Generation of a Socio-Economic Suitability Map for Nile Tilapia (*Oreochromis niloticus*) Culture using Free Geographical Information System (GIS) software and Spatial Multi-Criteria Evaluation (SMCE) in Kisumu County, Kenya

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Abstract

In recent years, aquaculture has accounted for roughly half of all fish consumed globally. Scholar's view aquaculture to have the potential to expand sustainably if suitable fish pond sites are located guided by socio-economic criteria. The need to generate socio-economic suitability map to guide location of fish ponds is therefore critical. This study generated a socio-economic suitability map for Nile Tilapia (Oreochromis niloticus) culture using Free GIS and SMCE Software in Kisumu County, Kenya. The criteria including; distance to water source, distance to fish feed source, distance to fingerlings source availability of animal waste, potentiality of farm gate sales, distance to market, and distance to all season roads were established, standardized, weighted and each criterion categorized into a five-level suitability scale of extremely suitable, suitable, averagely suitable, slightly suitable, and not suitable. The weighted criteria were combined using SMCE module in ILWIS. The generated site suitability map in terms of socio-economic factors indicates that 68.9 % of Kisumu county is extremely suitable, 25.5 % is suitable and 5.25% is averagely suitable for O. niloticus culture. It is concluded that based on socio economic suitability criteria, the County is highly suitable for O. niloticus culture.

Keywords: *O. niloticus***,** Aquaculture; socio-economic factors, GIS and SMCE Software

INTRODUCTION

Aquaculture forms the most diverse farming system in the world in terms of the number of species, methods of farming, and environments where farms are located (FAO, 2009). During 2013 – 2015, the total fish production for human consumption was 147 million tons (about 88% of the total), and aquaculture accounted for nearly 50% of the fish consumed (Popp *et al*., 2019). Fish originating from aquaculture are expected to represent 57% of the fish consumed by 2025 (FAO, 2018; FAO, 2020). The continued growth in fish consumption will mainly be derived from aquaculture production since wild fishery cannot be possibly expanded (OECD/FAO, 2017). Aquaculture has great potential to expand and intensify sustainably in order to meet the demand for fish in 2050, as the human population is predicted to continue to grow for the next 40 years (Kaminski *et al*., 2018; Obwanga *et al*., 2018). Due to its first growth and tolerance to a wide range of environmental conditions, *Oreochromis niloticus* is the species cultured intensively around the world and in Africa (Assefa & Abebe, 2018). The sustainable development of aquaculture requires adequate consideration of interactions among environmental factors: the social and economic factors that accompany any development (Popp *et al*., 2019). Suitability of socio-economic factors such as distance to market, distance to all season road, distance to source of water, distance to source of input as well as potentiality of farm gate sales must be identified to enable fish pond site location (Krause *et al*., 2015).

The key to success in small-scale farming including aquaculture is skillful marketing, because too often farmers focus mainly on production without considering whether the markets available to them will pay a profitable price (Dasgupta & Durborow, 2009; Bardhan *et al*., 2012). The recipe for a successful small-scale aquaculture business is to identify marketing opportunities and then develop market-based production and marketing plans (Nyaga, Nyikal & Busienei, 2016). These include gate farm sales to the neighbours and traders who come to the farms to purchase fish (Omiti *et al*., 2009). Factors that increase transaction costs such as distance to the market, distance to all-season road, and the distance to the sources of input and water, generally referred to as farming resources have also been discussed as deterring factors to small scale farmers including aquaculture (Dasgupta & Durborow, 2009; Omiti *et al*., 2009; Bardhan *et al*., 2012; Patrick & Kagiri, 2016).

Various efforts have been put in place to mitigate challenges facing small scale fish farmers. In 2009/2010, the Kenyan government launched the Economic Stimulus Programme (ESP) to kick-start the economy toward long-term economic growth (Gatonye & Gakuu, 2018). It featured the formation of the Fish Farming Enterprise Productivity Program (FFEPP), which was meant to enhance fish farming output and commercialization through government-subsidized financial assistance (Obwanga *et al.*, 2020). Through the programme, 200 earthen ponds were constructed where some of the beneficiaries' included institutions, primary and secondary schools and small-scale farmers from 140 constituencies (Gatonye & Gakuu, 2018).

Aquaculture output in Kenya surged significantly from 4,218 tons in 2006 to a record of over 24,000 tons in 2014, but decreased to 12,760 tons by 2017 due to a drop in quantities generated from ponds following the conclusion of the subsidy programs (Opiyo *et al.*, 2018). Warm water species of which Nile Tilapia constitute 75% dominate aquaculture production in Kenya (Obwanga *et al.*, 2020).

Despite the fact that they can incorporate low density of fish in the ponds, extensive aquaculture pond systems rely on natural production and physical water conditions with little or no control (Clough *et al*., 2020). The Western Kenya region of Lake Victoria is said to be the best region for farming *O. niloticus* in open systems such as earthen ponds, with water temperatures ranging from 24.1–28.8 °C in the Nyanza Gulf to 23.3–26.6 °C in the pelagic zone (Njiru, 2012). Despite this, Kisumu County, is not leading with number of fish ponds, in the Nyanza Gulf, but has only 2, 222 ponds occupying 66.66 ha compared to the five leading counties: Kakamega, Bungoma, Kisii, Meru, Nyeri with 8649 (259.2ha), 3972 (119.6ha), 3126 (93.78ha), 2950 (88.5ha), and 2381 (71.43ha) respectively (Opiyo *et al*., 2018).

Suitability analysis based on GIS layers has been widely utilized for site selection to analyze and pick a particular location based on its suitability criteria categorized according to specified metrics and methods (Malczewski, 2006; Malczewski & Rinner, 2015). GIS-based suitability analysis has been used by researchers to model potentially appropriate locations for aquaculture development in the Lake Tana basin (Assefa and Abebe, 2018); for designing site suitability for pond-based *O. niloticus* and *Clarias gariepinus* farming in Uganda (Ssegane, Tollner, and Veverica, 2012), for assessing the suitability of *O. niloticus* and *C.gariepinus* pond farming in Tanzania, and for site selection of seaweed farming information centre (Teniwut, Marimin and Djatna, 2019). Against this background, the overall goal of this study was to generate a suitability map based on socio economic criteria for *O. niloticus* culture using Free GIS Software and SMCE tools in Kisumu County, Kenya. The criteria used in this study were developed and standardized from 5 sub-criteria: distance to water source, distance to fish feed source, potentiality of farm gate sales, distance to market, and distance to all season road.

METHODS AND MATERIALS

Study Location

The study was done in Kisumu County located in the Western part of Kenya. The area lies between longitudes 33^0 20’E and 35^0 20’E and latitude 0^0 20’ South and 0^0 50’ South within the Lake Victoria Basin (Figure 1). The county is bordered to the North east by Nandi County, to the north west by Vihiga County, to the east by Kericho County, to the south by Homa Bay County, and to the west by Siaya County. Lake Victoria, the second biggest freshwater lake in the world with a land size of around 2086 km2, covers a portion of the region's surface area (approximately 567 km2).

Kisumu County is divided into seven Sub-Counties: Kisumu East, Kisumu West, Kisumu Central, Muhoroni, Nyando, Seme, and Nyakach. The county is divided into thirty-five wards. The county's climate is characterized by heavy rains from March to May and brief rains from September to November. Throughout the year, the monthly temperature ranges between 23°C and 33°C. During the long rains, the average annual rainfall is 1000-1800mm, while during the short rains, the average annual rainfall is 450-600mm.

The County has thirty-five wards. The climate of the county is characterized by long rains during March to May, and short rains during September to November. The monthly temperature is between 23^0C and 33^0C throughout the year. The average annual rainfall is 1000-1800mm during the long rains and 450-600mm during the short rains.

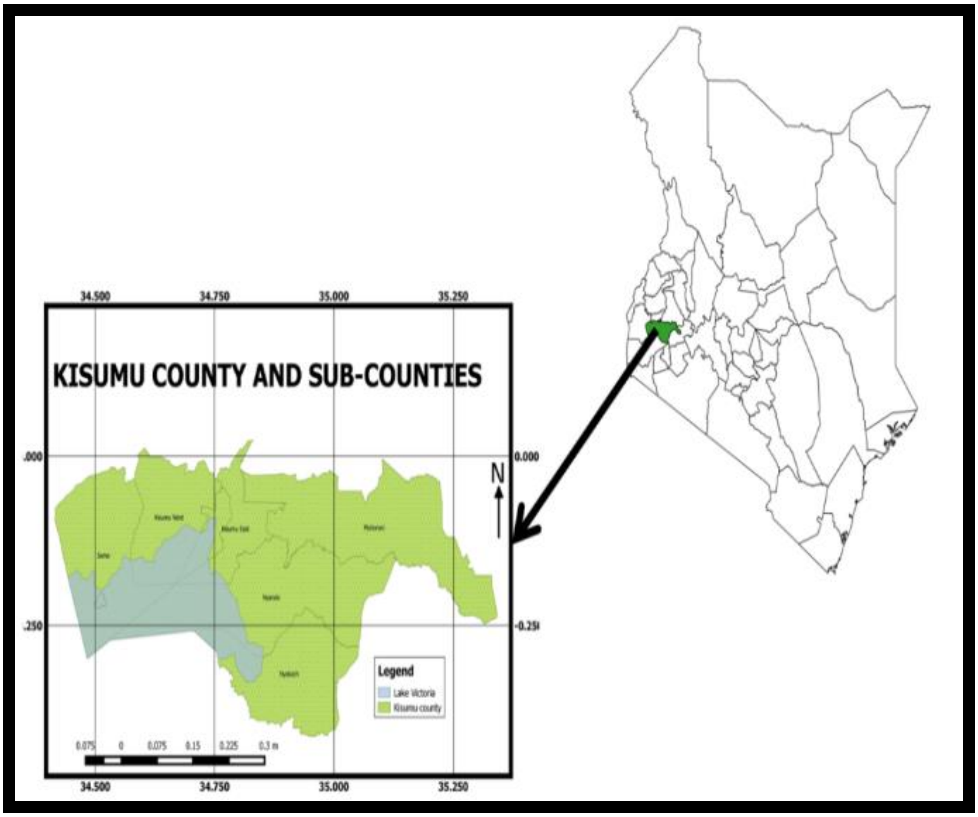

Figure 1: A map of Kisumu County (the study area) showing the location of Kisumu County in the map of Kenya and Kisumu sub-counties

Data Collection

The shape files representing various criteria including; towns, rivers, availability of animal wastes, markets, availability of farm gate sales and road networks were borrowed from International Livestock Research Institute (ILRI) and used to generate vector maps of Kisumu County in Quantum geographical information system (QGIS). Data indicating where the feed and fingerling supply agents were located were obtained by capturing coordinates during field survey. Information of on population distribution of livestock was obtained from the CIDP of the county (Kisumu CIDP, 2018-2022).

Data Validation for Suitability Maps

An experiment for establishing growth and production of *O. niloticus* was designed after the classification of various sites in the county as: extremely suitable, suitable, moderately suitable, marginally suitable, and not suitable. Three fish ponds of $300m^2$ were rented for the purposes of the experiment. The researcher disinfected each fish pond, stocked them with 1000 fingerlings and fed the fish with 25% crude protein diet twice daily for 6 days a week up to 8 months. Information related to geographic location of the farm, type and size of production system, water source, input source, population density in the proximity, and road networks were recorded in GPS alongside the coordinates. These were then compared to establish how different places were performing. To establish the effect of site suitability of fish production a fish production map was generated and overlaid with the suitability map.

Standardization of Raster Maps for each Criteria

Thematic maps and tables of the study area were derived from indicator maps out of classification of each raster map representing suitability levels and scores of criterion: using ILWIS GIS tools, you may determine if anything is extremely appropriate (5), suitable (4), somewhat suitable (3), marginally suitable (2), or not suitable (1) (Table 1) Each map's representation was altered to ensure that unsuitable areas were highlighted in red, marginally acceptable areas were highlighted in yellow, moderately suitable areas were highlighted in pale green, suitable sites were highlighted in green, and extremely appropriate areas were highlighted in dark green. This allowed data collected in different units to be compared.

The GIS – based AHP Model

The structure of the model for identifying suitable sites for farming tilapia in ponds was built using Analytical hierarchical process (AHP) which is a value structure (Berg, Mulokozi & Udikas, 2021). A total of seven sub-goals of socio-economic suitability were identified namely distance to roads, distance to the source of feeds, distance to the source of fingerlings, distance to the market; availability of animal waste, distance to the source of water, and availability of market for farm gate sales. In the hierarchical structure, the first level was assigned the main objective of the study namely; "generation of socio-economic suitability map for *O. niloticus* culture using Free GIS Software and SMCE tools in Kisumu County, Kenya.

The second hierarchy was assigned sub-goals namely; distance to roads, distance to the source of feeds, availability of animal waste, distance to the source of fingerlings, distance to the market; distance to the source of water, and availability of market for farm gate sales. The third level of the hierarchy was assigned attribute and spatial data (digital indicator maps and tables of the study area) for each *O. niloticus* culture site suitability assessment criteria. The fourth level of the hierarchy was assigned the sub-models (maps) created from each subgoal. The fifth level of the hierarchy was assigned the overall *O. niloticus* culture site suitability assessment model (map) which was built by a combination of various sub-goal maps.

Model possibilities were allocated to the sixth level of the hierarchy, which included extremely appropriate, suitable, suitable, somewhat suitable, marginally suitable, and unsuitable (Malczewski, 2006). Figure 1 shows the hierarchical model which was constructed during the study.

This study has two steps for evaluating each parameter for determining acceptable places for pond site selection. The first stage involves identifying and selecting possible criteria. The second stage, entailed weighting and calculating different criteria to obtain the final ranking of all criteria. Figure 4 presents the GIS – SMCE model for socio-economic characteristics.

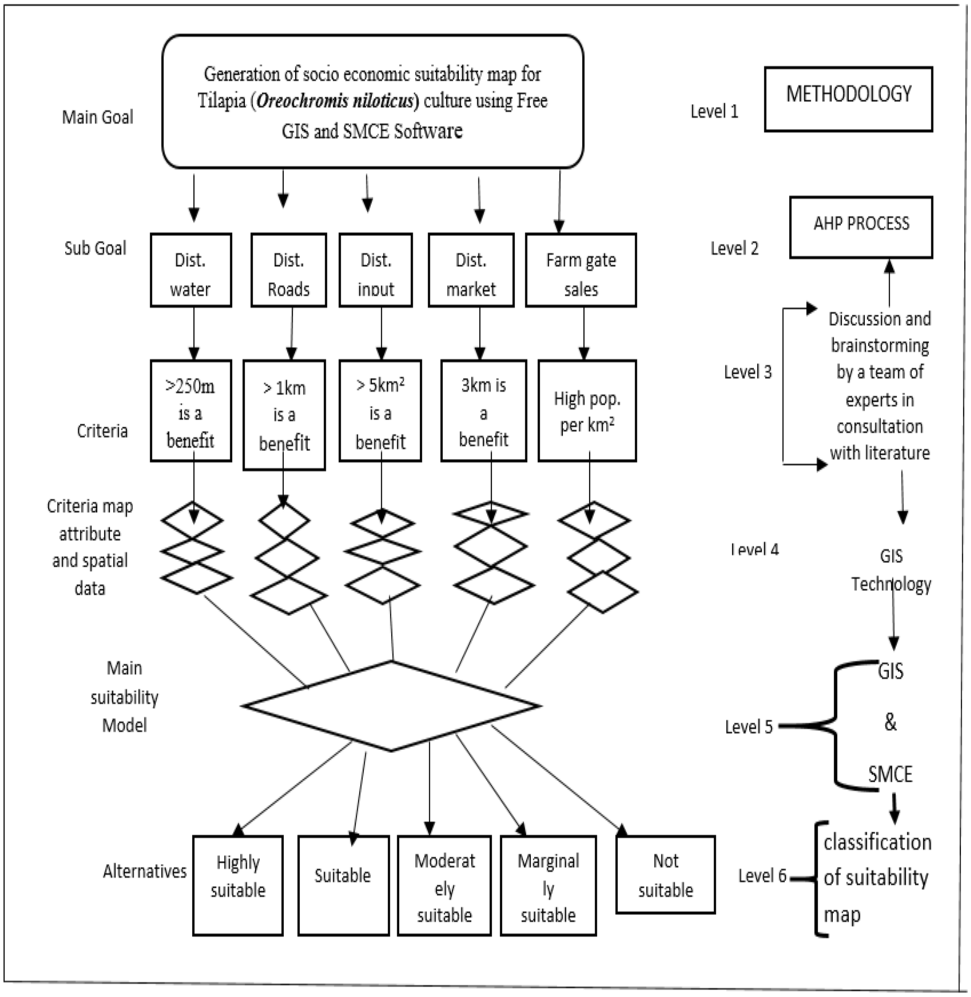

Figure 4: A schematic diagram showing the flow of activities in a GIS – AHP Model for a Socio-economic objective

Classification of Assessment Scale

The five-level scale was applied for all spatial assessments, allowing for the final combined overlay assessments of fish pond farming potential in Kisumu. The scoring levels (1to 0) were: very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (MS1), and unsuitable (US) (Adeleke *et al*., 2021). Table 2 presents this.

Table 2: Shows suitability classes for *O. niloticus* farming, ranging from the optimum, through the marginal to the unsuitable for each socio- economic criterion used in this study

Socio-economic characteristics	Classification of Criteria				
Suitability alternative	Very suitable (1)	Suitable (0.75)	Moderately suitable (0.5)	Marginally suitable (0.25)	Unsuitable (0)
Distance to source of water	<2km	2-5 Km	5km-10km	10-15km	<15km
Distance to road	<2km	2-5Km	5km-10km	10-15km	<15km
Farm gate sales (People per km^2)	200-1000	200-500	200-300	100-200	>150
Distance to markets	<2Km	5Km	10Km	15Km	<25Km
Distance to source of input	<2Km	5Km	10Km	15Km	<25Km

Weighting of criteria

Weights were assigned to each criterion by a team of experts in consultation with literature using pairwise comparison matrix available in the AHP process. In this matrix each criterion was compared to all other criteria and assigned weights according to its importance in determining site suitability through the experience of farmers and fisheries experts in consultation with literature.

Table 3: Relative Weight generated through pairwise comparison matrix

	DsW	DR	FGS	DM	DsI	DW
DsW	1	4/5	3/5	3/5	4/5	5
DR	4/5	1	3/5	2/5	3/5	4
FGS	2/5	3/5	1	2/5	1/5	2
DM	3/5	2/5	2/5	1	3/5	3
DsI	4/5	3/5	1/5	3/5	1	3

(*DM = Distance to market; DR=Distance to Road; DsI= Distance to source of Input; DsW= Distance to source of Water; DW=Derived Weight; FGS= Farm Gate Sales*)

Generation of indicator maps (models)

Expert opinion, field observations, semi-structured interviews, remote sensing, and GIS were used to derive the criterion dataset (Drobne & Lisec, 2009), which was represented as a spatial data (map) of the study area namely; an indicator map of the study area in respect of each criterion. The indicator maps were converted to thematic maps by being classified using the threshold values and suitability score of each criterion, assigning them weights generated by the team of experts, a georeference, a resolution, and a coordinate system of the study area.

Combination of models

Model combination involved production of individual thematic layers based on the suitability score which was saved with common coordinate system. The weight values derived from pairwise comparison using the AHP method, together with the suitability score, were used to produce sub-model suitability maps using the weighted linear combination mathematical technique (Miszewska *et al*., 2020; Adeleke *et al.*, 2020). This phase is commonly referred to as spatial multi-criteria assessment (SMCE), and it entails the integration of numerous aspects or criteria impacting the appropriateness of fish farming in one or more ways. Furthermore, a weighted linear combination was used to map the final overall aquaculture suitability maps (Drobne &Lisec, 2009; Adeleke *et al*, 2020). All sub-model were multiplied by the weights produced from the pairwise comparison matrix, then added together using map algebra methods. (Bartonek, Bureš & Švábenský, 2020; Yin *et al*, 2020). A common coordinate system, pixel size and geo-reference were used to save rasterized individual thematic layer which were then loaded to a criteria tree generated through MCE method and standardized based pairwise comparison combined to generate sub-model suitability maps in SMCE module in ILWIS (Adeleke *et al*, 2021). Multi-criteria evaluation (MCE) is a term used to describe a procedure that involves the integration of numerous aspects or criteria that influence the acceptability of a particular location (Lukoko & Mundia, 2016). The final aquaculture suitability was calculated using a weighted linear combination.

Data analysis

The data was analyzed using ILWIS and QGIS software. The spatial data analysis tools in ILWIS and QGIS were used to classify each criterion-based indicator map of the study to make them thematic. The thematic maps were then standardized and weighted using AHP process in excel software. The spatial multicriteria evaluation module in ILWIS assisted the researcher to combine the classified maps to produce the final suitability map. Classification of the final map was achieved through the criteria tree in SMCE module in ILWIS. ANOVA was used to compare the size of areas covered by different suitability classes for the final suitability map.

RESULTS

This section presents the results from the GIS analyses and interviews. Table 5 outlines areas assessed to be highly suitable, suitable, moderately suitable, marginally suitable, and unsuitable for location of fish pond farming based on socio economic criteria. The areas are also presented in the maps under each section.

Suitability Scores and Criteria of Socio-economic Factors

The criteria developed by the team of experts were weighted using AHP which used pair-wise comparison matrix (Table 3). Among the socio-economic factors, distance to market factors (0.0674), distance to roads (0.0175), followed by distance to source of input (0.0156) got higher values than distance to water source (0.0141) (Table 4).

Table 4: Area in km^2 covered by each socioeconomic suitability class for fish pond location in Kisumu County and criteria

Suitability alternatives/class			**Highly suitable**	**Suitable**	**Moderately suitable**	**Marginally suitable**	**Not suitable**	
Suitability scores for each alternatives/class			1	0.75	0.5	0.25	0	
			Dark Green	Green	Pale green	Yellow	Red	
Colour representing each Suitability alternative								
Socio economic Criteria,	Type of Factors /constraints	Weight of Each Criteria	Area in km^2 covered by each suitability class					Total area
Distance to water source	Below 200 m is a benefit	0.0141	16.48	24.72	41.2	41.2	1885.9	2009.5
Distance to input source	> 5 km^2 is a benefit <25 km^2 is a cost	0.0156	12.56	65.94	235	392.5	1256	2009.5
Farm gate sales (People per km^2)	High Population density is a benefit	0.1561	94	853	577	158	327.5	2009.5
Distance to Market	> 3 km is a benefit	0.0674	12.56	65.94	235	392.5	1256	2009.5
Distance to Roads	> 200m is a benefit	0.0175	17.9	27.8	46.4	46.4	1871	2009.5

Socio-economic maps

Socio-economic factors are very important in fish farming because they determine the cost of inputs, farm operations and production. *O. niloticus* fish ponds located and operated in areas with easy access to services, farm inputs and markets have high economic returns. The major economic factors ascertained during site suitability evaluation and used to construct a socio-economic model for *O. niloticus* culture in ponds were proximity to all-weather road connections, accessibility to both artificial and natural feeds, proximity to water sources, distance to markets, and availability of farm gate sales.

Distance to Source of Input

Distance from suitable sites for tilapia farming to the source of input were estimated and input agents located within 1km from the fish farms were considered suitable for tilapia farming. Distance to input supply agents of below 3km from the fish farms is a benefit but above that is a cost. Distance from 3km were considered suitable and classified into various levels of suitability. Each suitability level took up 12.56 km^2, 65.94. 235km^2, 392.5 km^2, and 1256 km^2 of land, correspondingly, for extremely appropriate, suitable, moderately suitable and marginally suitable (Table 4). The inappropriate location spans 1885.9 square kilometers. A distance to input agents map was scored taking into consideration the fact that short distance to the input supply agents is an advantage compared to long distances.

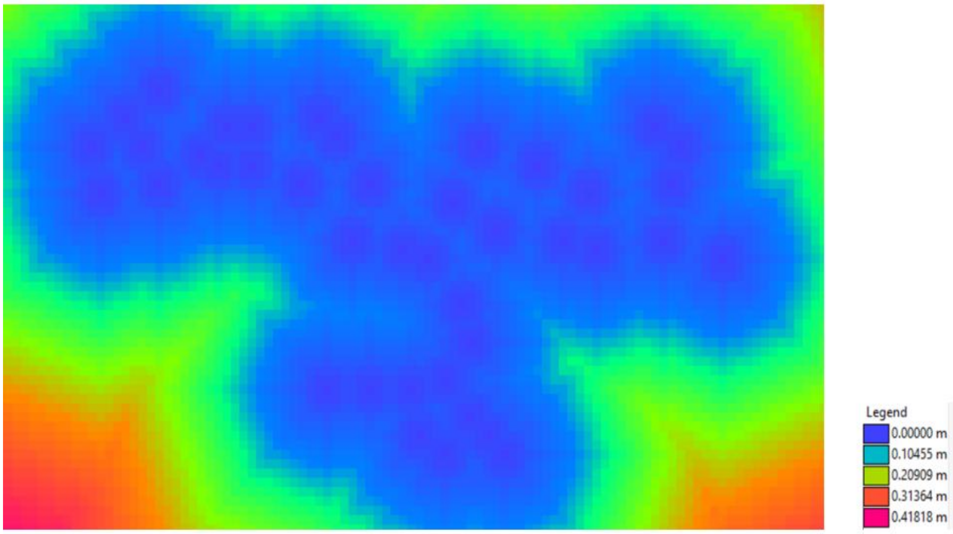

Figure 5: A map showing the distance to input source suitability factor.

The interviews with the Sub County Fisheries Officers revealed that farm input supply agents are basically located in urban centers as well as the main city of Kisumu. Therefore, distance to the input suppliers maybe long to fish farmers living in the rural areas such as Muhoroni, Nyakach, Seme and Nyando as opposed to those living areas like Ahero, Nyahera, Kajulu or Rabuor which are closer to urban centers and the city of Kisumu.

Distance to roads

Distance from suitable sites for *O. niloticus* farming to the roads in Kisumu County were estimated and roads located within 2km from the fish farms were considered suitable for tilapia farming. Distance to the road of below 2km from the fish farms is a benefit but above that is a cost. Distance from 2 km were considered suitable and classified into various levels of suitability. For very appropriate, suitable, moderately suitable, marginally suitable the area occupied by each suitability level was 17.86km^2, 27.8km^2, 46.37 km^2, and 46.37 km^2, respectively (Table 4 & Figure 6). The inadequate location covered an area of1256 km^2. A distance to roads map was scored taking into consideration the fact that short distance to the roads is an advantage compared to long distances. A shorter distance to the roads is an advantage compared to long distances.

During interviews with the Sub County Fisheries officers, it emerged that road network in Kisumu County is reliable with players in the road sub-sector including; Kenya National Highways Authority (KeNHA), Kenya Urban Roads Authority (KURA), Kenya Rural Roads Authority (KeRRA), Kenya Informal Settlement Improvement Projects (KISIP), and Kenya Roads Board (KRB).

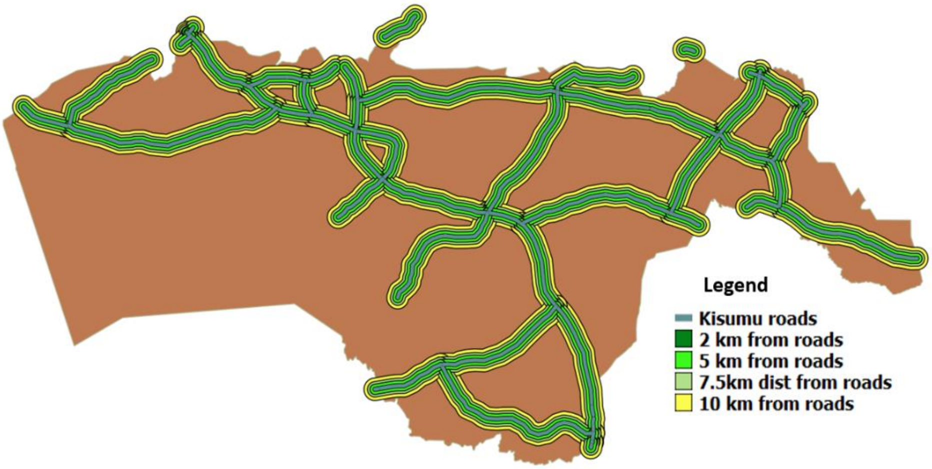

Figure 6: A map of showing distance to the road suitability

Distance to source of water

Distance from suitable sites for *O. niloticus* farming to the water source in Kisumu County were estimated. The water sources located 2km^2 from the fish farms were considered suitable for tilapia farming. Distance to the water source of below 2 km^2 from the fish farms is a benefit but above that is a cost. Distance to the water source from 2 km^2 were considered suitable and classified into various levels of suitability. The area occupied by each suitability level were 16.48 km^2, 24.72km^2, 41.2 km^2 and 41.2km^2 for highly suitable, suitable, moderately suitable and marginally suitable respectively (Table 4). The unsuitable site covers an area of 1885.9 km^2. A distance to source of water map was scored taking into consideration the fact that short distance to the water source is considered an advantage compared to long distances. The map for distance to source of water is presented in Figure 7.

The study also gathered during the interviews that Kisumu County is sufficiently within the proximity of diverse water sources. One major source is Lake Victoria and several rivers which are all-season Rivers by nature. These include River Nyando, River Sondu, River Kibos, River Ombeyi, and River Kisian among several small rivers which never dry up. The area is also well served with piped water particularly areas in the city of Kisumu and other peri urban areas like Kibos, Mamboleo, Nyahera, Kisian, Ahero, and Katito among others.

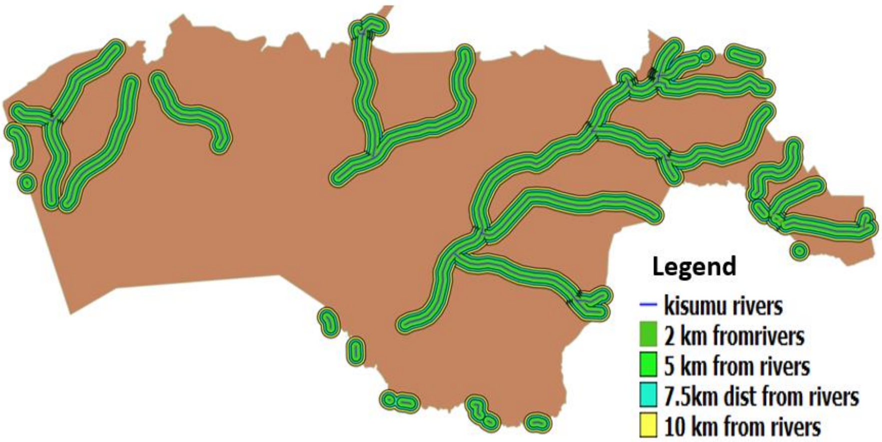

Figure 7: A map showing distance to water source suitability map

Distance to market suitability

Distance from suitable sites for tilapia farming to the market in Kisumu County were estimated and markets located within 2km from the fish farms were considered suitable for tilapia farming. Distance from the fish market to the fish farms of below 2km was considered as a benefit but above that was viewed as a cost. Distances above 2 km were assigned various levels of suitability. The area occupied by each suitability level were 12.56 km^2, 65.94 km^2, 235 km^2, 392.5Km^2 and 1256km^2 for highly suitable, suitable, moderately suitable, marginally suitable, and unsuitable, respectively (Table 4). A distance to market map was scored taking into consideration the fact that short distance to the market was an advantage and therefore highly suitable compared to long distances, considered as unsuitable (Figure 8).

The study also interviewed the Sub County Fisheries Officers to gauge their views regarding suitable sites for *O. niloticus* farming based on estimated distance to markets for the farmed fish. It emerged that although the population in diverse areas of Kisumu is relatively high, purchasing power of most of the people was low and they could not afford *O. niloticus* fish. The cost of one tilapia fish ranges from 250 – 450 Kenya Shillings, an amount which most families especially in areas like Nyakach, Muhoroni, Seme, and Nyando cannot afford. Farmers in the aforementioned areas are forced to travel to markets in Kisumu city so that they can fetch better prices for their harvests.

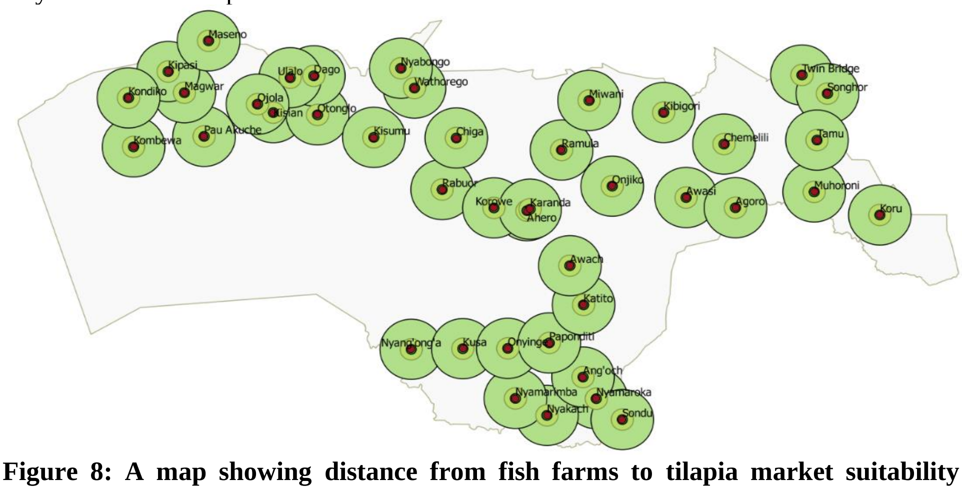

Figure 8: A map showing distance from fish farms to tilapia market suitability in Kisumu County

Availability of Farm Gate Sales

Availability of market for farm gate sales was estimated from the population density which is expected to provide market for the farm produce. A population density map was scored taking into consideration that the higher the population in an area where the fish pond will be located the better because high population is expected to provide the market for the harvested fish. High population density of above 200 people per km^2 is considered a benefit because it increases Farm gate sales but below that is a cost. Areas in Kisumu County with a population density of less 200 people per km^2 were assigned various levels of suitability. The area occupied by each suitability level is 94 Km^2, 853 Km^2, 577 Km^2 and 158 Km^2 for highly suitable, suitable, moderately suitable and marginally suitable respectively. The unsuitable site covers an area of 327.5 km^2 (Table 4). The map illustrating distribution of areas with various levels of suitability for farm gate sales for cultured tilapia are indicated in Figure 9.

The study obtained from interviews conducted with the Sub County Fisheries Officers that the population density in the county is fairly high, with almost each part of the region containing a population density of more than 150 people per Km$^{2.}$ The officers confirmed that in town centers like Ahero, Maseno, Katito, Chemilil and Muhoroni, the population density is even higher. Moreover, areas around Kisumu city like Nyamasaria, Dunga, Mamboleo in Kajulu and Otonglo, the population density rises to more than 500 people per Km$^{2.}$

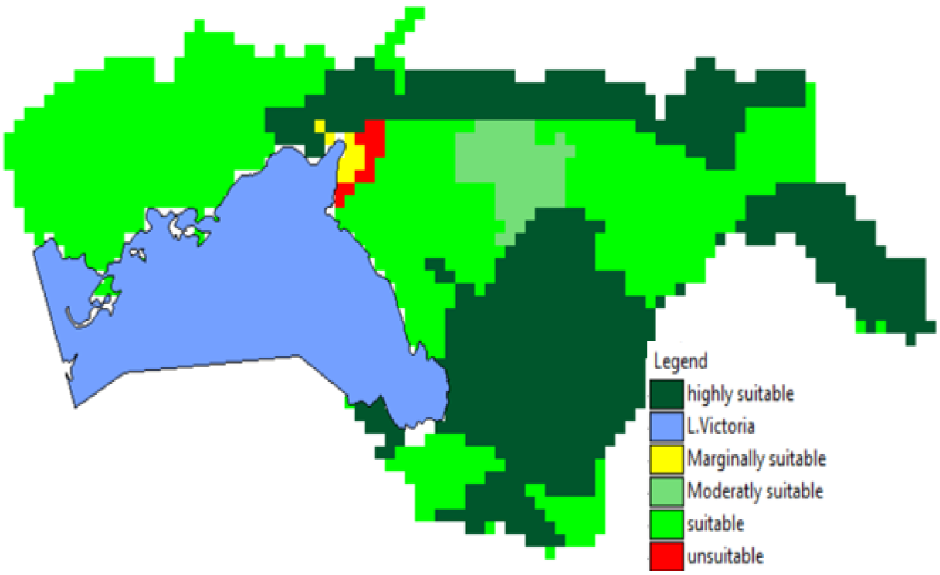

Figure 9: Farm Gate Sales Suitability Distribution Map of Kisumu County

Integrated Socio-economic model

Socio-economic factors are very important in fish farming because they determine the cost of inputs, farm operations and production. The maps which were combined to generate the socio-economic suitability model are; distance to roads, market, source of water, source of feeds, source of fingerlings, availability of farmgate sales, availability of animal waste and population distribution.

Tilapia fish ponds located and operated in areas with easy access to services, farm inputs and markets have high economic returns. The major economic factors ascertained during site suitability evaluation and used to construct a socio-economic model (Figure 3) during tilapia culture in ponds were proximity to all-weather road connections, accessibility to both artificial and natural feeds, proximity to water sources, distance to markets, and availability of farm gate sales.

Output from Socio-economic sub-model indicates that most parts of Kisumu County are highly suitable or suitable for aquaculture in terms of socio-economic factors except Muhoroni, Upper Nyakach and Seme sub counties which are far from Kisumu city. The farther the distance from the farm to Kisumu city the higher the cost of transportation of both the farm inputs and fish to the market. Places far from Kisumu city influences transportation of feeds, fish to the market and provision of farm gate sales. The County hosts Kisumu city, an international airport and one inland port at Kisumu city and five other urban centres namely Ahero, Katito, Muhoroni, Chemilil, and Maseno which are highly populated providing a large market for fish. Awasi, Pap-Onditi, Holo, Kombewa, and Sondu are five more developing fast-growing centers in the county. During the interviews with the sub county fisheries officers, most of the officers indicated that Kisumu County has all the socio-economic criteria characteristics assessed. There is adequate supply of water sources in the form of Lake Victoria, all-season Rivers, piped water network and dug wells and boreholes. The area is also adequately served with good road network, good market for fish harvest, and farm gate fish sales is also available due to high population density in each corner of the county.

The area occupied by each suitability level were 853km^2,780km^2, 49km^2 and 0km^2 for highly suitable, suitable, moderately suitable and marginally suitable respectively (Figure 4). Figure 4 shows the sliced map indicating the range of suitable sites based on socio-economic objective. The generated map of site suitability indicates that; 50.71 % of Kisumu county is highly suitable for tilapia, 46.37 % is suitable and 2.91% is moderately suitable.

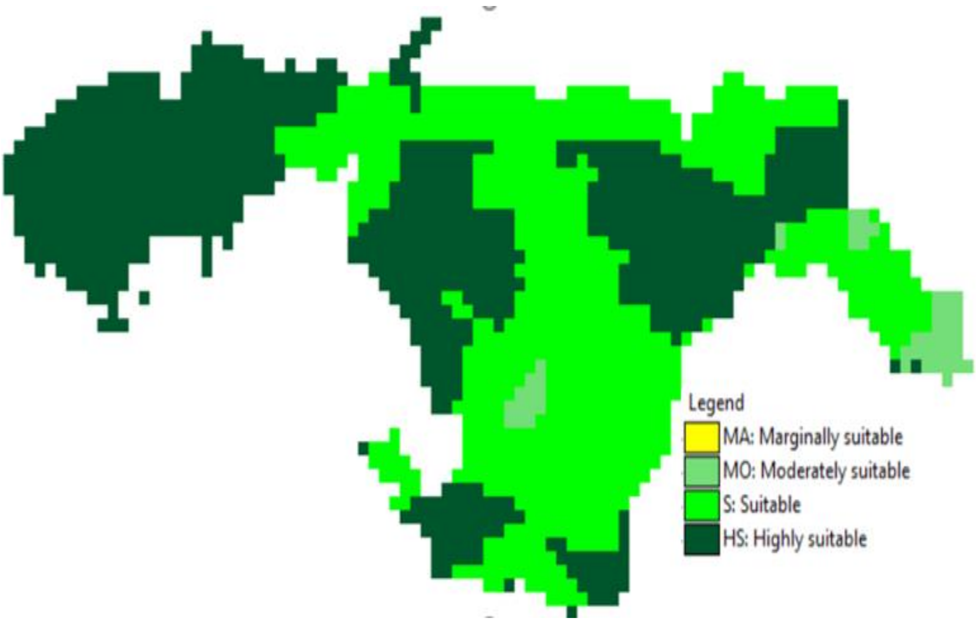

Figure 10: Socio-economic suitability map generated from the socio-economic factors.

Graphical representation of the area covered by each suitability site

The graph indicates that there is no significant difference between the area covered by the highly suitable and suitable area but the difference between these two suitability levels and moderately suitable area was significant.

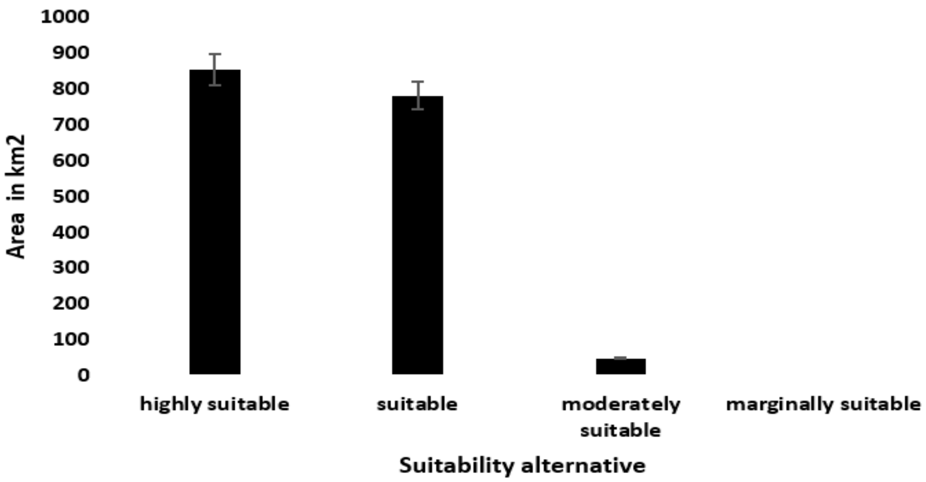

Figure 11: Area covered by the highly suitable and suitable area

DISCUSSIONS

The socio-economic criteria were developed by a team of experts whereby weights were generated using GIS based AHP for pair-wise comparison matrix (Table 3). Several studies have also successfully adopted GIS combined with AHP to solve spatial problem and to provide organized constructs for site selection based on different criteria (Malczewski, 2006; Ssegane et al, 2012; Malczewski & Rinner, 2015; Assefa & Abebe, 2018; Teniwut et al, 2019).

Among the socio-economic factors assessed, distance to market factors (0.0674), distance to roads (0.0175), followed by distance to source of input (0.0156) and farm gate sales (0.0156) got higher values than distance to water source (0.0141) (Table 4). This supports the potentiality of warm water species such as *O. niloticus* aquaculture in the area as revealed in Clough *et al*., (2020) and Obwanga *et al*., (2020).

With regards to distance to input supply agents, the study findings imply that in terms of distance to source of farm input supply agent, Kisumu County is moderately suitable. Farmers operating in rural areas are forced to travel long distances to access farm input from supply agents as opposed to those operating in urban and town centers. This seems to indicate that limited consideration has been made towards evenly distribution of farm input sources; a critical social determinant of success in any farming endeavors. This seems to concur with observation made by Krause *et al* (2015) which alluded to the fact that much focus in aquaculture has been production oriented more than varied dimensions of social, ecological and economic factors such as sources of farm input. In the analogy of Gatonye and Gakuu (2018), long distance to sources of farm input increases the cost of such resources hence making acquisition of them expensive. Patrick and Kagiri (2016) on their part revealed that high cost of input leads to less production. Perhaps this is a critical factor which makes the county not to be a leader in fish pond aquaculture production (Opiyo *et al*., 2018). The study additionally developed a map which identified specific sites for locating fish farming which are favoured by distance to input supply agents.

Part of the study also assessed the suitability of distance to all-season roads for the benefit of *O. niloticus* aquaculture. Findings tends to imply that Kisumu County has sufficient road network although it's served by diverse stakeholders including KeNHA, KURA, KeRRA and KRB among others. The suitability of Kisumu for *O. niloticus* aquaculture in terms of distance to all-season road is part of social dimensions which tend to make the area a suitable for fish farming as alluded by Njiru (2012) and Clough *et al*., (2020). In this regard, the study developed a site suitability map indicating specific areas with suitable areas in terms of roads for location of fish pond farms (Figure 6).

Another socio-economic criteria assessed was distance from suitable sites for *O. niloticus* farming to the water source in Kisumu County. Findings revealed that the area occupied by each suitability level were 16.48 km^2, 24.72 km^2, 41.2km^2 and 41.2 km^2 for highly suitable, suitable, moderately suitable and marginally suitable respectively (Table 4). The unsuitable site covers an area of 1885.9 km^2. This finding implies that the whole area of Kisumu County is suitable site for aquaculture in terms of distance to source of water. The area is well served with natural sources of fresh water such as Lake Victoria and several all-season rivers. The finding seems to concur with Clough *et al*., (2020) which concluded that extensive aquaculture pond systems depend on the natural physical conditions of the water. Source of water suitability associated with the area also supports the assertion by Obwanga *et al*. (2020) that *O. niloticus* forms 75% of warm water species in aquaculture production in Kenya. The study hence generated a distance to source of water map indicating specific suitable sites with suitable source to water distance (Figure 7).

Part of the study also assessed the suitability of distance from suitable sites for *O. niloticus* farming to the market in Kisumu County and findings showed that the area occupied by each suitability level were 12.56 km^2, 65.94 km^2, 235 km^2, 392.5 km^2 and 1256 km^2 for highly suitable, suitable, moderately suitable, marginally suitable, and unsuitable, respectively (Table 4). The finding implies that most areas in Kisumu have moderate and marginal suitability in terms of distance to market. It was also found that whereas the population in diverse areas of Kisumu is relatively high, purchasing power of most of the people was low and they could not afford the price of *O. niloticus* fish. Farmers in rural areas were therefore forced to transport their fish harvest to urban areas for good market thereby increasing transaction cost and limiting market participation. Long distances affected market participation and the quantity supplied due to increased transaction costs, according to Berdan *at al* (2012) and Omiti *et al* (2009). It also supports the arguments of Nyaga *et al*. (2016) and Gatonye & Gakuu (2018), who argue that farmers who live distant from market places spend more time and money on transportation, which reduces market participation. Therefore, a distance to market map was scored and developed indicating sites with suitability for aquaculture in terms of distance to market (Figure 8).

The study also assessed the suitability of farm gate sales based on estimation of the population density which is expected to provide market for the farm produce. Findings revealed that the area occupied by each suitability level was 94 km^2, 853 km^2, 577 km^2 and 158 km^2 for highly suitable, suitable, moderately suitable and marginally suitable respectively. The unsuitable site covers an area of 327.5km^2 (Table 4). This finding implies that, based on population density, there is no area in Kisumu which is unsuitable for *O. niloticus* aquaculture. Findings also showed that the population density in the county is fairly high, with almost each part of the region containing a population density of more than 150 people per $km^{2.}$ The finding that there is an opportunity for fish farmers to sell their products at the pond bank or the farm gate. Many small-scale farms are economically selling fish and crustaceans directly to clients at the pond bank, according to Dasgupta and Durborow (2009). According to Nyaga *et al* (2016), direct selling to neighbors is an important marketing route for fish growers. The study developed a map illustrating distribution of areas with various levels of suitability for farm gate sales for cultured tilapia (Figure 9).

CONCLUSION

The study concludes that GIS-AHP based spatial construction of socio-economic characteristics suitability assessment for *O. niloticus* aquaculture illustrated that Kisumu County is a suitable area. It is also concluded that due to good supply of natural sources of water, high population density and good road network respectively, all the areas assessed were suitable in terms of distance to source of water, farm gate sales and distance to the road. The study further concludes that low purchasing power of the neighbouring population, farm gate sales and distance to market are moderately suitable. The GIS – SMCE based suitability maps created should guide site location of fish pond for *O. niloticus* culture in Kisumu County, Kenya.

RECOMMENDATIONS

Its recommended that farmers be guided on where the suitable sites are located. More studies to show production capacity of the county in various suitable alternatives to be conducted. It's also recommended that these technologies be used to identify other suitable sites for the culture of other fish species.

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