane) from decomposition of wastes; depths greater than 20-m should be avoided for small cages since these depths tend to exhibit 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 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* concentration (μg/L)	7.5–4.5	<4.5–1.5	<1.5–0.5	>7.5 & <0.5
Temperature (°C)	30–28	<28–26	<26–24	>30 & <24
Dissolved oxygen (DO) concentration (mg/L)	≥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

occurred in Ramba near the cages (3.20 ± 0.17 m) and in the offshore zones (3.00 ± 0 m). The lowest water transparency among the sampling sites was measured at Ogal. No clear longitudinal trends in the Secchi depths, and no significant variations across the sampling sites ($p > 0.05$; F = 0.38; $\alpha_1 = 0.05$; $\alpha_2 = 0.025$), were observed. The water depth at the sampling sites was generally highest at Ramba, particularly at the fishing ground site (41.80 ± 0 m). The lowest depths were observed at Naya and Ogal (< 8.0-m). There was no clear trend in the maximum depths, with significant variations ($p < 0.05$; F = 38.57) among the sampled sites.

3.2 | Potential suitability of areas for cage culture

The areas of the Kenyan part of Lake Victoria that are potentially suitable, or totally unsuitable, for fish cage culture are illustrated in Figure 3. The less suitable sites occurred near the constraints on development, including water hyacinth and, moving island, hotspots, fish breeding grounds, and along the entire nearshore area around Kisumu Bay (Figure 3). Sites classified as 'most suitable' and 'suitable' for cage culture were 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 comprised 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 found to be potentially suitable for cage culture totalled 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 2,753 km^2 of less suitable areas and 984.5 km^2 of completely unsuitable areas. Fairly inaccessible areas for cage fish

TABLE 3 Average water quality values (± StDev) for major beaches with cage culture sites compared to 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)).

Station	Site	Chlorophyll-*a* concentration (μg L^{-1})	Temperature (°C)	Dissolved oxygen (DO) concentration (mg/L)	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

Site categorization: Lit, Littoral zone; Nea, near cages; Off, offshore; Fsg, = fishing ground and sampled quarterly between October 2016 and October 2018.

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

4 | DISCUSSION

The present study developed a lakescape approach for assessing areas that may be suitable for developing cage fish culture in the Kenyan part of Lake Victoria. The total area potentially suitable for cage culture was found to be about 362 km^2 (9%). It is suggested this information could be used to designate the part of the lake that could be used safely for cage culture if combined with 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 the existing cage culture establishments are located within 'less suitable' or 'constrained' areas (i.e., fish breeding grounds; water hyacinth; moving island hotspots). This fact probably explains the incidental water hyacinth or moving islands invasion of some of these installations, such as those reported for Dunga Beach

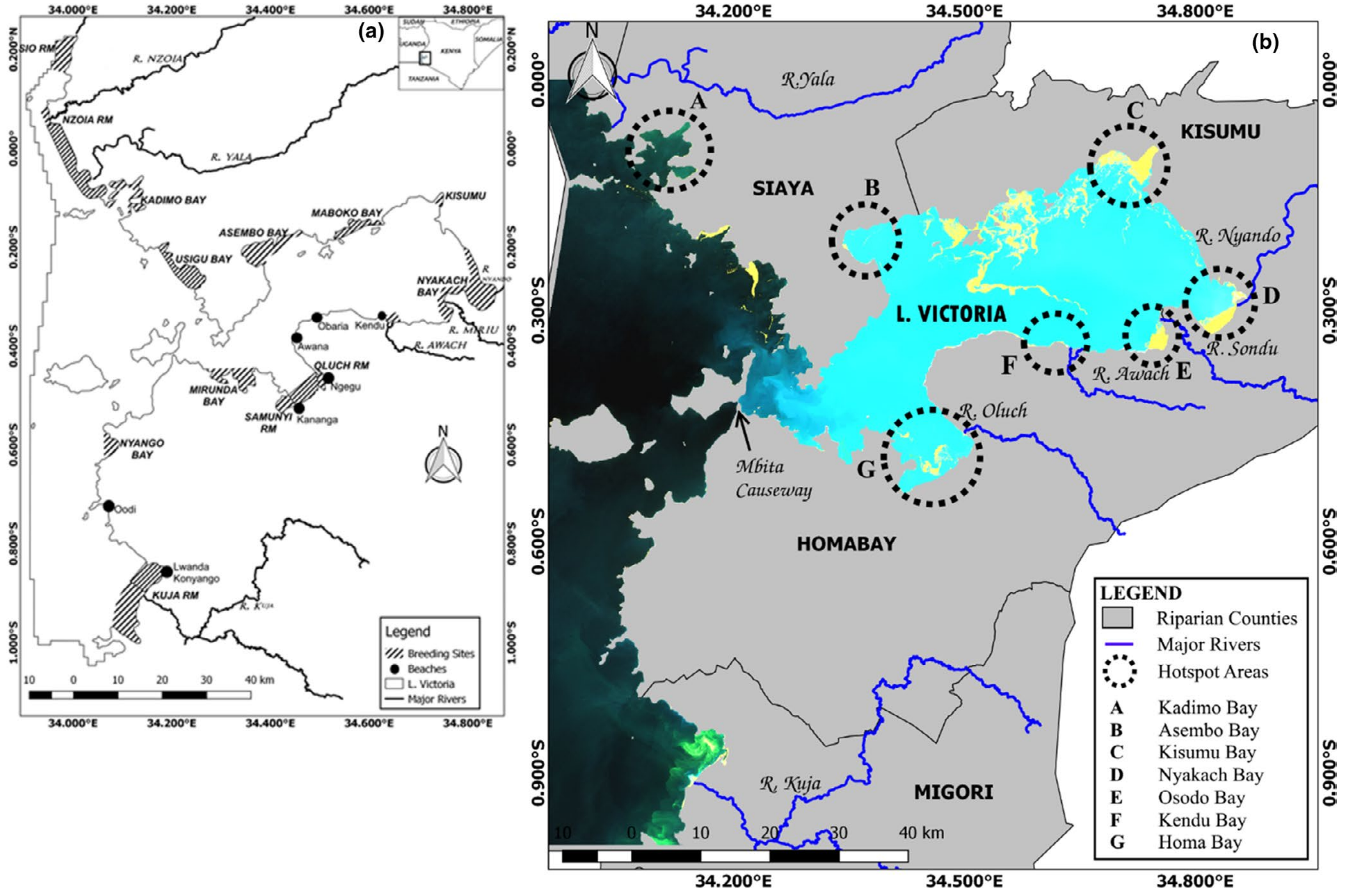

FIGURE 3 Maps showing (a) fish breeding sites (potential areas for protection), and (b) water hyacinth hotspots of Lake Victoria, Kenya (Adapted and modified from Ongore et al., 2018 and Aura, Nyamweya, et al., 2018).

TABLE 4 Surface area of Kenyan portion of Lake Victoria in each cage culture suitability class as determined by Table 3 criteria (values expressed as percentage of total potential area of approximately 4,100 km^2).

Parameter	Most suitable	Suitable	Less suitable	Unsuitable
Chlorophyll-*a* concentration (μg/L)	48.7	32.0	10.0	9.3
Temperature (°C)	52	33	8	7
Dissolved oxygen (DO) concentration (mg/L)	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

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 the moving islands.

The biophysical parameters influencing the suitability classification of the fish cage culture sites can also affect the ecological status of the lake, including its species composition and abundance of the aquatic organisms. However, the pattern of changes in the physical and chemical parameters across the Kenyan part of Lake Victoria is highly variable, therefore being unpredictable across the delineated sites. This may be attributable 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 driven by seasonal/diurnal changes in wind patterns and shear (Okely et al., 2010), agricultural land runoff, industrial effluent inputs and the nature of its inflows, in addition to natural processes.

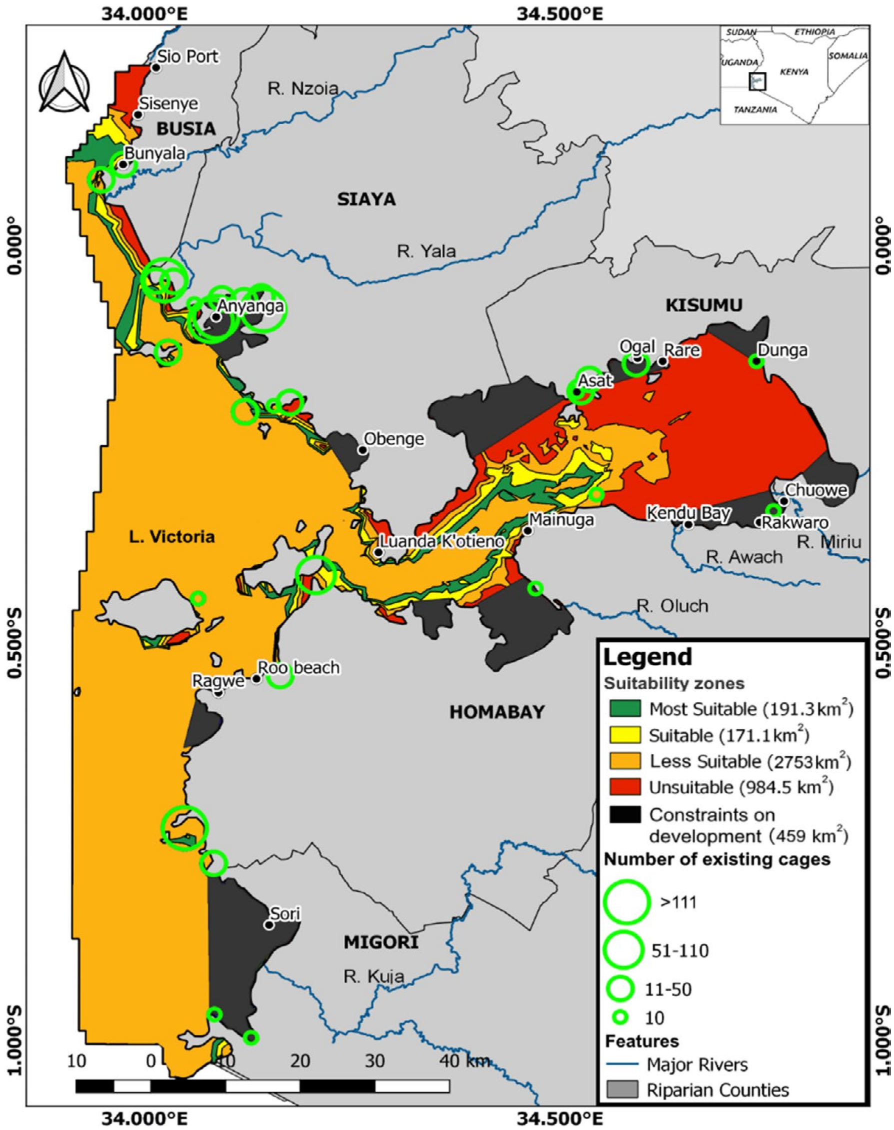

FIGURE 4 Map of Lake Victoria, Kenya, showing potential suitability for cage fish culture.

Lack of significant variations in the water temperatures suggest an even effect on the lake biogeochemical processes. In contrast, the relatively high chlorophyll-*a* concentrations in Anyanga near the areas containing cages, compared to other sites such as fishing grounds, indicated a marked increase in the 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 concentrations at the cage culture sampling sites were probably attributable to increased DO consumption by the cultured fish and the decomposition of their organic wastes (Longgen et al., 2009). The aforementioned could also have been the reason for the higher DO concentrations in the fishing grounds than in the cage culture sampling sites, and which could be considered as a main constraint on cage culture over 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 thatany 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 was as follows: depth >temperature > DO concentration >chlorophyll-*a* concentration >distance to land >distance to constraint (Table 4). This indicates depth could be considered the most important variable to consider in determining the suitability of cage culture sites, compared to other factors such as distance from the land. The nature of the bay (i.e., sheltered or open) and its proximity to land-based activities are also likely to influence levels of water quality and mixing at the sampling sites (Aura, Nyamweya, et al., 2018). Significant effects of bathymetry are mediated, principally through water depth, wind velocity and fetch, all which help to increase water circulation for better DO exchange and create high-water currents for a 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 reported at cage sites such as Anyanga and Nyenye Got in Siaya county (Njiru, Aura, et al., 2018).

This initial, desk-based approach to the delineation of areas suitable for cage culture has been shown to have the potential to support the suitable development of these systems, while at the same time minimising conflicts with other uses of this water resource. Future development, however, requires the incorporation of new data, including transportation routes, water abstraction points and carrying capacity, and validation of the outputs through stakeholder engagement activities.

5 | CONCLUSIONS AND RECOMMENDATIONS

The present study proposes a potential method for delineating areas suitable for cage fish culture. This method is based on biophysical factors and spatial interpolations. The order of suitability, based on biophysical parameter preferences, from most suitable to less suitable was depth >temperature > DO concentration >chlorophyll-*a* concentration >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 wastes. The low DO concentrations at cage culture sites are important because it is likely to be a precursor to fish kills, which can have an enormous impact on the local economy. A result of the present is the recommendation of fast-tracking regulations to control the location of new cage culture establishments, the relocation of existing cages to 'suitable' and 'most suitable' areas, and 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 in it. Future studies could consider inclusion of hydrography, wave height and carrying capacity data for additional refinement of the approach.

ACKNOWLEDGEMENTS

The authors express their gratitude to Lake Victoria Environmental Management Project Two (LVEMP II) and Kenya Marine and Fisheries Research Institute (KMFRI) for funding the water quality survey. Further, KMFRI provided logistics for the study. Some of this research was supported by the UKRI Natural Environment Research Council under the SUNRISE programme (NE/R000131/1), an Official Development Assistance award.

ORCID

Christopher Mulanda Aura https://orcid.org/0000-0001-9590-9652
Safina Musa https://orcid.org/0000-0002-8997-4148
Chrisphine S. Nyamweya https://orcid.org/0000-0002-7135-7379
James M. Njiru https://orcid.org/0000-0001-8874-6365
Stuart E. Hamilton https://orcid.org/0000-0001-8114-7247

REFERENCES

Abila, R. O. (2003). *Fish trade and food security: are they reconcilable in Lake Victoria?*. Expert Consultation on International Fish Trade and Food Security.

Aguilar-Manjarrez, J., & Nath, S. (1998). A Strategic Reassessment of Fish Farming Potential in Africa. FAO CIFA Technical Paper 32. FAO, Rome, 178 p.

Anyah, R. O., & Semazzi, F. (2009). Idealized simulation of hydrodynamic characteristics of Lake Victoria that potentially modulate regional climate. *International Journal of Climatology*, *29*, 971–981. https://doi.org/10.1002/joc.1795.

APHA (2005). *American Public Health Association Standard Methods for the Examination of Water and Wastewater*, 21 st ed. APHA-AWWA-WEF. ISBN 0875530478.

Aura, M. C., Musa, S., Osore, M. K., Kimani, E., Alati, V. M., Wambiji, N., Maina, G. W., & Charo-Karisa, H. (2017). Quantification of climate change implications using oyster suitability sites occurrence model along the Kenya Coast. *Journal of Marine Systems*, *165*, 27–35.

Aura, M. C., Musa, S., Yongo, E., Okechi, J., Njiru, J. M., Ogari, Z., Wanyama, R., Charo-Harrison, H., Mbugua, H., Kidera, S., Ombwa, V., & Abwao, J. (2018). Integration of mapping and socio-economic status of cage culture: Towards balancing lake-use and culture fisheries in Lake Victoria, Kenya. *Aquaculture Research*, *49*, 532–545. https://doi.org/10.1111/are.13484

Aura, M. C., Nyamweya, C. S., Njiru, J. M., Musa, S., Ogari, Z., & Wakwabi, E. (2018). Exploring the demarcation requirements of fish breeding sites to balance the management and conservation needs of the lake ecosystem. *Fisheries Management and Ecology*, *26*, 451–459. https://doi.org/10.1111/fme.12311.

Aura, M. C., Nyamweya, C. S., Njiru, J. M., Odoli, C., Musa, S., Ogari, Z., Abila, R., Okeyo, R., & Oketch, R. (2019). Using fish landing sites and markets information towards quantification of the blue economy to enhance fisheries management. *Fisheries Management and Ecology*, *26*, 141–152. https://doi.org/10.1111/fme.12334.

Aura, M. C., Nyamweya, C. S., Owili, M., Gichuru, N., Kundu, R., Njiru, J. M., & Ntiba, M. J. (2020). Checking the pulse of the major commercial fisheries of Lake Victoria Kenya, for sustainable management. *Fisheries Management and Ecology*, *00*, 1–11. https://doi.org/10.1111/fme.12414.

Aura, M. C., Saitoh, S.-I., Liu, Y., Hirawake, T., Baba, K., & Yoshida, T. (2016). Implications of marine environment change on Japanese scallop (*Mizuhopecten yessoensis*) aquaculture suitability: Comparative study in Funka and Mutsu Bays, Japan. *Aquaculture Research*, *47*, 2164–2182.

Balirwa, J. S., Wanda, F., & Muyodi, F. J. (2009). Impacts of water hyacinth and water quality change on beneficial uses of Lake Victoria, Uganda.13th World Lake ConferenceWuhanChina, 1–5 November, 2009.

Bascom, W. (1964). *Waves and Beaches: The Dynamics of the Ocean Surface*. Doubleday.

Batabyal, A. K., & Chakraborty, S. (2015). Hydrogeochemistry and water quality index in the assessment of groundwater quality for drinking uses. *Water Environment Research*, *87*, 607–617. https://doi.org/10.2175/106143015X14212658613956.

Berg, H., Troell, M., Folke, C., Michsen, P., & Troell, M. (1996). Managing aquaculture for sustainability in tropical Lake Kariba, Zimbabwe. *Ecological Economics*, *18*, 141–159. https://doi.org/10.1016/0921-8009(96)00018-3.

Beveridge, M. C. M. (2004). *Cage Aquaculture (3rd ed)* (p. 368). Blackwell Publishing.

Beveridge, M. C. M., & Phillips, M. J. (1993). Environmental impact of tropical inland aquaculture. In: R. S. V. Pullin, H. Rosenthal, & J. L. Maclean (Eds.), *Environment and aquaculture in developing countries*. ICLARM Conference Proceedings 31, 359 pp. (213–236).

Bhatnagar, A., & Devi, P. (2013). Water quality guidelines for the management of pond fish culture. *Int J Environ Sci.*, *3*(6), 1980–2009. https://doi.org/10.6088/ijes.2013030600019

Bremner, J., Lopez-Carr, D., Zvoleff, A., & Pricope, N. (2013). Using New Methods and Data to Assess and Address Population, Fertility, and Environment links in the Lake Victoria Basin.

Buitrago, J., Rada, M., Hernandez, H., & Buitrago, E. (2005). A single-use site selection technique, using GIS, for aquaculture planning: choosing locations for mangrove oyster raft culture in Margarita Island, Venezuela. *Environmental Management*, *35*, 544–556. https://doi.org/10.1007/s00267-004-0087-9

Cho, Y., Lee, W. C., Hong, S., Kim, H. C., & Kim, J. B. (2012). GIS-based Suitable Site Selection using Habitat Suitability Index for Oyster Farms in Geoje-Hansan Bay, Korea. *Ocean & Coastal Management*, *56*, 10–16. https://doi.org/10.1016/j.ocecoaman.2011.10.009

CIESIN. (2017). Gridded Population of the World, Version 4 (GPWv4): Population Density Adjusted to Match 2015 Revision UN WPP Country Totals, Revision 10. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, New York, USA.

Dias, J. D., Simões, N. R., & Bonecker, C. C. (2012). Net cages in fish farming: a scientometric analysis. *Acta Limnologica Brasiliensia*, *24*, 12–17. https://doi.org/10.1590/S2179-975X2012005000022.

EL-Sayed, A. F. M. (2006). Intensive Culture. In A. F. M. EL–Sayed. (eds) *Tilapia Culture*. (62pp.) : CABI Publishing.

FAO. (2016). The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all, Rome, Italy.

Garcia de Souza, J., Solimano, P. J., Baigun, C., & Colautti, C. D. (2013). Effects of stocking density and natural food availability on the extensive cage culture of pejerrey (*Odontesthes bonariensis*). *Aquaculture Research*, *2*, 1–13.

Hamilton, S. E., Gallo, S. M., Krach, N., Nyamweya, C. S., Okechi, J. K., Aura, C. M., Ogari, Z., Roberts, P. M., & Kaufman, L. (2020). The use of unmanned aircraft systems and high-resolution satellite imagery to monitor tilapia fish-cage aquaculture expansion in Lake Victoria, Kenya. *Bulletin of Marine Science*, *96*, 71–94.

Hecky, R. E., Mugidde, R., Ramlal, P. S., Talbot, M. R., & Kling, G. W. (2010). Multiple stressors cause rapid ecosystem change in Lake Victoria. *Freshwater Biology*, *55*, 19–42. https://doi.org/10.1111/j.1365-2427.2009.02374.x

Kashindye, B. B., Nsinda, P., Kayanda, R., Ngupula, G. W., Mashafi, C. A., & Ezekiel, C. N. (2015). *Environmental impacts of cage culture in Lake Victoria : The case of Shirati Bay Sota*. SpringerPlus. https://doi.org/10.1186/s40064-015-1241-y.

Kundu, R., Aura, M. C., Nyamweya, C. S., Agembe, S., Sitoki, L., Lung'ayia, H. B. O., Ongore, C., Ogari, Z., & Werimo, K. (2017). Changes in pollution indicators in Lake Victoria, Kenya and their implications for lake and catchment management. *Lakes and Reservoir Management*, *22*, 199–214. https://doi.org/10.1111/lre.12187

Longdill, P. C., Healy, T. R., & Black, K. P. (2008). An integrated GIS approach for sustainable aquaculture management area site selection. *Ocean & Coastal Management*, *51*, 612–624.

Longgen, G., Zhongjie, L., Ping, X., & Leyi, N. (2009). Assessment effects of cage culture on nitrogen and phosphorus dynamics in relation to fallowing in a shallow lake in China. *Aquaculture International*, *17*, 229–241. https://doi.org/10.1007/s10499-008-9195-5

Lung'ayia, H., Sitoki, L., & Kenyanya, M. (2001). The nutrient enrichment of Lake Victoria (Kenyan waters). *Hydrobiologia*, *485*, 75–82.

LVFO (2018). *Guidelines for Establishment and Operation of Cage Fish Farming in the East African Community*. Lake Victoria Fisheries Organization.

Lwama, G. K. (1991). Interactions between aquaculture and the environment. *Critical Reviews in Environmental Control*, *21*, 177–216. https://doi.org/10.1080/10643389109388413.

Malczewski, J. (1999). *GIS and multi-criteria decision analysis*. John Wiley & Sons.

MSINGI. (2018). *MSINGI: Aquaculture*. MSINGI.

Njiru, J. M., Aura, M. C., & Okechi, J. K. (2018). Cage fish culture in Lake Victoria: A boon or a disaster in waiting? *Fisheries Management and Ecology*, *26*, 426–434. https://doi.org/10.1111/fme.12283.

Njiru, J. M., van der Knaap, M., Kundu, R., & Nyamweya, C. (2018). Lake Victoria fisheries: Outlook and management. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *23*, 152–162. https://doi.org/10.1111/lre.12220.

Ochumba, P. B. O., & Kibaara, D. I. (1989). Observations on blue-green algal blooms in the open waters of Lake Victoria, Kenya. *African Journal of Ecology*, *27*, 23–34.

Odada, E. O., Olago, D. O., Kulindwa, K., Ntiba, M., & Wandiga, S. (2004). Mitigation of environmental problems in Lake Victoria, East Africa: Causal chain and policy options analyses. *Ambio: A Journal of the Human Environment*, *33*, 13–23.

OECD (1982). Eutrophication of Waters. Monitoring, Assessment and Control - 154 pp. Paris: Organisation for Economic Co-Operationand Development. https://doi.org/10.1002/iroh.19840690206

Okely, P., Imberger, J., & Antenucci, J. P. (2010). Processes affecting horizontal mixing and dispersion in Winam Gulf, Lake Victoria. *Limnology and Oceanography*, *55*, 1865–1880.

Ongore, C., Aura, M. C., Ogari, Z., Njiru, J. M., & Nyamweya, C. (2018). Spatial-temporal dynamics of water hyacinth, *Eichhornia crassipes* (Mart.), other macrophytes and their impact on fisheries in Lake Victoria, Kenya. *Journal of Great Lakes Research*, *44*, 1273–1280.

Opande, G. O., Onyango, J. C., & Wagai, S. O. (2004). Lake Victoria: the water hyacinth (*Eichhornia crassipes* [Mart.] Solms), its socio-economic effects, control measures and resurgence in the Winam Gulf. *Limnologica*, *34*, 105–109.

Perez, O. M., Telfer, T. C., & Ross, L. G. (2005). Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. *Aquaculture Research*, *36*, 946–961. https://doi.org/10.1111/j.1365-2109.2005.01282.x

Pillay, T. V. R., & Kutty, M. N. (2005). Aquaculture: principles and practices, 2nd Ed. Oxford, UK: Ames, IA : Blackwell Pub., ISBN: ISBN-10: 1-4951-0532-1; ISBN-13-978-1-4051-0532-3.

QGIS Development Team. (2009). QGIS Geographic Information System. Open Source Geospatial Foundation. URL: http://qgis.osgeo.org.

R Core Team (2014). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.R-project.org/

Radiarta, I. N., Saitoh, S.-I., & Miyazono, A. (2008). GIS-based multi-criteria evaluation models for indentifying suitable sites for Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, south western Hokkaido, Japan. *Aquaculture*, *284*, 127–135.

Ross, L. G., Falcone, L. L., Mendoza, A. C., & Palacios, M. C. A. (2011). Spatial modelling for freshwater cage location in the Presa Adolfo Mateos Lopez (El Infiernillo), Michoacan, Mexico. *Aquaculture Research*, *42*, 797–807.

Sitoki, L., Gikuchi, J., Ezekiel, C., Wanda, F., Mkumbo, O., & Marshall, B. (2010). The environment of Lake Victoria (East Africa): Current status and historical changes. *International Review of Hydrobiology*, *95*, 209–223. https://doi.org/10.1002/iroh.201011226

Sitoki, L., Kurmayer, R., & Rott, E. (2012). Spatial variation of phytoplankton composition, biovolume, and resulting microcystin concentrations in the Nyanza Gulf (Lake Victoria, Kenya). *Hydrobiologia*, *691*, 109–122. https://doi.org/10.1007/s10750-012-1062-8

Taabu-Munyaho, A., Marshall, B., Tomasson, T., & Marteinsdottir, G. (2016). Nile perch and the transformation of Lake Victoria. *African Journal of Aquatic Science*, *41*, 127–142. https://doi.org/10.2989/16085914.2016.1157058

United Nations Population Division. (1995). *World population prospects: The 1994 revision*. United Nations.

Venturoti, G. P., Veronez, A. C., Salla, R. V., & Gomes, L. C. (2016). Variation of limnological parameters in a tropical lake used for tilapia cage farming. *Aquaculture Reports*, *2*, 152–157. https://doi.org/10.1016/j.aqrep.2015.09.006.

Verschuren, D., Johnson, T. C., Kling, H. J., Edgington, D. N., Leavitt, P. R., Brown, E. T., Talbot, M. R., & Hecky, R. E. (2002). History and timing of human impact on Lake Victoria, East Africa. *Proceedings, Royal Society B: Biological Sciences*, *269*, 289–294. https://doi.org/10.1098/rspb.2001.1850

Villamagna, A. M., & Murphy, B. R. (2009). Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): A review. *Freshwater Biology*, *55*, 282–298.

Vincenzi, S., Caramori, G., Rossi, R., & De Leo, G. A. (2006). A GIS-based habitat suitability model for commercial yield estimation of *Tapes philippinarum* in a Mediterranean coastal lagoon (Sacca di Goro, Italy). *Ecological Modelling*, *193*, 90–104. https://doi.org/10.1016/j.ecolmodel.2005.07.039

Weston, M. (2015). Troubled Waters. Why Africa's largest lake is in grave danger. http://www.slate.com/articles/news_and_politics/roads/2015/03/lake_victoria_is_in_grave_danger_africas_largest_lake_is_threatened_by.html [uploaded 7/05/2016].

Wetzel, R. G., & Likens, G. E. (1991). *Limnological analyses (3rd Ed)* (p. 429). Springer Verlag.

Wu, Y. S., Forsyth, P. A., & Jiang, H. (1996). A consistent approach for applying numerical boundary conditions for multiphase subsurface flow. *Journal of Contaminant Hydrology*, *23*, 157–184. https://doi.org/10.1016/0169-7722(95)00099-2

How to cite this article: Mulanda Aura C, Musa S, Nyamweya CS, et al. A GIS-based approach for delineating suitable areas for cage fish culture in a lake. *Lakes & Reserv*. 2021;26:e12357. https://doi.org/10.1111/lre.12357