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REVIEW PAPER

Unlocking Aquaculture Potential of Arid and Semi-Arid Lands in Kenya for Food Security and Economic Growth

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Abstract

This review explores the untapped aquaculture potential in Kenya's arid and semi-arid lands (ASALs), highlighting the region's underutilized aquatic resources, including rivers, lakes, and dams. Despite Kenya's substantial water resources relative to top aquaculture producers like Egypt, aquaculture development in ASALs remains minimal, even though these regions cover 89% of the country. The study assesses ASAL water resource suitability for aquaculture, identifies key challenges, and proposes actionable solutions, drawing lessons from Egypt's successful aquaculture sector. A narrative literature review synthesizing high-quality scientific and grey literature was conducted. Findings reveal that ASALs possess significant aquaculture potential due to their favorable climate for species like Nile tilapia and African catfish, permanent rivers such as the Tana and Athi, and large reservoirs like the Seven Forks Dams. However, challenges such as water-level fluctuations, pollution, wildlife interference, stakeholder conflicts, and financial constraints hinder aquaculture development. The study highlights policy frameworks, financing models, and best practices from Egypt that Kenya could adopt to strengthen its aquaculture sector in the ASALs. It underscores the importance of integrated water management, stakeholder collaboration, and investment in capacity-building initiatives. Innovative approaches such as cage and pond aquaculture, supported by policies and infrastructure, are crucial for unlocking aquaculture's transformative potential in Kenya's food systems and rural economies. This review offers valuable insights for policymakers, researchers, and investors to advance aquaculture as a sustainable, scalable solution for economic growth and food security.

Introduction

Aquaculture has emerged as a critical driver of global food security and economic development, particularly in regions where limited arable land and overexploited fisheries pose significant challenges to food production. In 2022, global aquaculture production reached 130.9 million tonnes, valued at USD 312.8 billion, contributing 59% of global fisheries and aquaculture output (FAO, 2024). Notably, for the first time in history, aquaculture surpassed capture fisheries in animal production, with 94.4 million tonnes, accounting for 51% of global aquatic animal production and 57% of the production destined for human consumption (FAO, 2024). Despite this growth, aquaculture remains dominated by a few countries, leaving many low-income nations in Africa, Asia, Latin America, and the Caribbean lagging in realizing their aquaculture potential.

Recent studies have highlighted that aquaculture holds enormous promise, particularly in Africa, where untapped resources and underutilized potential could transform food systems (Karani et al., 2022). The need to urgently explore all available opportunities in aquaculture is pressing if the continent is to meet its growing demand for food in a sustainable way. Transformative actions are essential to make agri-food systems more efficient, inclusive, resilient, and sustainable, ultimately contributing to better production, improved nutrition, environmental sustainability, and enhanced livelihoods (Fresco, 2023; FAO, 2024). These transformative shifts are vital to address the existing gaps and ensure no one is left behind.

Egypt has become Africa's leading aquaculture producer despite severe water resources limitations. As of 2022, Egypt produced over 1.5 million metric tons of aquaculture products, making it the leading global aquaculture producer. Nigeria follows closely, with 260,000 metric tons of aquaculture production (FAO, 2024). Egypt's aquaculture sector thrives despite its dependency on the Nile River for 97% of its total renewable water resources, rendering it vulnerable to climate change and upstream human activities. With Egypt's per capita annual water share standing at 560 m^3—well below the international water poverty line of 1,000 m^3 per person per year—it is expected to drop further below 500 m^3, the threshold for absolute water scarcity by 2030 (Fouad et al., 2023). Despite these significant constraints, Egypt has optimized its limited water resources to sustain high aquaculture production levels.

In contrast, although Kenya does not rank among Africa's top aquaculture producers, it has a more favorable water resource base than Egypt. According to the Falkenmark Water Stress Index, Kenya's per capita water availability is 647 m^3 annually, which is comparable to Egypt's (Asaka et al., 2024). The Falkenmark Index classifies water scarcity with thresholds of 1,700 m^3 per person per year for water stress, 1,000 m^3 for water scarcity, and 500 m^3 for absolute water scarcity (Nyika & Dinka, 2023). Both countries face significant water stress; however, Egypt has managed to lead aquaculture production in Africa, far surpassing Kenya despite their similar water scarcity conditions. This discrepancy highlights Kenya's underdeveloped aquaculture sector, which still holds untapped potential, particularly in its arid and semi-arid regions (ASALs). These regions are rich in water resources such as permanent rivers, lakes, and dams that could be leveraged to enhance national food security and improve rural livelihoods. Under its Vision 2030 between 2009 and 2012, the Kenya national government identified fish farming as an alternative livelihood strategy for communities in Arid and Semi-Arid Lands (ASALs) (GoK, 2009).

The semi-arid regions of Kenya encompass Embu, Kajiado, Kilifi, Kitui, Kwale, Laikipia, Lamu, Makueni, Meru, Narok, Nyeri, Taita Taveta, Tharaka Nithi and West Pokot while the arid regions include Baringo, Garissa, Isiolo, Mandera, Marsabit, Samburu, Tana River, Turkana, Wajir (Figure 1). The ASALs cover nearly 89% of the country's total land area and are home to about 40% of the country's population (Odera & Matiy, 2023). Unpredictable rainfall patterns, extreme temperatures, and limited agricultural productivity often characterize ASAL regions. However, paradoxically, they are home to some of Kenya's major permanent rivers, such as the Tana and Ewaso Nyiro, which pass through vast expanses of largely unutilized land.

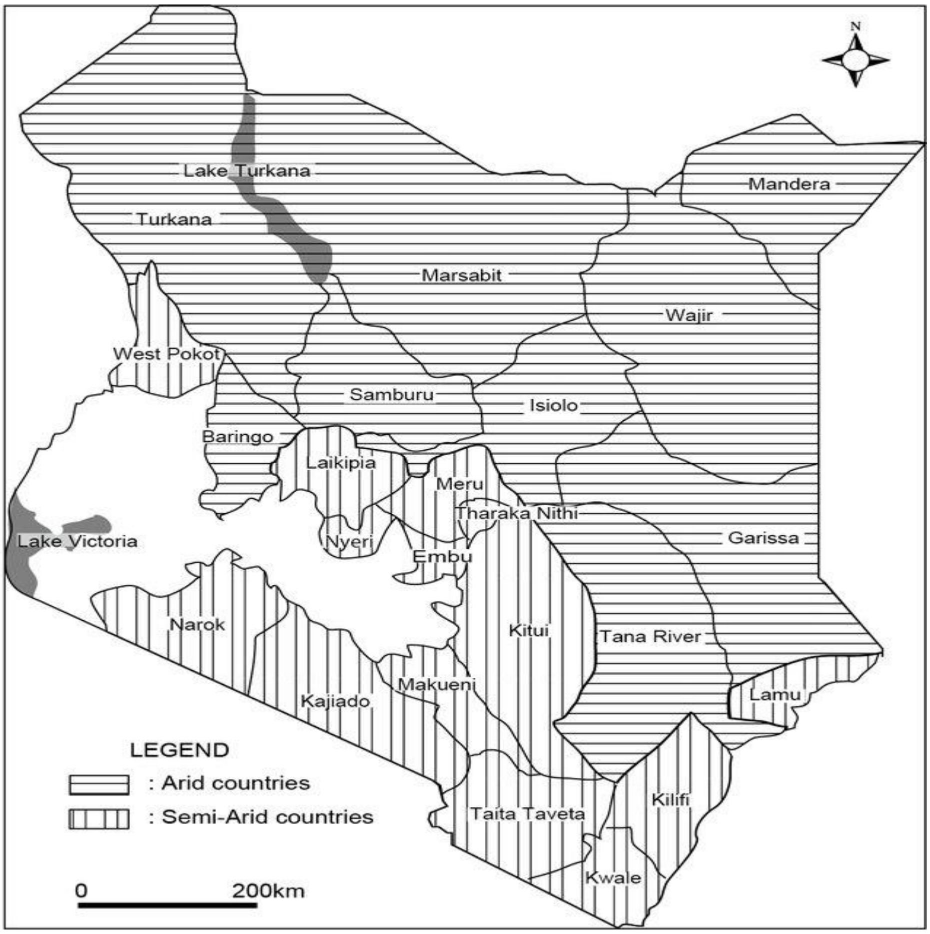

Figure 1. A map of Kenya showing the arid and semi-arid counties (Nyanjom, 2014).

In addition, the ASALs host critical water bodies such as Lake Turkana and the Seven Forks Dams along the Tana River are primarily used for hydroelectric power generation but have significant potential for aquaculture development, particularly cage aquaculture (Maina et al., 2017; Aura et al., 2022). Given Kenya's favorable climate characterized by optimum temperatures for Nile tilapia (*Oreochromis niloticus*) culture, the primary species cultivated in the country these regions offer an ideal environment for aquaculture expansion.

Despite the significant aquaculture potential in ASALs, these regions largely do not engage in aquaculture activities, resulting in a scarcity of information on their capabilities and optimal practices. Most aquaculture efforts in Kenya are concentrated in the lake, central, and coastal regions, and fish consumption in these areas is culturally ingrained and rainfall is adequate. Consequently, the ASALs—despite having abundant water resources like permanent rivers, lakes, and dams, as well as climates suitable for species such as Nile tilapia—remain underexplored and underutilized in this sector. As such many of the available water resources are underutilized or allocated solely for power generation and irrigation. The lack of data and research on effectively leveraging available resources and optimizing production in these areas hinders the development of tailored aquaculture systems that can thrive in the ASALs. Furthermore, rural communities in these regions face chronic food insecurity, exacerbated by climate change's effects, further hampering their agricultural productivity. Ironically, they continue to depend on government support for food aid while these counties are endowed with valuable resources. There is a critical need to develop sustainable food production systems in these regions to reduce vulnerability and foster resilience among these communities. Introducing aquaculture in these regions could diversify livelihoods, enhance household income, and improve nutritional outcomes by providing a reliable source of protein. Additionally, aquaculture development in ASALs could be crucial in addressing youth unemployment by creating new employment and business opportunities, thus mitigating migration pressures from these regions.

Therefore, this review explores the untapped aquaculture potential in Kenya's ASALs, focusing on the available water resources (including lakes, rivers, and dams) and climate suitability, and identifies the significant challenges impeding aquaculture expansion in these regions. Furthermore, the paper highlights lessons Kenya can draw from the aquaculture sector in Egypt, and proposes actionable solutions to unlock its potential. The review aims to provide policymakers, researchers, and investors a comprehensive framework to promote aquaculture as a sustainable and scalable solution for enhancing food security and rural development in Kenya's ASALs.

Review methodology

This review employs a narrative review methodology to synthesize existing literature, reports, and case studies on the potential for aquaculture development in Kenya's ASALs. A structured approach was used to collect, analyze, and comprehensively present relevant information. The literature search focused on identifying peer-reviewed journal articles, government reports, policy documents, and industry publications that provide insights into aquaculture development in Kenya's ASALs. Key sources included academic databases such as Google Scholar, Scopus, and Web of Science, as well as reports from organizations like the Food and Agriculture Organization (FAO). Search terms included "aquaculture in Kenya", "water resources in Kenya", "aquaculture challenges in arid and semi-arid regions," and "aquaculture in Egypt".

The review organizes the findings into key critical areas for understanding aquaculture's potential in Kenya's ASALs. These areas include the available water resources in ASALs in Kenya, challenges impeding aquaculture expansion, lessons from Egypt's aquaculture industry, and proposed strategies for unlocking Kenya's aquaculture potential. The section on water resources assesses the availability and accessibility of lakes, rivers and dams that could support aquaculture in ASALs. Climate suitability of these areas is examined by evaluating temperature, rainfall patterns, and environmental conditions that influence fish farming success. Additionally, the review incorporates a comparative case study approach, drawing insights from Egypt's highly successful aquaculture sector. This analysis identifies key strategies that have contributed to Egypt's growth in fish farming and evaluates their applicability to Kenya's ASALs. The review assesses Egypt's aquaculture production systems, governance frameworks, and financing models, highlighting best practices that Kenya could adopt to enhance its aquaculture sector.

However, this review acknowledges certain limitations. The availability and quality of data specific to aquaculture development in ASALs remain challenging, as research in these regions is relatively limited. Additionally, there may be gaps in policy implementation reports and a lack of empirical field-based studies that directly address aquaculture feasibility in ASALs. Despite these challenges, the review provides a structured and comparative assessment, offering practical recommendations to enhance aquaculture's role in food security and rural development in Kenya's ASAL regions.

Aquaculture potential of permanent rivers in Kenya's ASALs

Tana river

Geographical and hydrological overview

The Tana River, Kenya's longest and most significant watercourse, stretches approximately 1,014 kilometers from its origin in the Aberdare Mountains and Mount Kenya highlands to its mouth at the Indian Ocean, just north of Kipini (Bouillon et al., 2009). Tana River basin has a catchment area of 127,000 km^2, covering approximately 21% of Kenya's total land area (Njuguna et al., 2020; Ocholla, 2023). Main rivers draining into the Tana River include Chania, Thika, Maragua, Sabasaba, Rwamuthambi, Sagana, Thiba, Tanasagana, Ragati, Gura, Mathioya, and Rupingazi (Njuguna et al., 2020) The river traverses a diverse range of ecosystems, passing through several counties, including Nyeri, Murang'a, Embu, Kirinyaga, Kitui, Garissa, and Tana River County, the latter named after the river itself. The middle reach of the river constitutes 80% of the basin and is predominantly dry, with arid and semi-arid vegetation at an average altitude of about 500 m above sea level. Of particular interest for aquaculture development is the river's passage through the arid and semi-arid regions, notably Kitui, Garissa, and Tana River counties (Njuguna et al., 2020). Despite being predominantly dry and characterized by low rainfall, these areas are traversed by this permanent water source, making them highly suitable for aquaculture initiatives, which remain largely untapped.

The Tana River is fed by major tributaries such as the Thika River, Sagana River, and others originating from the central highlands (Botzen et al., 2015). These tributaries contribute significantly to the river's flow, making it a perennial river that sustains water availability year-round, even in arid and semi-arid regions. As it flows southeast from its source, the river supports numerous communities in these dry regions, but the potential for aquaculture remains underexploited. In counties like Kitui and Tana river, vast tracts of arid land adjacent to the river could be utilized for aquaculture ponds or integrated farming systems (Ochieng, 2018). Currently used for limited subsistence farming and livestock grazing, these lands hold tremendous potential for transformation into aquaculture zones, providing economic benefits and food security for the local populations.

Hydrologically, the Tana River experiences seasonal variations with higher flows during the long rainy season from March to May and the short rains from October to December (Lange, 2014). The upper Tana River basin is situated at an elevation higher than 1,300 m above sea level and is partly mountainous and hilly. It is characterized by relatively high rainfall, i.e., a yearly average of 1,050 mm with extremes up to 2,600 mm. In the upper basin, fast-flowing perennial rivers drain the eastern flanks of the mountains into the Tana River (Lange, 2014). The middle basin lies between 1,300 m and 500 m above sea level and is characterized by a semiarid to arid climate with rainfall ranging from 400 mm to 700 mm per year (Knoop et al., 2012). The lower Tana basin is below 500 m altitude and is water scarce. This is mainly due to low rainfall and high temperatures leading to evaporation rates of over 2,000 mm per year, far exceeding rainfall in this semi-arid region (Lange, 2014). Here, the Tana River is the only perennial stream. Only close to the Indian Ocean, there is relatively high rainfall in the lower basin. A significant part of the Tana flows through a (semi-) arid region. In the lower basin, the Tana River does not gain water from tributaries (except in the rainy season), but continuously loses water through evaporation (Lange, 2014).

Suitability of the Tana River arid catchment area for aquaculture

The potential for aquaculture is immense in the arid and semi-arid regions that the Tana river traverses. In counties like Garissa and Tana rivers, the river serves as a lifeline, providing water in an otherwise dry environment (Kipkemoi, 2018). These regions, often classified as marginalized due to their harsh climates and limited agricultural potential, could greatly benefit from the development of aquaculture. The river's flow through these arid counties offers a consistent source of water that can be harnessed for fish farming, particularly pond-based systems. The expansive, unused lands in these counties present an opportunity to establish large-scale aquaculture projects, which could improve local food security, provide employment, and boost the regional economy. Moreover, integrating aquaculture with existing agricultural practices, such as using irrigation runoff for pond systems, could create a more sustainable farming model suited to the conditions of these dryland areas (Chaibi et al., 2024).

The Tana river's hydrological characteristics make it ideal for various aquaculture systems, including pond and cage farming. Pond systems can be particularly effective in the vast plains of Kitui, Garissa, and Tana river counties, where large land areas are available for development. With proper water management, these ponds could support a variety of fish species, including tilapia and catfish, which are well-suited to the region's warm temperatures and variable water conditions (Abd El-Hack et al., 2022). Furthermore, the river's flow remains consistent enough to support cage aquaculture in deeper sections, especially in areas where the river forms natural pools or slow-moving stretches. The perennial nature of the river minimizes the risk of water scarcity, ensuring that aquaculture systems remain viable throughout the year, even during the prolonged dry seasons.

One of the most promising aquaculture sites is the Tana River delta in Tana River County. In 2023, this vibrant ecosystem recorded 133 metric tonnes of fish landings valued at Kshs 12.5 million—a notable increase from 129 MT and Kshs 11.6 million in 2022 (KeFS, 2024). The diverse catch, comprising Clarias (17%), Protopterus (15%), Alestes (14%), Synodontis (13%), Tilapia (10%), Labeo (8%), additional Tilapia varieties (10%), and other species (13%), underscores the delta's rich biodiversity and its potential to serve as a robust foundation for aquaculture (KeFS, 2024). Recognizing these opportunities, the Tana River County government has forged strategic partnerships with institutions such as the Kenya Marine and Fisheries Research Institute (KMFRI) to not only harness but also expand the region's aquaculture capabilities. These alliances have led to the adoption of modern production technologies and the enhancement of extension services, exemplified by the county's investment in advanced aquaculture training for its fishery extension officers in Mombasa under KMFRI's guidance (Science Africa, 2024). Furthermore, initiatives like the Kenya Marine Fisheries and Socio-Economic Development (KEMFSED) and the Agriculture Sector Development Support Programme (ASDSP) have been implemented to boost fish farming practices. While these programs provide critical short-term support, their intermittent nature highlights the pressing need for continuous capacity-building and infrastructure development to fully realize the delta's aquaculture potential and drive long-term food security and economic growth in this challenging yet resource-rich region (Science Africa, 2024).

Flooding, also offers opportunities for replenishing nutrients in aquaculture ponds or enriching fish habitats in cage systems with a potential risk (Kiptum et al., 2024). Flood management strategies such as constructing levees or using floodplain aquaculture techniques could mitigate the risk of damage while capitalizing on the natural processes that flooding brings. The river's ability to maintain a strong and steady flow also reduces the likelihood of seasonal reduction, impacting fish farming operations, a critical consideration for the success of aquaculture ventures in these dry regions (Langat et al., 2020).

Athi river

Geographical and Hydrological Overview

The Athi River, Kenya's second-largest river after the Tana River, spans approximately 390 kilometers and originates from the Ngong Hills, southeast of Nairobi (Masime, 2022). Athi River catchment covers Nairobi, Makueni, Taita Taveta, Kwale, and Mombasa counties, a part of Kiambu, Machakos, Kajiado, and Kilifi counties (Figure 2). The catchment area of the Athi river is 37,750 km^2, it accounts for about 57% of the Athi Catchment (Magondu et al., 2014). Along its course, the Athi river merges with several tributaries, including the Nairobi River and the Tsavo river, the latter contributing to its transformation into the Galana-Sabaki river as it passes through Tsavo National Park (Spinage & Spinage, 2012). The river has a vast catchment area of 58,639 km^2, encompassing some of Kenya's most densely populated regions, including urban and semi-arid zones (Kithiia, 2022). It flows through the dryland regions of southeastern Kenya, including the water-scarce Athi Plains and parts of Makueni and Machakos counties, before reaching the arid and semi-arid lands near the Indian Ocean.

The river's hydrology is defined by substantial seasonal variability, primarily influenced by Kenya's bimodal rainfall pattern. The basin experiences two rainfall seasons influenced by the convergence of the Southeast and Northeast monsoons in the inter-tropical convergence zone (Ojany & Ogendo, 1986). The Southeast monsoon (SEM) occurs between mid-March and mid-September while the Northeast monsoon (NEM) occurs between October and early March. Rainfall in the upper parts of the basin ranges from 1000 to 1200 mm yr^{-1} (Kitheka, 2019). However, rainfall is much lower ranging between 500 and 750 mm yr^{-1} in the lower regions. Along the coast, rainfall ranges between 750 and 1000 mm yr^{-1}. However, there are often large inter-annual variations in rainfall, partly due to El-Nino and La-Nina southern oscillation phenomena (Kitheka, 2019).

The seasonal reduction in flow creates challenges for water availability, especially for irrigation and aquaculture activities that depend on a steady water supply. The river is also prone to flooding during the rainy seasons, particularly in areas with steep terrain or where urbanization has disrupted natural drainage patterns. These flood events often result in the deposit of sediments and pollutants, further complicating the management of water resources along the river's course.

Water quality in the Athi River is a significant concern, especially considering the river's journey through some of Kenya's most urbanized and industrialized zones. As it passes through Nairobi and Machakos, the river becomes heavily polluted with industrial waste, sewage, and agricultural runoff, severely compromising water quality (Ngatia, 2022). Heavy metals such as cadmium and nickel have been detected in the river, primarily from industrial discharges and petroleum spillage, particularly in areas where garages and factories are prevalent (Masime, 2022). These heavy metals, alongside high concentrations of agrochemicals like pesticides and fertilizers, pose serious risks to both aquatic ecosystems and potential aquaculture activities. The river's pH levels are often impacted by chemical discharges, with water becoming more acidic in some regions, further reducing its suitability for fish farming (Mbaka, 2023). Dissolved oxygen levels in the river fluctuate, with higher levels observed in the upper reaches near the river's source, where water is cleaner and well-oxygenated and significantly lower downstream due to the high organic load from sewage and industrial effluents. The presence of nitrates and phosphates from agricultural runoff also contributes to eutrophication, leading to algal blooms and oxygen depletion, making it difficult for fish and other aquatic organisms to survive (Ashun & Tagoe, 2024). For aquaculture to thrive in the Athi River, extensive efforts to improve water quality will be essential, including reducing pollution inputs and implementing effective water management strategies to ensure that water parameters such as pH, dissolved oxygen, and pollutant levels are within suitable ranges for fish farming.

Suitability of the arid Athi River catchment for aquaculture

The Athi River flows through several arid and semi-arid counties in Kenya, including Makueni, Kajiado, and Kilifi, which present significant potential for aquaculture despite the current underutilization of this permanent water resource (Magondu et al., 2014). These regions experience water scarcity, yet the Athi River provides consistent water flow throughout the year, offering a critical opportunity for aquaculture development in these dry areas. The availability of permanent water in the Athi River, especially in sections where the river maintains a relatively steady flow even during dry periods, makes it a reliable source for supporting aquaculture operations. These arid regions also have expansive land areas suitable for establishing aquaculture farms, particularly pond-based systems that can be integrated into the landscape. For example, Makueni County alone spans approximately 8,008 square kilometers (Munuve, 2023), much of which remains underutilized for agricultural purposes due to water limitations. Yet, this land could support aquaculture if the Athi River's resources were harnessed.

Species compatibility in the river aquaculture

Regarding species compatibility, several types of fish species can thrive in the Athi River ecosystem, particularly in the arid and semi-arid regions through which it flows. Tilapia, a resilient and widely farmed species across Africa, is particularly well-suited to the conditions in these regions (El-Sayed & Fitzsimmons, 2023). Tilapia is known for its ability to tolerate a wide range of environmental conditions, including fluctuating temperatures and variable water quality (Makori et al., 2017), making it an ideal candidate for aquaculture in the arid sections of the Athi River basin. Nile tilapia (*Oreochromis niloticus*) has been successfully cultivated in similar river systems across Kenya, and its adaptability makes it a prime species for potential aquaculture ventures along the Athi River. In addition to tilapia, catfish (*Clarias gariepinus*) is another species that could thrive in these conditions. Catfish are particularly hardy, able to withstand low dissolved oxygen levels and poor water quality (Awoke et al., 2023), which can be shared in the lower stretches of the river where pollution and sedimentation are an issue of concern. Their ability to tolerate such conditions makes catfish farming viable in these arid and semi-arid zones, where water conditions may fluctuate throughout the year.

Aquaculture models that could be implemented in these regions include cage and pond-based systems, depending on the specific characteristics of the river's flow and the surrounding landscape. Cage aquaculture could be feasible in river sections where flow rates are stable, particularly in areas where the river forms deeper channels (Lebel et al., 2013). The consistent flow in the Athi River during the wet season, combined with the lower, but still sufficient, flow in the dry season, creates a suitable environment for cage systems that can support fish growth year-round (Kitheka et al., 2022). However, in some sections, sedimentation from upstream urban and industrial areas could pose a challenge, as it may affect water quality and the health of fish stocks. In these areas, pond-based aquaculture may be more appropriate. Pond farming, particularly in expansive dryland areas adjacent to the river, allows for greater control over water quality and nutrient levels. Large tracts of land in counties such as Kajiado and Makueni are available for this type of development, with the potential to establish extensive pond systems that the river can feed. For example, Kajiado County covers 21,292 km^2, much of which is underused (KNBS, 2015), and this land could be transformed into productive aquaculture farms with proper irrigation and water management systems. Integrating pond-based systems into the expansive drylands surrounding the Athi River could provide a stable environment for fish farming and help mitigate some of the challenges posed by fluctuating water flows and occasional pollution from upstream sources.

Risks of Kenyan river aquaculture and mitigation strategies

The potential for aquaculture development along the Athi River is promising, particularly in the arid and semi-arid regions where water availability is a major constraint to agriculture. However, several challenges and risks must be carefully considered and addressed to ensure the successful and sustainable utilization of this resource. The primary risks involve environmental concerns, water flow variability, and the possible introduction of invasive species or diseases that could undermine aquaculture operations.

Flooding

One of the most significant environmental risks is the potential for flooding, particularly during Kenya's rainy seasons, which typically occur between April and June and from October to December (Nathan et al., 2020). Like many rivers in Kenya, the Athi and Tana rivers are prone to seasonal flooding, especially in areas where rainfall intensity is high and the landscape has been altered by urbanization or deforestation (Githui, 2021; Kiptum et al., 2024). Flooding can wash away fish cages or ponds, resulting in the loss of fish stocks and damage to aquaculture infrastructure. For instance, during periods of heavy rainfall, the river can experience rapid increases in flow, inundating low-lying areas and causing sediment deposition. This sediment can clog fish cages or ponds, reducing water quality and increasing the risk of disease outbreaks. Flood events also carry debris, agricultural runoff, and pollutants from upstream urban and industrial zones, further exacerbating water quality issues (Giri, 2021). To mitigate this risk, aquaculture operations must incorporate flood management strategies, such as building flood-resistant infrastructure, using elevated ponds, or placing cages in more controlled, stable river sections. Proper land-use planning along the riverbanks, including restoring riparian vegetation, could also reduce the severity of flooding and minimize its impacts on aquaculture.

Water flow variability

The river's flow is highly seasonal, with high water levels during the rainy season and significantly reduced flow during the dry months (Venarsky et al., 2020).

In arid areas such as Kajiado and Makueni counties, where the Athi River serves as a critical water source, the flow can diminish to the point where river sections are reduced to small streams or pools during the peak dry season. This variability can be problematic for aquaculture, as low water levels can stress fish stocks, reduce dissolved oxygen levels, and increase the concentration of pollutants (Sarkar et al., 2021).

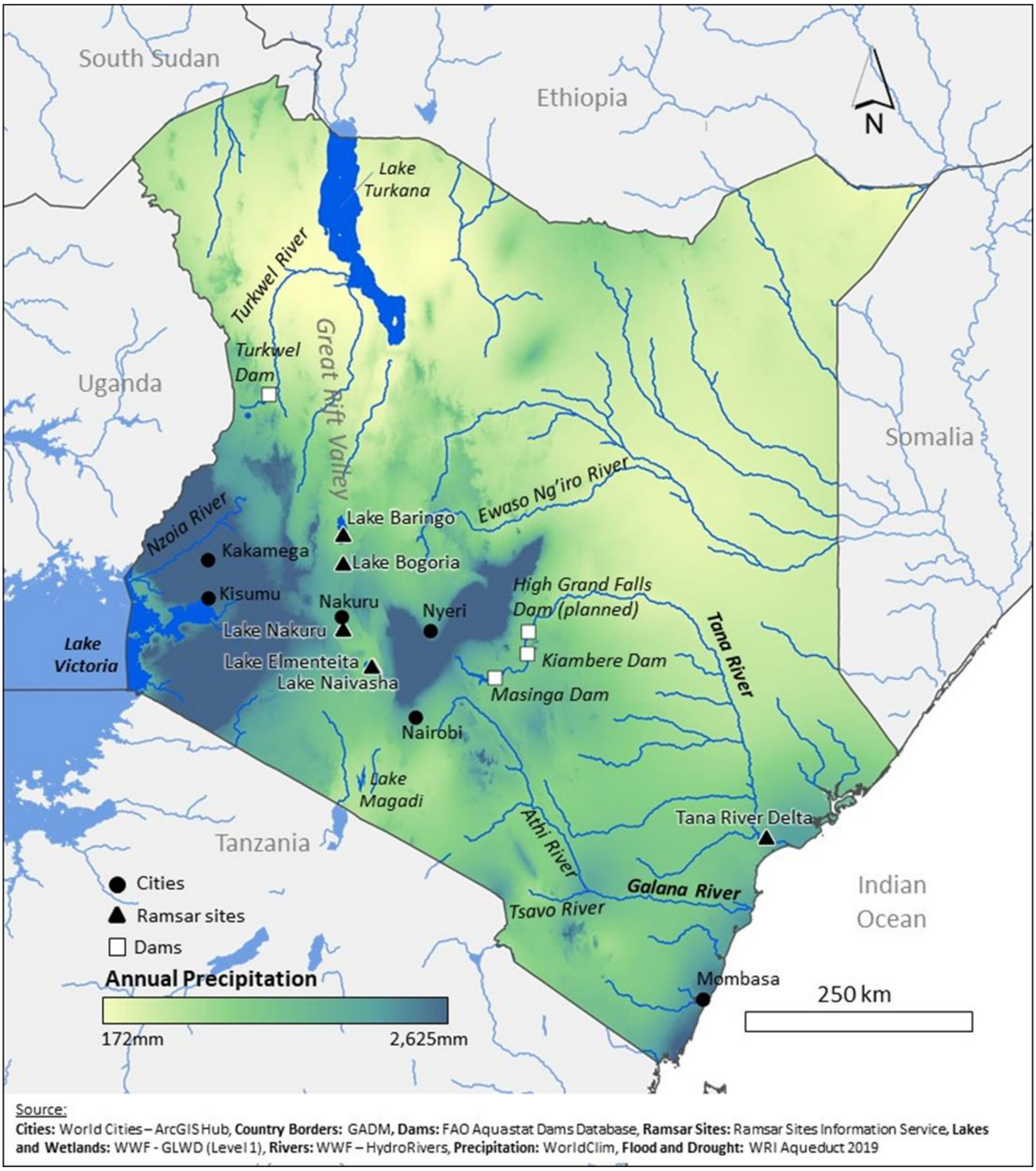

Figure 2. Map of Water Resources (USAID, 2021)

Kitheka (2019) notes that as far as salinity is concerned, the water quality of the Athi River declines during drought conditions when the streamflow becomes critically low. During this period, water use for irrigation tends to affect plant growth and productivity as confirmed by various farmers operating in the basin. This situation can be notably worse for the fish, especially Nile tilapia, which does not tolerate high salinity ranges.

During these periods, fish are more susceptible to diseases, and growth rates may slow, making it challenging to maintain a productive aquaculture system. Moreover, reduced flow rates limit the flushing capacity of the river, meaning pollutants and waste from aquaculture operations, as well as upstream sources, may accumulate, further degrading water quality. Water management strategies must be implemented to overcome this challenge, such as developing water storage systems to ensure a consistent supply during dry periods or using recirculating aquaculture systems (RAS) that reduce reliance on river flow. Additionally, aquaculture models like pond farming may offer better control over water levels than cage farming, making them more resilient to the river's seasonal fluctuations.

Pollution

Pollution from agricultural runoff and human activities poses a considerable threat to the viability of aquaculture in the Athi River, particularly in the lower sections where urban and industrial activities are concentrated (Mulwa, 2019). The river is currently burdened by high contaminants, including agrochemicals such as pesticides and fertilizers, heavy metals from industrial discharges, and untreated sewage from urban areas. These pollutants can affect fish health, reduce growth rates, and pose serious risks to human consumers, particularly if heavy metals or other toxins bioaccumulate in fish tissues (Rani et al., 2022). For example, high concentrations of cadmium, lead, and nickel have been detected in specific stretches of the Athi river, primarily due to unregulated industrial activities (Omanwa, 2015).

There is also a lot of pollution coming primarily from urban areas where these rivers pass through. In a study by Kitheka (2019) to assess the salinity and salt fluxes in a polluted tropical Athi river in Kenya, the highly polluted sub-basins draining through the City of Nairobi exhibited relatively higher salinity and salt fluxes as compared to non-polluted ones draining rural areas. The relatively high salinity and salt fluxes were attributed to the discharge of wastewater, seepage of groundwater, and irrigation return flows.

Further, the Athi River catchment with relatively high salt fluxes drains through the urban environment, particularly the expansive city of Nairobi and nearby Athi river-Kitengela towns. The high salt fluxes were relatively higher than the maximum salt flux and freshwater flux computed for the river downstream at Wamunyu RGS near Wamunyu (Kitheka et al., 2019). These differences were attributed to river water diversion for irrigation, water trapping in weirs, overbank flow in flood plains, and possible river discharge errors (Kitheka, 2019). The highly polluted Nairobi River contributes water to the Athi River in its upper course, which drains through the City of Nairobi, the capital of Kenya. The Kitheka (2019) study called for water pollution control, sustainable irrigation, and land use practices in the basin.

Addressing this issue will require significant efforts to improve water quality along the river's entire length. This could involve stricter enforcement of environmental regulations to prevent industrial and agricultural pollution, upgrading wastewater treatment facilities, and promoting best practices in farming to reduce runoff. In addition, aquaculture operators may need to implement filtration or water treatment systems to ensure the water used for fish farming is of sufficient quality.

Invasive species and fish diseases

Another potential risk is invasive fish species or fish diseases, which could disrupt aquaculture operations along the Athi river. Invasive species such as tilapia hybrids, Common carp (*Cyprinus carpio*) in Tana river or predatory fish and crocodiles in the Tana River and Lake Turkana could outcompete farmed fish for resources or prey on juvenile fish and even the adult fish, reducing the efficiency of aquaculture systems (Kyalo, 2008). In addition, bacterial or fungal infections are a common concern in aquaculture, particularly when fish are reared in environments with poor water quality or where stocking densities are high. The warm temperatures and variable water conditions in the arid regions could create an environment conducive to the spread of diseases, further complicating the management of fish health. Preventative measures such as regular water quality monitoring, the use of disease-resistant fish strains, and implementing biosecurity protocols will be essential to mitigating these risks. Additionally, the integration of aquaculture with other farming systems, such as polyculture, could help reduce disease prevalence by promoting a more balanced ecosystem that supports fish health.

Aquaculture potential of lakes in Kenya's ASALs

Lake Naivasha

Lake Naivasha is a shallow freshwater lake approximately 160 km^2. The Lake lies in a semi-arid zone with a rainfall of between 500-700 mm and high surface evaporation of 1336 mm. yr^{-1} (Richardson & Richardson, 1972). The Lake was found to support a diversity of activities (Fig 3), such as intensive agriculture under irrigation. This is one of the main foreign exchange earners and employs more than 300,000 people (Mageria et al., 2006). At 1,884 m (6,181 ft), Lake Naivasha is the highest point in the Kenyan Rift Valley. Its geological composition is a complicated mix of volcanic rocks and sedimentary deposits from a bigger Pleistocene Era lake. The lake is supplied by the perennial Malewa and Gilgil rivers in addition to ephemeral streams. Although there isn't a visible outlet, it is believed that there is one because the lake's water is relatively fresh.

Prior to 2010, the lake's surface area was typically 139 square kilometres (54 square miles); by 2020, it had grown to 198 km^2 (76 square miles). A marsh surrounds it, with a total area of 64 km^2 (25 square miles), though this can change significantly depending on rainfall. The lake is 6 meters (20 feet) deep on average, with Crescent Island having the deepest water with a maximum depth of 30 meters (98 feet). Formerly, the lake's exit, Njorowa Gorge, now stands high above the water and serves as Hell's Gate National Park's entrance. The town of Naivasha, originally known as East Nakuru, is located on the lake's north-eastern shore.

Lakes Naivasha is among the Great Rift Valley lakes that were formed about 25 million years ago by the violent separation of two of the earth's continental plates floating on the molten magma of its core. Lake Naivasha has a surface area of approximately 119,130 km^2, a catchment area of 3,200 km^2, and a mean depth of 4.1 m (Omondi et al., 2016). Lake Naivasha's water level has experienced great fluctuations, sometimes as much as 7 m over many years, attributed to large-scale climatic influence, also causing changes in water geochemistry (Omondi et al., 2016).

Aquaculture potential of Lake Naivasha

Lake Naivasha, situated in Kenya's semi-arid Rift Valley region, presents significant potential for aquaculture development due to its unique climatic and ecological characteristics. The lake and its basin offer warm temperatures averaging around 25°C, which are conducive to the growth of various fish species (Mageria et al., 2006). Additionally, the region boasts a high human population, providing a ready market for aquaculture products and the opportunity to enhance local livelihoods and food security while reducing fishing pressure on the lake's wild fish stocks. Water-based aquaculture emerges as a particularly promising avenue in Lake Naivasha. The presence of several small public water bodies within the basin, coupled with suitable climatic conditions, creates an ideal environment for fish farming using enclosures such as pens (Njiru et al., 2017). Species such as *Oreochromis leucostictus*, *Tilapia zillii*, and *Cyprinus carpio* are already present. They can be easily propagated and cultured at the farm level, offering immediate opportunities to increase fish production utilizing existing culture technologies (Mageria et al., 2006).

While cage culture is generally prevalent in lake aquaculture, it is not deemed suitable for Lake Naivasha due to the lake's shallowness and the potential for conflicts among fishers (Njiru et al., 2017). Instead, pen culture presents a viable alternative. Pens can be established using relatively simple technology, and although their initial setup costs may be considerable, they offer low operating expenses with or without supplementary feeding (Mageria et al., 2006; Njiru et al., 2017). Implementing pen culture in the papyrus swamps along the lake could also serve as a natural buffer for sewage water, mirroring successful practices in Asian countries with similar aquaculture systems. This approach increases fish production and provides opportunities for unemployed, landless, and fishers to engage in fish farming, promoting economic efficiency and sustainable livelihoods.

However, the development of pen culture faces challenges, primarily due to access restrictions. Much of Lake Naivasha's shoreline is privately owned, necessitating permission from the Lake Naivasha Riparian Association (LNRA) to use riparian land for aquaculture purposes. Overcoming this barrier requires collaborative efforts and supportive policies. Furthermore, government intervention is crucial to facilitate the provision of fingerlings, affordable fish feeds, credit facilities, training, outreach, and information dissemination to potential fish farmers (Njiru et al., 2017).

Land-based aquaculture around Lake Naivasha is currently underdeveloped, with very few fish farmers operating in the catchment areas and virtually none around the lake. Several factors contribute to this situation: the scarcity of available land due to the dominance of horticulture and floriculture industries and ownership by the LNRA; limited access to water resources; soils with high sand content that offer poor water retention for pond construction; a lack of knowledge and technical expertise in fish farming; high costs associated with pond construction and fingerling acquisition; and a general reluctance to undertake perceived risks (Mageria et al., 2006). Additionally, competition for land and resources with other agricultural activities, particularly horticulture farming, has hindered the exploitation of aquaculture potential in the region.

Despite these challenges, there are alternative strategies to promote land-based aquaculture. One option involves integrating fish farming into large agricultural farms by utilizing artificial wetlands designed to reduce pollution from wastewater from agricultural and residential areas. However, initial responses indicate that specialized farmers are reluctant to diversify their operations beyond their primary focus on flower or horticulture production, limiting this potential avenue (Mageria et al., 2006).

Another innovative approach is the introduction of finger ponds in the riparian zones, which are expanding due to the lake's receding water levels. Finger-ponds are constructed as finger-like extensions from the lake shoreline into the land and filled with lake water. This method capitalizes on the available riparian land with significant aquaculture potential. Nevertheless, implementing this option requires authorization because the riparian land is protected under the LNRA Management Act (Mageria et al., 2006).

Moreover, developing fish farming in smaller communal water bodies around Lake Naivasha and within the catchment areas presents additional opportunities. Many of these water bodies lack fish populations but offer excellent potential for restocking under communal management agreements. There is also scope for utilizing irrigation systems and land unsuitable for conventional agriculture, such as swamps, to support aquaculture activities (Mageria et al., 2006).

Integrating fish farming with other agricultural practices in the catchment areas holds considerable promise. Some private farms already possess ponds for multiple uses, although fish production has not yet been incorporated. Learning from Asian countries, where ponds initially constructed for purposes other than fish farming have evolved to contribute to livelihoods significantly, could inspire similar developments in the Lake Naivasha region (Mageria et al., 2006). By capitalizing on the synergies of integrated farming practices, agricultural land can benefit from adding fish culture, enhancing productivity and sustainability.

However, significant challenges persist in establishing land-based aquaculture in the Naivasha basin. The region's semi-arid nature means that water availability, both in terms of quality and quantity, is not guaranteed. Reliance on borehole water is often prohibitively expensive for local communities. Additionally, high evaporation rates necessitate a constant water supply, further escalating costs. Land availability is another constraint; few individuals own land, and even those who do face the aforementioned challenges mentioned above related to water and soil conditions (Mageria et al., 2006).

Lake Baringo

Geographical and hydrological overview

Lake Baringo is a freshwater lake situated in the eastern arm of Kenya’s Great Rift Valley, encompassing a surface area of approximately 130 km^2 and a catchment area of about 6,820 km^2, with a mean depth of 5.9 meters (Omondi et al., 2016). The lake is relatively shallow and functions virtually as a wetland throughout, with submerged aquatic vegetation such as *Ceratophyllum demersum* occurring in its deepest portions. It is designated as a Ramsar site, highlighting its significance as a wetland of international importance (Ramsar, 2002). More extensive marshes are also present at the mouths of rivers entering the lake from the south and east.

The region's climate is semi-arid, with an annual average rainfall of about 600 mm (Omondi et al., 2014). The dry season typically extends from

September to February, while the rainy season occurs between March and August (Odada et al., 2006). Due to heavy rains experienced in the Eastern African region in 2011, the lake's water surface area increased dramatically from 130 km² in 2010 (Omondi et al., 2014) to 207 km² in 2016 (Obando et al., 2016), and further to over 250 km² in 2020 (Nyakeya et al., 2020). Lake Baringo experiences a very high annual evaporation rate ranging from 1,650 to 2,300 mm (Odada et al., 2006). The lake has no known surface outflow and is supplied by inflows from both seasonal rivers—Endao, Lokesen, Makutani, and Ol Arabe—and perennial rivers—Perkerra and Molo. Underground seepage is believed to maintain the lake's freshness, with an estimated loss of approximately 108 m³ per year (Dunkley et al., 1993). The mixing of surface and bottom waters induced by wave action, combined with the clay soils of the catchment area, contributes to the lake's notably high turbidity, which has been reported to affect its primary productivity (Odada et al., 2006; Nyakeya et al., 2020).

Lake Baringo has a long history of water-level fluctuations (WLFs) (Aura et al., 2020). While reports have been made on the influence of these fluctuations on the lake's fisheries (Omondi et al., 2011), most studies have focused on interannual or semi-annual variations without accounting for long-term interannual variability. These water-level changes will likely affect the lake's physicochemical parameters and overall ecology.

Aquaculture potential of Lake Baringo

Lake Baringo's unique hydrological and ecological characteristics present both opportunities and challenges for aquaculture development. The lake faces human-induced and natural stressors resulting from land and water use systems and climate variability (Omondi et al., 2014). High turbidity levels, caused by the mixing of surface and bottom waters and the clay soils of the catchment, impact the lake's primary productivity by affecting phytoplankton growth, which is essential for the aquatic food web (Odada et al., 2006; Nyakeya et al., 2020).

Water-level fluctuations (WLFs) are a significant factor influencing the aquaculture potential of Lake Baringo (Aura et al., 2020). These fluctuations can alter habitat conditions for aquatic organisms and affect critical physico-chemical parameters necessary for fish growth and survival. Changes in water levels may also pose logistical challenges for installing and maintaining aquaculture infrastructure, such as cages or pens, necessitating adaptive management strategies to ensure sustainable operations.

Despite these challenges, the lake's status as a freshwater body in a semi-arid region offers considerable potential for aquaculture. The perennial inflows from the Perkerra and Molo rivers provide water reliability essential for aquaculture practices. Moreover, the absence of known outflows and underground seepage help maintain water levels and quality suitable for certain aquaculture species.

Addressing environmental stressors through effective land and water management practices is crucial to harnessing Lake Baringo's aquaculture potential. Research into suitable fish species that can thrive in high-turbidity conditions and fluctuating water levels is necessary. Implementing adaptive aquaculture systems, possibly incorporating resilient species and flexible infrastructure, could mitigate the impacts of environmental variability. Such developments could enhance fish production, contribute to food security, and support economic growth in the region, aligning with sustainable development goals.

Lake Turkana

Geographical and hydrological overview

Lake Turkana, with a surface area of approximately 7,560 km², is the world's largest permanent desert lake and Kenya's largest inland water body. Situated in the Arid and Semi-Arid Lands (ASALs) of northwestern Kenya, it is a transboundary resource shared among three Kenyan counties—Turkana, Samburu, and Marsabit—and extends into Ethiopia at its northern end (Keyombe et al., 2019). The northern region of the lake, dominated by the Omo Wetland, is the most productive area and is shared with Ethiopia. The Omo River, originating from the Ethiopian highlands, contributes approximately 90% of Lake Turkana's inflow, making it the lake's primary water source. The rivers, along with smaller seasonal rivers within Kenya (Keyombe et al., 2019).

Lake Turkana's unique geographical position in a desert environment and reliance on transboundary water sources present both opportunities and challenges, especially activities in the Omo River basin, which can affect water levels and, consequently, the ecological balance within the lake. Despite these factors, Lake Turkana remains a vital resource for the surrounding communities, supporting livelihoods through fishing and offering potential for aquaculture development.

Aquaculture potential of Lake Turkana

The aquaculture potential of Lake Turkana is significant, particularly with the possibility of deploying cage culture systems in the lake itself, the Turkwel River, and various dams in the region. Such developments have the potential to substantially increase the capacity for fish feed and fish seed production, which are critical components for the expansion of aquaculture activities (Kasuti et al., 2019). Cage aquaculture involves rearing fish in enclosed spaces within natural water bodies, allowing for high-density production and efficient use of resources.

Despite the clear potential, limited research has been conducted to assess Lake Turkana's suitability for various marketable aquaculture species in Kenya. This gap in knowledge hinders the effective planning and implementation of aquaculture projects that could capitalize on the lake's resources. Challenges facing Turkana County's fisheries and aquaculture sectors include environmental variability, limited infrastructure, and socio-economic factors that affect the adoption of new technologies and practices (Kasuti et al., 2019).

To fully exploit Lake Turkana's aquaculture potential, comprehensive studies are needed to evaluate the environmental parameters, identify suitable fish species, and develop sustainable management practices tailored to the lake's unique conditions. Such research would provide valuable insights into optimizing cage culture systems, addressing issues such as water quality, feed availability, and disease control. Moreover, engaging local communities and stakeholders is essential to ensure that aquaculture development aligns with socio-economic needs and promotes equitable benefits.

Aquaculture potential of dams in Kenya's ASALs

Dams are human-made structures constructed to obstruct or regulate water flow in rivers or streams, resulting in the formation of reservoirs that serve various purposes such as water supply, irrigation, hydroelectric power generation, and flood control (Angelakis et al., 2024). In Kenya's ASALs, these dams not only create standing bodies of water suitable for fish farming but also offer a unique dual benefit: they can all act as gene banks for threatened native species and be strategically utilized to regenerate fish populations essential for food and nutrition security. Typically, dams in Kenya range from 1.0 to less than 100 hectares, providing ample space for aquaculture development (ABDP-FCODA, 2022). Kenya boasts numerous dams, particularly in the Arid and Semi-Arid Lands (ASALs), which hold great potential for substantial fish production and aquaculture expansion (Aura et al., 2022; Munguti et al., 2014). These dams have historically contributed to food security among rural populations through fishing activities. Stocking dams with fish species provides a valuable source of protein but also plays a crucial role in poverty alleviation by generating income for local communities.

According to the most recent statistical bulletin by the Kenya Fisheries Service, Nile Tilapia (*Oreochromis niloticus*) and African Catfish (*Clarias gariepinus*) are the most dominant species harvested from dams, contributing 60% and 34% of the total catch, respectively. Other species collectively account for 6% of landings (KeFS, 2022). These statistics underscore dams' significant role in Kenya's inland fisheries and highlight their potential for aquaculture enhancement.

The construction of dams has been encouraged under various government initiatives, such as the Economic Stimulus Programme (ESP), to provide water for domestic and agricultural use and promote communal fish farming activities. However, despite the considerable potential, especially in ASALs in Kenya, fish farming in dams is not widely practiced and remains under-documented. The underutilization of dams for aquaculture presents an opportunity to enhance fish production in ASAL regions. Some dams have been utilized for experimental and research purposes, including housing cages for aquaculture trials. A notable example is the regional BOMOSA project (2006-2009), a multidisciplinary research initiative funded by the European Union, which explored integrated cage fish farming systems in reservoirs (Waidbacher et al., 2006). Such projects highlight the untapped potential of dams for aquaculture development in Kenya.

Turkwel Dam

Geographical and hydrological overview

Turkwel Dam is a significant multipurpose infrastructure located on the Turkwel River in West Pokot County, approximately 76 km north of Kapenguria (Nüsser & Baghel, 2017). Constructed between 1986 and 1991, the dam stands as the highest in Kenya with a height of 153 meters and a crest length of 150 meters. It serves multiple purposes, including hydroelectric power production, irrigation, tourism, and fisheries. The dam is strategically positioned on the border between the arid and semi-arid lands (ASALs) of West Pokot and Turkana counties, regions characterized by sparse rainfall and frequent droughts.

The Turkwel River originates from the slopes of Mount Elgon, flowing through the Cherangani Hills before entering the semi-arid plains of Turkana. The river basin covers an area of approximately 17,000 square kilometers. The dam impounds the Turkwel Gorge Reservoir, which extends upstream and has a storage capacity of about 1.6 billion cubic meters (KenGen, n.d.). The reservoir's surface area varies with seasonal rainfall patterns, influenced by the bimodal rainfall in the region, with long rains occurring from March to May and short rains from October to December.

Turkwel Dam supports the Turkwel Hydroelectric Power Station, the third-largest hydroelectric power plant in Kenya, with an installed electric capacity of 106 megawatts (142,000 hp) (KenGen, n.d.). The power station contributes significantly to the national grid, supplying electricity to both urban and rural areas. Additionally, the dam facilitates irrigation projects downstream, enhancing agricultural productivity in the otherwise dry region. The scenic landscape surrounding the dam and reservoir offers opportunities for tourism development, including activities like boating, sport fishing, and eco-tourism.

The reservoir created by the dam has become a habitat for various fish species, supporting capture fisheries. In 2023, a total of 93 metric tonnes (MT) of fish with an ex-vessel value of Kshs 28 million were landed from the dam (Kenya Fisheries Service [KeFS], 2024). The fisheries are comprised of two primary species: Nile Tilapia (*Oreochromis niloticus*) and African Catfish (*Clarias spp.*). Tilapia landings contributed 91% (85.1 MT) while Clarias contributed 9% (8.3 MT) during the review period (KeFS, 2024). The months of August and January recorded the highest catches, while December recorded the lowest catch in 2023.

Aquaculture potential in Turkwel dam

The aquaculture potential of Turkwel Dam is substantial yet largely unexploited (Munguti et al., 2014). The dam's large and relatively stable water body offers an ideal environment for fish farming. The water quality, temperature, and nutrient availability in the reservoir are conducive to the growth of commercially important fish species. To harness this potential, several strategies can be implemented. The introduction of cage culture could significantly increase fish yields, as the calm and deep waters of the reservoir are suitable for such aquaculture systems. Cage farming involves rearing fish in floating net enclosures, allowing for high-density production without the need for extensive land-based infrastructure. Establishing fish hatcheries near the dam would provide a consistent supply of fingerlings for stocking in cages or open waters, potentially producing improved strains with better growth rates and disease resistance.

Stocking the dam plays an important role in protein provision and alleviating poverty among the rural population. According to the most recent statistical bulletin produced by the Kenya Fisheries Service, Nile Tilapia and Clarias are the most dominant species, contributing 60% and 34% of the total catch, respectively, while other species accounted for 6% of the total landings (KeFS, 2024). This underscores the significant role that dams like Turkwel play in Kenya's inland fisheries and highlights their potential for aquaculture enhancement.

The construction of dams, including Turkwel, has been encouraged under various government initiatives not only to provide water but also to promote communal fish farming activities. However, the underutilization of dams for aquaculture presents an opportunity for enhancing fish production in ASAL regions. Some dams have been utilized for experimental and research purposes, such as the regional BOMOSA project (2009), a multidisciplinary research initiative funded by the European Union, which explored integrated cage fish farming systems in reservoirs. Such projects highlight the untapped potential of dams for aquaculture development in Kenya.

Tana River dams

Geographical and hydrological overview

The Seven Forks Dams, situated along Kenya's Tana River, exemplify the interplay between geographical and hydrological characteristics that define their pivotal role in the region's socio-economic landscape (Suda et al., 2024). These dams—Masinga, Kamburu, Gitaru, Kindaruma, and Kiambere—are strategically positioned across counties classified as part of Kenya’s arid and semi-arid lands (ASALs), specifically Embu, Kitui, Machakos, Tharaka Nithi, and Meru. The Tana River itself, spanning 1,014 kilometers, traverses diverse ecological zones, making it a lifeline for surrounding ASAL regions where water resources are critical for survival and development. This unique positioning underscores the hydrological significance of the dams, which form a cascade system designed to optimize water flow for multi-purpose uses.

Masinga Dam, the series' largest reservoir, straddles Embu and Machakos counties and boasts a substantial storage capacity of approximately 1.56 billion cubic meters with a surface area of 120 square kilometers (KenGen, 2025). As the system's upstream regulator, Masinga ensures controlled water release downstream, mitigating extreme hydrological fluctuations that would otherwise affect the operation of downstream dams. Its location at the confluence of administrative boundaries amplifies its importance, providing water resources for counties such as Tharaka Nithi and Kitui, characterized by erratic rainfall and persistent drought conditions.

Downstream, Kamburu Dam, located within Embu and Kitui counties, holds a storage capacity of 150 million cubic meters and spans 25 square kilometers (Aura et al., 2022; Ongwenyi, 1985). Its smaller size relative to Masinga belies its critical role in stabilizing water flow for power generation and irrigation systems. The dam's efficient hydrological integration into the Tana River's flow network supports various economic activities in these predominantly ASAL regions.

Gitaru Dam, with a 20 million cubic meters storage capacity, operates as a run-of-the-river facility, emphasizing its reliance on stable upstream flow regulation (Mutia et al., 2021). Although its reservoir is modest in size, its consistent water availability, derived from the upstream dams' regulation, positions it as a vital node in the Seven Forks cascade. Similarly, Kindaruma Dam, located in Tharaka Nithi County, features a storage capacity of 16 million cubic meters and is one of the older installations in the system, having been commissioned in 1968 (Kiprop, 2020). Despite its limited retention capacity, it plays an integral part in ensuring downstream hydrological consistency and enabling multi-sectoral water use.

Kiambere Dam, the series' terminal reservoir, straddles Embu and Kitui counties. It has a storage capacity of 585 million cubic meters and a surface area of 50 square kilometers (Botzen et al., 2015). Its substantial size makes it a critical resource in the cascade, particularly in buffering water supply for agricultural and domestic use during dry seasons. The dam's geographic positioning in ASAL regions underlines its importance for sustaining livelihoods in these water-scarce counties.

The geographical spread of these dams within ASAL counties and their hydrological interconnectivity offer substantial advantages. The cascading system ensures an efficient distribution of water resources, buffering against seasonal variations and supporting integrated water management. Such large reservoirs in arid regions provide a year-round water supply critical for sustaining local ecosystems, stabilizing river flow, and mitigating the impacts of climate variability. Furthermore, their locations within ASALs highlight their potential to transform water scarcity into an opportunity for economic growth and resource sustainability. Although primarily designed for hydroelectric power generation, the hydrological stability and strategic positioning of the Seven Forks Dams present untapped opportunities for resource optimization across multiple sectors, particularly in these underserved regions.

Aquaculture potential of Kamburu, Gitaru and Kindaruma dams

Although detailed scientific studies on the water quality and aquaculture potential of Kamburu, Gitaru, and Kindaruma Dams are currently lacking, the geographical positioning, hydrological stability, and existing fisheries activities indicate strong prospects for aquaculture development. These dams, located within Kenya's arid and semi-arid lands (ASALs), represent untapped resources with the potential to address food insecurity and poverty in these regions. The high capture fisheries production reported in Kamburu Dam (KeFS, 2023) strongly indicates the biological productivity and ecological suitability of these reservoirs for aquaculture systems. The presence of existing fisheries suggests a functional aquatic ecosystem capable of supporting aquaculture species, particularly Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*), which are known for their adaptability and high growth rates in controlled environments (Syanya et al., 2025).

The cascade system of the Seven Forks Dams, including Kamburu, Gitaru, and Kindaruma, offers inherently favorable ecological conditions for aquaculture, as the regulated water flow helps maintain stable hydrological conditions. This regulated flow minimizes the risks associated with water level fluctuations and enhances water quality consistency, two critical factors for the success of aquaculture operations (Zhang et al., 2022). Additionally, the lack of significant fish mortalities reported in these dams indicates stable environmental conditions that support fish welfare and survival, further strengthening their potential as aquaculture hubs. Despite the absence of systematic studies, these dams' hydrological and ecological characteristics make them prime candidates for cage aquaculture, which requires stable water bodies with good water exchange to ensure oxygenation and waste removal.

Given their location in ASALs, these dams offer an opportunity to contribute significantly to socio-economic development. The ASALs face a high poverty index and are marked by chronic food insecurity (Mganga, 2022). Aquaculture, as a high-yielding food production system, can transform these regions by creating employment, enhancing nutritional security, and generating income. However, the full aquaculture potential of these dams remains unexplored. It requires thorough research to establish baseline water quality parameters, such as temperature, dissolved oxygen, pH, and nutrient availability, which are critical determinants of aquaculture feasibility (Yusoff et al., 2024). Parameters such as ammonia and nitrite levels influence fish health in intensive systems and theymust also be studied to guide the development of sustainable aquaculture practices.

A systematic investigation into the trophic status of these dams would provide valuable insights into their capacity to support aquaculture. Primary productivityis driven by nutrient levels such as nitrates and phosphates and it is crucial in determining the carrying capacity of aquatic ecosystems for fish farming. While capture fisheries data provides preliminary evidence of their ecological functionality, targeted studies are necessary to quantify nutrient dynamics, plankton productivity, and other biological indicators that underpin aquaculture viability.

Aquaculture potential of Masinga and Kiambere dams

The aquaculture potential of Masinga and Kiambere Dams is strongly supported by their favorable hydrological and water quality characteristics, making them ideal candidates for sustaining aquaculture systems. Water, the primary medium for fish to perform all life functions such as feeding, growth, waste excretion, reproduction, and osmotic balance (Sibomana et al., 2022), necessitates the assessment of key biological, chemical, and physical properties. According to Abwao et al. (2023), critical parameters such as temperature, dissolved oxygen (DO), and pH in both dams fall within ranges optimal for aquaculture, mainly for tilapia (*Oreochromis niloticus*). Temperature measurements in the dams range from 24.3 to 28.39°C, aligning closely with the optimal range of 26–30°C reported by El-Sayed and Kawanna (2008) as essential for tilapia's growth and survival. Temperatures below 24°C are known to hinder growth rates and reduce feed utilization. Still, the consistent thermal conditions in Masinga and Kiambere Dams provide a favorable environment for efficient fish metabolism and growth. DO levels in the dams ranging between 5.57 and 7.71 mg/L (Abwao et al., 2023), are sufficient to support fish health and growth, meeting the recommended thresholds cited by Abd El-Hack et al. (2022). DO plays a crucial role in aerobic respiration and waste breakdown; low DO levels can result in fish mortality, increased stress, poor appetite, and slower growth rates. The recorded pH levels in the Seven Forks Dams range from 7.44 to 8.66 (Abwao et al., 2023). These values fall within the slightly alkaline range preferred by tilapia. This further highlights the suitability of these dams for aquaculture.

Nutrient concentrations in Masinga and Kiambere Dams further highlight their aquaculture potential. Nitrite levels were recorded at 0.66 to 0.89 µg/L, which are far below the critical threshold of 0.3 mg/L known to impact fish growth and physiology negatively (Abwao et al., 2023). Nitrate levels range from 0.94 to 1.46 µg/L, while phosphate concentrations are between 1.60 and 2.60 µg/L. These nutrients are integral to primary productivity within aquatic ecosystems, forming the foundation of a robust food web that supports aquaculture systems. Guo and Li (2003) highlighted that achieving a balanced ratio of nitrogen to phosphorus is essential for optimizing phytoplankton production, which, in turn, supports fish growth. Although the nutrient levels are currently low, they reflect an ecosystem with minimal risk of eutrophication, allowing for controlled nutrient supplementation through high-quality feeds to enhance fish yields. The absence of significant levels of unionized ammonia (NH_3) and nitrites (NO_2), commonly associated with water quality degradation in intensive aquaculture systems, is an additional advantage. However, as intensive culture systems often involve high stocking densities and nutrient-rich feeds, monitoring these parameters is recommended to ensure sustainable operations (Bahnasawy et al., 2009).

The hydrological and geographical attributes of Masinga and Kiambere Dams further reinforce their potential for aquaculture. Masinga Dam, with a surface area of 120 square kilometers and a storage capacity of 1.56 billion cubic meters (KenGen, 2025), offers expansive space for large-scale aquaculture systems, such as cage culture. Its stable hydrological conditions, supported by its role as an upstream regulator in the Seven Forks cascade, ensure consistent water availability and minimal fluctuations, which are critical for successful aquaculture operations. Kiambere Dam, with a surface area of 50 square kilometers and a storage capacity of 585 million cubic meters (Botzen et al., 2015), also provides substantial capacity for aquaculture. Its downstream position within the cascade system allows it to benefit from regulated water flow, reducing the risks associated with seasonal variations. The combination of stable water levels and favorable water quality parameters creates an environment conducive to aquaculture, with minimal challenges posed by hydrological instability.

Challenges and solutions to aquaculture in dams

Aquaculture in dams, while promising, faces numerous challenges that limit its potential to contribute significantly to food security, economic development, and rural empowerment. A study by Abwao et al. (2023) on the feasibility of cage culture in Masinga and Kiambere Dams highlighted that water level fluctuations are among the most significant constraints to aquaculture development. This issue is exacerbated by climate variability, which has led to prolonged droughts and reduced precipitation in arid and semi-arid lands (ASALs) where these dams are located (AECOM, 2021). Additionally, operational priorities such as hydroelectric power generation often result in fluctuating water levels (Ren et al., 2021), creating challenges for the stability of aquaculture infrastructure, particularly cages. The unpredictable nature of water levels can also disrupt fish health, growth, and feeding patterns, making establishing and maintaining aquaculture systems in these environments highly challenging.

Another major challenge Abwao et al. (2023) reported is fish theft and insecurity and theyare prevalent in these dams. This problem mirrors findings from a study in Lake Victoria, where Charo-Karisa et al. (2009) and Shitote et al. (2022) linked fish theft to high poverty levels in surrounding communities. The theft of fish and cages threatens investment security and dissuades new entrants from participating in aquaculture ventures. In the ASAL regions bordering these dams, poverty levels are among the highest in Kenya due to extreme climatic conditions and limited livelihood opportunities, further exacerbating this issue (Njogu, 2022).

Wildlife interference is another unique challenge to aquaculture in the Seven Forks Dams. The proximity of Masinga and Kiambere dams to game parks and reserves introduces interactions with animals such as hippopotamuses and crocodiles, which can destroy cages and cause fish escapes (Abwao et al., 2023; Charo-Karisa et al., 2009). Wildlife interference increases operational costs and poses a significant safety risk to workers. In Abwao et al. (2023), at least 16% of respondents identified wildlife as a hindrance to cage culture investment, making this an issue that requires innovative mitigation strategies.

Financial constraints are another critical challenge to aquaculture development in these dams. The high initial capital required for cage construction and the cost of quality inputs such as fingerlings and feeds limit entry for many potential investors. Abwao et al. (2023) reported that 8.9% of respondents identified a lack of capital as a significant barrier, while another 8.9% cited limited technical skills as a constraint. Although a smaller proportion (3.6%) identified a lack of quality inputs as a challenge, the importance of these inputs cannot be overstated. High-quality seeds and feeds are fundamental for achieving optimal growth rates, feed conversion efficiency, and overall aquaculture productivity (Munguti et al., 2022). The lack of access to affordable and reliable inputs further limits the scalability and sustainability of aquaculture in these dams.

Conflicts among dam water users present another significant barrier to aquaculture. Stakeholders such as local communities, Kenya Wildlife Service (KWS), Kenya Electricity Generating Company (KENGEN), and Tana and Athi Rivers Development Authority (TARDA) often have competing interests in the use of dam resources. For instance, conflicts may arise between hydroelectric power generation, water use for irrigation, and aquaculture development. Abwao et al. (2023) emphasized the need for structured stakeholder agreements to resolve conflicts and foster cooperation. Without a clear framework for resource allocation and dispute resolution, these conflicts will continue to undermine the aquaculture potential of the Seven Forks Dams.

To address these challenges and unlock the aquaculture potential of the dams, a multifaceted approach is required. A robust water management strategy must be implemented to mitigate the effects of seasonal water level fluctuations (Priyan, 2021). This could involve using floating cages with adjustable anchorage systems to accommodate varying water levels. Security measures such as community-based surveillance programs (Aura et al., 2024) and investment in monitoring technologies, such as GPS-enabled cage tracking, can help address fish theft and improve investment security (Ubina et al., 2021). Wildlife interference could be mitigated by installing protective barriers around cage culture sites or employing eco-friendly deterrents that discourage animals from approaching aquaculture facilities.

Capacity-building initiatives are essential to overcome financial and technical constraints (Kleih et al., 2013). Training programs to equip local communities with technical skills in cage construction, fish husbandry, and water quality management would empower them to participate in and benefit from aquaculture. Additionally, financial support through grants, loans, or subsidies for aquaculture startups could address the high capital requirements and encourage broader participation (Bennett et al., 2024). Establishing hatcheries and feed mills near the dams could further reduce the cost and improve access to quality inputs, addressing one of the critical barriers identified in Abwao et al. (2023).

To resolve conflicts among stakeholders, it is necessary to establish clear governance frameworks that promote equitable resource use and foster collaboration (Bellanger et al., 2020).

Multi-stakeholder platforms involving local communities, government agencies, and private investors could help streamline decision-making and create mutually beneficial agreements. For instance, agreements that allocate specific zones of the dams for aquaculture while preserving other areas for irrigation or wildlife can reduce conflicts and ensure sustainable resource use.

Lessons Kenya can draw from Egypt's aquaculture sector

Egypt's aquaculture sector has a long and rich history, dating back to ancient times when Egyptians practiced fish farming along the Nile River. According to FAO (2003), evidence from tomb friezes dating back to 2500 B.C. illustrates tilapia harvest from ponds, highlighting aquaculture as a traditional food source. Over the centuries, this practice evolved into more structured forms, such as the traditional *hosha* system in the Northern Delta Lakes, which relied on trapping wild fish in enclosures. Modern aquaculture in Egypt began in the mid-20th century, with the government introducing common carp for research in the 1930s. The first semi-intensive commercial fish farm was established in 1961, focusing on Nile tilapia, common carp, and grey mullet (FAO, 2003). By the late 1970s, a national aquaculture development plan was introduced, significantly increasing production through government investment in hatcheries, fish farms, and extension services. This period also saw the introduction of new aquaculture systems, such as tilapia cage culture in the Nile and common carp farming in rice paddies. By the 1990s, aquaculture exceeded 10% of fish production in Egypt (El-Gayar, 2003).

In the past two decades, Egypt has revolutionized its aquaculture sector, making it the country's largest source of fish supply. As of 2022, Egypt produced over 1.5 million metric tons of aquaculture products (FAO, 2024). More than 99% of this production comes from privately owned farms, with most aquaculture activities concentrated in the Nile Delta region (Nassr-Alla, 2008; Burma, 2018). The sector's rapid expansion has been driven by the adoption of intensive aquaculture systems, including earthen ponds, tanks, and integrated agriculture-aquaculture models (Soliman & Yacout, 2016; Kaleem & Sabi, 2021). Unlike the traditional semi-intensive pond systems, modern intensive farming techniques use smaller and deeper ponds with high stocking densities, aeration, and commercial feed inputs, significantly boosting productivity. Integrated desert agriculture-aquaculture projects have also emerged in Egypt's arid regions, maximizing water use efficiency by combining aquaculture with irrigation agriculture (Soliman & Yacout, 2016; Obwanga et al., 2018). These advancements have enabled Egypt to meet its growing domestic demand for fish while reducing its dependence on imports.

A key factor behind Egypt's aquaculture success is firm policy and institutional support. The Egyptian government has played an active role in promoting aquaculture through investments in research, the development of state-owned hatcheries and feed mills, and the establishment of pilot fish farms. Institutions such as the General Authority for Fish Resource Development (GAFRD) and the Central Laboratory for Aquaculture Research (CLAR) have facilitated research, technology transfer, and extension services to farmers (Burma, 2018). Additionally, government-backed initiatives have promoted genetically improved tilapia strains, all-male fingerlings, and semi-intensive farming techniques, enhancing productivity (Burma, 2018; Kaleem & Sabi, 2021).

Egypt has successfully harnessed its available water resources, including the Nile River, irrigation canals, reservoirs, and drainage water, to develop one of the most productive aquaculture sectors in Africa (Shaaban et al., 2022; Mehrim & Refaey, 2023). As the continent's largest aquaculture producer, Egypt has strategically utilized these water bodies to sustain and expand fish farming while balancing agricultural and environmental needs. The Nile River is the primary freshwater source in the country and plays a crucial role in aquaculture development. Traditionally, fish cages were commonly used in the river. However, due to concerns about water pollution and ecosystem health, stricter regulations have been introduced, limiting their use (Shaaban et al., 2022). Nevertheless, the river's branches, particularly in the Delta region, support small-scale aquaculture operations (Kaleem & Sabi, 2021; Shaaban et al., 2022).

Beyond the Nile, Egypt has extensively used its irrigation canal system, integrating fish farming with agriculture (Abdel-Latif et al., 2021). Many farms rely on drainage water from agricultural lands, ensuring water reuse while addressing water scarcity challenges (Shaaban et al., 2022). However, careful management is required to mitigate the risks of high salinity and contamination. In addition to river and canal systems, Egypt has capitalized on large dams and reservoirs for aquaculture. The High Aswan Dam, primarily built for hydroelectric power and irrigation, has also facilitated the development of fisheries and aquaculture in Lake Nasser (Abdel-Fattah et al., 2024; Alsadeq & Eldayem, 2025). This vast reservoir has become an important site for capture-based aquaculture, particularly for tilapia. Smaller reservoirs and barrages across the country further contribute to fish farming, enhancing Egypt's overall production capacity (Abdel-Fattah et al., 2024).

Kenya, particularly in its ASALs, can draw valuable lessons from Egypt's aquaculture transformation. Given the increasing demand for fish and the constraints posed by declining wild fish stocks, Kenya can expand aquaculture to improve food security and rural livelihoods. One of the key takeaways from Egypt's experience is the successful integration of aquaculture into desert agriculture, optimizing water usage in water-scarce environments. Kenya can implement similar approaches by utilizing rivers, irrigation dams, and reservoirs to enhance fish production. Moreover, fostering private sector investment through policy incentives such as subsidies for fish feed production and hatcheries can encourage more farmers to adopt aquaculture in ASALs. Strengthening research institutions and extension services will also be critical to ensuring farmers have access to the knowledge, technology, and resources needed to sustain profitable fish farming enterprises.

Another crucial lesson from Egypt is developing a strong aquaculture value chain to support sustainable sector growth. Egypt's well-developed market infrastructure ensures efficient linkages between fish producers, processors, and consumers (Burma, 2018). Kenya can enhance its aquaculture value chain by investing in local feed mills, hatcheries, and cold storage facilities to minimize post-harvest losses and increase profitability. Establishing fish farmers' cooperatives, similar to Egypt's aquaculture cooperatives, can facilitate knowledge exchange, improve access to credit, and strengthen market access. Additionally, government policies should support resilient aquaculture systems tailored to ASAL conditions, such as saline aquaculture and recirculating aquaculture systems (RAS), to optimize water efficiency. By adopting Egypt's successful strategies, Kenya can unlock the potential of aquaculture in its ASALs, driving economic growth, food security, and rural development (Bardach et al., 1972).

Conclusions

The findings of this review reveal the immense yet largely untapped aquaculture potential in Kenya's arid and semi-arid lands (ASALs), specifically in the permanent rivers, lakes, and dams that traverse these regions. These water bodies, including the Seven Forks Dams, offer ideal conditions for aquaculture development, driven by their stable hydrological features, ecological suitability, and proximity to underserved communities facing food insecurity and economic challenges. Moreover, all these dams hold additional promise as vital gene banks for threatened native species, serving as reservoirs of genetic diversity that can be harnessed to regenerate fish populations and bolster food and nutrition security. Despite these advantages, significant barriers persist, including water level fluctuations, financial constraints, wildlife interference, stakeholder conflicts, and limited access to quality inputs and technical expertise. The findings highlight some insights on the sustainable use of natural water resources for aquaculture in Egypt that Kenya could adopt to enhance its aquaculture sector. Addressing these challenges through strategic interventions, such as improved water management, stakeholder collaboration, capacity-building initiatives, and the adoption of innovative aquaculture technologies, can transform these water resources into hubs of aquaculture innovation. This transformation can contribute substantially to food security, rural development, and poverty alleviation, aligning with Kenya's development and broader global sustainability goals. Future research should focus on comprehensive assessments of water quality, nutrient dynamics, and aquaculture system optimization to provide a robust foundation for scaling up aquaculture in these regions and ensuring long-term sustainability.

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The authors declare that this study complies with research and publication ethics.

Informed consent

Not available

Data Availability

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Conflicts of Interest

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