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ORIGINAL ARTICLE

Use of GIS-based multicriteria evaluation for improved selection of suitable sites for cage fish farming in Mwanza Gulf, Lake Victoria

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Abstract

Stagnating capture fisheries and increasing fish protein demand necessitate aquaculture production to bridge the gap. Lake Victoria is a potential water body for increasing fish production through cage farming. The sustainability of Lake Victoria for cage farming depends on timely and holistic site selection. However, current site selection methods involve complex, resource-intensive field surveys that lack a holistic approach to integrate multiple factors. Accordingly, information regarding suitable sites for sustainable fish cage farming in Lake Victoria remains scarce. In this study, a transparent geographic information systems (GIS) and multicriteria evaluation (MCE) here after reffered to as GIS-MCE was used to reveal potential sites to be permitted or avoided during cage aquaculture development in the Mwanza Gulf of Lake Victoria (Tanzania). Our analysis involved weighting and integration of sub-models representing ecologically sensitive areas, physical environment, and socio-economic and water quality variables into a single spatial model portraying different site suitability levels in the Mwanza Gulf. The results indicated that the sub-models identified relatively larger suitable and most suitable sites compared to the overall model. No site maintained its status across all sub-models. The overall model designated a small area (5.10 km^2 or 1.52%) as the most suitable site, with 24.20 km^2 (7.44%) as suitable, 64.47 km^2 (19.82%) as less suitable, and 42.63 km^2 (13.12%) as unsuitable for cage fish farming. The remaining area (188.84 km^2 or 58.06%) was a constrained site to be avoided during cage aquaculture development. Taken together, the individual sub-models are ineffective in designating potential sites for fish cage culture and thus should not be used solely. The GIS-MCE general model provides a fast and timely method for identifying potential sites for cage farming in Lake Victoria. Fish farmers and managers should use the GIS-MCE overall model in inland waters to facilitate site selection for complying with licensing requirements and decrease field extensive surveys.

KEYWORDS
cage aquaculture, GIS, Lake Victoria, site selection

1 | INTRODUCTION

Stagnating capture fisheries and an increasing demand for fish protein to feed the growing population have created the potential for aquaculture production to bridge the gap (FAO, 2022). The role of aquaculture is envisaged to supplement the dwindling capture fish production and increase the per capita fish intake, especially in the Sub-Saharan region (Obiero et al., 2019). Fish culture is significant in realising sustainable development goals, including reduced hunger, poverty, and improved human health and well-being (FAO, 2018). Therefore, fish culture holds the future for food production.

Fish aquaculture production is often conducted in ponds, raceways, recirculating aquaculture systems, or cages (Barange et al., 2015). Among these aquaculture systems, fish pond farming has been widely practised, especially in many Sub-Saharan countries, including Tanzania (URT, 2022). However, increasing climate change impacts such as floods and extreme droughts affect fish pond production (Oyebola & Olatunde, 2019). Besides, the technology required for super-intensive pond production is unavailable to small-scale farmers, which characterise most producers in low-income countries. On the other hand, raceways and recirculating aquaculture systems require high investment costs, limiting their wide adoption in financially constrained countries like Tanzania. Therefore, cages remain the most appropriate culture structure for fish production to meet the increasing fish demand.

Cage aquaculture has attracted great attention in fish production in Africa (Ragasa et al., 2022) and has been suggested as an important driver for sustainable aquaculture growth, especially in most African countries (Musinguzi et al., 2019; Ragasa et al., 2022). Fish cage aquaculture has been proposed as one of the adaptation approaches to climate-related threats (Barange et al., 2015; Oyebola & Fada, 2020) and also provides opportunities for different farmers, including landless local communities (Beveridge, 2004). Furthermore, cage aquaculture provides higher investment returns and better profit than pond culture systems (Lisac & Muir, 2000). Despite its advantages, unplanned and poorly managed cage aquaculture activities have been blamed for causing social conflicts among water users (Akyol et al., 2019). Moreover, cage aquaculture has also been associated with various environmental concerns, such as water quality pollution (Risk et al., 2021) and alteration of natural ecosystems (Strictar-Pereira et al., 2010). However, these concerns can be avoided through proper site selection (Pérez et al., 2003), leading to sustainable cage aquaculture. Proper site selection helps resolve competing demands for space, avoid undesirable environmental impact, and guarantee the operation's profitability. Accordingly, the Food and Agriculture Organization of the United Nations (FAO) emphasises that site selection processes should adhere to the principle of the ecosystem approach to aquaculture (EAA) (Telfer et al., 2013). Under the EAA, site selection entails the delineation of areas, which are economically, socially and environmentally available for aquaculture investment (Aguilar-Manjarrez et al., 2017; Soto et al., 2008). However, delineating optimal location in cage aquaculture is often not based on one criterion, rather simultaneously considering multiple criteria (Cardia et al., 2017). Therefore, successfully delineating optimal cage aquaculture locations requires a robust method that simultaneously integrates such multiple criteria (Hunter, 2009).

Previous studies have achieved site selection for a range of aquaculture activities using techniques such as geographic information systems (GIS) and multicriteria evaluation (MCE) (Pérez et al., 2003; Ross et al., 2011; Vianna & Filho, 2018; Yin et al., 2018). For instance, Pérez et al. (2003) used GIS-MCE to locate potential sites for marine fish cages to coexist with the tourism industry in Tenerife (Canary Islands). However, most previous studies focused on the marine environment, with limited studies on inland aquaculture (Asmah et al., 2021; Aura et al., 2021; Njoku et al., 2022). Moreover, most factors (such as socio-economic and legal requirements) considered during GIS-MCE-based aquaculture site selection are site specific. Accordingly, there is a need for specific studies in each water body or country, such as the Tanzanian part of Lake Victoria, for sustainable cage aquaculture.

Lake Victoria is the largest water body in Africa, with untapped potential for cage aquaculture. Given the increasing interest in cage aquaculture investment in the study area, the potential for cage aquaculture expansion is high. Currently, the number of fish cage farms in the Tanzanian part of Lake Victoria is estimated to be over 900 (URT, 2023). Nevertheless, Lake Victoria is recognised as an ecologically sensitive water body and is currently under various threats such as increased eutrophication (Abo-Taleb et al., 2023; Olokotum et al., 2020), overfishing (Outa et al., 2020), and climate change (Luhunga & Songoro, 2020). Thus, proper site selection is critical not only for cage aquaculture sustainability but also for conserving the environment (Kimirei et al., 2017) and biodiversity (Mgaya et al., 2017) of the Lake Victoria. However, most areas in the Tanzanian part of the Lake Victoria are yet to be identified from spatial perspectives. Existing approaches to site selection mainly rely on conventional field surveys by using the Global Positioning System (GPS) to draw point-based maps on small areas (ESRF, 2016; Tanzania Fisheries Research Institute, TAFIRI, 2015).

Furthermore, approval and licensing of cage farms currently rely on strategic Environmental Impact Assessment (EIA), which is usually done by the TAFIRI (van der Heijden and Shoko, 2018). The strategic EIA is usually based on individual fish farmers' requests. Hence, it is usually carried out in a single area, with most data being recorded on a point basis. However, these single-site assessments cannot be used with a high degree of certainty to inform aquaculture policy and planning from broader spatial perspectives. Furthermore, individual customer-driven strategic EIA makes site selection less participatory, potentially leading to the inclusion of unsuitable sites for cage aquaculture and social conflicts due to competing demands. Therefore, a transparent and proactive method capable of integrating multiple criteria and spatially revealing potential sites at varying degrees of suitability is essential for sustainable cage aquaculture planning and investment in Lake Victoria. This approach would help to avoid conflicts and enhance stakeholder participation in aquaculture site selection processes. Currently, no study has identified and quantified suitable sites for fish cage culture on the Tanzanian side of Lake Victoria by using the GIS-MCE method.

Therefore, this study employed a transparent and step-by-step GIS-MCE method to integrate multiple criteria and identify spatially suitable sites for sustainable fish cage farming in the Mwanza Gulf of Lake Victoria (Tanzania). The GIS-MCE method incorporated spatial data for ecologically sensitive areas (ESAs), water quality, physical environment, and socio-economic factors, as well as local people's opinions to develop suitability maps. The primary objective was to identify areas where cage aquaculture is constrained and to determine different suitability levels in the remaining sites. We also used the GIS-MCE method to determine the suitability of sites for the existing cages in Mwanza Gulf. The resulting outputs are suitability models (maps) that aid in visualisation, spatial planning, and decision-making for cage fish farming in Lake Victoria.

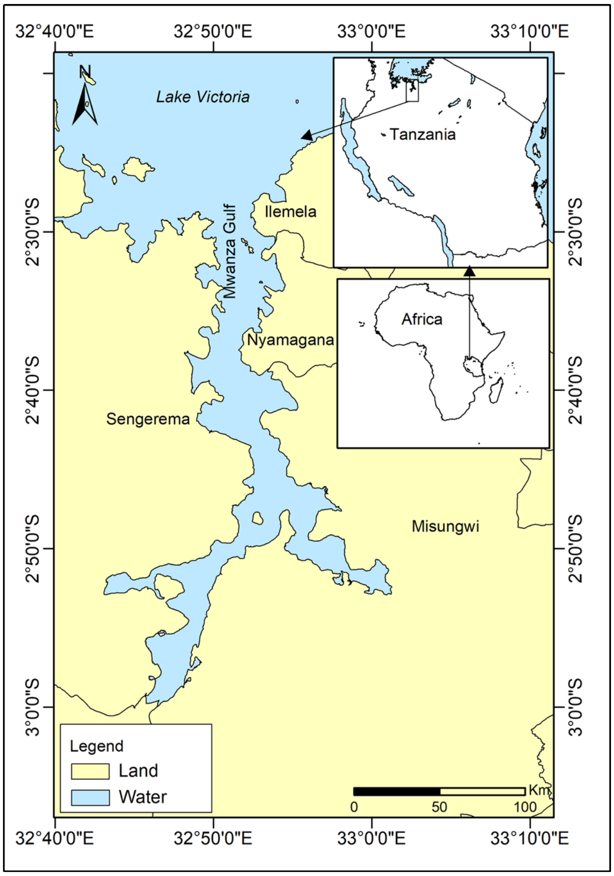

FIGURE 1 Map of Tanzania showing the Mwanza Gulf of Lake Victoria. *Source*: Tanzania Bureau of Statistics online GIS Database (https://www.nbs.go.tz).

2 | MATERIALS AND METHODS

2.1 | Description of the study area

The study covered the Mwanza Gulf, situated at the southern end of Lake Victoria (Figure 1). The Mwanza Gulf is about 60 km long and 2.5–11 km wide (TAFIRI, 2015). The Mwanza Gulf was chosen because it is one of Lake Victoria's most ecologically important areas. On the other hand, the Mwanza Gulf is a significant transport corridor heavily used for shipping and ferrying from Mwanza City to nearby towns such as Sengerema, Ukerewe, and Bukoba. In addition, this area is used as a direct extracted point of water for domestic use by the riparian communities in Mwanza City and neighbouring regions such as Shinyanga and Tabora. Furthermore, some areas of the Mwanza Gulf are used for security purposes. In addition, the well-known cultural and recreational sites like Bismarck Rocks and the Saanane Island National Park are located in the Mwanza Gulf. Therefore, Mwanza Gulf offers an ideal area to study multiple factors and competing interests for sustainability of Lake Victoria.

2.2 | Assessment of ecologically sensitive areas

The ecologically sensitive areas (ESAs) around the Mwanza Gulf included the entire shoreline area, Islets, riparian wetlands, sheltered bays, rocky outcrops, river mouth, and protected areas (LVBC, 2011). These areas act as important nursery grounds, fish breeding habitats, and refugia in Lake Victoria (Aura et al., 2019). These areas need to be avoided and protected during cage aquaculture development. Maps for islets and shorelines were digitised in high-resolution Google Earth images. The maps for sheltered bays, submerged rocky outcrops, and river mouths designated as ESAs were sourced from the TAFIRI—Mwanza Centre Office. The digital shapefiles for the boundaries of the Saanane National Park were obtained from the Saanane National Park Office (Mwanza Centre). Furthermore, data for the fringing wetlands were obtained by classifying Sentinel 2 satellite level 2A imagery in Google Earth Engine (GEE) using the Random Forest method (Amani et al., 2019). The classification was based on median imagery created by compositing images acquired between June and September 2019.

To conform with the local regulations, we generated buffer zones around all layers of ESAs (Table 1) following Lake Victoria Fisheries Organization guidelines (LVFO, 2018). We assumed a steady increase in site suitability as one moves away from the outer margin of the buffer zone of the constrained areas (ESAs). Therefore, we used a Euclidean distance tool in ArcGIS 10.8 to create distance raster layers as proxy indicators for suitability. The maximum limit of the Euclidean distance from the outer margin of the ESA was set as the shoreline

TABLE 1 Buffer zones around ecologically sensitive areas in the Mwanza Gulf.

Criterion	Buffer distance
Shoreline area	200 m
Islets	500 m
Wetlands	500 m
Sheltered bays	500 m
Rocky outcrops	500 m
River mouth	3 km
Protected area	500 m

Note: The buffer distances were adopted from LVFO (2018).

layer. In the northern part, where the gulf connects to the open lake, the limit was arbitrarily defined to include only areas with a depth of less than 20 m and less exposure to the open and turbulent lake, as these areas are currently preferred for small-scale cage fish culture. All the maps for various ESAs including their buffer zones are presented in Figure S1.

2.3 | Assessing socio-economic constraints

Pre-existing socio-economic activities limit the availability of certain areas for cage aquaculture due to conflicts with other users (Hofherr et al., 2015; Njiru et al., 2019; Ross et al., 2013). This study identified major socio-economic activities that make certain areas of the Mwanza Gulf unavailable for fish cage culture. These included (1) existing domestic water extraction points, (2) recreational sites, (3) navigation lanes for ships and ferries, (4) important traditional fishing grounds, (5) areas of security interest or activities, (6) established harbours, and (7) fish landing sites.

We mapped the spatial location of these activities through feature digitisation in Google Earth. The mapping process was participatory; it featured all key user groups from the mentioned activities, including cage fish farmers. Accordingly, we adopted the LVFO (2018) guidelines to generate buffer zones around the areas used for the abovementioned activities. Similar to the assumption made under the ESAs, the site suitability was assumed to decrease as one moves close to the buffer zone of conflicting water uses. The buffer zones delineated are indicated in Table 2. All the boundary maps for various activities that use water space are presented in Figure S2.

Besides human activities, we also considered the distance from the cage culture location to the land-based facilities as an additional socio-economic consideration. This is because it influences access to the cage culture sites while delivering goods and services and ease of patrol and monitoring. In this regard, we considered land-based features such as shorelines, fish landing sites, and roads as additional socio-economic activities. Layers of distances from these features were generated by using the Euclidean tool in ArcGIS 10.3. The limit of Euclidean distances was set to be consistent with the Euclidean distances from the ESAs.

TABLE 2 Buffer zones around areas of pre-existing socio-economic activities in the Mwanza Gulf.

Activity	Buffer distance	Reference
Existing domestic water extraction points	1 km	LVFO (2018)
Recreational facilities	500 m	LVFO (2018)
Navigation lanes for ships and ferries	500 m	LVFO (2018)
Important traditional fishing grounds	1 km	LVFO (2018)
Areas of security interest or activities	2 km	This study
Established harbours	500 m	LVFO (2018)
Fish landing sites	500 m	LVFO (2018)

2.4 | Determination of water quality parameters

Good water quality is critical for the health and growth of cultured fish and must fall within its tolerance ranges (Shoko et al., 2014). This study considered temperature, chlorophyll-*a*, suspended sediment, turbidity, Secchi depth, and dissolved oxygen as critical parameters in tilapia cage culture (Table 3). We selected water quality parameters for tilapia because it is currently the most important fish species cultured in cages in Lake Victoria (URT, 2023). These parameters were selected based on the guidelines for cage fish farming in the East African Community (LVFO, 2018), expert opinions, and data availability.

Temperature, chlorophyll-*a* concentration, suspended sediment, turbidity, and Secchi depth are typical data that can be extracted from satellites and used in aquaculture research (Ross et al., 2013). We used GEE to pre-process Sentinel 2 Surface Reflectance (SR) and Landsat-8 satellite Thermal Infrared Sensor (TIRS) into median composite imageries for dry (June to September) and wet (December to March) seasons between June 2016 and September 2020. Landsat-8 satellite TIRS were used to estimate the water temperature according to Bonansea et al. (2015). On the other hand, Sentinel 2 SR median composites were used to estimate chlorophyll-*a* concentration suspended sediment, turbidity, and Secchi depth. All these satellite-derived water quality parameters were validated using in situ match-up data obtained from the TAFIRI office and field measurements. The difference between the satellite imageries and field data samples was ±2 weeks.

Unlike other selected parameters, dissolved oxygen has no detectable spectral signal and cannot be measured directly from remote sensing data (Topp et al., 2020). We, therefore, generated map layers for dissolved oxygen concentration based on spatial interpolation techniques of in situ measured data (Mantzafleri et al., 2009). We used in situ data from TAFIRI (collected from 2016 to 2020), while additional field measurements were collected during the dry season (June to September 2019) and wet season (December to March 2020), using a DO meter (Yellow Springs Instrument model 57). The maps indicating the average conditions of selected water parameters

TABLE 3 Recommended ranges for water quality variable in tilapia culture.

Variable	Recommended ranges for tilapia culture	Reference
Temperature (°C)	27–31	Loka et al. (2012)
Chlorophyll-*a* (g/L)	1–15	Bhatnagar and Devi (2013)
Suspended sediment (mg/L)	<10	Loka et al. (2012)
Turbidity (Nephelometric turbidity units - NTU)	30–80	Bhatnagar and Devi (2013)
Secchi depth (m)	>0.7	Aura et al. (2021)
Dissolved oxygen (mg/L)	>5.0 and <9.5	Asmah et al. (2021)

(between 2016 and 2020) in the Mwanza Gulf are presented in Figure S3.

2.5 | Evaluation of physical environmental parameters

Information on the physical characteristics of the potential sites is important for cage aquaculture production (Falconer et al., 2013). This study considered bathymetry and relative wave exposure index (REI), which represents the effect of exposure to wind-driven waves (Burrows et al., 2008; Garcon et al., 2010). These parameters were selected based on their importance in site selection, as reported in previous studies (Martin et al., 2021; Navas et al., 2011; Vianna & Filho, 2018). Sufficient depth below the cage bottoms (>4 m) facilitates water exchange, allowing dissolved oxygen exchange and dispersion of accumulated uneaten feeds, faecal materials, and debris before settling to the lake bottom.

This study used Sentinel 2 L2A SR imageries acquired from 1 June to 31 August 2019 to retrieve water depth. The images were first pre-processed in GEE to remove clouds and associated shadows. The images were downloaded and exported into the R software (R Core Team, 2021) for further analysis. The bathymetry was retrieved by using the support vector machine (SVM) algorithm, which yielded the best accuracy after comparing it with other commonly used methods such as Stumpf Method (Stumpf et al., 2003), Random Forest (Breiman et al., 2001), Gradient Boosting Machine (Friedman, 2001), Extreme Gradient Boosting (Kaixiang et al., 2020), and Artificial Neural Network (Grigorieva et al., 2017). We used log-transformed bands (band2/band3 and band4/band2), principal component analysis (PCA) outputs (PC1, PC2, and PC3), and on-site collected depth points to create raster layers of continuous water depth based on the SVM (see Mabula et al., 2023 for details).

On the other hand, an REI model for Mwanza Gulf was developed using the Wave Exposure Model (WEMo) 4.0 software and the Kriging technique in the ArcGIS 10.3 software (Fonseca and Malhotra, 2010). The inputs in the REI model were bathymetry (from this study), wind fetch, wind speed, duration, and direction data. Wind fetch, an unobstructed distance that wind can travel over water in a constant direction, is an important characteristic for open water because longer fetch can result in larger wind-generated waves (Rohweder et al., 2008). The wind-related data for the years 2015 to 2019 were obtained from the Tanzania Meteorological Agency (TMA) at Mwanza Airport weather station, ~1 km from Mwanza Gulf. Within the WEMo 4.0 software, the REI was computed by averaging the sum of the product between effective fetch, wind speed, and duration in a particular direction as per Equation (1) (Fonseca and Bell, 1998):

$$\mathrm{REI} = \left(\sum_{l=1}^{8} EffF_i \, V_i \, D_l \right) / 8, \tag{1}$$

where V_i is the wind speed for the *i*th direction, D_i is the wind duration for the *i*th direction, 8 is the eighth sectors of 11.25° intervals to account for irregularities in shoreline geometry that could misrepresent the potential of wind-generated waves (USCOE, 1977), and $EffF_i$ is the effective fetch for the *i*th direction.

The computation of the effective fetch was based on Equation (2). More details regarding the formulation procedures for REI are found in the National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum (Malhotra & Fonseca, 2007):

$$EffeF = \left(\sum_{j=0}^{4} f_j \cos\left(\frac{\pi}{16j}\right) + \sum_{j=5}^{8} f_j \cos\left(\frac{\pi}{16\,(j-4)}\right) \right) / \left(\sum_{j=0}^{4} f_j \cos\left(\frac{\pi}{16j}\right) + \sum_{j=5}^{8} \cos\left(\frac{\pi}{16\,(j-4)}\right) \right), \tag{2}$$

where *EffeF* is the effective fetch for the *i*th direction and *fj* is the length for *j* radiating ray after clipping to the shoreline and interrogating water depth. The maps for bathymetry and relative wave exposure are presented in Figure S4.

2.6 | Data organisation and standardisation for the GIS-MCE framework

The numerous data obtained were organised into a spatial database (in ArcGIS 10.8 software) with four thematic layers: ecological, socio-economic, water quality, and physical factors. For each thematic layer, we organised the individual datasets into either constraints (criteria that eliminate the geographic space from consideration) or factors (criteria that provide feasible space for conducting the activity and enhance site suitability) based on user preferences (Malczewski & Rinner, 2015). After obtaining the constraints and factors, the next step

TABLE 4 Classification scheme for variables within sub-models developed for cage sites in the Mwanza Gulf.

		Classification				
Sub-model	**Criterion**	**Unsuitable (score = 1)**	**Less suitable (score = 2)**	**Suitable (score = 3)**	**Most suitable (score = 4)**	**Reference**
ESA	Shoreline area (km)	<0.2	0.2–0.4	0.4–0.6	>0.6	LVFO (2018)
	Islets (km)	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
	Wetlands (km)	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
	Sheltered bays (km)	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
	Rocky outcrops (km)	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
	River mouth (km)	<3	3.0–6.0	6.0–9.0	>9.0	LVFO (2018)
	Protected area (km)	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
Socio-economic	Domestic water extraction points (km)	<1	1.0–2.0	2.0–3.0	>3	LVFO (2018)
	Recreational sites	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
	Navigation lanes for ships and ferries (km)	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
	Important traditional fishing grounds (km)	<1	1.0–2.0	2.0–3.0	>3	LVFO (2018)
	Areas of security interest or activities (km)	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
	Established harbours (km)	<0.5	0.5–1	1–1.5	>1.5	LVFO (2018)
	Fish landing sites (km)	<0.5	0.5–1	1–1.5	>1.5 and <3	LVFO (2018)
	Distance to land-based facilities (km)	>1	1–0.7	0.7–0.5	<0.5	This study
Water quality	Temperature (°C)	>30 and <24	<28–26	<28–26	30–28	Loka et al. (2012)
	Chlorophyll-*a* (g/L)	<0.5	<1.5–0.5	<4.5–1.5	7.5–4.5	Bhatnagar and Devi (2013)
	Suspended sediment (mg/L)	>10	10–7.5	7.5.0–2.5	<2.5	Loka et al. (2012)
	Turbidity (NTU)	>50	40–50	30–40	<30	Bhatnagar and Devi (2013)
	Secchi depth (m)	<0.3	0.5–0.3	0.7–0.5	>0.7	Aura et al. (2021)
	Dissolved oxygen (mg/L)	<5	5.0–6.0	6.0–7.0	>7	Asmah et al. (2021)
Physical	Water depth (m)	≤4 or ≥10	<6–4	<8–6	<10–8	Beveridge (2004)
	REI	<2 and >10	2–3	3–5	5–8	Beveridge (2004)

Abbreviations: ESA, ecologically sensitive area; REI, relative wave exposure index.

was transforming the datasets in each thematic layer to a comparable scale. The constraint criteria were converted to 0 Boolean values, while the factor layers were rescaled from 1to 4 values, as unsuitable to most suitable conditions based on procedures suggested by Malczewski (2000). The scaling of individual factors in different suitability levels is shown in Table 4.

2.7 | Criteria weighting and aggregation of the GIS-MCE data

After transforming the datasets to a comparable scale, the next step was to estimate the weights for each criterion. The authors of this article (modellers) consulted 40 stakeholders with different interests in cage fish farming, following a practice suggested in previous studies on site selection (Aura et al., 2021; Ross et al., 2011, 2013; Soto et al., 2008) and EAA (Telfer et al., 2013). The stakeholders used in this study included fishers (9), fish cage farmers (6), aquaculture and ecology experts from TAFIRI (2), environmental experts from Lake Victoria Environmental Management Program (LVEMP) (2), Fisheries officers from District Councils (4), wildlife conservationist from Saanane National Park (2), environmental specialists from the Tanzanian Lake Victoria Basin Water Board (LVBWB) (2), ferry operators (4), Tanzania Ports Authority (TPA)—Mwanza Office (2), Police and Military officers (3), water quality technicians from Mwanza Urban Water Supply and Sanitation Authority (MWAUWASA) (2), and Kahama-Shinyanga Water Supply and Sewerage Authority (KASHWASA) (2).

We consulted the above stakeholders to understand the relative importance of various factors during sites selection for cage aquaculture. To achieve this, we used a well-known method called the 'analytical hierarchy process (AHP)', which was developed by Saaty (1977). AHP is a structured decision-making technique that helps

TABLE 5 Scales for pairwise comparisons.

Importance scale	Definition of importance scale
1	Equal important
2	Equal to moderately important
3	Moderately important
4	Moderately to strongly important
5	Strongly important
6	Strongly to very strongly important
7	Very strongly important
8	Very strongly to extremely important
9	Extremely important

Note: Adopted from Saaty (1977).

TABLE 6 The rationale for scoring and reclassifying cage culture suitability.

Suitability level	Score	Description
Constrained area	0	Restricted area due to conflicting uses or factors that prevent cage culture development
Unsuitable	1	Low score based on all criteria
Less suitable	2	Low suitability based on more than one criterion
Suitable	3	High suitability based on most criteria
Most suitable	4	Very high suitability based on all criteria

in comparing and prioritizing different criteria or factors. The participants in the study were asked to express their opinions on the importance of these factors. Each participant was required to perform pairwise comparisons of two factors at a time, rating the relative importance of one factor compared to the other on a scale from 1 to 9 (Table 5). A rating of 1 meant that the two factors were equally important, while a rating of 9 indicated that one factor was extremely important compared to the other.

To ensure the reliability of these pairwise comparisons, the researchers checked for consistency. The consistency was considered acceptable when it fell within the threshold of 0 to 0.1, as suggested by Saaty (1977). This step was important in ensuring that the participants' ratings were reliable and internally consistent (Saaty, 1977). Furthermore, we also estimated the level of group consensus among the stakeholders. To do this, we computed the consensus level by using the Shannon index, which is a mathematical measure used to assess diversity corresponding to the degree of agreement among the participants in this study (Goepel, 2013). A higher Shannon index indicates a higher level of group consensus among the stakeholders and vice versa. The group consensus was preferred over individual disparities to minimise evaluation mistakes and ensure that the final solution is of acceptable consensus and consistency among most stakeholders (Bahurmoz, 2006; Dong & Saaty, 2014; Le Pira et al., 2015).

After generating the AHP weights, we multiplied the AHP weights by their corresponding factor in each thematic layer. We then used weighted sum overlay tool (in ArcGIS 10.8) to aggregate the weighted datasets in each thematic layer into sub-models representing cage culture suitability maps as per Equation (3) by Malczewski (2000):

$$\mathbf{S} = \left(\sum_{\mathbf{j}} \mathbf{w_j r_{ij}}\right)\left(\pi_j \mathbf{r^*_{ik}}\right), \tag{3}$$

where r^*_{ik} is a value assigned to the *i*th cell on the *k*th constraint map layer, w_j is an AHP weight, and r_{ij} is the attribute transformed into the comparable scale.

We developed four suitability sub-models (maps), namely, ecological, socio-economic, water quality, and physical sub-models. These suitability sub-models were re-weighed and then combined into a final cage culture suitability map, reclassified into four suitability levels: most suitable, suitable, less suitable, and unsuitable (Table 6). Furthermore, the transition in site suitability levels between the overall model and its sub-models was examined by utilizing an alluvial diagram. This analysis was conducted with the *ggalluvial* package in the R programming environment (Brunson, 2020).

The overall suitable sites for cage aquaculture within the Mwanza Gulf were determined by combining the results from the four sub-models by using the GIS-MCE process (Figure 2).

3 | RESULTS

3.1 | Suitability of potential sites based on ecologically sensitive areas

In this study, the ESAs considered together with the buffer zones covered an area of ~143.88 km^2, which accounts for 44.24% of the total area of Mwanza Gulf. These areas were classified as 'constrained' (Figure 3). The order of importance based on AHP weights from most sensitive to less sensitive was protected area (0.39) > fringing wetlands (0.21) > sheltered bays (0.16) > rocky outcrops (0.08) > islands (0.04) river mouth (0.09) and shoreline (0.02). The stakeholders' consensus was high (97.20%), and the AHP consistency ratio was = 0.05, well within the recommended threshold of 0 to 0.1. It was identified that about 45.23 km^2 (13.91%) was unsuitable site, and 40.68 km^2 (12.51%) area was less suitable for cage fish farming. The unsuitable and less suitable sites were located near the constraint areas, mostly at the northern end of the gulf. The suitable and most suitable sites were 65.79 km^2 (20.23%) and 29.66 km^2 (9.12%), respectively (Figure 3). The suitable and most suitable areas were located in the innermost and southern parts of the gulf (Figure 3). Overlay analysis showed that 13 out of 15 existing tilapia cage farms (86.7%) were located in constrained and unsuitable sites. In addition, two existing tilapia cage farms (13.3%) were found in less suitable sites. In contrast, no existing farm was located in the suitable and most suitable sites.

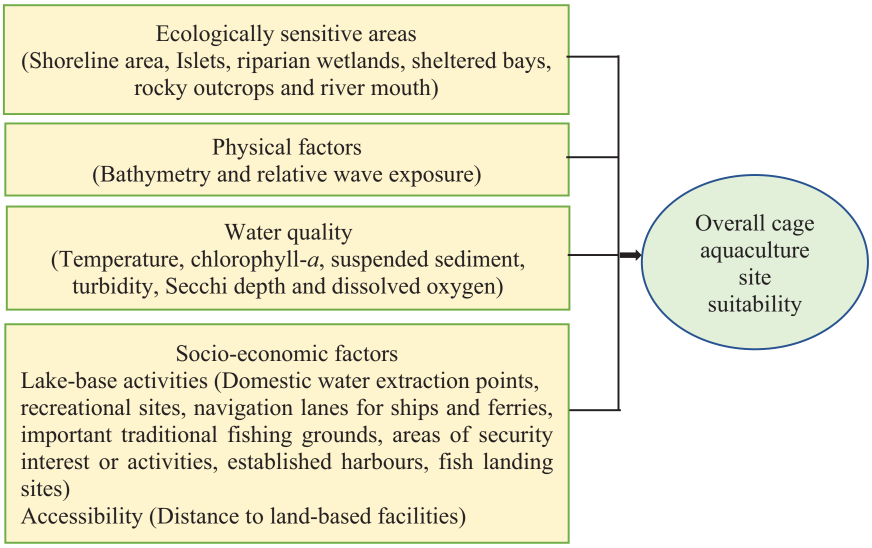

FIGURE 2 A geographic information systems-multicriteria evaluation (GIS-MCE) process for determining suitable areas for potential cage fish culture within the Mwanza Gulf.

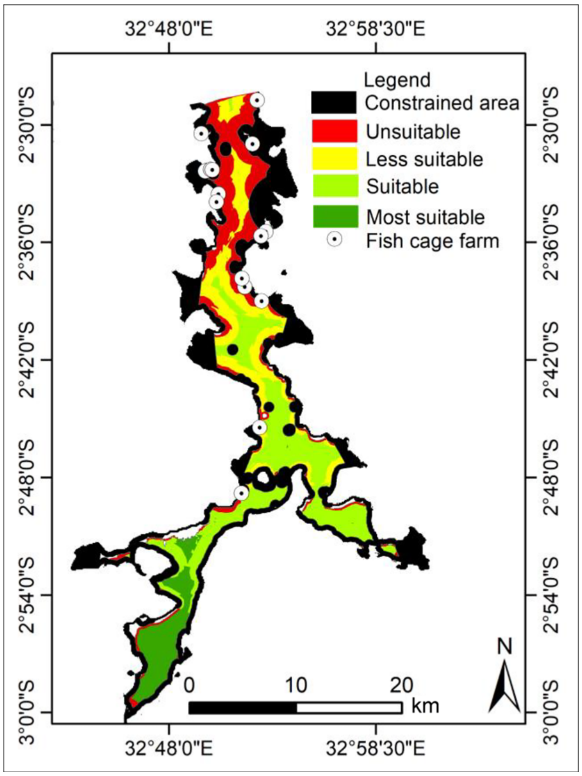

FIGURE 3 The suitability of the Mwanza Gulf sites to cage aquaculture based on ecologically sensitive areas and the existing fish cages.

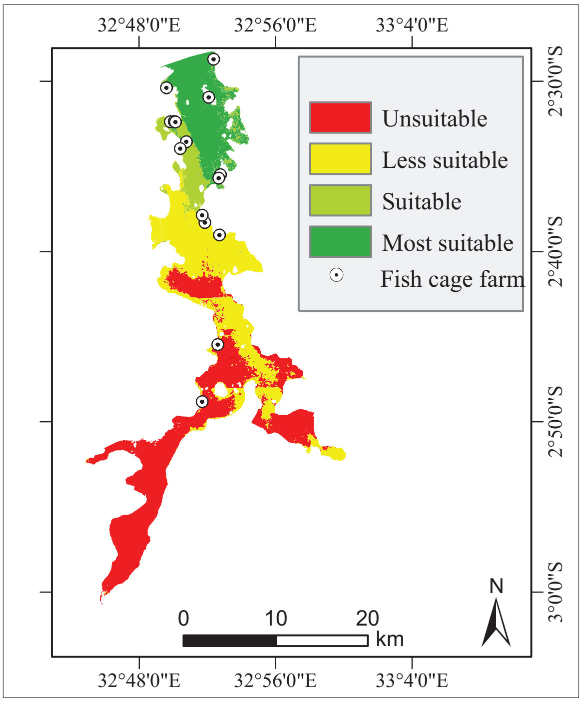

FIGURE 4 Suitability of the Mwanza Gulf based on water quality variables.

3.2 | Suitability of potential sites based on water quality parameters

The suitability levels for cage culture based on water quality criteria are presented in Figure 4. The order of importance, as determined by AHP weights, ranges from most important to less important, with dissolved oxygen ranking the highest at 0.33, followed by temperature at 0.27, and chlorophyll-*a*, turbidity, Secchi depth, and suspended sediments all sharing equal importance at 0.10 each. The resulting consistency ratio of the AHP pairwise comparison matrix was 0.04, falling within the recommended range of 0 to 0.1. The consensus among stakeholders was also high (90.20%).

In terms of site suitability, the most suitable areas encompassed ~60.74 km^2, constituting 18.68% of the Mwanza Gulf. Additionally, the suitable areas covered 27.39 km^2, equivalent to 8.42% of the total. Together, these most suitable and suitable sites accounted for a

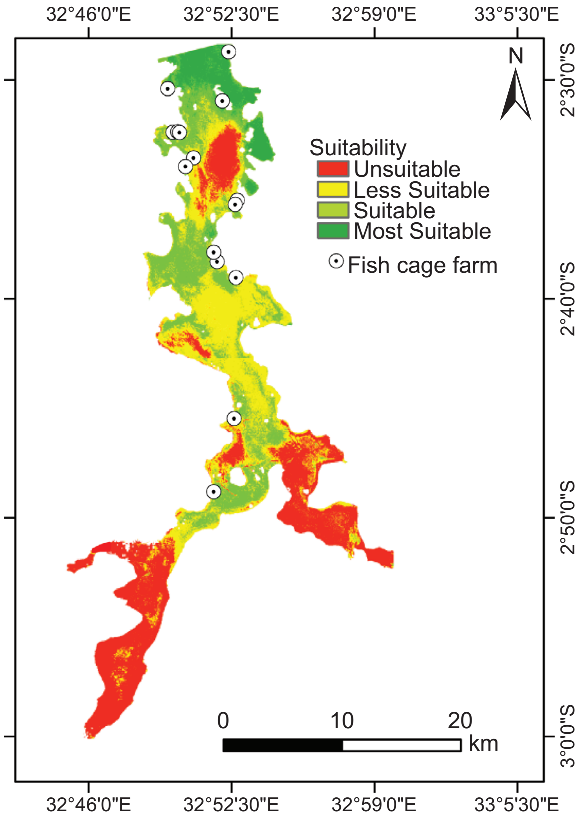

FIGURE 5 The physical suitability of the Mwanza Gulf based on bathymetry and relative wave exposure index (REI).

combined area of 88.13 km^2, representing 27.10% of the studied region, primarily concentrated in the northern parts of the gulf.

Conversely, areas considered less suitable and unsuitable extended over 101.04 km^2 (31.07%) and 136.07 km^2 (41.84%), respectively, comprising a substantial 237.11 km^2 (72.90%) of the study area. Furthermore, the findings revealed that only one existing tilapia cage was located in an unsuitable site. Of the 15 tilapia cage farms assessed, seven (46.7%) were situated in the most suitable sites, while three (20%) fell within the suitable sites. Conversely, four tilapia cage farms (26.7%) were situated in the less suitable areas (see Figure 4).

3.3 | Suitability of potential sites based on physical environmental parameters

Based on opinions from the experts, the water depth was more important (APH weight = 0.60) than the relative wave exposure index (APH weight = 0.40). The stakeholders involved had a high degree of consensus (90.60%) among participants. The consistency ratio for AHP pairwise comparison matrices was 0.07, within the acceptable threshold range of 0 to 0.1. The physical environmental parameters sub-model showed that ~30.26 km^2 (9.30%) of the gulf was most suitable and that 43.46 km^2 (13.36%) was suitable sites for cage aquaculture (Figure 5). The most suitable and suitable sites were restricted to the innermost-northern portion of the Mwanza Gulf. The results also showed that ~120.18 km^2 (36.95%) and 131.34 km^2 (40.38%) of the Mwanza Gulf were less suitable and unsuitable sites for fish cage aquaculture, respectively (Figure 5). The unsuitable areas were located at the southern end of the gulf (Figure 5). Overlay analysis indicated that 13 (86.7%) of the available tilapia cage farms were located in suitable sites and that two (13.3%) were situated in the most suitable sites. In contrast, no existing tilapia cage farm was located in areas considered less suitable or unsuitable sites.

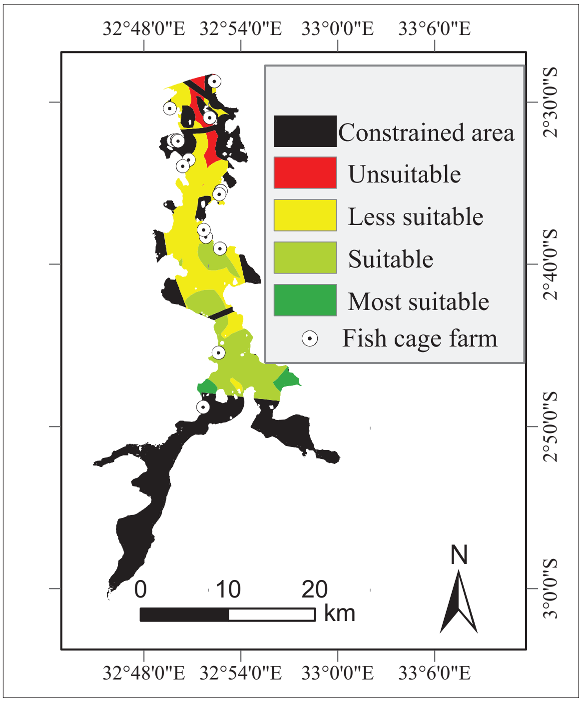

FIGURE 6 Cage aquaculture site suitability of the Mwanza Gulf based on the socio-economic criteria.

3.4 | Potential suitable cage sites based on socio-economic factors

The order of importance for socio-economic factors based on AHP weights from most important to less important was domestic water extraction points (0.22) > navigation lanes for ships and ferries (0.17) > areas for security activities (0.15) > established harbours (0.13) > fishing grounds (0.12) > landing sites (0.1) > recreational sites (0.09) > access to land-based facilities (0.02). The stakeholders involved in the analysis had a high degree of consensus (95.60%) among participants. The obtained consistency ratio for the AHP pairwise comparison matrices was 0.02, which falls within the acceptable range of 0 to 0.1.

Based on the socio-economic sub-model, 160.09 km^2 (49.22%) of Mwanza Gulf was classified as a constrained site. This site was predominantly located on the north-western side and the southern end of the gulf (Figure 6). A total of 10.55 km^2, ~3.24% of the gulf area, was categorised as unsuitable sites. The less suitable site occupied 84.97 km^2

(26.13%), while the suitable sites covered 62.68 km^2 (19.27%). Surprisingly, only 6.95 km^2 (2.14%) of the area was considered 'most suitable' site for fish cage culture. The results indicate that eight out of the 15 (53.3%) existing tilapia cage farms were located in less suitable sites, whereas five (33.3%) were operating in constrained sites. Only two (13.3%) tilapia cage farms fell in the suitable sites. No existing tilapia cage farms were located in the most suitable sites (Figure 6).

3.5 | Overall suitability of sites for cage fish culture in Mwanza Gulf

The final (overall) site suitability model integrated all the four sub-models of ecologically sensitive areas, socio-economic activities and access, physical factors, and water quality parameters. Based on the respondents' opinions, the ecologically sensitive areas sub-model was deemed most important, with an AHP weight of 0.42, followed by the physical environment (0.26), socio-economic activities and access (0.2), and finally, the water quality parameters (0.12). The overall consensus among stakeholders was high (94.80%). The consistency ratio for the AHP pairwise comparisons was 0.07, within the acceptable limit of 0 to 0.1.

The final site suitability model for cage culture in the Mwanza Gulf is presented in Figure 7. Spatial analysis revealed that 188.84 km^2 (58.06%) of the area was under the constrained site. Only 5.10 km^2 (1.52%) and 24.20 km^2 (7.44%) of the area of the Mwanza Gulf was suitable and most suitable sites for fish cage culture, respectively. These sites were in the inner parts of the Mwanza Gulf. Conversely, 42.63 km^2 (13.12%) of the area was identified as unsuitable sites, while 64.47 km^2 (19.82%) of the area was classified as less suitable sites for cage culture development. When the locations of the existing tilapia cage farms were visualised based on the final model, 12 (or 80%) cage farms were found in the constrained site, whereas only two (13.33%) were located in unsuitable sites and one (6.67%) in a less suitable site. In contrast, no existing tilapia cage farm was found in the suitable and most suitable sites.

3.6 | Transition in suitable fish cage sites in the overall model across the sub-models

When constructing the final model, we conducted an analysis of the variability in site suitability across the sub-models, as depicted in Figure 8, using an alluvial diagram. The results revealed that suitability levels in one model exhibited division and alterations in value when observed at precise spatial locations within the context of another model. For instance, areas previously designated as most suitable sites (indicated by a dark green colour) in the ESAs sub-model transitioned to unsuitable (indicated by red color) in the physical factor sub-model. Additionally, areas categorised as suitable sites in the ESAs (dark green colour) were further subdivided, ultimately being classified as less suitable and unsuitable sites within the physical factor sub-model.

Interestingly, the physical factor and water quality sub-models exhibited consistent findings concerning the positions of suitable sites. However, the sites deemed most suitable in the physical and water quality sub-models were reclassified as less suitable and constrained sites within the socio-economic sub-model. Moreover, the results demonstrated that a substantial proportion of the constrained sites in the overall model stemmed from the constrained sites identified in the socio-economic sub-model. The alluvial diagram effectively illustrates that each sub-model yields disparate outcomes concerning the suitability of potential fish cage sites.

4 | DISCUSSION

This study used the GIS-MCE approach to identify potential suitable sites for cage aquaculture in the Mwanza Gulf—Lake Victoria. The approach integrated ecologically sensitive areas, physical environment, water quality parameters, and socio-economic variables and incorporated the opinions of local people through AHP weights. Our findings indicate inconsistency in the location and size of suitable and most suitable areas across the individual sub-models. The areas identified as suitable and most suitable in the individual sub-models were relatively larger compared to their counterparts in the overall model. In addition, no suitable or most suitable sites maintained their status across all the individual sub-models (Figure 8). This is not surprising because each sub-model focuses on specific criteria. The observed inconsistency in the size and position of suitable sites based on the individual sub-models suggest their limited use in delineating potential sites. Relying solely on the individual sub-models or a few variables to select a site for cage aquaculture may overestimate suitable areas, leading to the inclusion of unsuitable sites or an inability to locate suitable sites. Including unsuitable areas or an inability to locate suitable sites may result in conflicts with conservation objectives and other water users as reported in other countries such as Turkey (Hofherr et al., 2015) and China (FAO, 2022). Therefore, it is advisable to utilise individual sub-models solely as an initial step in the process of constructing the overall model, rather than relying on them as independent tools for making the final decision in fish cage site selection.

The overall model revealed a relatively small area suitable for cage fish farming, accounting for 24.20 km^2 (7.44%), with the most suitable sites covering 5.10 km^2 (1.52%). Notably, a substantial portion of the Mwanza Gulf, ~58.06%, was deemed unsuitable for fish cage culture installation due to constraints arising from multiple factors. This outcome aligns with findings from other regions, including Lake Victoria in Kenya (Aura et al., 2021), and various other studies (Asmah et al., 2021; Njoku et al., 2022; Ross et al., 2011). The limited extent of suitable sites identified by the overall model is attributed to its comprehensive approach to fish cage site selection. The overall model takes into account various factors such as ecologically sensitive areas, the physical environment, water quality parameters, socio-economic variables, and stakeholder opinions. This holistic approach aligns with the need to estimate ecological, production, and social carrying capacities (Landuci et al., 2020; Ross et al., 2013) and ensures compliance with local

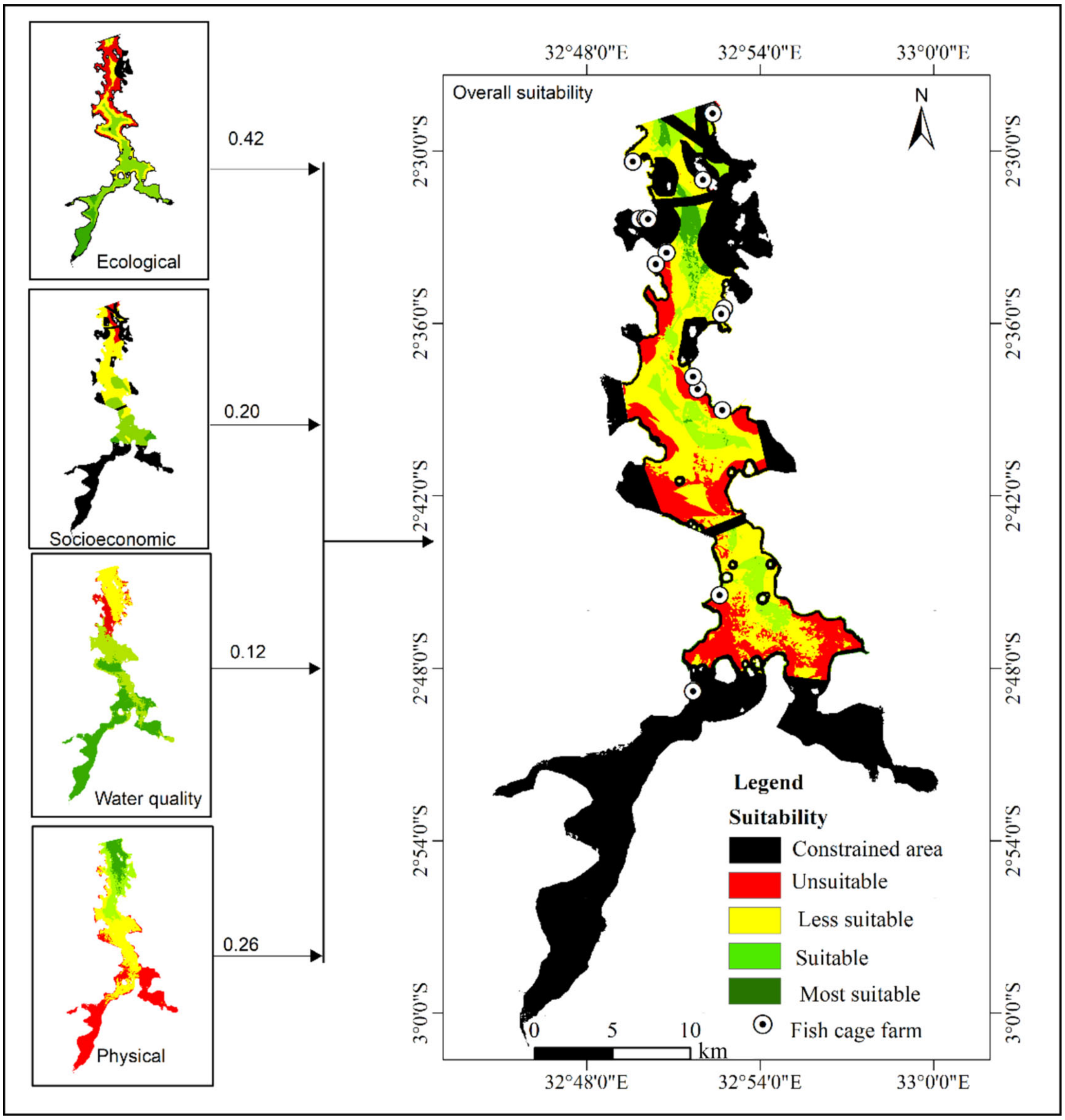

FIGURE 7 The final (holistic) site suitability model for cage aquaculture in the Mwanza Gulf.

regulations and the East African Community's requirements. Therefore, the overall model holds the potential to ensure the sustainable development of fish cage culture in Lake Victoria when implemented adequately.

The GIS-MCE overall model represents a proactive method for integrating multiple criteria and spatially revealing potential sites across a large area. Compared to conventional field surveys and current strategic EIAs, this method improves significantly cage site selection. This approach is particularly vital for addressing the growing demand for fish production without jeopardizing the lake ecosystem and the well-being of riparian communities, a crucial concern in the Lake Victoria, which is currently facing various threats such as eutrophication (Abo-Taleb et al., 2023; Olokotum et al., 2020), overfishing (Outa et al., 2020), and climate change (Luhunga & Songoro, 2020). Thus, the GIS-MCE overall model can be applied not only in Lake Victoria but also in other aquatic environments to identify suitable sites for fish cage investments, contributing to the conservation of aquatic ecosystems.

To illustrate the utility of the GIS-MCE approach in site selection, we examined existing tilapia cage farms in the Mwanza Gulf by using both the sub-models and the overall model. Intriguingly, the physical sub-model indicated that all existing tilapia cage farms were situated in suitable (86.3%) and most suitable (13.7%) sites. However, when the existing tilapia cages were assessed by using the overall model, none of the fish cages were located in suitable or most suitable sites. Instead, the overall model revealed that 80% of the installed tilapia cages in the Mwanza Gulf occupied constrained areas, 6.67% were in less suitable sites, and 13.33% were in unsuitable sites. This discrepancy highlights a limitation in the conventional EIA approach, which is typically undertaken for fish farm licensing (van der Heijden & Shoko, 2018). These EIAs are often customer driven, focused on a single site, and consider limited variables such as water depth and water quality

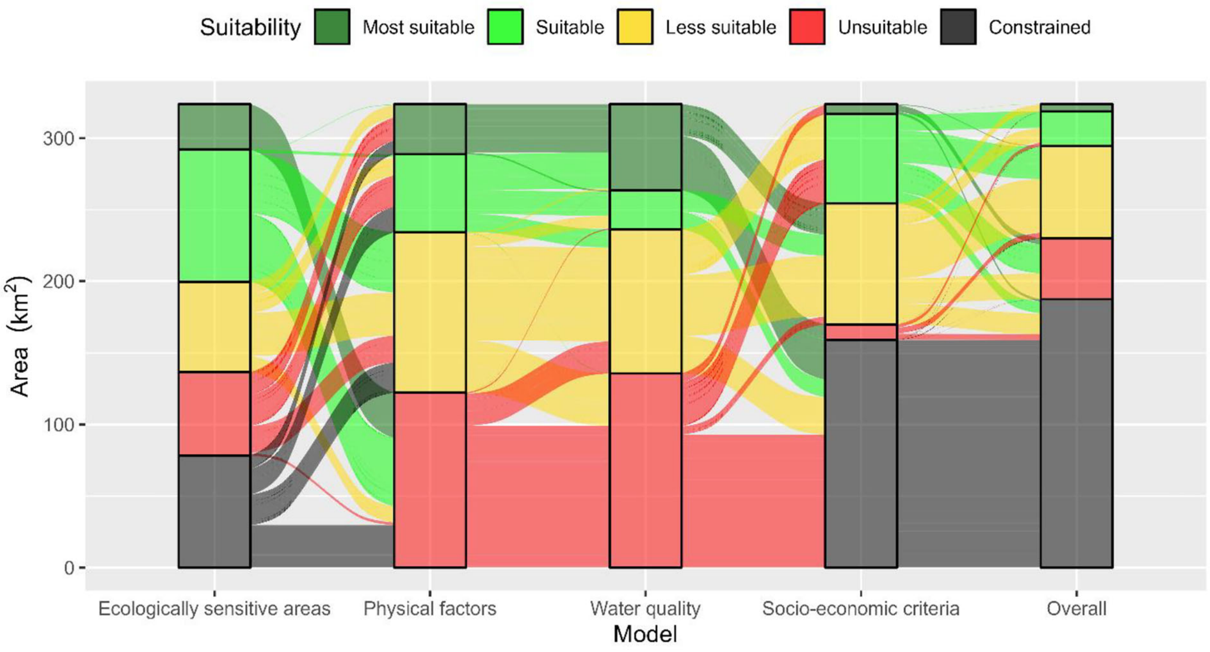

FIGURE 8 The alluvial diagram showing the changes in area suitability in sub-models through the overall model. *Note*: The columns represent the suitability models, which consist of the overall model and sub-models for ecologically sensitive areas, physical environment, water quality, and socio-economic criteria. These columns are horizontally connected by wide coloured lines that illustrate divergent and convergent suitability status in the final model in the context of the sub-models. The width of each line represents the area size that converges or diverges in the preceding and proceeding suitability model.

parameters. Such an approach lacks the capacity to identify proactively the suitable sites across multiple criteria over a broader area, as demonstrated by the sub-model results in this study. Consequently, it falls short in assessing the suitability of tilapia cage aquaculture sites comprehensively. Our study underscores the efficacy of the GIS-MCE, particularly the overall model, in addressing this limitation. It provides a spatially explicit representation of cage culture site suitability across the entire Mwanza Gulf. We recommend the adoption of GIS-MCE by the lake management authorities to determine available sites for potential tilapia cages, both for current investments and future initiatives in Lake Victoria.

However, it is essential to acknowledge certain limitations in our study. First, while we utilised the relative exposure index as a proxy for wind-generated waves, we did not directly investigate actual water currents and wave patterns in the Mwanza Gulf. This limitation prevents a comprehensive assessment of the winds' ability to disperse and flush out waste materials from cage aquaculture into the open water, which is crucial for understanding potential eutrophication in the lake environment. Second, the GIS-MCE models employed in this study are static and do not adapt dynamically to unforeseen changes resulting from socio-economic and environmental factors, including unprecedented human population growth in the region (McGranahan et al., 2020). Exploring the transformation of these static models into intelligent, data-driven spatial tools, such as the Norwegian AquaSpace model (Strand et al., 2017), presents a promising avenue for future research and refinement of site selection methodologies.

5 | CONCLUSION

Our study used a GIS-MCE approach, which integrates multiple criteria that vary in space and carry different weights to select suitable sites for fish cage culture in the Mwanza Gulf of Lake Victoria. The study found that individual sub-models are ineffective in designating potential sites for fish cage culture and thus should not be used solely. The GIS-MCE overall model as a holistic approach combining all criteria is appropriate for selecting suitable sites for fish cage culture. The GIS-MCE overall model showed its usefulness by indicating that most of the available tilapia cages are located in less recommended sites of the Mwanza Gulf. Therefore, fish farmers and managers should use the GIS-MCE overall model for complying with licensing requirements. Future studies are required on the assessment of waves and currents at the gulf, estimation of carrying capacity for sustainable cage aquaculture industry, and converting the used static GIS-MCE models to live and interactive methods.

AUTHOR CONTRIBUTIONS

Makemie Jumanne Mabula: Conceptualisation; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; validation; visualisation; writing—original draft; writing—review and editing. **Danielson Kisanga**: Supervision. **Siajali Pamba**: Supervision. **Samwel Mchele Limbu**: Writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data that support the findings of this study are available from the corresponding author upon reasonable requests.

ETHICS STATEMENT

This study did not involve animal experimentation. All human subjects gave their consent before participation.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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