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Use of scenarios with multi-criteria evaluation to better inform the selection of aquaculture zones

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ABSTRACT

The allocation of zones for aquaculture development is a strategic problem as it involves long-term outcomes and many stakeholders with competing interests. Resource planners require tools to support such complex allocation decisions, but these are either lacking or with serious limitations. This paper presents an approach that improves the traditional method of developing aquaculture zoning model. Four scenario narratives describing potential development pathways for aquaculture in Nigeria were used to guide the model development, from selection of suitability factors to evaluation of alternatives. The modelling objective was to identify a suitable location for zoning small-to-medium scale commercial pond catfish production in Nigeria. So, a GIS-based multi-criteria evaluation (MCE) was used to produce a suitability map, from which five alternative zones were extracted. These zones were then compared using three sustainability criteria that were designed based on future uncertainties highlighted by the four scenarios. Results show that 4 of the 5 zones are concentrated in the north-eastern part of Nigeria, while the other one occurred in the north-west. Furthermore, this study found two top-ranking zones that can be selected in all the scenarios, meaning the two zones with the most potential to support the sustainable development of small-to-medium scale aquaculture in Nigeria. As these two were almost tied in ranking, sensitivity analyses across the scenarios revealed the most stable zone to changes in the criteria scores. These findings can be used to inform aquaculture expansion policy in Nigeria and integrate the activity into wider land use planning. Overall, the new approach advances the traditional method of developing GIS-based MCE models for aquaculture zoning, as it generates options and relevant information to facilitate strategic decision-making.

1. Introduction

Spatial planning is the procedure employed by authorities at different levels to distribute people, infrastructure and activities in a manner that addresses their social, economic, and environmental concerns (Taylor, 2010). Spatial planning is also an essential part of promoting sustainable aquaculture development (Brugère et al., 2019; FAO, 2013), and research efforts focused on developing tools for aquaculture siting are usually location-specific, primarily based on Geographic Information Systems (GIS) and spatial models (Falconer et al., 2018). Given the growing competition for space and resources, as well as new challenges due to climate change, it is becoming increasingly important to improve on existing tools for aquaculture spatial planning, in terms of scope and usability (Falconer et al., 2020).

With many different activities competing for natural resources, aquaculture zoning can be a way of managing aquaculture development in the most appropriate location. An aquaculture zone is an area that is specifically designated for aquaculture purposes. Aquaculture zoning must be strategic, especially as it involves long-term development goals, and resource allocation is complicated with conflicting objectives and interacting uncertainties (Aguilar-Manjarrez et al., 2017; Couture et al., 2021). For strategic decision-making, the factors considered for modelling the suitability of areas for aquaculture need to be evaluated against potential future changes. Ellen et al. (2016) suggest the conditions for strategic planning to be effective as follows: participatory, transparent, comprehensive, rigorous, and scenario based. Therefore, spatial tools for aquaculture zoning should be responsive to diverse views from stakeholders and future uncertainties, while generating development options, to enhance their applicability and longevity in tackling real-world challenges.

In strategic planning, scenarios are defined as plausible and simplified descriptions of how the future may develop (Schoemaker, 1995;

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Van Der Heijden, 1996). In other words, scenarios are narratives developed to stimulate thinking about possible future occurrences with a view to developing alternative action plans (Alcamo, 2008; Jarke et al., 1998). The capability of scenarios to serve multiple purposes during planning, explains the considerable attention it has received from both researchers and practitioners, particularly in changing the world-view of decision makers (Malinga et al., 2013; Ram and Montibeller, 2013; Trutnevyte et al., 2012). However, it should be recognized that a scenario is not a prediction or representation of future reality but a critical way of thinking about the future as documented by those involved in the scenario development (Godet, 2000).

Scenario-based modelling has been used in various fields of study such as Transportation planning (Schroeder and Lambert, 2011); Human-Computer Interaction and Software Engineering (Jarke et al., 1998). The general concept of a scenario-based modelling approach is that scenario narratives are used to provide context for the design, development, and use of decision support tools (Alcamo et al., 2011; Delen, 2019; Hertzum, 2003; Jarke, 1999; Rosson and Carroll, 2002). Hence, aquaculture site suitability modelling that is scenario-based can focus on usability through the anticipation of future changes along with potential implications on what and how factors are selected and weighted. Land can be used in many ways, for a range of environmental, social, and economic purposes, and there will be different priorities depending on the stakeholders involved (Kaim et al., 2020). Differences in priorities manifest in the suitability factors and thresholds that are considered in building a model as well as the relative importance (weighting) used to combine these factors through Multi-Criteria Evaluation (MCE). Also, considering that aquaculture development does not occur in isolation from other land use change, the use of common modelling approach that indicate the suitability of areas only based on current conditions may not provide sufficient information for decision makers during aquaculture zoning. Thus, it may be useful to develop new modelling approaches that identify a range of potential zones as well as short- and long-term changes in the modelled suitability factors that can indicate potential conflict areas with other developments, such as agriculture and housing.

Use of scenarios together with GIS-based site suitability models can help aquaculture planners identify suitable locations for development based on the potential interventions that will be needed to allow aquaculture to meet a particular goal. A set of scenarios to 2035 was previously developed by Yakubu et al. (2022) for pond aquaculture in Nigeria, portraying how key issues currently facing the sector might evolve and shape its future, including opportunities and risks (insights) for planning. The four scenarios developed represented four different futures; i) business as usual, ii) unsustainable development, iii) long-term planning initiatives for development of the sector, and iv) reduced support for the sector. The results indicate that across all scenarios it will be difficult to achieve the Government's estimate of 2.5 million metric tonnes (mt) production in 2035 without interventions (Yakubu et al., 2022). A potential intervention strategy could be to identify suitable zones for small-to-medium scale commercial aquaculture, with the goal of enhancing the sector's contribution to poverty alleviation. With a long-term vision for sustainable development, the associated socio-economic benefits would also attract further support and interventions that could increase opportunities to expand the sector in Nigeria. Thus, the aim of the present study was to use scenarios to develop a GIS-based MCE approach for aquaculture zoning at a national scale in Nigeria, with focus on African catfish production. The first step involved developing a GIS-based aquaculture suitability model. Then five zones (each approximately 200 km^2) were identified as the top 5 clusters with the highest sum of modelled areas (pixels) suitable for aquaculture development The final step was to compare the zones using some key sustainability criteria highlighted by the scenarios, i.e., seasonal variation, long-term variation, and potential conflict with rice-producing areas.

2. Study area and future scenarios for aquaculture development

Nigeria is the most populous country in Africa with a population of approximately 200 million, which is projected to double by 2050 (UN., 2019). The country is divided into 36 states with varying population densities. About half of the population lives in urban areas. This is growing along with total population, causing increased pressure on the country's diverse natural resources, from the tropical rainforests in the south to the Sahelian savannas in the north (CILSS, 2016). The time series mapping of land use and land cover in Nigeria between 1975 and 2013 shows a considerably changing landscape, mostly to agricultural land (Tappan et al., 2016). There is approximately 127,000 km^2 of protected land area (14 % of Nigeria's total area), most of which is forest reserve (UNEP-WCMC, 2019), and therefore not available for aquaculture use.

There are two seasons in Nigeria, but the timing of these varies with geographical location. The wet season lasts from March to November in the south and from May to October in the north (NIMET, 2018). The day and night temperatures range between 30 and 38 °C and 19-25 °C respectively in the north, 30-32 °C and 20-23 °C in the central and 28-32 °C and 19-25 °C in the south. However, there are some notable high elevation areas (Fig. 1) where daytime temperatures rarely exceed 25 °C. The mountain, Chappal Waddi in Taraba state is the highest elevation point in Nigeria, although most of Plateau state is on very high elevation in contrast to the rest of the country, making it the coldest state. The annual rainfall increases southward from 500 mm in the north to about 2000 mm, with the Niger Delta region recording up to 3500 mm (NIMET, 2018).

Aquaculture especially of African catfish (*Clarias gariepinus*) is an important industry in Nigeria, providing a vital source of nutrition, income, and employment. Catfish production takes place mostly in static water ponds and tanks, with groundwater as a major water source. The earthen ponds are wholly or partially dug into the ground. Similarly, concrete ponds built using concrete/bricks may be cast below ground level, although most concrete ponds extend above the ground. Grow out ponds have depths ranging between 1.2 and 2 m. In some cases, the earthen pond walls are reinforced with stones, sandbags, or sand-filled tyres. The configuration of the water inlet and outlet largely depends on the water source. A farm that is supplied by borehole water is more likely to have an overhead water inlet pipe with an outlet made up of stand/elbow pipes. For such farms, slope has more to do with pond layout and construction cost than water management. A full production cycle takes 6 months, from stocking juvenile fish of approximately 30 g to harvesting 1.2 kg average weight. Stocking density varies between one and ten catfish/m^2 in earthen ponds. Farmers use sinking or floating pellets, which are either imported or locally produced. However, farm accessibility is key for a successful business. Aquaculture business in Nigeria is private sector-led, motivated by the increasing fish demand (Anetekhai, 2013; Jamu et al., 2012), although, it is also being used by government and NGOs in the fight against poverty in rural areas. The increase in clustering of fish farms in peri-urban areas (Miller and Atanda, 2011) is also noteworthy, given the potential benefits such as better access to support services. However, there is little or no mechanism for collecting statistical information required for planning and management of aquaculture throughout Nigeria.

3. Methodology

The approach in this study (Fig. 2) was framed in Simon's model for decision making (Simon, 1977). According to Simon (1977), every decision-making task can be classified into three broad phases: intelligence, design, and choice. The traditional practice of suitability modelling for aquaculture is that problem definition and identification of data requirements are done in the intelligence phase, but often considering only past to present situation of relevant factors. The design phase involves data reclassification and weighting based on perceived

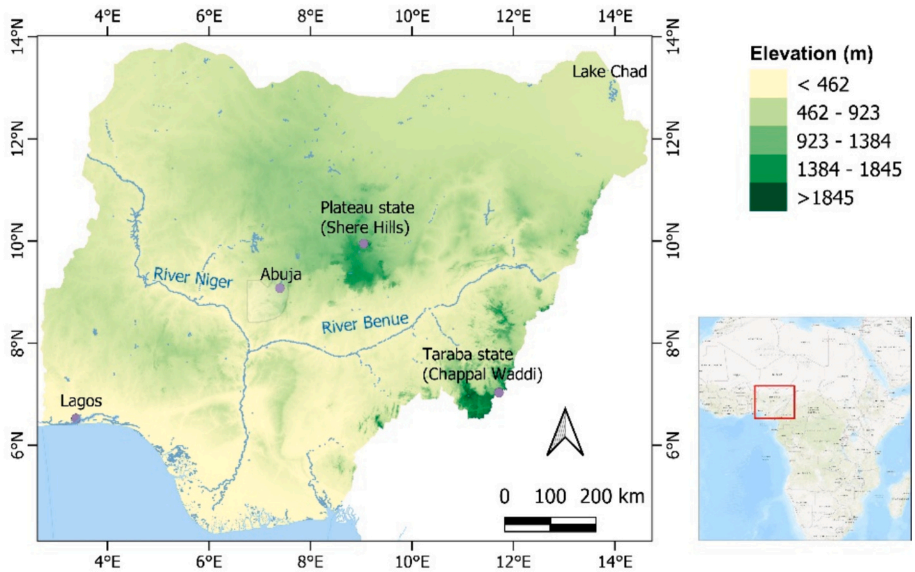

Fig. 1. Relief map of Nigeria (Data source: Jarvis et al., 2008) with two very high elevation points in Taraba and Plateau states. Abuja is the federal capital and Lagos, the commercial hub of Nigeria.

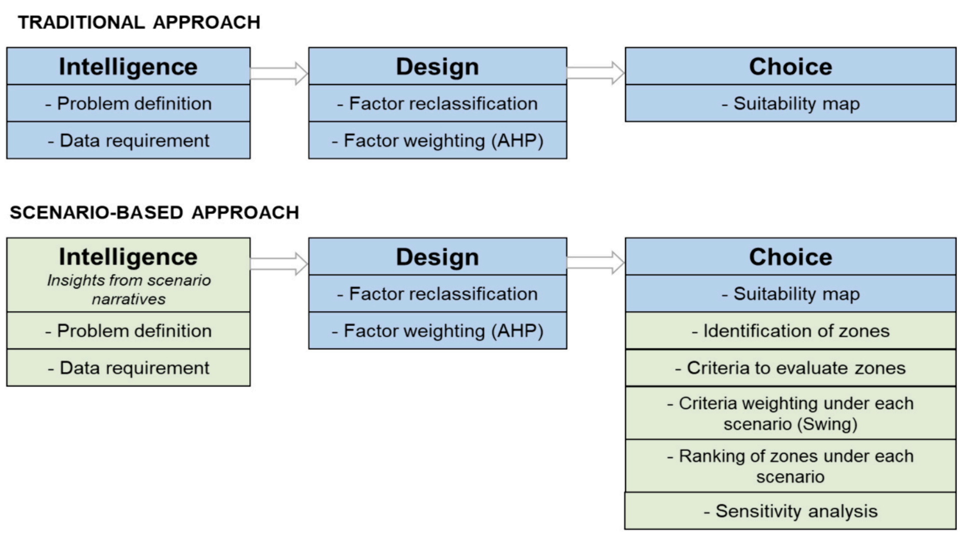

Fig. 2. Conceptual diagram of the modelling process showing differences between the traditional (blue) and the additional proposed scenario-based approach (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relative importance. The MCE, which generates a map indicating suitable areas, is done in the choice phase.

While the traditional practice produces a general output of areas suitable for aquaculture and can be used to identify potential zones (blue in Fig. 2), the scenario-based approach builds on this by enabling a further evaluation of the zones (green in Fig. 2). This can better inform allocation decision that is strategic (i.e., anticipates and incorporates potential future changes of suitability factors or scenarios into planning). Therefore, the most suitable zone is that with the highest aggregate score or ranking across the different scenarios.

3.1. Intelligence phase: problem definition and data requirement

According to the scenario narratives in Yakubu et al. (2022), land and water resource regulation and climate change will pose problems for aquaculture in the future. This means that, to future-proof aquaculture development, there is need to identify areas that are most suitable for aquaculture now and potentially in the future. Thus, the overall goal of this modelling exercise was to identify such areas at a national scale, targeting small-to-medium scale commercial farming of African catfish. Small-to-medium scale commercial farming was prioritized because of its high potential contribution to poverty alleviation, and thus could attract further support through government policies and external investments.

To identify the suitability factors that would be included in the zoning model, i.e., the factors that determine the suitability of a location for pond aquaculture, the key drivers of aquaculture in Nigeria found in Yakubu et al. (2022) were used to categorize and specify factors (Table 1).The categories, ‘water requirement’, ‘pond construction’ and ‘land cover’ considered two key drivers — land use regulation and climate change. Other categories, ‘social and economic environments’ were linked to input availability and the role of government policies in shaping aquaculture business. As the study focuses on pond aquaculture system, the following constraints (land areas where aquaculture cannot or should not take place) were used: protected areas, urban centers, waterbodies, and areas with very steep slopes.

Table 1
Summary of factors and constraints dataset. Note that 1 arcsecond is equivalent to 30.9 m at the equator.

	Category	Layer	Data (unit)	Format (original resolution)	Data source
Factors	Water requirement	Rainfall	Precipitation (mm/month)	Raster (30 arcseconds)	WorldClim 2.0 (Fick and Hijmans, 2017)
		Water temperature	Air temperature (^{o}C/month)	Raster (30 arcseconds)	
		Groundwater	Groundwater flow rate (l/s)	xyzASCII text file (3 arcminutes)	British Geological Survey digital GW maps for Africa (MacDonald et al., 2012)
		Drought risk	Drought frequency based on historic data	Polygon vector	Aqueduct Global Maps 2.0 (Gassert et al., 2013)
	Pond construction	Percent soil clay	Soil clay content (%)	Polygon vector (30 arcseconds)	HWSD 1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012)
		Slope	Elevation (m)	Raster (3 arcseconds)	Hole-filled SRTM for the globe Version 4. (Jarvis et al., 2008)
		Flood risk	Flood frequency based on historic data	Polygon vector	Aqueduct Global Maps 2.0 (Gassert et al., 2013)
	Land cover	Land use/land cover	Land use/land cover	Raster (10 arcseconds)	ESA CCI Land Cover time-series v2.0.7 (1992–2015) (ESA, 2017)
	Social environment	Distance to major road	Road	Line vector	Digitized major roads in Nigeria 2019 (Google Earth, 2019) Major roads in Nigeria 2009 (World Bank, 2009)
		Distance to major airport	Major international and domestic airports	Text	Global airports (Karakostis, 2019)
		Social interaction	Population density (persons/ km^2)	Raster (30 arcseconds)	Landscan 2000 & 2018 datasets (ORNL, 2019, 2020)
	Economic environment	Share of local fish market	Artisanal fish production by state. Area of Nigeria by states (km^2)	Data table	Fishery statistics 2008–2015 (FDF, 2017) (NBS, 2020)
		Multidimensional poverty index	Multidimensional poverty index (MPI) by state	Data table	Multidimensional poverty peer network (UNDP, 2018)
		Change in fish price	Fish price by state (₦/kg)	Data table	Fishery statistics 2008–2015 (FDF, 2017)
Constraints		Protected areas	Protected areas	Polygon vector (30 arcseconds)	World database of protected areas (UNEP-WCMC, 2019)
		Waterbodies Urban areas	Land use/land cover	Raster (10 arcseconds)	ESA CCI Land Cover time-series v2.0.7 (1992–2015) (ESA, 2017)
		Slope	Elevation (m)	Raster (3 arcseconds)	Hole-filled SRTM for the globe Version 4. (Jarvis et al., 2008)

3.2. Design phase: factor reclassification and weighting

In the intelligence phase, the difference between the traditional and scenario-based approach is that the latter considers future uncertainties in describing the modelling objective and data requirements in (Fig. 2). There is no difference in the design phase between the two approaches. In the choice phase however, the scenario-based approach goes beyond the suitability map. The model framework is such that every category of factors or sub-model can be assessed separately (Fig. 3), allowing users to understand their effect on the suitability map (also known as overall suitability model). To produce this suitability map, the modelling procedure was carried out in TerrSet [Clark Labs, MA, USA] GIS software

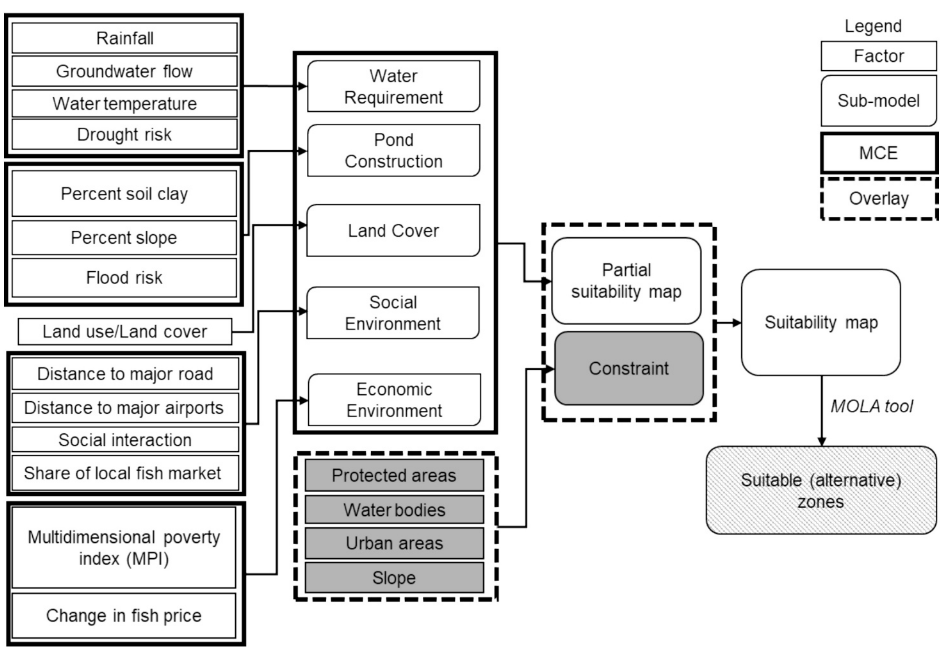

Fig. 3. Structure of the aquaculture suitability model. MOLA (Multi-Objective Land Allocation) is a program module in TerrSet GIS software for solving land allocation problems.

and involved: input data preparation into maps of factors that are compatible; reclassification of factor values into suitability classes; determination of relative importance (weight) of factors and finally, combination of factors (MCE) in the choice phase into sub-models, then into a suitability map.

3.2.1. Input data preparation

Input data layers were preprocessed to fit the study area and projected to CLABSHA (Clark Labs Hammer-Aitoff) reference system for Africa, a projection file provided in TerrSet. This was necessary in this study because the study area spans three UTM zones (30 N, 31 N and 32 N) and does not have a harmonized national grid for projection. The spatial resolution adopted for the model was 300 m to balance data quality with the large size of the study area.

3.2.2. Factor reclassification

Fuzzy set (sigmoidal) function (Eastman, 2016) was used to reclassify the factors into suitability scores of 0 to 1 as a set of continuous values, where 0 represents non membership (constraint) and 1, complete membership or highly suitable condition. Suitability thresholds were obtained from the literature, except where otherwise stated.

3.2.3. Determination of factor weights

Factor weights for developing the suitability map were assigned by the three authors using the pairwise comparison method, also known as the Analytic Hierarchy Process (AHP) developed by Saaty (1987). In AHP, factors are compared in pairs to assess their relative importance using a numerical scale (1–9). It is particularly useful where consistency is required. The 'weight' tool in TerrSet was used to facilitate the process, considering our focus on suitability mapping for small-to-medium scale commercial aquaculture aimed at poverty alleviation. Once the weights are computed, a consistency ratio (CR) is generated alongside, with CR $\leq$ 0.10 meaning consistent or acceptable weights. A summary of factor reclassification and weights that were used in this Design phase are given in Table 2 and described in the subsequent paragraphs.

The first factor in the 'water requirement' category, average rainfall was used as a proxy for groundwater availability rather than direct source of pond water since borehole is the major source of farm water supply in the study area. Actual groundwater availability data is important but not readily available compared to rainfall data at a national scale in Nigeria. Average water temperature was estimated using Eq. (1). (Kapetsky, 1994). Water temperature influences fish growth performance and most tropical warmwater fish species have been found to grow at temperatures ranging between 20 and 35 °C, with optimum for African catfish at 28 °C (Conceição et al., 1998). For groundwater, a suitable area should be able to supply water at a minimum rate of 5 l/s (MacDonald et al., 2012). Drought risk was also considered, as informed by the scenarios presented in Yakubu et al. (2022).

$$Tw = -6.35 + 1.3\,(Td) \tag{1}$$

Where, Tw is mean monthly water temperature and Td, mean monthly daytime air temperature.

For 'pond construction' category, soil with 15–35 % clay content was considered optimal for pond construction (Table 2). Slope and flood risk can influence land use/regulation which is a key driver of the scenarios under consideration. Slope is an important consideration in designing pond layout, and consequently to determine construction cost and water exchange efficiency. A slope of less than 2 % is deemed most favourable for pond construction, and above 8 % is technically unfeasible (Aguilar-Manjarrez and Nath, 1998). Slope was calculated from the elevation data. Flood risk here is the frequency of occurrence based on historic data (Gassert et al., 2013). Although the risk of an area flooding is determined by the level of rainfall and the steepness of slope among other determinants, this study assumed that all the factors are independent.

In the 'social environment' category, the form of social interaction (including exchange and competition) that may occur as determined by population density was considered a suitability factor (Giap et al., 2005; Falconer, 2013). High population density can be viewed as positive, providing better access to the consumer market and workforce or negative because of potential increase in pollution and cost of land. To achieve a balance between the potential effects of low or high population density on aquaculture suitability, a range of 100 to 500 persons/km^2 was defined as most suitable in Table 2. The two major means of transportation in Nigeria are road and airport (Onokala and Olajide, 2020). Consequently, a good aquaculture zone should be within reasonable distance of these facilities, to enable both national and international access. The share of local fish market was created by dividing artisanal fish catch (metric tonnes) in 2015 for each state (FDF, 2017) by their respective area (km^2). The assumption was that high artisanal fish catch in a state means less opportunity for small-to-medium scale aquaculture as livelihood activity within that state (Table 2).

In the 'economic environment' category, Multidimensional Poverty Index (MPI) and price change (%) of fresh fish in each state (Table 2) were the two factors considered. MPI is a measure of household poverty both in terms of income level and deprivation (UNDP, 2018). It was assumed that a high MPI indicates a high potential for aquaculture to be adopted as a livelihood. The price change of fish was calculated as the percentage difference of fresh fish price between 2008 and 2015 based on FDF (2017) dataset. For each state in Nigeria, it was assumed that suitability is inversely proportional to change in fish price (or price risk). This is important because fluctuations in prices affect production cost,

Table 2
Factor reclassification and weight.

Factor (unit)	Weight	Suitability threshold*				Function	Reference
		a	b	c	d	Shape	
Rainfall (mm/month)	0.4167	90	$\geq$ 180	n/a	n/a	Increasing	van der Mheen (1999)
Groundwater flow (l/s)	0.0833	0.5	$\geq$ 5	n/a	n/a	Increasing	MacDonald et al. (2012)
Water temperature (°C)	0.4167	20	28	32	35	Bell-shaped	Conceição et al. (1998)
Drought risk (index)	0.0833	5	1	n/a	n/a	Increasing	Handisyde (2014)
Soil clay (%)	0.4054	10	15	35	60	Bell-shaped	(Boyd et al., 2003; Tucker and Hargreaves, 2008)
Slope (%)	0.4806	0	0.5	2	8	Bell-shaped	(Aguilar-Manjarrez and Nath, 1998)
Flood risk (index)	0.1140	4	1	n/a	n/a	Increasing	(Handisyde, 2014)
Social interaction (persons/km^2)	0.3000	0	100	500	5000	Bell-shaped	(Falconer, 2013; Giap et al., 2005)
Distance to major road (km)	0.3000	n/a	n/a	10	50	Decreasing	(Díaz et al., 2017)
Distance to major airport (km)	0.1000	n/a	n/a	10	100	Decreasing	Assumed
Share of fish market (t/km^2)	0.3000	10	0	n/a	n/a	Increasing	Assumed
MPI (index)	0.7500	0.01	0.64	n/a	n/a	Increasing	Assumed
Price change of fish (%)	0.2500	n/a	n/a	0	100	Decreasing	Assumed

* Suitability thresholds: *a, b, c*, and *d* represent control points; where *a* is start and *b* is end for monotonically increasing fuzzy (sigmoidal) function. Suitability in the monotonically decreasing function starts from *c* to *d*; and for bell-shaped function, it starts from *a*, reaches its peak at *b* – *c* before decreasing to *d*. Columns with n/a means not applicable.

profitability, credit availability and the ability to forecast and plan for the future (Claessens and Duncan, 1994).

Land use/land cover is a key consideration for aquaculture land suitability assessment. Land use change data can be used to inform a zoning model so that, future development of aquaculture or other activities do not adversely impact the existing users of an area (Falconer, 2013). In the present study, land cover data layer was based on FAO's classification system in Table 3. This is categorical information, so values were standardized from 0 to 1, to ensure compatibility throughout the modelling process (Assefa and Abebe, 2018; Falconer, 2013; Handisyde, 2014). There was no need for weighting because this sub-model consists of only one factor. All the output images were displayed using QGIS v3.16.11 (QGIS Development Team, 2020).

3.3. Choice phase

3.3.1. Suitability map

Under each category, factors were combined using Multi-Criteria Evaluation (MCE) into a sub-model based on AHP derived weightings. The sub-models were then combined using the same MCE method and added to the constraints map to produce the suitability map. The Weighted Linear Combination (WLC) method of MCE was used to combine factors in a compensatory manner (tradeoff) as expressed in Eq. (2), to create the water requirement, pond construction, social environment and economic environment sub-models. The land cover sub-model did not require an MCE because it is composed of only one factor.

$$P = \sum Xi.Wi \tag{2}$$

Where P = Suitability, Xi = Score of factor i and Wi = Weight of factor i for a set of n (factors).

The weighting of sub-models (Table 4) was guided by the assumption that all are equally important (with the 'water requirement' slightly more), which ensures that the overall suitability model reflects the contribution of each sub-model. The constraints map was created by multiplying the maps of urban centers, protected areas, waterbodies, and slope. All areas with slope greater than 8 % were considered a constraint.

Table 3
Reclassification of land cover data.

Value	Label	Suitability class (score)
10	Cropland, rainfed	Suitable (0.85)
20	Cropland, irrigated or post-flooding	Highly unsuitable (0.15)
30	Mosaic cropland (>50 %) / natural vegetation (tree, shrub, herbaceous cover) (<50 %)	Unsuitable (0.50)
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50 %) / cropland	Unsuitable (0.50)
50	Tree cover, broadleaved, evergreen, closed to open (>15 %)	Unsuitable (0.50)
60	Tree cover, broadleaved, deciduous, closed to open (>15 %)	Highly unsuitable (0.15)
100	Mosaic tree and shrub (>50 %) / herbaceous cover (<50 %)	Highly unsuitable (0.15)
110	Mosaic herbaceous cover (>50 %) / tree and shrub (<50 %)	Unsuitable (0.50)
120	Shrubland	Suitable (0.85)
130	Grassland	Suitable (0.85)
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15 %)	Highly suitable (1)
170	Tree cover, flooded, saline water	Highly unsuitable (0.15)
180	Shrub or herbaceous cover, flooded, fresh/saline/ brackish water	Highly unsuitable (0.15)
190	Urban areas	Highly unsuitable (0.15)
200	Bare areas	Highly suitable (1)
210	Waterbodies	Highly unsuitable (0.15)

Table 4
Sub-model weights in the overall suitability model.

Sub-model	Weight (CR = 0.03)
Water requirement	0.2566
Pond construction	0.1941
Land cover	0.1941
Social environment	0.1609
Economic environment	0.1941

3.3.2. Identification of zones

In Fig. 2, the suitability map is the end point of the traditional approach, but it is also an input for the scenario-based approach. Unlike site selection model, the use of a zoning model is to regulate development, minimize conflict and maximize complementary use of land and water resources (Aguilar-Manjarrez et al., 2017). Hence, five zones were identified using the MOLA (Multi-Objective Land Allocation) tool available in TerrSet. The suitability map was used as an input to MOLA which ran a spatial optimization algorithm to identify five zones of approximately equal area or clusters of pixels with the highest possible sum of suitability values. This implies an optimal solution based on the spatial objective (5 contiguous allocations of pixels totaling 1000 km^2) set for the algorithm.

After identifying suitable zones, the next step in a zoning process is to identify risks (Aguilar-Manjarrez et al., 2017). Based on some key sustainability issues highlighted by the four scenarios (Fig. 4), three evaluation criteria for comparing the zones were specified, namely, seasonal variation, long-term variation, and potential conflict with other activities e.g., rice production (Table 5). It is possible to include other criteria, however, we specified these three to demonstrate the proposed approach, while conforming to the scenario narratives in Yakubu et al. (2022) as highlighted in Fig. 4. In Table 5, 'benefit' means that a higher score on this criterion is preferrable, whereas a lower score on a 'cost criterion' is preferrable.

3.3.3. Criterion score

To evaluate the zones against seasonal variation (C1), two 'water requirement' suitability maps were developed using average rainfall and water temperature for each season (wet and dry). The seasonal maps were combined to indicate areas where suitability value did not drop below 0.7 (persistence map). Then, the map of the zones (Section 3.3.2) was overlaid on the persistence map and the area of overlap (km^2) was recorded for each zone and standardized using Eq. (3) (Voogd, 1982). This represents the score of each zone when assessed in terms of seasonal variation, so that the higher the score, the more suitable the zone.

For C2, previous datasets (early 2000) were used to construct another suitability model for comparison with the current version. Due to unavailability of data, the only components of the suitability model that were set to change are 'land cover' and 'social environment' sub-models. The map of suitable zones was also overlaid on the map indicating areas where suitability value remained ≥0.7 from early 2000 to current date. Like C1 above, each zone had a score representing long-term suitability, where the higher the value, the more suitable the zone.

A map of rice-growing areas in Nigeria was obtained from the CGIAR rice database (https://ricepedia.org/) for the C3 criterion. The area of overlap by each zone with rice-growing portions was computed. Since C3 was a 'cost' criterion, the standardization for C3 was achieved using Eq. (4) (Voogd, 1982). The zones therefore had scores representing potential conflict with rice production, where the lesser the value, the more suitable the zone.

$$SSb = \frac{Zi}{Zmax} \tag{3}$$

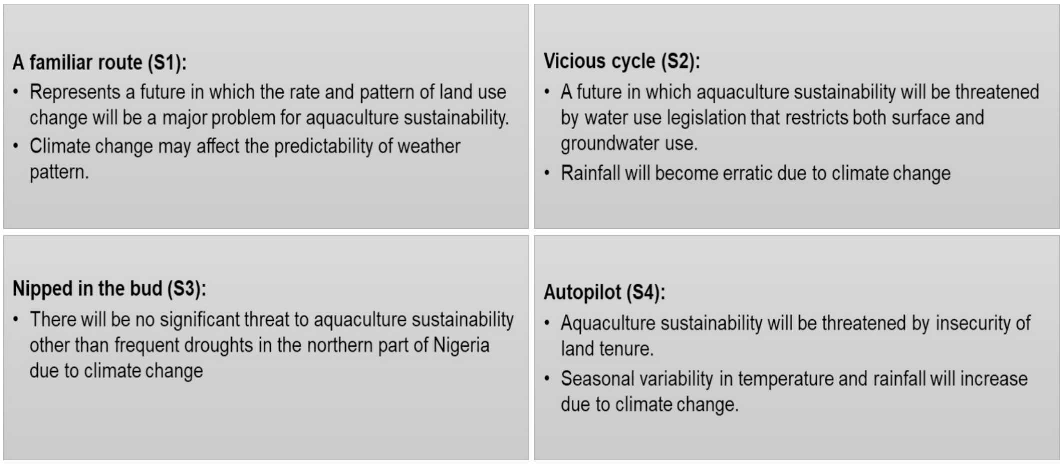

Fig. 4. Aspects of the scenarios by Yakubu et al. (2022) used in the present study to define sustainability criteria for comparing the zones.

Table 5
Set of criteria used in the present study to evaluate the alternative zones.

Criterion (km^2)	Label	Cost/Benefit	Type
Seasonal variation	C1	benefit	temporal
Long-term variation	C2	benefit	temporal
Overlap with rice-producing area	C3	cost	spatial

$$SSc = 1 - \left(\frac{Zi}{Zmax}\right) \quad (4)$$

SSb and *SSc* refer to standardized score for benefit and cost criteria respectively, *Zi* is the area of overlap by zone *i* and *Zmax* is the maximum area of overlap that can be achieved by zone *i*.

3.3.4. Criterion weighting

Weighting is required to allow for the zones to be evaluated and compared. The swing weighting method (von Winterfeldt and Edwards, 1986) as adapted by Ram et al. (2011) was used to generate the criteria weights under each scenario (S1, S2, S3, S4 as excerpts from Yakubu et al., 2022). The swing weighting method was used instead of AHP as it allowed for direct weight assignment without the need for pairwise comparisons. The swing weighting method relies on the judgement of the practitioner rather than forcing a logical consistency check that are required in the AHP.

The weighting exercise was conducted online involving a survey in four parts with two groups of experts and seven participants per group. Group 1 included experts in environmental management of aquaculture, and Group 2 included experts in aquaculture society and technology. In Part 1 of the survey, each participant was presented with a description of the three criteria:

- *Criterion 1 (C1): An area with good water availability/quality that is consistent throughout the year.*
- *Criterion 2 (C2): An area where the land use/local market potential to support pond fish farming remained high after it was identified 10–15 years ago.*
- *Criterion 3 (C3): An area that is less likely to compete with rice farming.*

Each participant was asked to assign a weight of 100 to the criterion they thought was most important, before assigning weights to the remaining two criteria relative to 100. No other contextual information was provided in Part 1, so was assumed to represent an ideal situation which is the perspective of both researchers and practitioners when determining criteria weights. Scenarios can inform different views, including anticipation of potential future changes. The ideal situation is most like Scenario S3, therefore the resulting weights from this part of the exercise were assigned to S3.

In Part 2, the participants were presented the following contextual information, representative of Scenario S1, and again were asked to assign a weight of 100 to the criterion they thought was most important, before assigning weights to the remaining two criteria relative to 100.

In country 'X', land use regulation and tax regimes are weak, such that extensive land around peri urban areas is easily converted from one use to another. It is not clear how much progress has been achieved in the use of local feed materials and brood stock development due to lack of reliable data for evaluation. The impacts of changes in temperature, rainfall pattern and desertification on pond farms across geographical regions are not understood.

In Part 3, the participants were presented the following contextual information, representative of Scenario S2, and again were asked to assign a weight of 100 to the criterion they thought was most important, before assigning weights to the remaining two criteria relative to 100.

In country 'X', the water use legislation is in force, so measures are becoming stricter for conserving ground & surface waters along with aquatic resources. Other challenges include the growing competition for land between large-scale ponds and rice farmers in some states. Allocation decision requires local knowledge, but there is insufficient data on both resource use efficiency and household economies. More erratic rainfall and reduced stream flow is being experienced, even in the southern region, known for high amount of rainfall.

In Part 4, the participants were presented the following contextual information, representative of Scenario S4, and again were asked to assign a weight of 100 to the criterion they thought was most important, before assigning weights to the remaining two criteria relative to 100.

In country 'X', built-up areas are more compact in the supposed peri urban areas as population density increases. Many local authorities do not have legal restrictions on land conversion, and aquaculture widely remains a peri urban affair. Due to aquafeed price fluctuations, many small-scale fish farmers are cutting down on production cost by using waste food materials, including from slaughterhouses. Some have resorted to seasonal farming following the availability of these materials. Others do so in response to seasonal variation in temperature and rainfall.

Once all participants had completed the questionnaire, the weights were then standardized for each Group and the mean values taken. This meant that four sets of criteria weights were generated, one for each scenario.

3.3.5. Criteria evaluation

The aggregate score for each zone, *Pi* was computed using the scores, *Xc* derived in Section 3.3.3 and the weights, *Wcs* elicited in Section 3.3.4, according to Eq. (5) (Stewart et al., 2013). This produced a ranking of the five zones under each scenario.

$$Pi = \sum Xc.Wcs \quad (5)$$

Where i denotes a set of alternative zones = {1, 2, 3, 4 and 5}; c is a set of criteria = {C1, C2 and C3}; and a set of scenarios, s = {S1, S2, S3 and S4}.

3.3.6. Sensitivity analysis

Finally, a sensitivity analysis was conducted to assess the robustness of the ranking of zones due to 5, 10 and 20 % changes in criteria scores. Changes in a score can be associated with data error or measurement uncertainty. It should be recalled that scenarios were used to capture differences in stakeholder's perspectives and value judgement as reflected by the weightings elicited. The sensitivity analyses were conducted using DEFINITE v3.1 [Decision making software for a finite set of alternatives, SPINlab, Amsterdam] (Janssen and Van Herwijnen, 2006). The software automatically calculates the Pi per scenario 2000 times. In the case of 5 % change for example, the calculations are done with random scores that are within 5 % higher or lower than the original criteria scores (assuming deviation is normally distributed).

4. Results

4.1. Sub-models, suitability map and potential zones for aquaculture

The sub-models in Fig. 5 and suitability map (Fig. 6) indicate areas suitable for aquaculture based on the factors used in this study. Looking at the suitability map, areas with high suitability appear to be localized across northeast-to-west. The five alternative zones (Fig. 6b) further display the pattern of spatial distribution of suitability in the overall model. These zones represent the top five clusters (approximately 200 km^2 each) with the highest sum of suitability and potential to be designated as zones for small-to-medium scale aquaculture to support poverty alleviation measures in Nigeria.

4.2. Criteria scores and weights

Table 6 presents the area of each zone and the extent to which it meets the three evaluation criteria respectively. Zone 1 has the most land area, up to 202 km^2 generated by the MOLA algorithm, followed by Zone 2 and so on. The remaining columns show the scores on each criterion. For example, Zone 1 achieved a value of 100 km^2 when assessed against the seasonal variation criterion, meaning that only about half of the 202 km^2 zone area occurred where suitability will remain $\geq$0.7 throughout the year. Since C1 and C2 are benefit criteria, a high value achieved on these criteria means higher standardized scores as given in parenthesis. In column C3, the values represent the area of rice field covered by each zone, so that the higher the value the lesser the criterion score.

The outcome of the swing weighting exercise for the different scenarios is given in Table 7. The criteria weights in scenario S3 reflected those expected under an ideal situation, i.e., where the experts were not provided with contextual information. Criterion C1 was assigned the most weight, consistently greater than 0.40 across the four scenarios. Interestingly, criterion C3 appeared more important in scenario S2, probably due to the mention of rice farmers in this scenario. Overall, the order of weightings assigned to criteria across scenarios was C1 > C2 > C3, except in S2 scenario.

4.3. Ranking of the zones

The rankings of the five zones resulting from the criteria evaluation under the different scenarios are given in Fig. 7. There is no marked difference between the scenarios. However, Zone 5 ranks highest across the scenarios, with aggregate scores slightly more than those scored by Zone 1. Zone 2 was also consistently the lowest ranking across scenarios, while Zones 3 and 4 were very close in ranking. There is some variation in the relative contributions by individual criterion between scenarios, especially for 'overlap with rice area' (C3) under scenario S2, which increased to 0.3 from less than 0.25 in other scenarios.

4.4. Sensitivity of rankings to changes in criteria score

The sensitivity analyses results in Fig. 8 show the effect of 5, 10 and 20 % changes in criteria scores on the probability of each zone to maintain its ranking. Across the scenarios S1 to S4, there is higher probability that Zone 5 will rank in first place (up to 68 % in S4 based on 5 % change). Although the probability of Zone 1 to rank in the same position is high, it will mostly rank in second place with slight changes in criteria scores. With a higher change of 20 %, Zone 1 outcompetes Zone 5. Overall, it means that Zone 5 is more stable in first position than Zone 1, considering that the latter is more likely to occur in lower positions with changes in criteria score.

5. Discussion

The identification of specific zones suitable for aquaculture development is a strategic problem. Zoning is a long-term planning issue, involving many different stakeholders. Such planning requires

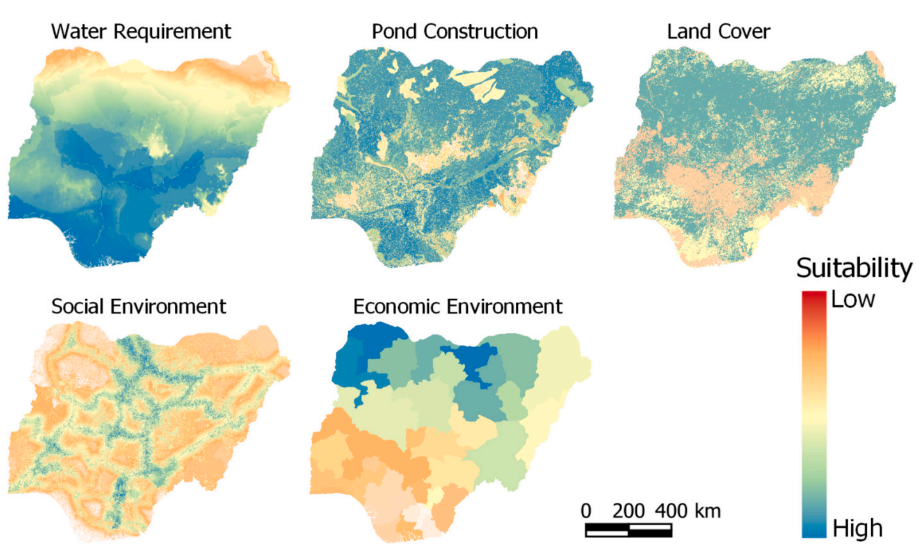

Fig. 5. Output images of sub-models that fed into the suitability map.

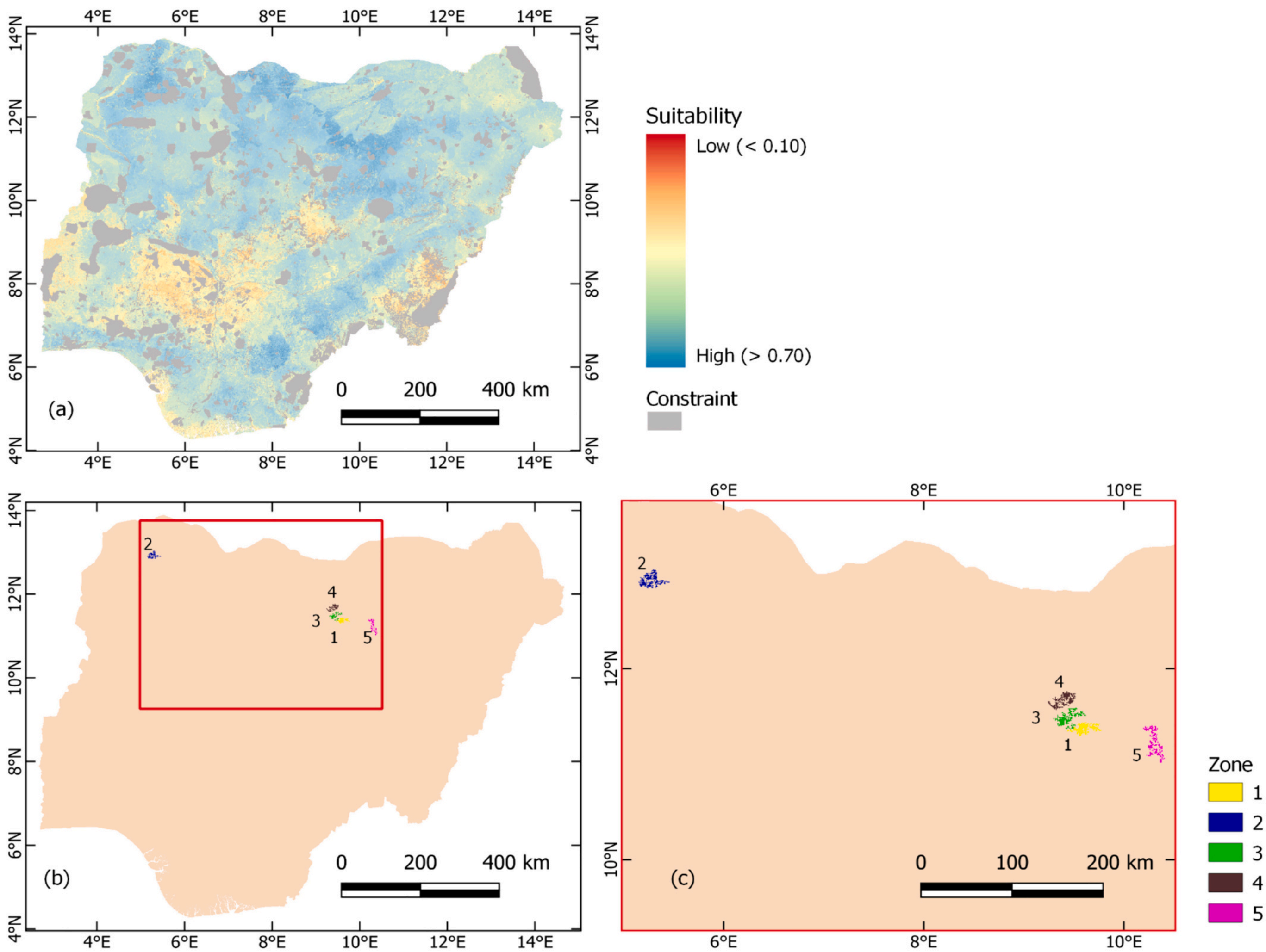

Fig. 6. Model outputs showing (a) the suitability map (b) the identified zones which are zoomed in (c).

Table 6
Original values and standardized (criteria scores) in parenthesis.

Zone	Zone area (km^2)	Area of overlap (km^2) with map of:		
		Seasonal variation (C1)	Long-term variation (C2)	Rice field (C3)
1	202	100 (0.495)	199 (0.986)	2 (0.988)
2	201	0 (0.000)	197 (0.981)	0 (1.000)
3	200	97 (0.485)	198 (0.987)	38 (0.811)
4	199	75 (0.376)	197 (0.988)	0 (1.000)
5	198	99 (0.500)	197 (0.993)	0 (1.000)

Table 7
Criteria weightings (mean) elicited from the two groups of aquaculture experts.

Criteria	Scenario			
	S1	S2	S3	S4
Seasonal variation (C1)	0.452	0.417	0.453	0.405
Long-term variation (C2)	0.340	0.278	0.336	0.345
Overlap with rice area (C3)	0.209	0.306	0.211	0.250

environmental assessments, implementation policies, and regulatory support. This study has shown that an approach that combines scenarios and MCE can be useful to identify and prioritize suitable zones for aquaculture development. Although this study has focused on Nigeria, the approach can be adapted for other countries or at sub-national scale.

5.1. Aquaculture suitability model

According to the model (or suitability map) developed in this study, there is a greater extent of suitable land for small- to medium-scale aquaculture across the north than southern Nigeria. This contrast is interesting considering that the 'water requirement' sub-model was more favourable in the southern area and assigned higher weight. There was some similarity in suitability distribution between the 'pond construction' and 'land cover' sub-models. The effect of these sub-models is visible in the overall model because the areas with low-medium suitability are strongly expressed. As for the 'social environment', the high suitability areas appeared to be influenced more by the factor (distance to road), such that despite being assigned the lowest weight, the effect of the sub-model can be traced on the overall model. Finally, the 'economic environment' sub-model, unlike 'water requirement', was more favourable in the northern area. However, the two sub-models appeared to have similar magnitude of effects on the overall model. At a sub-national scale, some datasets like groundwater availability may be more robust or easier to access. In this case, the model may be improved by using actual groundwater availability instead of the proxy (rainfall) used in the present study. Other factors such as distance to waterbodies and distance to market may be considered.

Spatial modelling approach for zoning freshwater pond aquaculture was developed and demonstrated in this study based on the goal of

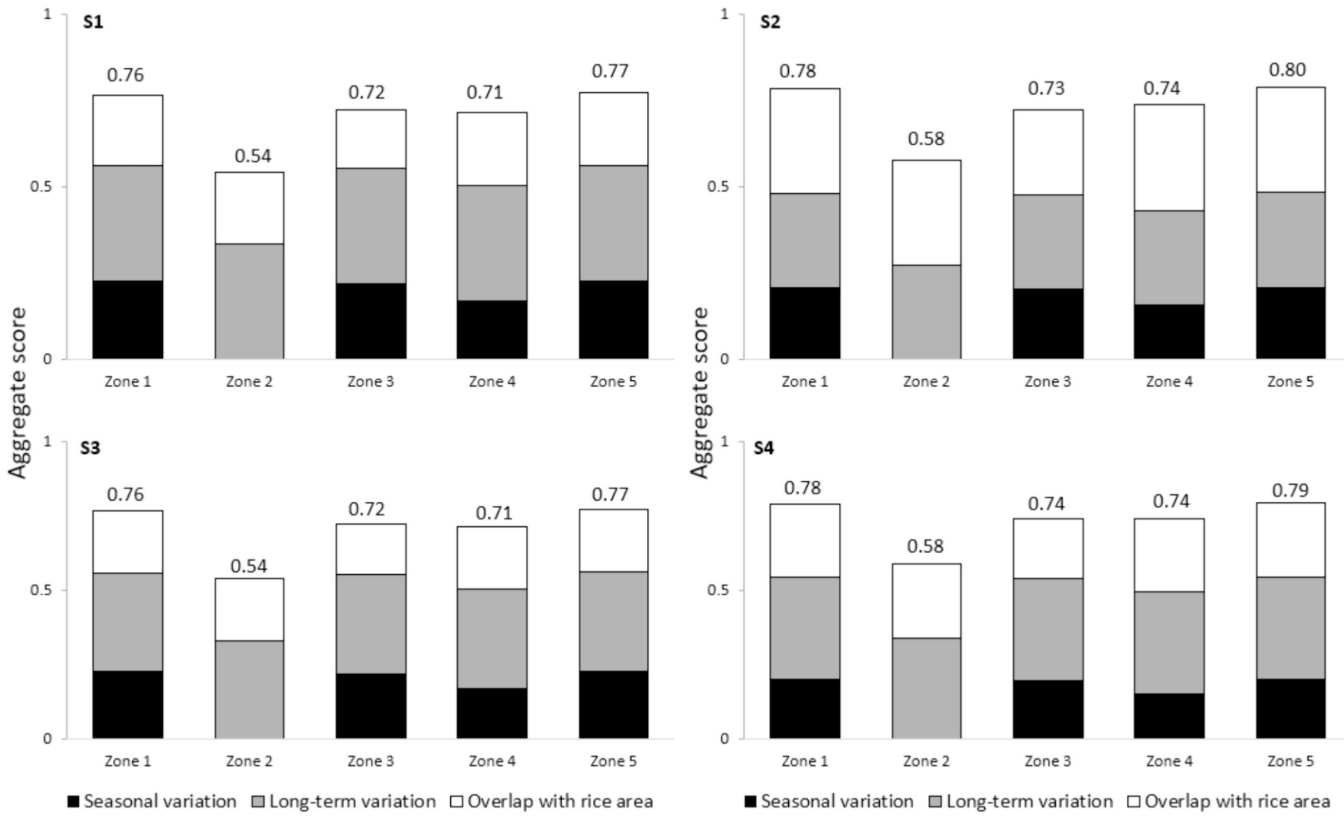

Fig. 7. Ranking of zones under different scenarios (S1 – S4), with the highest aggregate score signifying 1st and the lowest as 5th position. The contribution of each criterion is indicated by black, grey, or blank stack.

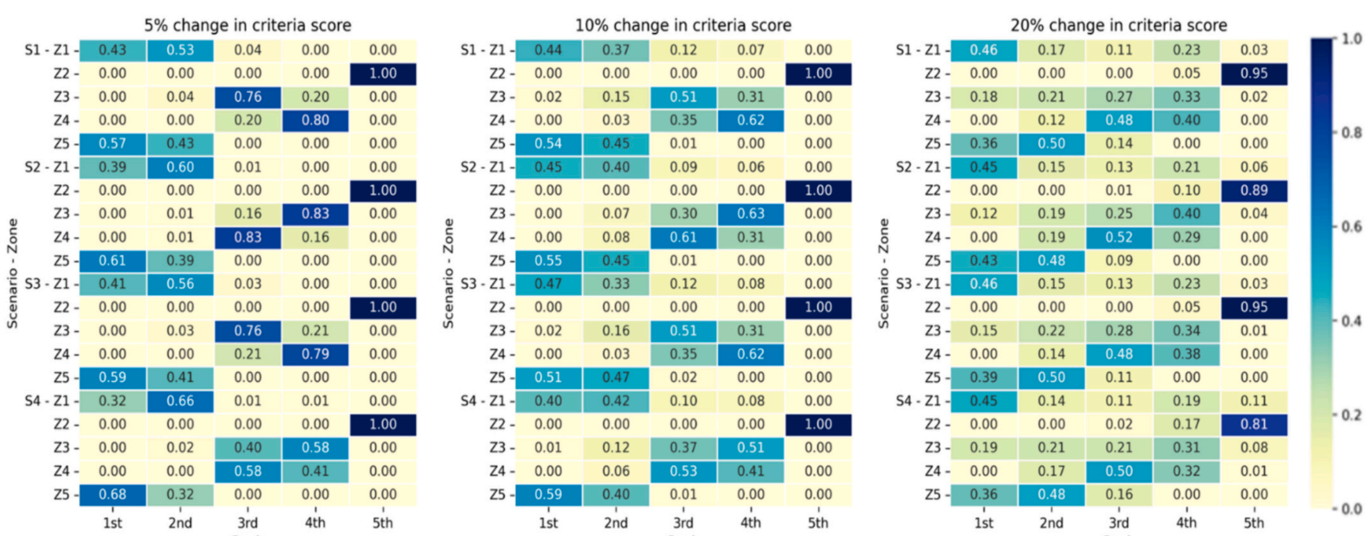

Fig. 8. Probability of zones to rank in the 5 positions due to 5, 10 and 20 % changes in criteria scores. S1 to S4 means Scenarios 1 to 4 and Z1 to Z5 refers to Zones 1 to 5.

identifying areas where aquaculture could be developed to maximize its contribution to the fight against poverty. This goal is like those defined for previous GIS-based models that have been developed for socio-economic assessment of aquaculture potential. For example, Van Brakel and Ross (2011) estimated that aquaculture development could significantly increase the income of poor farmers in Cambodia, provided their access to market is improved. Other studies include Salam et al. (2003) and Ferreira et al. (2015) which simulated the potential economic benefits of aquaculture. These studies used the suitability maps to calculate economic benefits, whereas the present study took a different approach to identify zones from the suitability map, not only for maximizing economic benefits but minimizing sustainability risks. This was demonstrated by ranking zones under different scenarios, so that the best zone was that which obtained the highest ranking across the scenarios.

There are several studies that have integrated scenario planning with MCE (Marttunen et al., 2017), however, few studies have included spatial aspect. To the authors' knowledge, the present study is one of the first attempts in aquaculture research to integrate scenario planning with GIS-based MCE with the aim of providing decision support for aquaculture zoning. This is a useful consideration in the EAA (Ecosystem Approach to Aquaculture) discourse since the identification and allocation of suitable areas in the form of aquaculture zone is a critical step in the EAA implementation process (Soto et al., 2008). Land use conflicts are increasing throughout the world, and the conversion of cropland and other land use/cover for aquaculture expansion are being restricted or even prohibited in some countries (Filipski and Belton, 2018). In such areas, and where similar restrictions may be considered in future, the result of this study further highlights the importance of a strategic approach to modelling and implementation of aquaculture spatial plans.

5.2. Rankings and sensitivity of the alternative zones for aquaculture

Several studies have developed suitability models for land and water-based aquaculture (e.g. Aguilar-Manjarrez and Nath, 1998; Asmah et al., 2021; Barillé et al., 2020; Díaz et al., 2017; Falconer et al., 2013). In this study, alternative zones for aquaculture were identified from the site suitability model output and then ranked, based on their performance under different scenarios. The temporal criteria used, i.e., seasonal, and long-term variations in land suitability for aquaculture are applicable to many other study areas. Whereas the spatial criterion (overlap with rice-producing area) was identified based on the scenario narratives of Yakubu et al. (2022) where it was specifically described as a key spatial problem for future pond aquaculture in terms of competition for land in Nigeria.

Land use and land cover was one of the key components of the suitability model used to investigate long-term variations in suitability. However, as is the case in many studies on land suitability assessment, a large portion of the land cover in this study area is classed as suitable land for aquaculture. As a result, it was difficult to visualize changes in suitability with land cover changes. One of the reasons for having a large area of land cover in the present study classed as suitable is because agricultural land which makes up over 40 % of the land cover map is often considered suitable for aquaculture, regardless of type of crop, expansion rate, likelihood of conversion to fishpond, etc. This has implications for long-term planning, particularly over a large area. It is important to note that most freely available land cover datasets neither separate agricultural land by type of crop nor have fishpond as a land use class. As such this study obtained a map, specifically of rice-growing areas in Nigeria and used the occurrence of rice fields as a criterion to indicate the risk of conflict in potential areas for aquaculture zoning. Rice is a major crop important for both economic gain and food security in Nigeria. Although this study focused on the potential for conflict between rice production and aquaculture, other types of intensive agriculture often require significant water resources and could lead to conflicts over use of land and water resources. Furthermore, urbanization around major cities and towns in Nigeria could significantly affect the availability of land for pond aquaculture due to increase in prices or water pollution (Abubakar, 2021). Other possible conflicts may arise from deforestation and infrastructural development, as these can alter local water cycles, potentially reducing the availability of freshwater needed for aquaculture or leading to seasonal changes that are unfavorable for pond management. With sufficient data, the model could be expanded to account for these other potential land use conflicts.

There were no major differences in the overall ranking of zones when tested under the different scenarios, thus suggesting that the order of the zones was suitable across all the scenarios. Such a result can provide support to decision makers when confirming selection of zones, and in this case the results suggest Zone 5 would be the best option. In other situations, there may have been increased contrast and the stakeholders would then have to prioritize which scenario was most important for them and select the best performing zone in that scenario. Decision-makers may have to select zones that perform well under several scenarios, at the cost of other scenarios.

As noted by Falconer et al. (2020) and Gonzalez and Enríquez-De-Salamanca (2018), to bridge the gap between research and practice, the development of spatial models for environmental assessments and planning must begin with the "What", "Why" and "How" the models will be used in real-world decision making. These questions are critical, evidence of which can be seen from the scenario-based modelling approach and outputs generated in this study. There was consistency in criteria weighting across scenarios which could mean consensus, as Ram et al. (2011) found across 12 scenarios while comparing 5 investment options for improving food security in Trinidad and Tobago. Criteria scores and weightings that are consistently high or low across scenarios produce MCE results that do not significantly vary within and between scenarios. This was typical of the present study, with the criteria score of the alternative zones showing similar values, except for Zone 2 which scored zero on criterion C1, resulting in a marked difference between Zone 2 and others. Also, criteria weightings were consistently higher for C1, followed by C2 and least for C3, except under scenario S2. Therefore, it is not a surprise that zone 5, having scored highest on each criterion, ranked top across all the scenarios. Although sensitivity analysis can help to understand the effects of changes in criteria scores and weights due to uncertainty, the outputs of the sensitivity analysis depend on both the original score/weights and the uncertainty range. In line with the objectives of this study, only the sensitivity of rankings to changes in criteria score was tested.

In essence, the role of scenarios as a guide to elicit value judgement by stakeholder/expert was explored. Where it is difficult to assemble the required stakeholders or reach a consensus through a fair process, experts' judgement is often used. But experts' thoughts are informed by knowledge and experience and are not necessarily location specific. This limitation was highlighted by the findings of the scenario-based weights elicited in this study. For example, Scenario S2 emphasized a high conflict potential between aquaculture ponds and other resource users, which may have caused the C3 criterion weighting to vary from other scenarios. Without providing such context, the experts will automatically think of an ideal situation under which to assign weights. In addition, strategic planning is not based on what is already known for sure, but rather on what could happen in the future, and for which planning must start in the present day. Therefore, the rankings and sensitivity results obtained in this study can be used as a decision support for selecting the best zone for small-to-medium scale aquaculture development in Nigeria based on the three criteria specified. Further study could develop additional evaluation criteria, including those that can measure the level of achievement of the economic benefits (or goal of poverty alleviation) by alternative zones. Also, the effects of a large set of criteria on weighting, as well as ranking and sensitivity of alternative zones can be explored.

6. Conclusion

In this study, a scenario-based approach was used to develop a zoning model for pond aquaculture in Nigeria at a national scale. It was found that there is considerably more suitable land for small- to medium-scale aquaculture across the north than southern Nigeria. The study also identified a range of potential zones which provide options for decision makers. Based on the criteria used to evaluate these zones and the sensitivity analyses conducted across scenarios, the most appropriate location for small- to medium-scale aquaculture zoning in Nigeria was identified. Importantly, the study was designed, built, and demonstrated for catfish pond aquaculture targeted at poverty alleviation in Nigeria. By so doing, the usability of the model was defined at the beginning, thus eliminating the potential for misuse, such as testing with different species and estimation of the country's overall aquaculture potential. The results can be used by planners and regulatory agencies to integrate aquaculture into wider land use planning in Nigeria towards more efficient resource use for sustainable development of the aquaculture sector.

CRediT authorship contribution statement

Suleiman O. Yakubu: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lynne Falconer:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Conceptualization. **Trevor C. Telfer:** Writing – review & editing, Visualization, Supervision, Resources, Project administration.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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