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Exploring the potential of small water bodies as an integrative management tool for fisheries production

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Abstract

Understanding the potential of small water bodies (SWBs) will open greater opportunities in investment towards increased food and energy production. This study established the carrying capacity for fisheries development in SWBs in eight counties in Central and seven counties in Western Kenya. The carrying capacity of SWBs was calculated using socio-economic index (SI), trophic status index (TSI), and summaries of socio-economic and limnological data from 74 SWBs. The central region had a potential of 72,447 t in 37 sampled SWBs, whereas that of the western region had only 447 t in a similar number of sampled sites that forms part of the total national aquaculture potential. The higher potential in the central region is attributed to the relatively larger hydroelectric dams located in the area. To boost production in SWBs with low carrying capacities, restocking with native endemic fish species, which require limited or no supplementary feeding, is recommended. However, in SWBs, where depths reach 3.0 m or more, which optimises on intensive feeding and good water circulation, cage culture reared fish coupled with a strong local community association would be recommended. The indexing holistic approach herein forms an integrative management tool for fisheries production.

KEYWORDS

blue growth, carrying capacity, ecology, integration, socio-economic, suitability

1 | INTRODUCTION

Water resources, such as small water bodies (SWBs), are vital to support biodiversity and provide socio-economic benefits to local communities (Hajkowkz, 2006). SWBs often represent examples of intact freshwater resources, such as dams (dammed reservoirs), which are free from anthropogenic inputs, in that they remain unpolluted, and they are often a refuge for species that have all but disappeared from larger, more degraded, and polluted water bodies (EPA, 2005; EEA ETC/ICM, 2009). SWBs and associated drainage ditches are essential elements of the agricultural landscape (Downing & Duarte, 2009). As ecosystems, they serve many important biocenotic, hydrological, and economic functions (Fleischer et al., 1996). With the exclusion of ponds and rivers, SWBs are defined as standing waters that have been created as a result of erected barriers to stop or restrict the flow of water or underground streams (Haycock et al., 1996). In terms of their size, SWBs are usually greater than 1.0 ha but are less than 100 ha (EPA, 2005; EEA ETC/ICM, 2009).

SWBs differ in terms of their origin, with some formed naturally in dry depressions as a result of an accumulation of water from local surface runoff (Haycock et al., 1996) and being similar to that of morainal lakes. Artificially formed SWBs of anthropogenic origin are mainly formed from peat borrow pits filled with water and are typically of regular form. The latter SWBs are frequently determined by the presence of shallow groundwater (European Commission, 2008).

In most developing countries, SWBs remain among the least investigated part of the water environment and are largely excluded from fisheries management planning (European Commission, 2008; Fisheries Annual Statistics Bulletin, 2016). For example, although there are at least 1000 dams in Kenya, many of which are stocked with fish, national statistics capture only three main SWBs in their studies, that is, Jipe, Tana, and Turkwel (Aura et al., 2020b; Fisheries Annual Statistics Bulletin, 2016). Understanding of these resources has now changed, with most governments and private sectors focusing on fisheries and aquaculture as key drivers of the blue economy for sustainability and food security. This is to ensure further utilisation of SWBs to increase food and nutrition security in the rural and peri-urban areas. It is, however, imperative that the promotion of sustainable fisheries development does not degrade the environment and takes into account all sectors and resource users involved with the inclusion of the SWBs (EEA ETC/ICM, 2009).

Although there are numerous dams and small reservoirs in most developing nations, including in Africa, there is the potential to increase fisheries production using SWBs at local levels to bridge the fish consumption deficit per capita of 10 kg/person/year nationally (FAO, 2019). Owing to their relatively small size and being either state-owned or communal property, these SWBs fisheries could be easily managed by local governments or dependent communities to enhance their productivity (Bolgrien et al., 2009). With the observed reduction in fisheries contribution to most gross domestic products (GDPs) due to declines in capture fisheries (Aura et al., 2020b), the utilisation of SWBs (dams, pans, and reservoirs) for fisheries production could significantly increase productivity and fisheries yield and therefore reduce food insecurity and malnutrition (FAO, 2019). For example, in Kenya, the lower fish consumption per capita has been cited as a major contributor to high prevalence of malnutrition in most parts of rural Kenya (Ogello & Munguti, 2016). In the fish production debate, fisheries cultivation can have the potential to bridge the fish supply gap and enhance national fish consumption per capita (FAO, 2019; Musa et al., 2014). This stands against the backdrop of the total national aquaculture potential of 11 million t, and the production from capture fisheries is contributed largely by landings from Lake Victoria (90%) at 143,900 t in 2006 (FAO, 2016).

Due to increased pressure on global inland and marine fisheries to increase production, restocking of SWBs has emerged as one of the most used enhancement techniques (Welcomme & Bartley, 1998). Therefore, with proper management and husbandry, SWBs can promote community aquaculture initiatives to increase fish production and availability in rural areas (Gibbs, 2004). Furthermore, the Mekong River Commission (MRC, 2008) provides examples of how SWBs can be focal points for rural and peri-urban multi-uses such as irrigation, hydropower generation, and fisheries. They show how the SWBs can also be used for rural irrigation to promote the production of other food sources as an additional dietary supplement. To this end, SWBs appear to be a neglected "hotspot" for rural fisheries production, hence the need for effective management strategies. Such strategies on effective management of SWBs are an initiative that resonates with the Sustainable Development Goals, especially SDG1—no poverty; SDG2—zero hunger; SDG3—good health and well-being; SDG 13—climate action; and SDG 14—life below water (Government of Kenya Report, 2007). The strategies also support Africa's Agenda 2063 on rural food production and other national pillars targeting food and nutrition security (FAO, 2019; ICES, 2005).

Given the two most common fisheries innovations for SWBs composed of stocking and cage culture, fish stocking is probably the oldest and most successful intervention from a fishery development perspective, when used in the right manner and in the right location (Aura et al., 2013). Cage culture is less preferable as an alternative innovative technology due to the relative shallowness of water depths observed in SWBs, which can lead to floatation challenges for cages during dry seasons and more importantly problems associated with enhanced eutrophication (Aura et al., 2018; Njiru et al., 2019). However, proper management stocking of juvenile fish can maintain fish populations or supplement those produced naturally, thereby increasing fish abundance and fisheries yields (Musinguzi et al., 2019). However, care must be taken as regards fisheries stocking; in that some instances, these introductions could be counterproductive or may exhibit undesirable impacts such as disruption of native fish communities, loss of wild strains, and reduced genetic diversity (Aura et al., 2013; Newell, 2004; Read & Fernandes, 2003).

Nonetheless, before undertaking the stocking of SWBs, there are several precautionary approaches that need to be carefully considered to mitigate against adverse impacts on the environment, biota, and livelihoods of riparian communities (Souchu et al., 2001). The assessment of socioecologically sustainable fisheries production in SWBs poses a major challenge, given the range of issues that must be taken into account. They include the interactions between natural and social components and the coupling between the SWB basin and the watershed (Inglis et al., 2000; ICES, 2005). Along with biodiversity loss, environmental pollution, and resource exhaustion induced by rapid economic development and population growth, sustainable development concerns have spawned the concept of carrying capacity (Arrow et al., 1995). Policy recommendations are being made to encourage nations to produce fish species through cultivation as an environmentally sound activity (Gibbs, 2004). If we are to exploit an SWB, the concept of carrying capacity has to be prioritised and addressed (Raillard & Ménesguen, 1994).

According to GESAMP (1986), carrying capacity refers to the ability of the environment to accommodate a particular activity or rate of activity without unacceptable impact. Several authors have developed various carrying capacities on different activities. For example, ecological carrying capacity (Monte-Luna et al., 2004), environmental carrying capacity (Liu & Borthwick, 2011), land carrying capacity (Cheng et al., 2016), agricultural carrying capacity (Peters et al., 2007), tourism carrying capacity (Bera et al., 2015), and mineral carrying capacity (Wang et al., 2016).

Sustainable carrying capacity for fisheries production has four components, categorised according to physical, production, ecological, and social aspects (Inglis et al., 2000; McKindsey et al., 2006). These four components can be modulated by scaling, usually considered to be either system scale (i.e. SWB) or local scale (invested SWB through restocking to cocreate a farm). Furthermore, socio-economics as a component might be analysed in terms of resource use classification (system scale), whereas farm siting might draw on space availability for competing uses (physical), food availability (production), and local biodiversity concerns (ecological) (Inglis et al., 2000; McKindsey et al., 2006). However, there is limited information addressing the carrying capacity of SWBs for fisheries production at local, regional, and global levels. Yet, it is important to assess the carrying capacity of an area prior to the establishment of any form of cultivation, to ensure an adequate food supply for the anticipated production and to avoid or mitigate any ecological impacts (Gangery et al., 2001; Nunes et al., 2003).

This paper undertook the estimation of carrying capacity for SWBs, with specific reference to inland systems. This is because, within an ecosystem-based management approach, carrying capacity (expressed in tonnes) has been identified as the key consideration that helps to set the upper limits of production given the environmental limits and social acceptability (Cross, 2013). Notably, this study will be used to estimate the carrying capacity potential of SWBs with specific reference to 15 counties found in the Kenyan inland systems and used as a decision support tool for investment in fisheries production. This study takes a key step towards providing the evidence base that is needed to support sustainable use of SWBs in the Kenyan inland systems by addressing the following research questions:

(i) Were high fish production potential possible using ecological and socio-economic factors that affect fisheries management?
(ii) What is the type of fisheries development to be undertaken in specific SWBs?
(iii) What are the possible strategies to boost blue economic investment in SWBs?

2 | MATERIALS AND METHODS

2.1 | Study area

This study was conducted in eight counties in the central ecoregion of Nyeri, Kirinyaga, Meru, Tharaka Nithi, Embu, Kiambu, Kajiado, and Machakos and seven counties in western ecoregion of Migori, Kisii, Homabay, Kisumu, Siaya, Busia, and Kakamega in Kenya (Figure 1). The two regions are major multifunctional ecosystems with a connection between conflict and food security (Aura et al., 2017). The target counties were those with high concentrations of aquaculture activity, high production, existing sectoral infrastructure (processing, marketing, and research), adequate water resources, and marketing potential (ABDP Aquaculture Blue Book, 2021; Munguti et al., 2014). They contain the highest number of SWBs in the country, but a recent survey found both regions to be 65–79% food insecure with an incidence of poverty at 62–71% (Government of Kenya Report, 2007). Furthermore, both regions comprise several areas of rivers, forests, woodland, and grassland, which are minor centres for species endemism (IUCN, 2012; Osipova et al., 2020).

2.2 | Determination of the potential of SWBs

The procedure to assess the carrying capacities of SWBs is outlined in Figure 2. The methodology was divided into the establishment of socio-economic characteristics, selected water quality, and the SWB's morphology parameters, existing fisheries and calculation, and validation of the estimated carrying capacities.

2.2.1 | Socio-economic characteristics

A multistage sampling approach was adopted in the socio-economics survey entailing either an inclusion and/or exclusion criteria within clusters and elements of the sampling frame to accord representative samples (Sedgwick, 2015). Sampling was based on the features of the SWBs for which a benchmark for selection was set. A sample survey was preferred to a complete assessment of all the SWBs within the target counties, due to financial constraints, logistics, time, and quality benefits. The selection criteria took into account sub-county representation, dam acreage (preferably ≥5 acres), permanence of the water source, and ownership status (mostly communal or government owned) to exclude or include dams in the assessment. Various data collection methods and visualisations were adopted to capture socio-economics data (as summarised in Table 1).

Observations on the general environmental conditions of the SWB catchment, including the land use patterns, substrate types, basin vegetation cover, and the climatic elements, were recorded immediately on arrival at the site. The format for the questionnaire survey was built from a community index approach (Aura et al., 2021) but with modifications to collect 5-Likert point perceptions on water usage, resource use conflicts, gender and group dynamics, climate risks, ancillary services, social acceptability, and investment scale. Coding of the data was done to allow for thematic analyses that involved identification of patterned meaning in the dataset (Aura et al., 2021).

2.2.2 | Water quality and SWB parameters

Assessment of water characteristics followed published standard methods for aquatic environmental studies (APHA, 2000). Portable

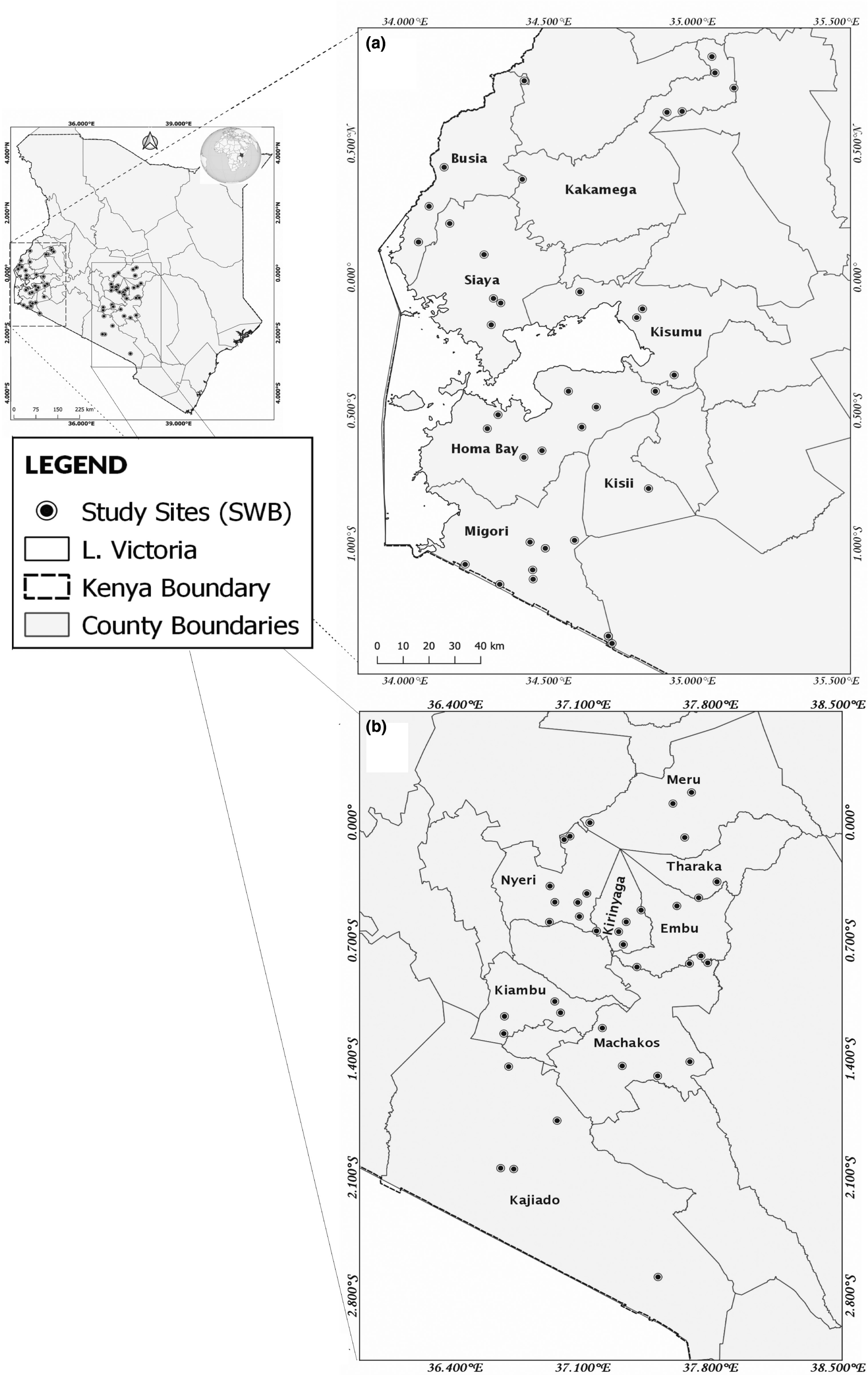

FIGURE 1 Study sites in (a) western and (b) central regions of Kenya. SWB, small water body

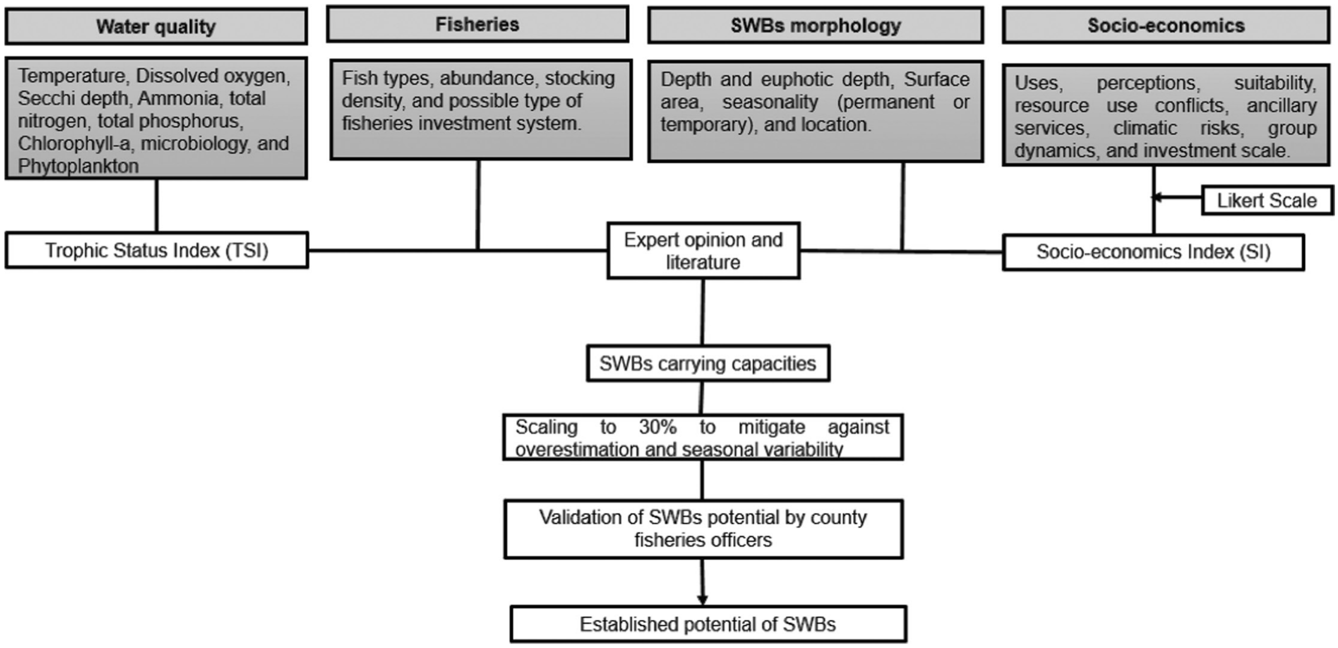

FIGURE 2 Schematic representation towards the establishment of carrying capacities of small water bodies (SWBs) for fisheries production

TABLE 1 Key tools used in the socio-economic analysis in the small water bodies survey in the determination of carrying capacity for fisheries production

Tool/method	Aim
Semistructured questionnaire	To generate socio-demographic information and perceptions on fisheries development indicators
Participant observation and transect walks	To verify socio-economics activities and existing resources in the community, establish a rapport with community members, and to debrief stakeholders on current research activities
Composite indices	To provide weighted aggregated scores for the indicators for establishing the general community perceptions
Spider web analysis	To describe the variations in socio-economic indicators across the study sample

water physico-chemical electronic sensor-based probes were used to take measurements at every SWB sampling site in triplicate.

The main physical and chemical parameters measured were column depth (m), temperature (°C), dissolved oxygen (DO mg/L), and pH. Water transparency measured as Secchi depth (SD; photic depth) was undertaken using a standard Secchi disk of 20-cm diameter.

Optimal levels of nutrients (nitrogen and phosphorus) are important for autotrophic productivity that forms the primary source of energy for the heterotrophic predators (Aura et al., 2020). Elevated or reduced nutrient levels would lead to a shift in habitat characteristics with consequential impact on biotic health, structure, abundance, and overall change to ecological processes (Masese et al., 2013). The shifts from optimal levels will ultimately result in reduced fish productivity in the water body (Aura et al., 2020b). Therefore, the present study also investigated the levels of ammonium–NH_4^+–N and total nitrogen (TN) and total phosphorus (TP) (Kundu et al., 2017). Three sites were identified and sampled where possible, two in the littoral areas and one in the centre of the SWB. The samples were then composited to make one sample. Water samples were collected using a Van Dorn water sampler at the surface. The water samples were then filtered for soluble nutrient fractions and stored in polyethylene bottles under refrigeration at about 4°C for further laboratory analyses. Samples for TN and TP were refrigerated without filtration (APHA, 2000).

Chlorophyll-*a* (Chl-*a*) as a measure of levels of primary production was also measured, by filtering with GF/C filters securely wrapped in aluminium foil before refrigeration ≈4°C. Samples were then transported to the laboratory and analysed according to methods adopted from APHA (2000).

Microbiology analysis for total and faecal coliforms was undertaken according to methods described in APHA (2000). Water samples were collected and analysed in the field using a portable incubator test kit Wagtech Potalab +(M). The Membrane Filtration method was used to determine the total coliforms and faecal coliforms at 37°C and 44°C, respectively. Total and faecal coliforms were detected and quantified using selective and differential culture media. Lauryl Sulphate Broth was used for cultivation of the organisms, where three composite samples were analysed for each SWB. Sample volumes depended on the water turbidity of the sampled dam.

Phytoplankton samples were taken using a horizontal 2.2-L Van Dorn sampler from a subsurface depth of about 0.5 m. A portion of the sample (25 ml) was preserved in acidic Lugol's solution. A Utermöhl sedimentation chamber was used to process the samples ahead of microscopic examination. Phytoplankton cells were identified to species level where possible and counted using a Zeiss Axiovert 35 inverted microscope. The taxa were identified using the methods of Huber-Pestalozzi (1938). Phytoplankton diversity and abundance reflect an SWB's ecosystem health and productivity. For example, phytoplankton is an important bio-indicator of heavy metal pollution in aquatic ecosystems due to its capacity to eliminate them from the water and to accumulate and store them over long periods even when the concentrations in the water are low (Aura et al., 2020a; Kundu et al., 2017).

2.2.3 | Fisheries

Fish samples were collected and assessed as described by Kundu et al. (2017) using a 50-m-long beach seine net with a depth of 3 m and a stretched mesh size of 2.54 cm (1 in.). The data collected were supplemented with commercial catches from fishers where possible. Fish specimens were identified to species level using updated FishBase identification guides (Froese and Pauly, 2021). Fisheries and aquaculture restocking possibilities were evaluated using a semistructured questionnaire administered to community leaderships, surrounding communities, aquaculture systems farmers, hatchery owners, and feed processing owners.

2.2.4 | Calculation of carrying capacity

The estimation of fisheries carrying capacity of an SWB with the interaction of various parameters involved in is shown in Figure 3.

A composite socio-economic index (SI) was calculated as a measure of the general socio-economics carrying capacity acceptable for any fisheries development interventions in the SWBs. This percentage score was derived from weighted averages of the specific ordinal scores subject to the Likert scale ratings of various socio-economics perception indicators (Aura et al., 2021). The overall sociometric scale was segmented as follows: 0 ≤ Unsuitable <0.2; 0.2 ≤ Subsistence <0.4; 0.4 ≤ Low-scale commercial <0.6; 0.6 ≤ Medium-scale commercial <0.8; and 0.8 ≤ Large-scale commercial <1.0 (FAO, 2019).

Additionally, biological productivity of any given water body can be limited by either light or nutrient availability (Aura et al., 2020a). Light irradiance in the water column would therefore be influenced by algal or suspended sediment turbidity. Trophic status of SWBs was assessed to understand the consequences of restocking and management actions and the importance of ecological processes. Trophic status index (TSI; Carlson, 1977) is an indicator of algal biomass in limnological systems as a response to nutrient concentrations, light availability, and/or other factors influencing primary production. Biomass surrogates that were used to calculate TSI were Chl-*a*, SD, TN, and TP. TSI averages range from ultraoligotrophic (approximately TSI =0) to hypereutrophic (TSI >1.0) (USEPA, 1998).

The calculation of TSI therefore took into consideration the SD measurement and concentration levels of TN, TP, and Chl-*a*. The TSI was first calculated for individual parameters before calculating the average value of all the parameters according to Carlson (1977) and Carlson et al. (2005) but with slight modifications to suit local conditions.

$$\mathrm{TSI}\ (\mathrm{SD}) = 10 * \left(6 - \left(\frac{ln\,(SD)}{ln2}\right)\right), \quad (1)$$

$$\mathrm{TSI}\ (\mathrm{Chl} - a) = 10 * \left(6 - \left(\frac{2.04 - 0.68ln\,(Chlor.)}{ln2}\right)\right) \quad (2)$$

$$\mathrm{TSI}\,(\mathrm{TP}) = 10 * \left(6 - \frac{\frac{ln48}{TP}}{ln2}\right), \quad (3)$$

$$\mathrm{TSI}\ (\mathrm{TN}) = 54.45 + 14.43\ln(\mathrm{TN}), \quad (4)$$

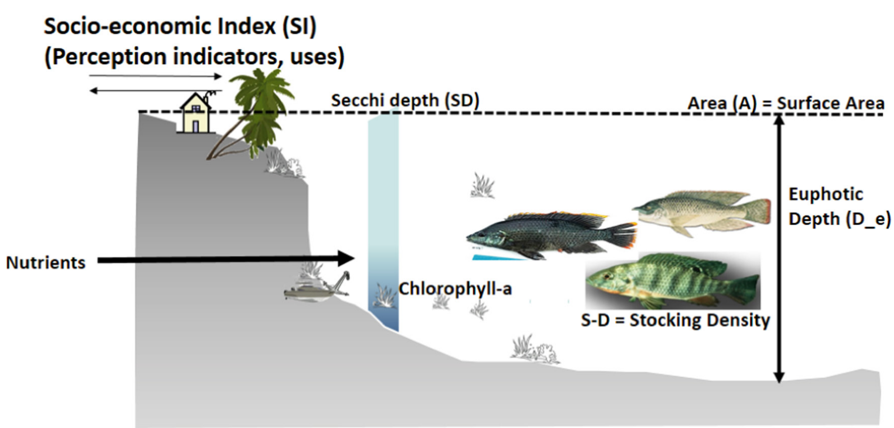

FIGURE 3 Possible parameters for the calculation of carrying capacity based on the potential interactions in a typical small water body ecosystem

$$TSI = (TSI(SD) + TSI(Chl - a) + TSI(TP) + TSI(TN)) / 4 \quad (5)$$

Therefore, the carrying capacity takes into account the SI, TSI, and physical size (area and euphotic depth) of the system (Cross, 2013). The estimated carrying capacity was scaled down by 30% to mitigate against overestimation given that SWBs' physical–chemical attributes exhibit huge seasonal variability (Cross, 2013; GESAMP, 1986).

$$C = ((A * D\_e * SD) * SI * TSI) \times 30\%, \quad (6)$$

where C = carrying capacity (mt), A = area of SWB, D_e = euphotic depth, SD = stocking density of fish in kg/m^2, SI = socio-economic index, and TSI = trophic status index. The carrying capacity was further classified into low (≤30 t), medium (31–100 t), and high (≥100 t) levels based on the estimations obtained.

The study used SPSS version 21 (SPSS Inc.) and R version 3.5.0 (R Core team 2014) for statistical analyses. The level of significance was estimated at $p < 0.05$.

3 | RESULTS

3.1 | Water quality and SWBs parameters

Significant variations ($p < 0.05$) were noted between western and central regions for dissolved oxygen, ammonium, TN, TP, Chl-*a*, and total and faecal coliforms, which could be attributed to varying anthropogenic activities surrounding the sampled SWBs (Table 2). The western region had a relatively higher extent of human activities than the central region.

The physiological analysis revealed the occurrence of six phytoplankton groups (Figure 4) with a predominance of diatoms in the central region: the concentration of diatoms (52.96 Ind/L) in the western region was ranked second after Euglenophyceae (68.59 Ind/L). There was increased presence of Chlorophyceae especially in the central region's SWBs, which was predominated by a species in the Order Chlorococcales. There was no significant difference ($p > 0.05$) in water temperature in the western region compared with the central region.

3.2 | Fisheries

A total of 28 fish species in 74 SWBs were recorded (Table 3). The central region had the highest proportion of relative fish abundance (66.67%) when compared with western Kenya's fish abundance (33.33%). One species, Nile tilapia *Oreochromis niloticus* (L.), dominated SWBs within both regions.

3.3 | Socio-economic index

The socio-economic carrying capacity indicators significantly varied ($p < 0.05$) across the SWBs in the western and central regions (Figure 5). The central region exhibited a relatively higher carrying capacity than the western region. Based on the socio-economic environment, fisheries development in SWBs in the central region was more viable than in the western region. Generally, livestock and farm-based agricultural communities perceived fishing and fish farming as less important entrepreneurial ventures within their sociocultural backgrounds. Furthermore, some dams provided more prospects for livelihood improvement from other socio-economic activities than capture or culture fisheries development. For instance, most urban dams were suited for ecotourism activities.

Most dams in the present study performed poorly (<15%) on group formation and integration dynamics, conflict resolution, and gender mainstreaming. The low indications of community-based group formation and lower social acceptability score generally compromised the scale of potential investment achievable.

3.4 | Trophic status index

There were significant variations ($F = 110$; $p = 0.04$) in the TSI across all the SWBs surveyed (Table 4). The TSI ranged between 0.14 and 0.68 and revealed the eutrophic state of SWBs but at different levels of nutrient enrichment. Unlike central Kenya, all the SWBs surveyed in western Kenya had TSI ≥0.50.

3.5 | Carrying capacity

The SWBs surveyed had a carrying capacity of about 72,894 t of fish potential, out of which Masinga dam constituted about 51,217 t, followed by Kamburu (15,135 t), Kindaruma (2409 t), and Gitaru (2351 t) (Table 5).

In the western Kenya region, Yao Kosiga Dam in Homa Bay County exhibited the highest potential (47.0 t). This was followed by Olasi (41.98 t) and Karamu (39.46); both of which are in Migori County. Migori and Kakamega Counties have the potential for increased water retention. The SWBs with shallow depths and with low estimated fish carrying capacities (≤30 t) constituted 81% of those surveyed and were found to be common in the western region.

An example of an advisory framework that was shared with the county fisheries officers and the national fisheries authorities as a decision support tool for possible fisheries investment in each viable SWB is shown in Table 6.

4 | DISCUSSION

4.1 | Water quality and SWBs parameters

The variations in physiochemical parameters found in SWBs in the current study are typical of those associated with human activities (Catalan et al., 2006). The western region had a relatively higher extent of human activities than the central counterpart, which included,

TABLE 2 Water quality parameters for the sampled small water bodies for both western and central regions of Kenya

Parameter	Western		Central	
	Mean ± SE	Range	Mean ± SE	Range
Temperature (°C)	24.57 ± 0.36	19.7–30.2	22.91 ± 0.4	20.30–26.4
Dissolved oxygen (mg/L)	5.13 ± 0.35	1.07–9.71	6.82 ± 0.22	4.81–8.23
Ammonium (μg/L)	76.17 ± 11.96	1.56–251.56	54.75 ± 9.89	10.94–175.31
pH	7.40 ± 0.10	5.64–8.46	8.22 ± 0.11	7.08–9.08
Secchi depth (m)	0.32 ± 0.05	0–1.5	0.55 ± 0.08	0.2–1.1
Total nitrogen (μg/L)	425.86 ± 45.39	86.53–1103.37	521.44 ± 97.91	234.95–1487.05
Total phosphorus (μg/L)	96.48 ± 10.98	14.71–310.4	102.65 ± 39.97	1.86–657.57
Chlorophyll-*a* (μg/L)	52.04 ± 6.75	5.63–310.4	31.21 ± 4.71	1.80–85.05
Total coliforms/100 ml (cfu)	2547.37 ± 463.59	300–10,000	975.51 ± 379.05	6–12,000
Faecal coliforms/100 ml (cfu)	457.89 ± 103.54	0–3000	254.62 ± 100.91	0–3000
Depth (m)	2.14 ± 0.18	1.0–6.0	3.9 ± 0.61	1–18.1

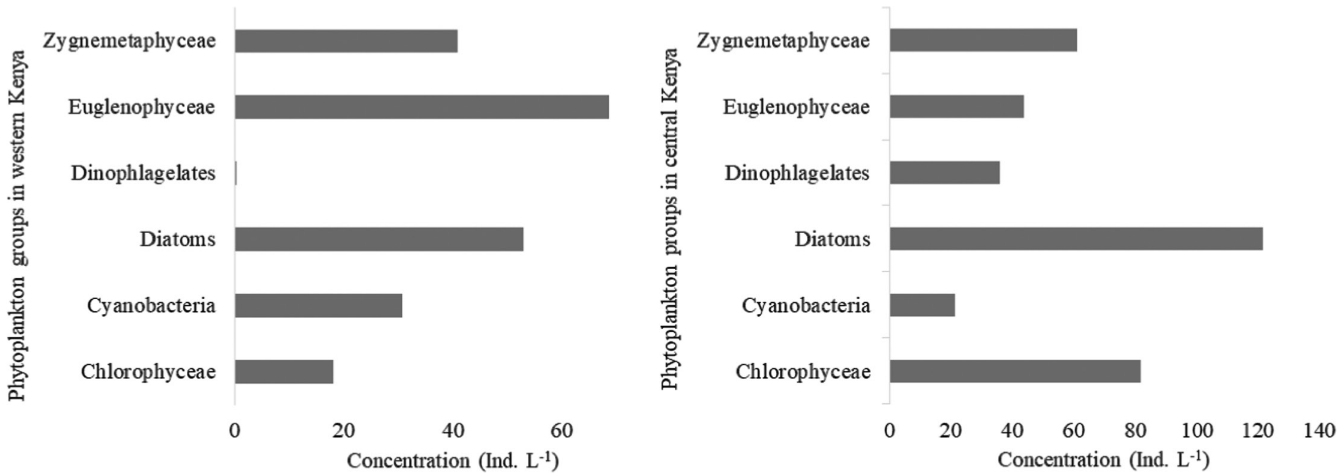

FIGURE 4 Concentrations of phytoplankton abundance (Ind/L) in the surveyed small water bodies of western and central regions of Kenya

but not limited to, wetland reclamations, increased discharges of domestic and industrial wastes, fertiliser runoff from agricultural-based farms, and sediment transported by rivers (Lung'ayia et al., 2001). Such apparent poor water quality attributes, driven by human activities at the catchment level, would contribute to high TSI and hence negatively affect the carrying capacity and potential for fisheries development. Moreover, poor water quality also lead to unavailability of such water for other economic uses. This makes the mixed use approach become more complicated and could result in resource use conflicts (Fleischer et al., 1996).

Quantitative analysis revealed a predominance of diatoms in the central region, which are adaptations to lower temperatures, typically found in this region, and are usually replaced by cyanobacteria with increased temperatures (Nowrouzi & Valavi, 2011). However, diatoms are used as indicators of both fertile and contaminated water (Trobajo et al., 2009), a scenario that could be associated with the presence of total and faecal coliforms within the SWBs surveyed and the presence of moderate concentrations of cyanobacteria. The increased presence of Chlorophyceae, especially in central region SWBs, was dominated by species in the Order Chlorococcales, indicating the likelihood of increased ambient primary productivity, and has been shown to increase in shallow aquatic systems typically found in this region (Tavernini et al., 2009). Environmental management of these SWBs, combining enhanced conservation measures such as afforestation and strict adherence to contaminant and discharge regulations, alongside investment in fisheries production management, is necessary to mitigate or moreover prevent water quality degradation.

4.2 | Fisheries

The differences in contribution of fish abundance in both regions were linked to better water quality in the central region than the western region. Water quality is a key determinant of biota occurrence in aquatic systems, with fish also used as an indicator of water

TABLE 3 Fish relative abundance (%) during the survey on small water bodies in western and central regions of Kenya

No.	Species	Central (%)	Western (%)
1	*Barbus* spp.	0.11	
2	*Barbus appleurogramma*	0.66	
3	*Barbus paludinosus*	5.01	
4	*Barbus paludiusus*	0.11	
5	*Cambarus sp.*	2.62	
6	*Clarias gariepinus*	1.96	3.70
7	*Cyrinus carpio*	0.33	
8	*Coptodon zilli*	3.27	
9	*Gambusia* sp	0.65	
10	*Haplochromis* sp	2.51	26.36
11	*Labeo gregorii*	0.76	
12	*Labeo victorianus*	1.63	0.22
13	*Micropterus salmoides*	0.54	
14	*Oreochromis esculentus*	0.11	
15	*Oreochromis leucosticus*	0.11	24.62
16	*Oreochromis niloticus*	48.91	33.55
17	*Oreochromis variabilis*	2.83	
18	*Tilapia mosambicus*	5.77	
19	*Tilapia rendalii*	11.76	
20	*Tilapia variabilis*	9.80	
21	*Unidentified tilapia*	0.22	
22	*Enteromius jacksonii*		0.65
23	*Enteromius kerstenii*		1.31
24	*Enteromius neumayeri*		0.22
25	*Enteromius paludinosus*		8.50
26	*Oreochromis zilli*		0.22
27	*Protopterus aethiopicus*		0.22
28	*Labeobarbus altianalis*		0.22

Note: Empty spaces indicates absence during sampling period.

quality due to their sensitivity to pollution (Masese et al., 2020; Mora et al., 2003, 2008).

The dominance of Nile tilapia in both regions despite differences in ambient water quality could partly be due their high tolerance to poor quality conditions (Masese et al., 2020). This resilience, combined with its fast growth rate, tolerance for overstocking (high stocking densities), adaptability to differing culture systems, and its high market value, makes this fish ideal for restocking in SWBs where it is already endemic (Musa et al., 2014).

4.3 | Socio-economic index

The current study depicted the central region with a relatively higher carrying capacity than the western region. This implies that, based on the socio-economic environment, fisheries development in SWBs within the central region was more viable than within the western region. Since the recent uptake and growth of aquaculture, this carrying capacity has continued to be relatively higher in the central than the western region (Ochieng, 2017). One reason is that the western region and its communities are largely linked to Lake Victoria, the largest open-access capture fishery in Kenya. The perception of ease of access to fish locally could be the single factor responsible for most communities in this region not recognising fisheries or aquaculture as being viable in SWBs (Shitote et al., 2013).

These findings confer with Stiftung (2012), who indicated that central Kenya as an ecoregion is much more developed in terms of physical infrastructure, for example, social amenities and the availability of ancillary services, than in the western region. Furnished with good road infrastructure and communication networks, growing industries, and numerous fish processing factories, the central Kenyan region provides a perfect environment for growth in both fish aquaculture markets and its associated inputs (ABDP Aquaculture Blue Book, 2021). Overall, this study

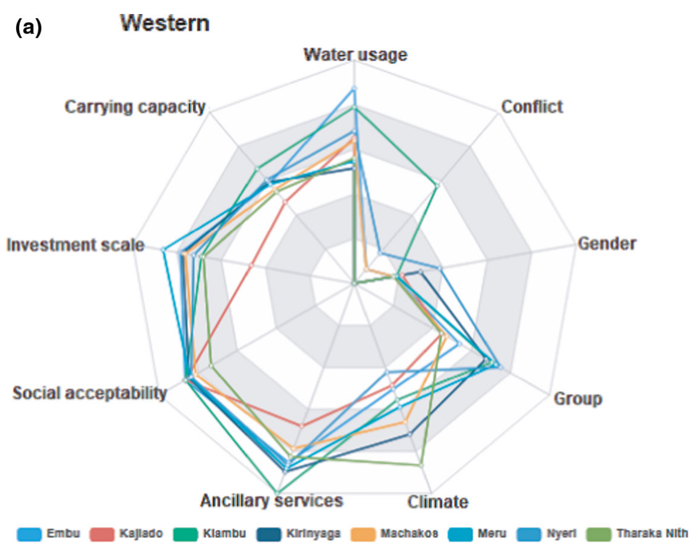

FIGURE 5 Variations in socio-economic indicators associated with small water bodies in western and central regions of Kenya

TABLE 4 Estimated and classified carrying capacities (mt) of small water bodies (SWBs) using water depth, socio-economic index (SI), and trophic status index (TSI) for western Kenya

Western Region							
County	**SWB**	**Size (ha)**	**Depth (m)**	**SI**	**TSI**	**Carrying capacity (t)**	**Remarks**
Busia	Buhuyi	5	2	0.47	0.58	8.12	Low
	Changara	0.84	4	0.51	0.65	3.34	Low
	Munana	10	3	0.51	0.54	24.79	Low
	Namalenga	8.5	2.5	0.56	0.6	21.4	Low
	Namonye	5	2	0.41	0.54	6.642	Low
Homabay	Kobodo	2.5	2	0.41	0.54	3.32	Low
	Konyango	7	1.5	0.55	0.64	11.09	Low
	Yao Kosiga	8	6	0.48	0.68	47.00	Medium
	Kouma	1.8	5	0.38	0.5	5.13	Low
	Oseno	20	2	0.54	0.58	37.58	Medium
	Pap Orage	1	1.5	0.52	0.66	1.54	Low
	Ramula	3	1.5	0.56	0.6	4.54	Low
	Yongo	8	1.5	0.5	0.58	10.44	Low
Kakamega	Mumonyonzo	1.5	1	0.5	0.67	1.51	Low
	X-Rasa	2	1.5	0.49	0.60	2.65	Low
	Lugulu	1.4	3	0.45	0.62	3.52	Low
	Lumino	7	1	0.48	0.62	6.25	Low
	Musembe	6	3	0.53	0.59	16.89	Low
Kisii	Ibeno	2	1	0.47	0.73	2.06	Low
Kisumu	Buoye	0.8	1.5	0.44	0.59	0.93	Low
	Hejope	0.5	2	0.6	0.66	1.19	Low
	Huma	1	1	0.48	0.53	0.76	Low
	Kere	0.26	1.5	0.48	0.61	0.34	Low
Migori	Konyona	0.25	2	0.43	0.66	0.43	Low
	Gwitembe	1	1.5	0.49	0.57	1.26	Low
	Karamu	18	2	0.63	0.58	39.46	Medium
	Mahena	1	2	0.47	0.65	1.83	Low
	Silanga Mubachi	11	2	0.49	0.61	19.73	Low
	Nyamome	8	3.5	0.51	0.60	25.70	Low
	Olasi	20	2	0.53	0.66	41.98	Medium
	Siabai	3	1	0.49	0.62	2.73	Low
	Silanga	6	2	0.49	0.51	8.99	Low
Siaya	Mauna	15	2	0.54	0.51	24.79	Low
	Nyadong	2	1	0.45	0.56	1.51	Low
	Nyagoko	8.6	1.5	0.46	0.68	12.11	Low
	Ochot	11	2.5	0.48	0.48	19.01	Low
	Uranga	11	3	0.51	0.52	26.25	Low

has indicated that the central region (compared with its western counterpart) has shown potential for investment and development in understanding the socio-economic benefits beyond the prevailing development.

The specific mainstay of local livelihoods and cultural eating habits was also found to shape the interest and participation of the local communities in fisheries development initiatives within the dams (Requier et al., 2020). Generally, livestock and farm-based agricultural communities perceived fishing and fish farming as less important entrepreneurial ventures within their sociocultural backgrounds. This statement could imply that there is a requirement for improved communication and discussions to understand the potential of SWBs fisheries investment as a viable livelihood alternative to the current sociocultural orientations.

TABLE 5 Estimated and classified carrying capacities (t) of small water bodies (SWBs) using water depth, socio-economic index (SI) and trophic status index (TSI) for central Kenya

Central Region							
County	**SWB**	**Size (ha)**	**Depth (m)**	**SI**	**TSI**	**Carrying capacity (t)**	**Remarks**
Embu	Gitaru	290	9.1	0.55	0.54	2351.35	High
	Ithatha	3.3	1.6	0.47	0.54	4.02	Low
	Kamburu	1125	15.1	0.54	0.55	15135.90	High
	Kindaruma	1000	3.5	0.51	0.45	2409.75	High
	Masinga	12000	5.7	0.52	0.48	51217.9	High
Kajiado	Enkaroni	5	3	0.44	0.63	12.474	Low
	Iyarat	3	3.5	0.4	0.66	8.316	Low
	Kiserian	41.8	18.1	0.48	0.48	522.95	High
	Olmirrui	0.1	3	0.45	0.58	0.25	Low
	Olokii	10	2.5	0.47	0.66	23.27	Low
Kiambu	Kimunyu	0.27	3	0.51	0.52	0.64	Low
	Rungiri	3	6.5	0.51	0.49	14.62	Low
	Tigoni	10.19	2.5	0.4	0.64	19.56	Low
	Twiga	3	6.2	0.48	0.47	12.57	Low
Kirinyaga	Ahiti Ndomba	2	4.4	0.48	0.43	5.45	Low
	Kangai	0.53	2.4	0.55	0.52	1.09	Low
	Karura	10	1.7	0.52	0.52	13.79	Low
	Njuki-ini	2	4.3	0.52	0.51	6.84	Low
	Thiba	0.75	1.5	0.61	0.65	1.34	Low
Machakos	Katangi	5	4.1	0.47	0.55	15.90	Low
	Kwale	10	3.5	0.47	0.65	32.08	Medium
	Muthetheni	10	3.2	0.51	0.57	27.91	Low
	Muoni	13	3	0.48	0.53	29.76	Low
Meru	Kaguru	1.5	1.5	0.46	0.46	1.43	Low
	Nguthuru Laingo	6.5	1.5	0.53	0.54	8.37	Low
	Nkunga	68	1.5	0.55	0.41	69.00	Medium
	Ontulili	68	1.5	0.53	0.42	68.12	Medium
Nyeri	Chinga	175	2.8	0.54	0.50	396.90	Medium
	Gaikuyu	0.59	2.2	0.54	0.43	0.90	Low
	Guara	2	2	0.54	0.58	3.76	Low
	Hohwe	3	3.6	0.47	0.40	6.09	Low
	Ichamara	2	2	0.57	0.31	2.12	Low
	Kiboya	0.85	2	0.42	0.33	0.71	Low
	Kiunyu	0.85	1	0.51	0.55	0.72	Low
	Njengu	9	3.1	0.57	0.42	20.04	Low
Tharaka Nithi	Gatonto	0.75	2	0.47	0.14	0.30	Low
	Ndetha	0.75	2	0.47	0.59	1.25	Low

Furthermore, some dams provided more prospects for livelihood improvement from other socio-economic activities than capture or culture fisheries development. For instance, most urban dams were suited for ecotourism activities. Adaptation to the socio-economic dynamics of the dam's situation, such as developing sport fishing in a tourist-centric location (Smucker & Detenbeck, 2014) or cage culture and irrigation, provided good prospects for multiple livelihood activities in these SWBs. Using these socio-economic dynamics in an integrated approach would improve the management and scale of the potential fisheries development, and, conversely, this would then not impinge on livelihoods and activities based in and on the SWB.

Most dams in the present study performed poorly (<15%) on group formation and integration dynamics, conflict resolution, and

TABLE 6 A typical tabulation of socioecological characteristics of each small water body (example shown is Ithatha dam in Embu County) as conclusive remarks for the potential of fisheries investment

Parameter	Observed value	Reference value	Remarks/interpretation
Socio-economic index	0.54	0.4 ≤ low-scale commercial <0.6	Recommended for low-scale commercial fish farming
Trophic status index	0.55	0.50–0.70 (eutrophic)	Can support fairly high productivity
Ammonium (µg/L)	37.8	2000 µg/L	Within the recommended limit for fish growth
Dissolved oxygen (mg/L)	8.2	5 and above mg/L	Favourable for fish growth
Temperature (°C)	23.5	20–31 for warm temperature adaptive fish<20 for cold adaptive fish	Preferred temperature for fish growth
pH	7.1	6–9	Best for fish growth
TN:TP	23.8	10 – 30	No limiting nutrient and can support diverse population of algae
Secchi depth (m)	0.4	0.35–0.5	If turbidity is from phytoplankton only, the dam is in good condition. Notably high phytoplankton abundance recorded (last row)
Fish condition factor	1.84 (*T. m*), 2.55 (*T. r*)	2.9–4.8	*T. m* had poor performance, whereas *T. r* had fair performance. *O. n* and *C. g* recommended for restocking at semi- intensive levels
Microbial contamination indicators (faecal coliforms) cfu/100 ml)	160	10^3–10^4	1. Presence of fishing beach site with settlement 2. Surrounded by forest trees
Phytoplankton Shannon index H	2.98	H′ ≥2.5	Good availability of plankton and both wild restocking and cage fish farming involving food supplements recommended
Phytoplankton abundance (Ind/L)	159	300 and above	Conducive for fish farming if enhanced with supplementary feeds

Note: In this case, the species recorded in this dam during the survey were Tilapia mosambicus (T. m), Oreochromis niloticus (O. n), Tilapia rendalii (T. r), Clarias garepinus (C. g), and Barbus sp. The study recommends restocking at semi-intensive levels (based on SI and carrying capacity attained of 4.02 mt) of endemic O. n and C. g given that other fish species exhibited low abundances.
Abbreviations: TN, total nitrogen; TP, total phosphorus.

gender mainstreaming. The low indications of community-based group formation and lower social acceptability score generally compromised the scale of potential investment achievable (Stephenson et al., 2020). As such, capacity building initiatives meant to promote group cohesion and skills, coupled with a proper community engagement and involvement framework, are required for these SWBs to improve fisheries development prospects.

4.4 | Trophic status index

The study recorded a TSI range of between 0.14 and 0.68, which indicated the eutrophic state of SWBs but at different levels of nutrient enrichment. Those SWBs with TSI >0.5 were indicative of highly fertile systems (USEPA, 1998) with increased concentrations of TN, TP, and total and faecal coliforms. Unlike central Kenya, TSIs ≥0.50 in all the surveyed SWBs in western Kenya were indicative of increased nutrient enrichment. Runoff from agricultural land, inputs of industrial and human settlement effluent, the predominantly urban setting, and the nature of its inflows into the SWBs may have generated these eutrophic patterns (Mwamburi, 2016). This situation makes these SWBs unsuitable for uses like supply of domestic water and watering livestock. Moreover, utilisation of such water bodies for fisheries may only be possible within the less eutrophic systems, and some may require integrated management approaches that also address the catchment sources of eutrophication.

4.5 | Carrying capacity

All the four dams with the highest carrying capacity are in Embu County and within the River Tana system with depths >3.5 m that are ideal for cage culture due to their improved water exchange (Aura et al., 2018; Njiru et al., 2019). However, it should be noted that dams that had high carrying capacities (>100 t) are not accessible to local communities, which raises the need to agree a memoranda of understanding between KenGen—a national government power generating company—and the local associations to have an integrated system. In this case, both biological principles and stakeholder engagement are key in exploiting their potential (Worldfish, 2020). Other dams with substantial carrying capacity were Kiserian (522.95 t, Kajiado County) and Chinga (396.90 t, Nyeri County). Generally, these estimates show the need to invest in SWBs and enable such systems to be integrated in the mainstream fisheries production for blue growth. These efforts would help supplement capture fisheries sources that are being overfished and are on the decline (Fisheries Annual Statistics Bulletin, 2016). Notably, with 15% of the world's reported fish catch coming from inland waters, most of which emanates from tropical systems such as those in Kenya, the true contribution of tropical inland fisheries is likely to rise with further investment and production from SWBs in relation to the carrying capacity recorded in the current study (Worldfish, 2020).

In the western Kenya region, Migori and Kakamega Counties have the potential for increased water retention that could favour aquaculture production, for example, topography and soil type (ABDP Aquaculture Blue Book, 2021; Musa et al., 2014). The SWBs with shallow depths and low estimated fish carrying capacities (≤30 t), which constituted 81% of those surveyed and were common in the western region, are recommended for wild restocking with endemic fish species with limited or no supplementary feeding to avoid the effects of acclimatisation and adaptation to new environments (Fleischer et al., 1996). In as much as their collective carrying capacity remains proportionately low, they present the easiest opportunity for fisheries development due to their ease of access and community management. Additionally, those SWBs classified with medium capacities could require semi-intensive fisheries production with a moderate supplementary feeding regime (Musinguzi et al., 2019).

The inventory of the sampled fish species from each surveyed county was shared with the respective Directorates of Fisheries to inform and support possible restocking activities. If fisheries and aquaculture production is exclusively practiced in the studied SWBs, the central region with a potential of 72,447 t and that of the western region with 447 t could form part of the total inland fisheries and aquaculture production. Such production would be equivalent to about half of the Lake Victoria's total annual production of 143,900 t in 2006 (FAO, 2016).

However, most of the surveyed SWBs had multiple socio-economic uses—a possible recipe for conflict among resource users. To avoid conflicts and improve on performance, the development of SWBs strategy would be recommended. The strategy will, among other things, detail potential investments under the blue economy precipice and optimise operation by redefining the SWBs objectives, rehabilitation, remediation of sedimentation, and research. Further studies on the carrying capacity predictions based on the introduced investment opportunities could improve the methodological approach used in the present study for further fisheries management growth and improved conservation management of the systems.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data for this manuscript will be available upon request.

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