GEOGRAPHIC DISTRIBUTION AND IDENTIFICATION OF PATHWAYS OF INTERACTIONS OF TILAPIINE SPECIES BETWEEN NATURAL AND AQUACULTURE SYSTEMS IN UPPER TANA RIVER BASIN, KENYA

By

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Thesis submitted in Partial Fulfillment of the Requirements for the award of the Degree of Master of Arts in Biodiversity and Natural Resources Management,

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October 2020

DECLARATION

This thesis is my original work, and has not been presented for award of any degree in any other university. Where other people's work has been used, this has been properly acknowledged and referenced in accordance with the University of Nairobi's regulations.

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This work is dedicated my parents, Thomas Oginga and Pamela Akinyi for their continuous advise and encouragement since the beginning of my education and my son Thomas Hensley Otieno for inspiration.

ACKNOWLEDGEMENT

I would like to express my gratitude to God for his eternal guidance in my life.

My sincere thanks to my supervisors: Prof. Francis Mwaura, Prof. Nathan Gichuki, Dr. Wanja Nyingi and Prof. George Turner for their guidance and supervision of my study. To all Ichthyology section, National Museums of Kenya particularly Joseph Gathua, and Justus Ochong for their great assistance in field and laboratory work. I thank the staff of the Department of Geography and Environmental Studies (University of Nairobi) and who contributed to my work in one form or the other, you are sincerely appreciated and remembered.

I sincerely acknowledge the fish farmers (Michael Manyeki, Francis Githinji, Ann Njura, Sis. Margaret Wangechi among others), Fisheries Officers (Samwel Gicheru, Ann Kaguta and Samwel Ireri), Fish traders, and Fishermen (Kennedy Owiti, Dennis Mwaniki and Francis Wachira) for the important roles they played during data collection process.

This study was made possible by funding from East Africa Tilapia Conservation project funded by the JRS Biodiversity Foundation (Grant number 60602), to Bangor University (UK), with National Museums of Kenya as Kenya partner. I am indeed grateful for Dr. Wanja Nyingi for nominating me for this opportunity. I would like to acknowledge Kenya Wetlands Biodiversity Research Group (KENWEB) hosted by the National Museums of Kenya for involving me in the student’s mentorship programme that has led to this project, and for providing the office space and internet facilities for my work. I particularly acknowledge advice from Prof. Nathan Gichuki in ensuring a successful study, and thank all KENWEB mentors and students for their support.

ABBREVIATIONS AND ACRONYMS

CIDP	County Integrated Development Plan
ESP	Economic Stimulus Programme
FAO	Fisheries and Agriculture Organization
GK	Government of Kenya
GPS	Geographical Positioning System
GSMFC	Gulf State Marine Fisheries Commission
KENWEB	Kenya Wetlands Biodiversity Research Group
KMFRI	Kenya Marine and Fisheries Research Institute
KNBS	Kenya National Bureau of Statistics
NARDTC	National Aquaculture Research and Development and Training Centre
NBSAP	National Biodiversity Strategy and Action Plan
NMK	National Museums of Kenya
NTU	Nephelometric Turbidity Units
PC	Principal Component
PCA	Principal Component Analysis
QGIS	Quantum Geographic Information System
TPS	Thin-plate spline
TPSDig	Thin-plate spline Digitizer
TPSUtil	Thin-plate spline Utility

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ABSTRACT

Freshwater fish habitats are highly threatened, facing impacts from habitat degradation, overfishing, and the introduction of non-native invasive species. Tilapia fishes are at the center of freshwater fishes due to their essential in fisheries and aquaculture production and preferences. This study investigated the impacts of introduced tilapia species on close relative native tilapia species in the Upper Tana River in Central Kenya. Tilapia specimen were collected in 24 sampling sites, their body morphometric data obtained and then used to assess hybridization rate between introduced and native tilapia species and sites mapped for the tilapia distribution. A basic water quality parameters measured in all the sampling sites including rivers, dams and fish ponds. Also, a social survey was undertaken to evaluate the human activities triggering the fish interaction. The results showed the presence of non-native tilapia in the upper catchment of the Tana River: Nile tilapia (*Oreochromis nioticus),* Redbreast tilapia *(Coptodon zilli),* Redbelly tilapia *(Coptodon rendalli),* and Mosambique tilapia *(Oreochromis mossambicus)* alongside native species, Sabaki tilapia (*Oreochromis spilurus).* The Nile tilapia had a wider survival range compared to normal ranges, especially temperature (17-31°C). The aquaculture (demand and preference of tilapia) was the main driver of tilapia introduction. It was concluded that widespread stocking of non-native tilapia strains will likely harm the persistence of natural strains, through ecological competition and hybridization. Zonation of aquaculture activities; proper implementation of the fisheries acts and policies and genetic analysis to provide evidence of tilapia hybridization were recommended.

CHAPTER ONE: INTRODUCTION

1.1: Background information

East Africa is a hotspot for native tilapia of genera *Oreochromis spp* (Gunther 1889), *Alcolapia, Coptodon* (Smith 1840) and *Sarotherodon* (Rupper 1852). Most of these native tilapia contain unique genes for resistance to diseases and environmental extremes. These genetic qualities are vulnerable due to fish interactions between aquaculture systems and natural water bodies (Canonico & Arthington, 2005; Munguti *et al*., 2014). Tilapia have been widely introduced for various reasons such as biological control of insects and aquatic weeds, aquaculture and capture fisheries, and to augment capture fisheries (Raadik, 1992; Kerr & Grant, 2000). However, tilapia introduced into natural water bodies can replace native strains via competition and hybridization leading to loss of pure native strains as a result of invasion (Mboya *et al*., 2005; Njiru *et al*., 2006).

The 2000-2005 National Biodiversity Strategy and Action plan (NBSAP) highlights the need to preserve endemic species for their ecological importance over commercial species, as a priority for Kenya (GK, 2000). However, the NBSAP is yet to impact policies or practice on the freshwater fishes of Kenya and has not been updated for the past 15 years (Aloo, 2006; FAO, 2013). In addition, invasive species continue to pose a problem to both the native species and ecosystem through degradation and competition. In Kenya, tilapia is poorly characterized in terms of their fisheries and aquaculture potential, with little current information on their distribution and population status (Fitzsimmons, 2001; Wasonga *et al*., 2017, Nyingi, 2011).

The known tilapia species in Kenya includes: Nile tilapia (*Oreochromis niloticus,* Linnaeus, 1758), Sabaki tilapia (*Oreochromis spilurus,* Gunther 1894*),* Jipe tilapia (*Oreochromis jipe,* Lowe 1955), Lake Chala tilapia (*Oreochromis hunteri,* Gunther 1889), Lake Victoria tilapia (*Oreochromis variabilis,* Boulenger 1906) Graham's tilapia

(*Oreochromis esculentus,* Graham 1928), Redbreast tilapia (*Coptodon rendalli,* Boulenger 1896), Redbelly tilapia (*Coptodon zillii,* Gervais 1848), Mango tilapia (*Sarotherodon galilaeus,* Linnaeus 1758*),* Lake Magati tilapia *(Alcolapia graham,* Boulenger 1912*)* and Natron tilapia *(Alcolapia alcalica,* Hilgendorf 1905*)* (Nyingi, 2013; Seegers *et al*., 2003; Trewavas, 1983). The sub species includes *Oreochromis niloticus niloticus, Oreochromis niloticus baringoensis, Oreochromis niloticus sugutae Oreochromis niloticus vulcani, Oreochromis spilurus spilurus, Oreochromis spilurus percivali and Oreochromis spilurus niger.*

The geographic distributions of the tilapia species were well known in Kenya before 1980s with clear zonation of both native and non-native species (Trewavas, 1983). The known distribution of tilapia fishes in Kenya before the 1980s was as follows: *Oreochromis niloticus vulcani* and *Sarotherodon galilaeus* are native to Lake Turkana; Baringo tilapia (*Oreochromis niloticus baringoensis)* and *Oreochromis niloticus sugutae* are endemic to Lake Baringo and Suguta River respectively. Both *Oreochromis esculentus* and Victoria tilapia (*Oreochromis variabilis)* are native to Lake Victoria, (Trewavas, 1983; Lowe-McConnell, 2006). The Sabaki tilapia (*Oreochromis spilurus)* subspecies are native to eastern flowing rivers of Kenya, according to Trewavas (1983) and Lowe-McConnell (2006). The distribution of Sabaki tilapia subspecies is as follows: *Oreochromis spilurus spilurus* is native to Ewaso Ng'iro River, Coastal Rivers like Sabaki-Galana and Ramisi; *Oreochromis spilurus niger is* native to Athi River and its tributaries above Lurgard’s falls and the upper tributaries of Tana River*; Oreochromis spilurus percivali* is endemic to Ewaso Ng’iro River specifically Buffalo, Shaba and Gotu springs. Other tilapia were found in areas like, *Oreochromis jipe* is endemic to Lake Jipe; *Oreochromis hunteri* and *Oreochromis korogwe* are native and non-native to Lake Chala respectively (Lowe-McConnell, 2006; Seegers *et al*., 2003; Trewavas, 1983) (Trewavas, 1983; Seegers *et al*., 2003; Lowe-McConnell, 2006) *Alcolapia grahami* and *Alcolapia* *alcalica* are endemic to Lake Magadi and Lake Natron respectively; *Oreochromis leucostictu*s had been introduced into Lake Victoria, Lake Naivasha and a dam in Tebere from Lake Albert in the 1950s and 1960s; Nile tilapia (*Oreochromis niloticus),* Redbelly tilapia *(Coptodon rendalli),* and Redbelly tilapia *(Copodon zilli)* had been introduced into Lake Victoria in 1950s (Trewavas, 1983; Seegers *et al*., 2003; Njiru *et al*., 2006; Russell, 2011; Kishe-Machumu & Vianny, 2018).

Kenya is divided into five primary drainage basins, i.e. Lake Victoria, Rift Valley, upper Ewaso Ng'iro, Athi-Galana-Sabaki River, and Tana River basins (Nyingi, 2013). Tana River basin is the largest basin occupying approximately 17% of the country geographical area, with Tana River being the longest river in Kenya of about 1000km (Gikonyo & Kiura, 2014). Tana River originates from Mount Kenya, Aberdare Ranges, and Imenti Hills of the central part of Kenya (Gikonyo & Kiura, 2014). Tana River basin is divided into the Tana delta (Lower Tana), Mid Tana and upper Tana. In the upper Tana basin, a dense network of tributaries drains water from smaller catchments into the main river.

The upper Tana River basin is comprising of rivers, streams, dams, water pans and human-made ponds (Gikonyo & Kiura, 2014). The upper Tana River basin houses the Kenyan warm and cold water hatcheries, namely, National Aquaculture Research Development and Training Centre (NARDTC) Fish Farm in Sagana, and Kabaru Trout Hatchery in Kirinyaga and Nyeri Counties respectively, which are the primary sources of both tilapia and trout fingerlings in the country (Emerton, 2018). Apart from the government farms, there are several private farms, which also contribute to the fingerling and fish production in the country.

In 2008, the Government of Kenya initiated a rapid economic growth strategy, adopted by all ministries and departments to salvage the country from the losses incurred during the 2007/2008 post-election violence and the world economic crisis known as

Economic Stimulus Program (ESP). The ESP was to relieve Kenya from the declined economic growth from 7.1% in 2007 to 1.7% in 2009 (Munguti *et al*., 2014; Musyoka and Mutia, 2016). The Fisheries Department of Kenya took on aquaculture as its key ESP intervention, implemented by construction of ponds and distribution of fingerlings throughout the country to boost economic growth (Mwangi, 2008; FAO, 2013b; Charo-karisa, 2014; Munguti *et al.,* 2014; KMFRI, 2017). The project used mainly Nile tilapia, *Oreochromis niloticus,* Linnaeus, 1758 and Sabaki Tilapia, *Oreochromis spilurus spilurus* fingerlings due to their faster growth to maturity (Munguti *et al.*, 2014; KMFRI, 2017). From the ESP project and similar projects in the past, it has become increasingly challenging to identify and understand the distribution of tilapia fishes in Kenya due to hybridization as acknowledged by Seegers *et al*., 2003; Lowe-McConnell, 2006; Nyingi *et al*., 2009; Wasonga *et al*., 2017; Dieleman *et al*., 2018.

The upper Tana River region has in the past two decades had a high level of aquaculture uptake, mainly using tilapia species provided by NARTDC. However, there is a high risk of fishes escaping from fish ponds to the natural water bodies due to flash floods occasioned by steep land gradients, uncontrolled pond management practices among other factors (Gikonyo & Kiura, 2014; Njogu & Kitheka, 2017). Tilapia fish introduction affects ecological balance leading to the competition for the resources between native and non-native species and ultimately evolution of tilapia hybrids (Mboya *et al.*, 2005; Angienda *et al*., 2011). Therefore, the study explored the current status of the tilapia species in upper Tana River basin in light of the invasive Nile Tilapia species.

1.2: Problem statement

Kenya is endowed with great diversity of eleven endemic tilapia species and six subspecies (Nyingi, 2013). These fishes are facing a serious threat of extinction as a result of over fishing and more recently, due to the introduction of Nile tilapia (*Oreochromis niloticus niloticus*) to boost the fisheries in both the natural waters and fish farms in Kenya (Elder, 1971; Ogutu-ohwayo, 1990; Kerr & Grant, 2000; Canonico & Arthington, 2005; Njiru *et al.*, 2006; Hallerman & Hilsdorf, 2014).

The Nile Tilapia, affects other fish by destroying their breeding grounds, competition on the food resources and hybridization. For instance, Nile tilapia as replaced Lake Victoria tilapia (*Oreochromis variabilis*) and Graham's tilapia (*Oreochromis esculentus*) through hybridization, feeding and mating competition and alteration of their aquatic habitats. Currently, Lake Victoria tilapia can only be found in the satellite lakes (Ogutu-ohwayo, 1990; Mboya *et al.*, 2005; Njiru *et al.*, 2006; Kishe-Machumu & Vianny, 2018). If fish interaction is not controlled, the country may lose most of her native species of tilapia which are also part of the natural heritage (Canonico & Arthington, 2005; Njiru *et al.*, 2006).

There have been efforts to restock the natural rivers and lakes around the country particularly driven by country governments and the Fisheries Department of Kenya. Some examples of these include Tharaka Nithi County, Lake Victoria, Lake Naivasha among others with fish species such as Nile tilapia, Redbelly tilapia, and Redbreast tilapia to improve fisheries (Njeru, 2016; Wasonga *et al.*, 2017). Tharaka Nithi Country Government restocked the rivers in Tharaka-Nithi County to improved fisheries by releasing the fingerling into the rivers in 2016 (Njeru, 2016). The fish in these rivers being at a high altitude are likely to move to downstream there by affecting the whole river.

The upper Tana River basin has been a source of tilapia fingerling through the National Aquaculture Research Development and Training Centre (NARDTC) in Sagana Town (Kirinyaga County). NARDTC farm is supplying fingerling to most of the government fisheries projects, and individual's farms with Nile tilapia being the main fish reared in the farm followed by catfish (KMFRI, 2018). The study aimed at mapping the occurrence and geographic distribution of native and non-native tilapia fish species in the upper Tana River basin. The study also identified risks associated with interactions between the native and non-native species.

1.3: Research questions

1. What is the composition of the tilapia fish species in upper Tana River?
2. What is the geographical distribution of tilapia in natural and aquaculture systems in upper Tana River?
3. What are the connectivity pathways between natural and aquaculture systems in upper Tana River?
4. What are the drivers of tilapia introductions into natural systems in upper Tana River?

1.4: The aims and objectives

1.4.1: General objective

To map the geographic distribution and model pathways of the interaction of tilapia fish species between natural and aquaculture systems in upper Tana River basin.

1.4.2: Specific objectives

1. To identify the taxonomic status of tilapia fish species assemblage in upper Tana River.
2. To map the geographical distribution of tilapia in natural and aquaculture systems in upper Tana River.
3. To identify the connectivity pathways between natural and aquaculture operations in upper Tana River.
4. To determine the drivers of tilapia introductions into natural systems upper Tana River

1.5: Hypotheses

H_0: There were no significant differences in water quality parameters among the fish habitats

H_1: Alternative

H_0: There were no significant differences in the altitudinal gradients among the fish habitats

H_1: Alternative

1.6: Scope of the study

The research focus was on mapping the geographical distribution and modeling pathways of the interaction of tilapia fish species between natural and aquaculture systems in the upper Tana River basin. The Tana River basin covers an area of 17,420 km^2 and spanning six counties (Murang'a, Meru, Tharaka Nithi, Nyeri, Kirinyaga and Embu). Out of these, 24 sites were sampled within three counties namely Nyeri, Kirinyaga and Embu. For the aquaculture systems, it entailed mapping the fish ponds, sampling of tilapia fishes from ponds, measuring their altitudes and physic-chemical parameters.

The mapping of the natural and aquaculture systems was done precisely using the coordinates of the sampling points. The altitudes, and physic-chemical parameters were also measured in the specific sampling points. The socio-economic survey was undertaken with respondents drawn from farmers, traders, fishers, and fisheries officers.

1.7: Definition of terms

Aquaculture: The means the cultivation, propagation or farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants whether from eggs, spawn, spat, seed or other means

Biogeography: the study of the distribution of species and ecosystems in geographic space and through geological time

Economic Stimulus Program: A spending plan initiated by the Government of Kenya to boost economic growth and lead the Kenyan economy out of a recession at the end of the first decade of the 21st century

Endemism: Ecological state of a species being unique to a defined geographic location, or habitat type; organisms that are indigenous to a place are not endemic to it if they are also found elsewhere

Hybridization: The process of an animal (fish) breeding with an individual of another species or variety.

Invasive species: is a non-native species to a specific location (an introduced species), and has a tendency to spread at higher degree causing damage to the environment, human economy or health of fellow species

Tilapia: The common name for mainly four genera (*Oreochromis, Coptodon, Alcolapia* and *Sarotherodon*) of family Cichlidae, they are mainly freshwater fish and partly saline inhabiting shallow streams, lakes, wetlands, ponds, rivers and less commonly found living in brackish water.

TilapiaMap: A mobile application software developed by Geosho.com for Tilapia Map project, used for mapping, and simple identification of tilapia fishes in Kenya and Tanzania

CHAPTER TWO: LITERATURE REVIEW

2.1: Introduction

This section deals with the related work done on the topic of study and arranged according to the thematic areas related to the mapping of the geographic distribution and modeling pathways of the interaction of tilapia fish species between natural and aquaculture systems. The section also includes the theoretical and conceptual framework of the study.

2.2: Fish biogeography

Frank (2007) believes that before the formation of geographic barriers to the movement of aquatic organisms like mountains, waterfall, catchment divides, and oceans among others, the aquatic organism were less diverse since the geographic conditions were shared over large geographical areas. The barriers have led to the evolution of distinct biotas at different drainage units. Biogeographic barriers determine the species that colonize a specific local habitat. The biogeographic walls are viewed in terms of continent, inter-basin, or within a basin (Milner *et al.*, 2006; McManamay *et al.*, 2018;). The barriers isolate faunas by their inability to cross oceans, climb mountains, survive in different salinity conditions, temperature ranges among other environmental parameters (Frank, 2007).

The fishes are often considered in light of Wallace's six zoogeographic regions that reflect continental-scale differences in fish composition (Munguti *et al.*, 2014). Before human intervention, no freshwater fish species occurred in all the six zoogeographic regions, and very few occurred in more than one region (Turner *et al.*, 2001). However, rainbow and brown trouts, mosquito fish, guppy, common carp, tilapia fishes and goldfish recently occur in all six zoogeographic regions (Trewavas, 1983; Martins *et al.*, 2004; Munguti *et al.*, 2014;). Jonathan *et al.*, (2000), suggested that understanding of the occurrences of fishes concerning the current biogeography is equally essential to the fish conservation. Kenya consist of three distinct water areas: the Lake Victoria, associated with west-flowing rivers of Kenya; The eastward flowing rivers, rivers flowing into the Indian Ocean; and the Rift Valley which is approximately north-south separating the other two drainage areas. The three drainage areas can hardly interact without human intervention.

2.3: The family Cichlidae

Cichlids are known to be among the most diverse fishes on earth there by occupying a number of geographic areas. They are found in almost all aquatic habitats. The family has 150 genera out of which, four are found in Kenya. It has at least 1,300 confirmed species and with estimates approaching 1900 species (Perez *et al*., 2010). They inhabit fresh and brackish waters and almost geographically distributed in all continents (Kullander, 1998). Cichlids are known by family, genus, species-level or local names, commonly with an adjective to distinguish well-marked species, for example, *Ngege* referring to Nile tilapia (Dieleman *et al.,* 2018). In Kenya, most of the species of tilapia have their local names and can easily be identified by the locals. This makes it easy to monitor any change in the morphology of such fish, for example, the *Oreochromis korogwe* is known as *Bandia* (false or fake) meaning it's not the original species which was in the lake probably introduced (Dieleman *et al.,* 2018). Cichlid diversity has been explained by both their advanced brood care and by the versatile design of the pharyngeal jaw complex used for food mastication (Kamau & Omwenga, 2017). The genera in Kenya includes *Oreochromis, Coptodon, Alcolapia* and *Sarotherodon*. The most diverse is genus *Oreochromis* with *O. niloticus, O, spilurus, O. variabilis, O. jipe, O. hunteri, O. esculentus* native to Kenya (Nyingi, 2013).

2.4: The Cichlid's speciation

Cichlids are the fishes which undergo speciation at a faster rate, which can also be called explosive speciation. There is a general belief that there are more than a thousand species of cichlids in Lake Victoria, Tanganyika, and Malawi only (Turner *et al.,* 2001). Cichlids represent the most diverse and species-rich family in terms of founding lineages and age of radiations (Alexey & Fayodor, 1999). Turner *et al.,* (2008) also suggested that "the study of cichlid fishes may offer unique opportunities in understanding taxonomic and geographical distributions of species richness and functional diversity." This was after realizing that smaller lakes and rivers have few numbers of tilapia species and are not well studied. Indeed, the suggestion hold and necessitated the work by Nyingi (2013) to providing a common guide of freshwater fishes in Kenya.

2.5: Tilapia fish hybridization in Kenya

Fish hybridization is the process of fish breeding with an individual of another species to give an offspring. Fish ponds in NARDTC and Tebere in eastward flowing rivers which are in the natural distribution range of 2 sub species of Sabaki tilapia have had several trials to improve tilapia in Kenya. There are several published records of hybrids of *Oreochromis* species both from field studies and crosses under farmed and laboratory conditions (Trewavas, 1983). Tilapia fishes are well known for interbreeding both under natural and artificial conditions (Lowe-McConnell, 2006).

In 1959, the ponds in Tebere revealed the presence of a suspected hybrid which was identified by their aberrant coloration and gasping. The hybrid was from *Oreochromis spilurus niger* and Redbelly tilapia (Elder *et al.,* 1971). The hybrid was also noticed in Lake Naivasha in 1960; the lake was stocked with Sabaki tilapia and Redbelly tilapia (Elder *et al.,* 1971). Further analysis confirmed that five categories of tilapia could be distinguished by phenotypic characters out of three fishes introduced into Lake Naivasha; *Oreochromis spilurus niger,* Redbelly tilapia, and *Oreochromis leucostictus* plus two hybrids.

2.6 Tilapia fish introductions and distribution in Kenya

An non-native species refers to any species intentionally or accidentally transported and released into an environment outside its present range (Mboya *et al.,* 2005). There were already 1,354 introductions of 237 species into 140 countries documented worldwide by 1995 (Hickley, 1994; Pitcher, 1995). Of these, 147 introductions of 50 fish species have been done in Africa, with 23 of these being from outside Africa. Kenya's freshwater lakes have had about 14 introductions properly documentation with six non-native species in Lake Victoria, 7 in Lake Naivasha and 1 in Lake Baringo (Mboya *et al.,* 2005).

Generally, there have been different reasons for introducing fish into Kenyan waters, but the major reasons are like to create a fishery for commercial purposes, improve fisheries by enhancement of the present stocks, ornamental purposes, to control weeds or disease vectors and accidental introductions or escapees from confinement (Raadik, 1992; Kerr & Grant, 2000; Mboya *et al*., 2005; Njiru *et al.,* 2006; Aloo *et al.,* 2013) . Nile tilapia is the main tilapia species introduced in Kenya, it is native to the Nile River basin, Lake Chad, the Niger, Benue, Volta, and Senegal Rivers (Njiru *et al.,* 2006; FAO, 2012). The Nile tilapia has had many adverse ecological effects in the waters it has been introduced to, bringing to light the effects of fish introductions worldwide. Similarly, the Nile tilapia have been introduced to at least 88 countries and has established in at least 49 of them (Casal, 2006).

In Kenya, the Nile tilapia was introduced into Lake Victoria and Lake Turkana in the early 1950s along with other tilapiine species. These non-native tilapia were introduced in an attempt to restore the tilapia fishery that was previously based on native species and was severely overfished (Ogutu-ohwayo, 1990). The Nile tilapia is now the most abundant and commercially important tilapiine in Lake Victoria (Aura *et al.,* 2017). The Nile tilapia was introduced in Lake Naivasha around 1967 but disappeared in 1971 for reasons that are still unclear to date. It was later reintroduced by the Government of Kenya between 2010 and 2013 to boost the local fisheries in the lake (Keyombe *et al.,* 2018). Studies have shown in recent past a marked increase in Nile tilapia landings since its reintroduction into the lake and thus an improvement in the fishery and the fishing community.

Redbelly tilapia, is found widely in Africa and the Middle East but has been introduced in different areas worldwide for commercial purposes. It was introduced into Lake Victoria along with other tilapiine species like Nile tilapia and Redbreast tilapia in the early 1950s in an attempt to restore the tilapia fishery that was previously based on native species and was severely overfished. The species is found in numerous freshwater bodies in Kenya like Lake Victoria, Lake Naivasha, and Lake Turkana. Redbelly tilapia is important as a source of food and in aquaculture enterprises. It has also been introduced in numerous water bodies for use as a biological control mechanism for aquatic weeds. However, Redbelly tilapia is known to alter benthic communities by the elimination of macrophytes and can exhibit aggressive behavior towards other fishes. It is also thought to have contributed in outcompeting the two native tilapia of Lake Victoria, *Oreochromis variabilis*, and *Oreochromis esculentus* (Wasonga *et al.,* 2017).

The Lake Magadi tilapia, *Alcalapia grahami*, a benthopelagic fish endemic in Lake Magadi inhibits hot, alkaline waters in springs and lagoons around hyper-saline lakes (Nyingi, 2013; Akinyi, 2018). Magadi tilapia was introduced to Lake Nakuru in 1959 (Vareschi & Jocobs, 1984). The Lake Magadi tilapia in Lake Nakuru have switched to filter-feeding of *Arthrospira* and supports a wide variety of fish-eating birds in the lake especially flamingoes (Akinyi, 2018). According to the IUCN Red List, it is a vulnerable species. The threats are not certain, but the population is thought to be declining (Bayona & Akinyi, 2006).

2.7: Tilapia introduction in Tana River basin

Tana River is the largest river in Kenya draining eastward from Mount Kenya, Aberdare Ranges and Imenti Hills of central Kenya to the Indian Ocean. The cold upper Tana River was stocked with trout in colonial times mainly for sport fishing (Seegars *et al*., 2003). Further downstream, there are dams impounded the upper Tana River; Masinga, Kamburu, Gitaru, Kindaruma and Kiambere which have produced increasing amounts of tilapia and African catfish believed to have escaped from NARDTC Fish Farm (Jumbe, 1997). According to Seegars *et al.*, 2003 the fish communities of the lower courses of Tana River, below the rapids at Kora, seem to be fairly undisturbed with higher population of native fishes.

The non-native tilapia species recorded in Tana River includes; Redbelly tilapia, Redbreast tilapia, Nile tilapia, and Mozambique tilapia with all having records in fish farms in the area. They are believed to have escaped from the farms and established wild populations in the river.

2.8: Implication of fish species introductions

Fish introduction has several implications to the other aquatic community, environment, and the ecosystem at large. Some of the negative repercussions of fish introductions in natural aquatic systems can be summarized as follows.

a) Resource competition – new species often compete with resident species for food and breeding space. The competition usually results in the partitioning of the habitat and food resource evidenced by the shift in the distribution and abundance of the native fishes in Lake Victoria (Kerr & Grant, 2000).

b) Predation on the native species – non-native species often feed on the native ones when they happen to be carnivores. Predation reduces typically or eliminates resident species. This occurs at any life stage of resident species leading to suppressing of native species population (Russell, 2011).

c) **Hybridization** – the fish introduction can also have genetic impacts as reviewed by Canonico & Arthington of 2005. Introgressive hybridization reduces the adequate population size on the resident species by increasing inbreeding leading to the potential elimination of different genomes (Elder *et al.,* 1971). Interspecific hybridization can also give infertile hybrids with intermediate characteristics of parents.

d) **Fish community alteration** – introductions upset the natural balance of the fish community by creating ecological instability. Modification can be manifested in terms of stranded growth, reduced survival range of resident species and fisheries yield decline has reported in Lake Victoria and Kyoga after the introduction of Nile tilapia and Nile perch (Ogutu-ohwayo, 1990).

2.9: Aquaculture in Kenya

The aquaculture is the cultivation, propagation or farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants whether from eggs, spawn, spat, seed or other means (KMFRI, 2018). The Kenyan aquaculture sector is broadly categorized into freshwater aquaculture and Mari-culture (Munguti *et al.,* 2014).

Freshwater aquaculture in Kenya has recorded significant progress over the last decade; the mari-culture sector has yet to be fully exploited (Mwamuye *et al.,* 2012). The Kenyan aquaculture industry had seen slow growth for decades until when the government-funded Economic Stimulus Program increased fish farming nationwide (KMFRI, 2017). Indeed, national aquaculture production grew from 1,000 MT/y in 2000 (equivalent to 1% of national fish production) to 12,000 MT/y, representing 7% of the national harvest, in 2010 (Munguti *et al*., 2014). The dominant aquaculture systems in Kenya include earthen and liner ponds, dams, and tanks distributed across the country (Ngugi *et al.,* 2007). The most farmed fish species is Nile tilapia. which accounts for about 75% of the production, followed by African catfish, *Clarias gariepinus*, which contributes about 21% of aquaculture production (FAO, 2019). Other species include common carp *Cyprinus carpio*, rainbow trout *Oncorhynchus mykiss*, koi carp *Cyprinus carpio carpio*, and goldfish *Carassius auratus*. Recently, Kenyan researchers have begun culturing native fish species such as *Labeo victorianus* and *Labeo cylindricus* at the National Aquaculture Research Development and Training Centre in Sagana (KMFRI, 2018).

Tilapia are used widely in aquaculture because of their fast growth, tolerance of a wide range of environmental conditions, and ability to feed at different trophic levels (Costa, 2001; Canonico & Arthington, 2005). These attributes make tilapia a good fish for aquaculture. However, the same attributes make tilapia be able to colonize new habitats, therefore making them very successful as invasive species.

2.10. Fish and citizen science

For over years now, the studies have been carried out with the scientists and non-scientists. Citizen science is an initiative aimed at making biodiversity monitoring more effective by giving scientists more datasets, proving follow up support from citizens and enabling training of a large number of data collectors (TBA, 2019). The citizen science gives opportunities for ecosystem assessments, evaluation of trends, challenges, and opportunities of utilizing resources (Schröter *et al*, 2017). Most of the citizen science initiatives involves use of simple mobile applications or web based applications by different people to collect data. TilapiaMap application is one of the mobile tools used by citizens to collect data on tilapia distribution in East Africa (Tilapiamap.org, 2019). Usually citizen science gives room for collection of multiple data for different places by different people over short period of time.

2.11: Tilapia habitats

Tilapia inhabits freshwater and brackish waters with different water quality parameters. Tilapia can be found in lakes, rivers, estuaries and wetlands among different habitats. These habitats are differentiated by water quality parameters. The survival range of tilapia is relatively wide, explaining its survival in several habitats (Mboya *et al.*, 2005). Water quality is key to any aquatic organism survival. It plays a role in the health of aquatic organisms, and change could cause stress leading to diseases (Padmavathy & Aanand, 2017). The water quality parameters influences and interacts with each other (Joseph, 1993). The temperature ranges for tilapia is usually 27 to 34ºC, making them tolerate high temperatures (GSMFC, 2006). Their sensitivity to salinity also varies significantly among species with some species fully tolerating seawater (Mozambique tilapia) (GSMFC, 2006) while others do not. Tilapia requires a pH range of 6.4 to 8.5; this is also wide enough to accommodate several habitats (Dudgeon *et al.,* 2015). Dissolved Oxygen, which reflects the physical and biological processes in water, should also be of about 5 mg/l (Padmavathy & Aanand, 2017).

2.12: Research gaps

A number of research work has been identified on the fish distribution generally by Trewavas, 1983; Seegers *et al.*, 2003; Lowe 2006 and Nyingi, 2013. Although these studies form the basis of my work, they are mainly giving the distribution native fishes. These studies have not been able to address the following areas:

1. The specific geographical location of the species the tilapia fishes.
2. The use of citizen science (mobile application) to map the distribution of tilapia fishes in Kenya.
3. The current tilapia taxonomic status of Tilapia fishes in upper Tana River basin
4. The implication of aquaculture systems on the fish introduction and hybridizations.

2.13: Theoretical framework

The most suitable theory explaining the study topic is community assembly theory (CAT) which is associated with (Elton, 1958); this theory stresses on processes, history and seeks an explanation for community patterns in the context of dynamic community structure rather than static. It holds that all communities were built through sequential invasions and extinctions processes which are continuous. This theory is the basis of the present-day study of species invasions (Lodge, 1993). The discovery of assembly rule could, therefore, serve as a light to put community ecology on a more predictive basis (Keddy, 1992). CAT has been explored through the examination of natural patterns (Diamond, 1975) laboratory and field experimentation, and computer simulation (Post & Pimm, 1983). Generalizations emerging from CAT examination includes: invasion success decreases with species richness; the strength of invasion resistance increases with the strength of community interaction coefficients; final community state depends on invasion order, thus, multiple stable states are possible from a single species pool and communities can shift among alternative and predictable states as invasions and extinctions proceed (Case, 1991).

2.14: Conceptual framework

The conceptual framework developed illustrates tilapia fish distribution, natural and aquaculture systems interactions, tilapia fish species composition and drivers of tilapia introduction in upper Tana River basin (Figure 1). It implies that fish introduction and distribution is driven by human intervention. The fish introduction process can lead to ecosystem competition, habitat and fish community alteration and change in the gene pool among other impacts. To understand the dynamics, the water quality parameters and fish introductions assessments, and mapping of the fish occurrences was done. Mapping the distribution helps in understanding the population geographic change (expansion and reduction). The population change can be influenced by ecological factors like both the chemical, physical and biological water quality parameters and nature of the fish species involved. The interaction of different species of fish in the same geographical space can be as a result of the natural occurrences, accidental introduction or intentional introduction. The accidental and intentional fish introduction are mainly human driven due to food production or weakness in management of the natural resources.

The variables are influenced by the National and County governments' policies dictating the use of fisheries resources and prevailing economic conditions both locally and globally. Strict implementation of fisheries regulations can drastically reduce the impacts of fish introduction into the wild.

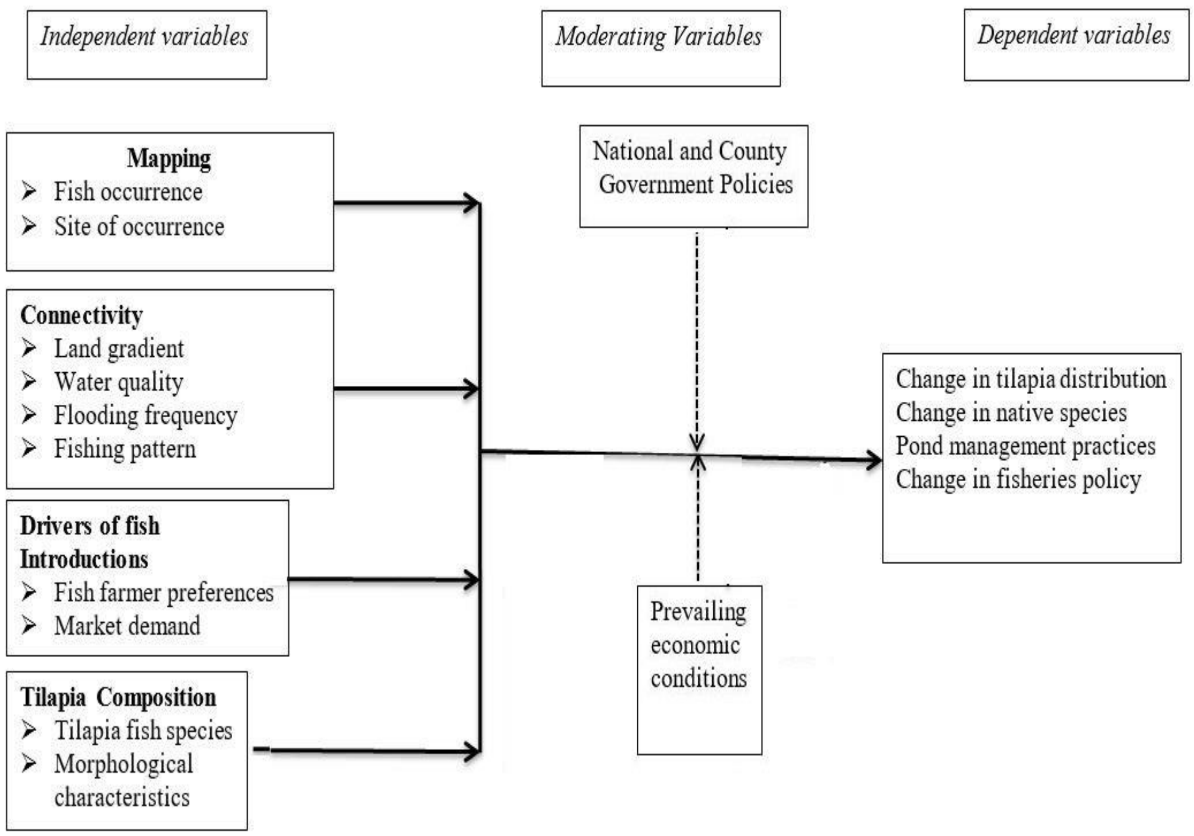

Figure 1: The flow diagram of the conceptual framework

CHAPTER THREE: MATERIALS AND METHODS

3.1: The study area

The study was conducted in the upper Tana River basin, which is originating from Mount Kenya and Aberdare Ranges up to the Masinga dam. The upper Tana River covers an area of approximately 17,420 km^2 and lies between latitudes 00.005^0 and 00.924^0 south and longitudes 36.607^0 and 37.945^0 east (Gikonyo *et al.*, 2014; GK, 1992).

The study was carried out in Nyeri, Kirinyaga and Embu counties in the rivers, dams and fish farms (Table 1).

Table 1: 24 sampling sites in the study area, upper Tana River

Habitats	**Embu**	**Kirinyaga**	**Nyeri**
Fish farms	Eeepo, Nyati and Good Shepard	Emmi, NARDTC, MweaAqua, Kiama, Kariuki and Joy	Daniel, Wahome and Mutone
Rivers	Rupingazi and Ena	Sagana, Nyamindi and Ragati	Gura and Honi
Dams	Masinga	Nyando	Chinga

Gura and Honi rivers originate from Aberdares while Ragati, Nyamindi, Rupingazi and Ena rise from Mount Kenya. Sagana River has tributaries from both catchments. Fish and water quality sampling were done in all sampling sites and units (Figure 2), as rivers (green lines), fish ponds (red stars) and dams (green squares). Questionnaire was administered to fish farmers in their farms, Fisher-folks while in fishing areas, fish traders in markets and fisheries officers in their duty stations.

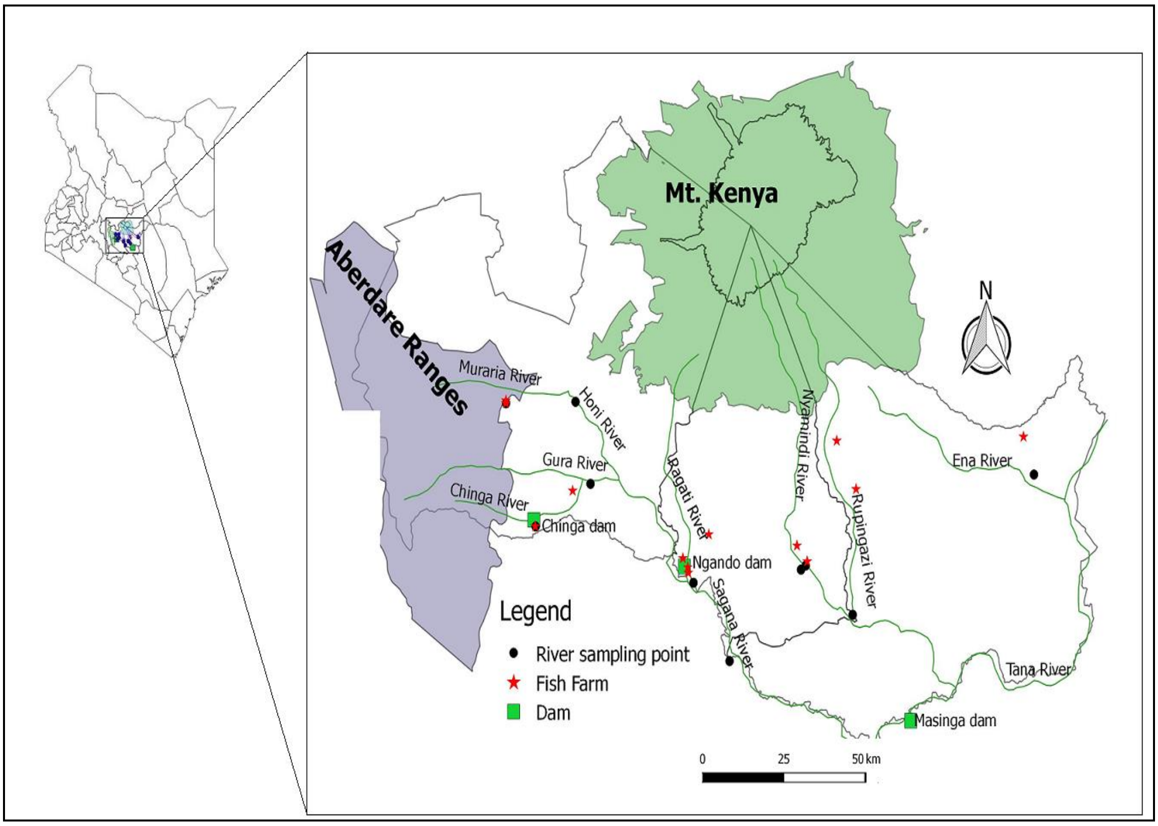

Figure 2: 24 sampling sites of upper Tana River basin (Author: Kashim Oginga)

3.1.1: Drainage and hydrology

Upper Tana Basin, which is the upper catchment of the Tana River basin, which is the largest and most important basin in Kenya, which is approximately 1000km long (Kiteme & Gikonyo, 2002). Its catchment covers an area of 95,950 km^2 (approximately 17% of Kenya's landmass), and the flow of the Tana River basin constitutes 27% of the total mean discharge measured along rivers in the country's major drainage basins (Gikonyo *et al.*, 2014). The Upper Tana catchment has its tributaries in Mt. Kenya and Aberdare Ranges. The rivers associated with Mt. Kenya such as Nyamindi, Rupungazi, Ena, Ragati among others which flow through coffee and tea plantations and forest zones and joins downstream while those associated with the Aberdares sub-catchment (Mathioya, Maragua, Thika, Sabasaba, Gura, Chania and Amboni) flow through deep valleys cutting through forests, tea, and coffee zones (UTNWF, 2014).

The drainage of upper Tana main rivers, and their tributaries are determined by the slope and shape of the tertiary volcanic materials; the direction of the slopes of the

Aberdare range and Mt. Kenya; and the structure of the basement rock system (Emerton, 2018). Aberdare ranges have several perennial rivers flowing in moderate valleys to the southern end of profound valleys to the basement system(Bay *et al.*, 2010).

3.1.2 Fisheries

The upper Tana River basin has a dense network of freshwater streams, numerous dams, and fish ponds, and major cold and warm water hatcheries in the country. The National Aquaculture Research Development and Training Centre (Sagana, Kirinyaga County) was established in 1948 by the colonial government has been serving the country with tilapia and catfish fingerlings. Kabaru trout hatchery in Nyeri was established for cold water trout fishes.

The main fisheries activities are in the dams, river fisheries, and pond fish farming. The main fish species in this area are tilapia, catfish, and trout (GK, 2013, 2018a, 2018b). Fishing is not a dominant economic activity in the area though it is gaining momentum. By 1960s, the area did not have full-time fisher-folk or commercial fishermen but usually have fishermen occasionally supplementing diet and income (Mann, 1969).

3.1.3: Climate

The climatic condition in upper Tana catchment widely varies as also observed in the larger Kenya. The climate responds to the Inter-tropical Convergence Zone, but is considerably influenced by the relief of Mt. Kenya and Aberdare Ranges (Gikonyo & Kiura, 2014). The region experiences bimodal rainfall regime with long rains occurring between March and June and short rains between October and December. The region lies in five agro-ecological zones, namely agro-alpine, high potential, medium potential, semi-arid and arid zones with rainfall ranging from as low as 410mm in lower areas of Embu to 2700mm per annum in Mt. Kenya and Aberdare Ranges (Ngigi *et al.,* 2007; Gikonyo & Kiura, 2014; Njogu & Kitheka, 2017). Apart from the areas with medium and high rainfall distribution, an annual variation on low rainfall regime areas are relatively large with quite erratic rainfall. In upper parts of Nyeri, besides the two seasons, there is a short period of drizzles between July and October.

3.1.4: Population and settlement

The population in Nyeri, Kirinyaga, and Embu counties was 1,978,174 people, according to the 2019 Kenya Population and Housing Census (KNBS, 2019). The three counties have an estimated population density of 250 people per square kilometer against the national average of 66 people per square kilometer. The forested areas in Mt. Kenya and Aberdare have a low population density of approximately two people per square kilometer (Gikonyo & Kiura, 2014). Settlement patterns in the upper Tana have been determined by the food availability, climatic conditions, infrastructure, and proximity of the urban centers.

Most population in upper Tana River region have settled in higher altitude zones. These areas are agriculturally vibrant with great natural resources such as forest and water endowment (Kiteme & Gikonyo, 2002). The farming type also influences the settlement patterns with upper zones attracting a higher percentage of the population, where cash crops are mostly grown. Other areas also have a high concentration of people due to the presence of major roads. The population is low in semi-arid areas such as lower parts of Embu county (Kiritiri and Makima divisions) where the density is as low as 35 people per square kilometer (Njogu & Kitheka, 2017). In these areas, people mainly settle along the major permanent water sources such as rivers, furrows, and dams where irrigation, farming, and fishing are carried out (Ngigi *et al.*, 2007).

3.2: Study design

The study involved the sampling of fish and water quality, interviews through administration of a questionnaire and literature review. Rivers, dams and fish ponds were sampled for the tilapia fish and physic-chemical parameters (temperature, pH, turbidity, electrical conductivity and dissolved oxygen). These parameters were hypothesized to affect fish distribution and abundances. The altitude of each sampling point was measured to obtain the gradient of fish ponds to adjacent the rivers and dams. Fish sampling was done in eleven fish farms, seven rivers, and three dams. Physic-chemical parameters were taken in 44 ponds, 32 river points, and 16 dam points.

A social survey involving fisheries officers (9), fishermen (41), fish traders (32) and fish farmers (32) was conducted to obtain data on fishing activities and fish pond management practices in the study area. The survey was also intended to document fish introductions and fish marketing chains. Fisheries officers were visited in their respective offices, farmers in their homes/farms, fishermen in the fishing grounds such as dams and rivers while fish traders were interviewed in market places (Figure 3).

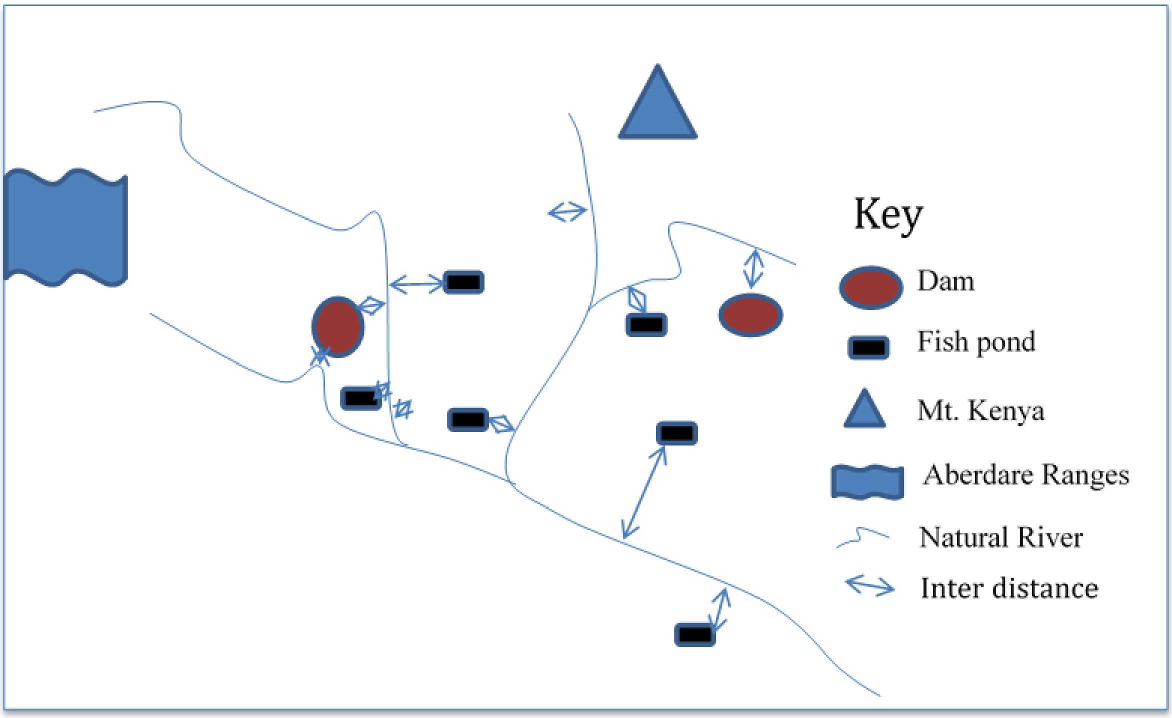

Figure 3: Sketch diagram showing the study design for the upper tana River sub catchments

3.3: Materials and methods

3.3.1: Taxonomic status of tilapia species assemblages in upper Tana River basin

a. Fish sampling method and sample size

A total of 383 individual fish samples were collected from 24 sampling site fish farms, dams, and rivers (Table 2). Fish samples were collected either using seine net, gillnet or electrofisher.

Table 2: Summary of number of tilapia fish collected per sampling site

County	Sub-catchment	Sampling site	No. specimens
Embu	Rupingazi River	River	0
		Good-Shepard Aqua farm	21
		Nyati Aqua farm	15
	Ena River	River	34
		Eeepo Aqua farm	18
	Masinga dam	Dam	29
Kirinyaga	Sagana River	River	44
		NARDTC Aqua farm	60
		Kiama Aqua farm	12
		Emmi Aqua farm	15
		Ngando dam	17
		Ragati-Mathioya	0
		Kariuki farm	0
	Nyamindi River	Mahinga-ini canals	21
		Mwea Aqua farm	15
		Joy Aqua farm	17
Nyeri	Gura River	River	3
		Chinga dam	17
		Ichamara River	0
		Mutone Aqua farm	15
		Daniel Aqua farm	4
	Honi River	River	0
		Muraria River	0
		Wahome Aqua farm	26
Total			**383**

Fishing in ponds was done using seine net of a mesh size 1mm and of 2m by 1m of length and width respectively (Plate 1). The selected mesh-size allowed the collection of fish of different sizes. The fish samples from the river were collected using gillnets of 60mm and 100mm mesh-sizes, electro-fisher, and seine net. Seine net and electrofisher were used in shallow water and rocky places. Dams were sampled using rented boats by use of passive gear, gillnet set and waited for 30 minutes.

Plate 1: Fish sampling using seining at Good Shepard Aqua, Embu County (Photo credit: Kashim Oginga)

Fish caught were sorted into their respective species and later confirmed using the identification guide book and checklist (Seegers *et al.,* 2003, Nyingi, 2013 and Trewavas, 1983) and counted. The standard length (SL) of the fish samples were measured using a meter rule mounted on the specimen board to estimate their sizes (Plate 2).

Plate 2: *Fish measurement on measuring board fitted (Photo credit: Kashim Oginga)*

Fish were anesthetized using 50 mg/L of Tricaine mesylate (Euthanasia Agent) (FAU IACUC, 2014) before fixing them in 10% formalin for 10 days. The fish samples were transported to the Ichthyology Section at the National Museums of Kenya, for processing and incorporation into the museum reference collections and registration (Annex 2 and 3). During preparation, the excess formalin was washed in running water for 24 hours and voucher specimens preserved in transparent containers half filled with 70% ethanol (Plate 3).

Plate 3: Fish specimen identification and curation in Ichthyology laboratory, NMK (Photo credit: Kashim Oginga)

b. Geometric morphometrics

The geometric morphometric method was used in quantifying the body forms through the use of a landmark-based geometric method (Rohlf & Marcus, 1993). Images of the preserved specimen were obtained by using a digital camera (model Canon EOS400D SLR), from a standard angle (i.e., perpendicular to the dorsoventral and anteroposterior axis). The photos were imported into the Thin-plate spline (TPs) utility programme using theTPsUtil software version 1.76 (Rohlf, 2015). A total of 16 landmarks (positions on the body of the fish) were chosen based on their capacity to capture overall body shape, and their coordinates (x, y) digitized using the TPsDig software version 1.40 (Rohlf, 2015) (Annex 1) according to Dieleman *et al.*, (2018). The fish size was calibrated using a 30 cm rule permanently fixed on the specimen pinning board. The specimen's standard sizes ranged from 48mm to 240mm. The two genera considered for analysis were *Coptodon* (98 specimens) and *Oreochromis* (285 specimens).

3.3.2: Mapping the distribution and occurrence of tilapia fishes

The geographic distribution of tilapia was assessed using primary data collected by handheld GPS gadget (Garmin eTrex 10) and Android smartphone application (TilapiaMap application). A handheld GPS was used for site mapping where three GPS coordinates were taken in every sampling point and later averaged to give sampling point coordinates. The key features and sampling site names were recorded in the field notebook.

TilapiaMap Application is an Android application software developed by Geosho (www.geosho.com) and available for free download in the Google play store. The application was used for tilapia fish species mapping. All the tilapia fish collected in the field were recorded using the App by filling in each fish specimen details namely: suggested name of the specimen, standard length, and the number of anal spines, locality details, and the specimen's photo. The information was then submitted to TilapiaMap Server for verification by the fish experts at Bangor University (UK), National Museums of Kenya (Kenya) and Roehampton University (UK) (TilapiaMap, 2017). The verified records were posted on TilapiaMap website (www.tilapiamap.org) for public use.

The TilapiaMap application divides Kenya the following catchments: Lake Victoria basin, Pangani system, Lake Elmentaita, Lake Nakuru, Lake Naivasha, Lake

Magadi, Ramisi River, Sabaki-Galana River, Athi River, Lower Tana, Upper Tana, Lake Turkana, Suguta River, Ewaso Ng'iro basin, Lower Ewaso Nyiro basin and Lake Baringo basin catchments. Different species of tilapia are known to occur in these areas.

3.3.3: Assessment of the connectivity pathways between natural and aquaculture systems

a. Water quality measurements

Physic-chemical parameters could form a barrier to fish distribution. Hence, they were measured *in-situ* before fish sampling in the ponds, rivers, and dams were done between December 2018 to May 2019 in Nyeri, Kirinyaga and Embu counties in upper Tana River Basin using a Multimeter probe model YSI model 80/50 (Plate 4). The water quality measurements were taken from 96 sampling units found in the 24 sampling sites. The units the fish ponds in a fish farm, different points in a rivers and dams.

Plate 4: Measurement of physic-chemical parameters using Multi-meter probe at Francis Wahome's pond in Tetu division, Nyeri County (Photo credit: Kashim Oginga)

The parameters measured were temperature, dissolved oxygen, turbidity, electrical conductivity and pH listed with acceptable ranges for "good" water quality according to national and international standards, NEMA (2006) and WHO, (2006) (Table 3). The water quality parameters were measured in rivers, ponds, and dams at a depth of 5cm, 10cm and 20cm, respectively due the varied depths of the habitats. The ponds were selected randomly depending on the total number of ponds in a fish farm. Three measurements were conducted in every pond at different points, which were subsequently averaged to get one pond measurement. The nearest point of the adjacent river to fish farms was determined based on land use, and accessibility. In rivers, two different points were measured, at the periphery and approximate middle section of the river. In dams, three different points were measured in at an interval of 5m from the show.

The field measurements were recorded in a data sheet attached as annex 5. Three measurements were taken for all the parameters between 11.30 am to 2 pm. Turbidity was measured using turbidity tube in centimeters and later converted to NTU using Turbidity conversion chart (Water Action Volunteers, 2008).

Table 3: The standard guidelines for water quality parameters according to NEMA and WHO standards

Parameters	**NEMA**	**WHO**
Chemical parameters		
Electrical Conductivity (μS/cm)	0-800	Max 2500
Dissolved Oxygen (mg/l)	3 to 7	
pH	6.5-8.5	6.5-8.5
Physical parameters		
Temperature (°C)	30	30
Turbidity (NTU)	50	5

a. Altitudinal gradient

The sampling point's altitudes were measured to understand the land gradient/slope. This helped in interpreting the flash flood risks. The altitudes of the fish farms, dams, and rivers adjacent to the fish were recorded by use of a handheld GPS. At every sampling point, there were three measurements of altitudes which were averaged to give one sampling point altitude.

b. Socio-economic Survey

A socio-economic survey was conducted to determine how fish farms were connected to the natural water bodies, pond management practices, and fish preferences. The socio economic survey had two sections. The first section dealing with the respondent and geographical information while second was dealing with farm management practices, fishers, fishing activities, fisheries management and fish marketing chains for fish farmers, fisheries officers and fish traders respectively. The interviews were done in order to understand the different pond management practices carried out by the farmers, tilapia fish farmed, the topography, weather conditions experienced, the river fishing activities, local knowledge on exotic and native tilapia species, fish demand and supply and marketing of fish as shown in annex 6. All the respondents were selected randomly on the accessibility basis and interviewed (Table 4). Farmers were interviewed in their homes/farms, and the fishermen from the known fishing grounds (dams and rivers) in the three counties while traders were interviewed in market places.

Table 4: Distribution of the responses by category and county

	Number per county			
Respondents	**Kirinyaga**	**Nyeri**	**Embu**	**Total**
Fish farmers	16	18	11	**45**
Fishermen	17	16	8	**41**
Fisheries officer	3	3	3	**9**
Fish traders	12	12	8	**32**
Total	**48**	**49**	**30**	**127**

3.3.4: Determination of the drivers of tilapia introductions into natural systems

The drivers were enumerated through socio-economic surveys conducted to the farmers, fishers and fisheries officers in the second section of the questionnaires and review of the existing and relevant Kenyan legislation from 1901 to 2016. Further information was gathered through physical observations of the nature of the ponds and geographic orientation. The field observations included the nearness of ponds to the natural water body, and presence/absence of pond in and outlet filters/screens. In Kenyan legislations and policies, the documents were review for the fish introduction concerns, management and aquaculture issues. The presence or absence of these issues were highlighted.

3.4: Data Analysis

3.4.1: Taxonomic status of tilapia species

Analysis of the digitized data was carried out using the MorphoJ software, version 1.07a. MorphoJ software is a geometric morphometric software used for the morphological analysis (Klingenberg, 2011). The analysis was conducted to establish morphological variations between different species population and sub-populations of tilapia fish asobtained from different sites in the upper Tana River basin. The digitized landmark dataset was aligned via procrustes superimposition in the MorphoJ software program.

The Principal Component Analysis (PCA) was conducted to visualize the variations by plotting multivariate ordination of specimens on the 2^{nd} and 3^{rd} Principal Component (PC) axes. PC2 and PC3 were used due their strength to discriminate based on finer features other than the specimen sizes. Principal Component's loadings were observed to establish shape features that had the greatest influence on each Principal Component (Annex 4). The first analysis was done on the 383 specimens to isolate the two genera of interest. The specimens that overlapped and outliers were removed to get pure *Coptodon* and *Oreochromis,* which were taken for further analysis. The data were divided into two groups (*Coptodon* and *Oreochromis*), which were analyzed independently to subspecies level where possible.

Relative abundance of fish across different sampling sites was calculated by using the following formula in excel:

$$Relative\ abundance = \frac{Number\ of\ samples\ of\ particular\ species\ X\ 100}{Total\ number\ of\ samples}$$

The species diversity was calculated using Simpson index, and Margalef richness index. Simpson index was used to measure the diversity taking into account both richness and evenness. Calculated using the formula:

$$D = \Sigma\ (n / N)^2$$

Whereas D-Simpson index, n- the total number of organisms of a particular species, N- the total number of organisms of all species.

Margalef richness index is the measure of diversity counting for the number of different species in a given area. Calculated using formula:

Margalef richness index = (S-1)/log (n)

Where: S= total number of species, n= total number of individuals in a sample

3.4.2: Tilapia distribution mapping

The site GPS coordinates were entered into an excel spreadsheet in the order in which they were recorded, in degrees, minutes and seconds. The coordinates were converted into decimals using the formula Degrees + (minute/60) + (seconds/3600). The results were then fed into Quantum Geographical Information System (QGIS) version 3.6.3 (Copyright (C), 1989) to produce distribution maps.

The TilapiaMap application data was downloaded from the TilapiaMap.org inform of maps and quantitative data in spreadsheet form and analyzed to show the coverage and use by the computation of descriptive statistics.

3.4.3: Assessment of connectivity pathways between natural and aquaculture systems

Water quality data were tested for normality using the Shapiro-Wilk test and analysed in SPSS software version 20.0. One-way ANOVA and MANOVA were used to test the significant differences between the habitats (ponds, dams, and rivers) physic-chemical parameters. Tukey's HSD test was done for post hoc comparison of different habitats at $p < 0.05$. Pearson correlation analysis was done to show the degree of association between the parameters and the altitudes. A paired student T-test was performed to show the significant differences between the habitats altitudinal gradients. Descriptive statistics were used to display the flash flood frequency in upper Tana River basin using the mean.

3.4.4: Determination of the drivers of tilapia introductions into natural systems

The primary and secondary data obtained were entered into the excel spreadsheets then analyzed using descriptive statistics in SPSS software version 20.0.0, evaluating the strengths and frequencies of the drivers.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1: Fish fauna

4.1.1: Fish species composition and abundance in upper Tana River basin

Six hundred and five fish specimens were captured, comprising of 16 species belonging to 5 families (Table 5). The Cichlids (family *Cichlidae*) had the highest diversity of number of species followed by Carps (family *Cyprinidae*) with seven and six species respectively. The other three families: Air-breathing catfishes (*Claridae),* African Mountain catfishes (*Amphilidae*) and Live Bearers *(Poecilidae)* had one species each. The Cichlids were the most abundant family occurring in almost all the study sites except Ragati, Honi and Rupingazi Rivers. The Air-breathing catffishes and Live Bearers were only recorded in two sites each. African Mountain catfishes was recorded in Gura, Honi and Rupingazi Rivers.

The relative abundance of Nile tilapia accounted for 31% of the total numbers and occurred in 54% of the sites sampled. Mudfish (*Clarias gariepinus*) had the least relative abundance of 0.5%. The fish farms had 48% of the total specimen collected, 23% from dams whereas 29% obtained from rivers. The most abundant fish in the farms was Nile tilapia, followed by Sabaki tilapia at 58% and 17% respectively. The relative abundance ranged from 21% of Redbreast tilapia to 3% of Straightfin barb (*Enteromius paludinosus)* in dams. Redspot barb (*Enteromius kerstenii)* was the most commonly caught fish species in the river followed by Neumayer's barb (*Enteromius neumayeri)* and *Oreochromis spilurus niger.*

Table 5: Composition of fish assemblages and relative abundance of fish species

	Family	CICHLIDAE							*CYPRINIDAE*						CLARIDAE	AMPHILIDAE	POECILIDAE
County	Locality	*Cr*	*Cz*	*On*	*Osn*	*Oss*	*Om*	*Pmv*	*Gd*	*Ep*	*En*	*Lc*	*Ek*	*Lo*	*Cg*	*Au*	*Pr*
Embu	Embu Aqua	-	-	42	-	10	-	-	-	-	-	-	-	-	-	-	-
	Rupingazi R.	-	-	-	-	-	-	-	6	-	11	15	23	6	1	5	-
	Ena River	-	-	-	22	12	-	-	-	-	-	-	-	-	-	-	34
	Masinga dam	17	-	9	3	-	-	-	-	4	-	27	-	-	-	-	1
Kirinyaga	Sagana River	-	11	21	6	6	-	-	-	-	-	1	-	-	-	1	-
	Kirinyaga Aqua	2	23	69	2	20	5	-	-	-	-	-	-	-	-	-	-
	Ngando dam	13	-	-	4	-	-	-	-	-	-	-	-	-	-	-	-
	Ragati-Mathioya	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mahinga-ini canals	-	-	-	10	11	-		-	-	-	-	-	-	-	-	-
Nyeri	Nyeri Aqua		2	41	-	2	-	-	-	-	-	-	-	-	-	-	-
	Gura River	-	-	3	-	-	-	3	-	2	17	-	-	-	2	5	-
	Chinga dam	-	12	3	2	-	-	17	15	-	-	-	-	-	-	-	5
	Honi River	-	-	-	-	-	-	-	-	-	-	-	20	-	-	2	-
	Total	**32**	**48**	**188**	**49**	**61**	**5**	**20**	**21**	**6**	**28**	**43**	**43**	**6**	**3**	**13**	**40**
	R. A	**5**	**8**	**31**	**8.1**	**10**	**0.8**	**3.3**	**3.5**	**1**	**4.6**	**7**	**7**	**1**	**0.5**	**2.1**	**6.6**

***Note**: Cr-Coptodon rendalli, Cz-Coptodon zilli, On-Oreochromis niloticus, Osn-Oreochromis spilurus niger, Oss-Oreochromis spilurus spilurus, Om-Oreochromis mossambicus, Pmv-Pseudocrenilabrus multicolor victoriae, Gd-Garra dembeensis, EP- Enteromius paludinosus, En-Enteromius neumeyeri, Lc-Labeo cylindricus, Ek-Enteromius kerstenii, Lo-Labeo oxyrhynchus, Cg-Clarius gariepinus, Au-Amphilius uranoscopus, Pr-Poecilia reticulata*

4.1.2: Composition and relative abundance of tilapia species in upper Tana River

A total of 383 tilapia fish specimens comprising of two genera (*Coptodon* and *Oreochromis*) were collected. Five species includes: Mozambique tilapia, Nile tilapia, Sabaki tilapia, Redbreast tilapia and Redbelly tilapia belonging to the two genera (Table 6). Out of the five tilapia species collected from the study area, all occurred in fish farms, four in rivers, and four in dams. Mozambique tilapia only occurred in fish farms. The highest number of fish specimens was collected from fish farms (52.7%).

The genera *Coptodon* had a lower relative abundance compared to genera *Oreochromis*. Redbreast tilapia was only recorded in the National Aquaculture Research Development and Training Centre, Sagana while Redbelly tilapia was recorded in two farms National Aquaculture Research Development and Training Centre and Daniel's farm. Nile tilapia, was the most commonly occurring species at (49.1%) in almost all sites. Mozambique tilapia had the least relative abundance at 1.1%.

There were two subspecies of Sabaki tilapia recorded in the area, namely, *Oreochromis spilurus spilurus* and *Oreochromis spilurus niger.* Sabaki tilapia was the second most abundance tilapia caught at 15% while the other at 12%. Sabaki tilapia was the second most abundant in the farms. NARDTC fish farm recorded all five tilapia species. Sagana River recorded highest number of tilapia species compared to other rivers in the area (Nile tilapia, Sabaki tilapia and Redbelly tilapia). The native Sabaki tilapia was purely recorded in Mahinga-ini rice canals and Ena River. More tilapia were recorded in downstream below 1100m above sea level.

Tilapia fish were represented by four species. The most common were Nile tilapia and Sabaki tilapia with relative abundance of 49.1 and 28 % respectively (Table 6). The least common were Redbelly tilapia, Redbreast tilapia and Mozambique tilapia with relative abundance of 12.5, 8.4 and 1.3 % respectively. The rivers, dams and fish ponds showed differences in the abundances of various species of fish. Samples from fish farms contributed 52.7% of the total samples (383). Dams and rivers contributed 26.3% and 21% respectively of the total fish caught. The non-native tilapia were: Nile tilapia, Redbreast tilapia, Redbelly tilapia, Mozambique tilapia while Sabaki tilapia is native species. The non-native tilapia had a relative abundance of 71.3% while the native species contributed 28.7% relative abundance.

Table 6: Composition and relative abundances of tilapia species sampled in upper Tana River basin

		Non-native				Native	
Habitat	**Locality**	***C. rendalli***	***C. zillii***	***O. mossambicus***	***O. niloticus***	***O. spilurus niger***	***O. spilurus spilurus***
Fish ponds	Eeepo farm	-	-	-	11	-	7
	Nyati farm	-	-	-	13	-	-
	Emmi farm	-	-	-	11	-	-
	NARDTC farm	2	23	1	22	2	17
	Mwea Aqua	-	-	-	13	-	1
	Joy farm	-	-	-	15	-	2
	Daniel's farm	-	2	-	2	-	-
	Wahome's farm	-	-	-	24	-	2
	Mutone's farm	-	-	-	15	-	-
	Good Shepard farm	-	-	-	18	-	3
	Kiama's farm	-	-	4	8	-	-
Rivers	Ena River	-	-	-	-	22	12
	Sagana River	-	11	-	21	6	6
	Gura River	-	-	-	3	-	-
Rice canal	Mahingaini Rice canal	-	-	-	-	10	11
Dams	Chinga dam	-	12	-	3	2	-
	Masinga dam	17	-	-	9	3	-
	Ngando dam	13	-	-	-	4	-
	Total	32	48	5	188	49	61
	Relative Abundance	**8.4**	**12.5**	**1.3**	**49.1**	**12.8**	**15.9**

4.1.3: Diversity of tilapia fishes in fish ponds, dams and rivers of upper Tana River basin

The diversity and abundance of tilapia fishes varied widely among the fish ponds, dams and rivers (Table 7). Fish farms recorded the highest Simpson diversity index of richness and evenness of 0.53. The fish farms had five species of tilapia with almost the same population collected, followed by rivers and dams at 0.44 and 0.22 respectively. Rivers had four species also with almost the same number of individual specimens while dams recorded less diversity due to low number of species and varied number of individual species collected. The species richness was highest in fish farms (Margalef richness index = 1.4) as most of the specimen collected were form the farms. Dams had the second level of richness (Margalef richness index = 0.89) followed rivers (Margalef richness index = 0.66) with lowest species richness.

Table 7: Diversity indices of tilapia species in fish farms, rivers and dams

Diversity characteristics	**Habitats**		
	Farm	**River**	**Dam**
Simpson index (D)	0.53	0.44	0.22
Margalef richness index (J)	1.4	0.66	0.89

Previous studies have shown that the Upper Tana River basin harbors numerous fishes ranging from high altitude fishes, such as brown rout, rainbow trout and mountain catfishes to mid-altitude fishes like tilapia and *Enteromius* (Trewavas, 1983; Seegers *et al*., 2003 & Nyingi, 2013). However, the fishes reported here are not the exact representation of upper Tana River fish fauna where the National Museums of Kenya has recorded 21 fish species. Just like Lake Victoria basin, Tana River basin has numerous non-native fishes such as rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*), common carp (*Cyprinus carpio*), mosquito fish (*Poecilia reticulata*), European eel (*Anguilla anguilla)* and the tilapia species complexes. This study primarily focused the tilapia species because of their rapid multiplication, high hybridization rates and usefulness as human food.

4.2: Taxonomic status of tilapia fishes of upper Tana River basin

4.2.1 Morphological characteristics of cultured and wild tilapia fishes in upper Tana River basin

i. Shape variation among tilapia species in upper Tana River basin

PCA was carried out on 383 specimens drawn from all populations from all study area. They were differentiated using 2nd and 3rd principal components (18% and 12%). Five tilapia species were recorded with a high overlap among all the species. The highest overlap of about 75% recorded between Sabaki tilapia and Nile tilapia. Redbreast tilapia and Redbelly tilapia had about less than 5% overlap as opposed to the information on shape variation within the genus *Oreochromis* (Figure 6). The two *Coptodon* species were distinct from the three *Oreochromis* species in terms of shape. The variation in PC2 and PC3 were 17% and 10% respectively. *Oreochromis mossambicus* also had a small overlap with *Oreochromis niloticus* (Figure 8). Mozambique tilapia also had a small overlap with Nile tilapia wit total overlap with Redbreast tilapia (Figure 8). Most of the differences were observed in eye diameter, mouth-eye distance, and body depth.

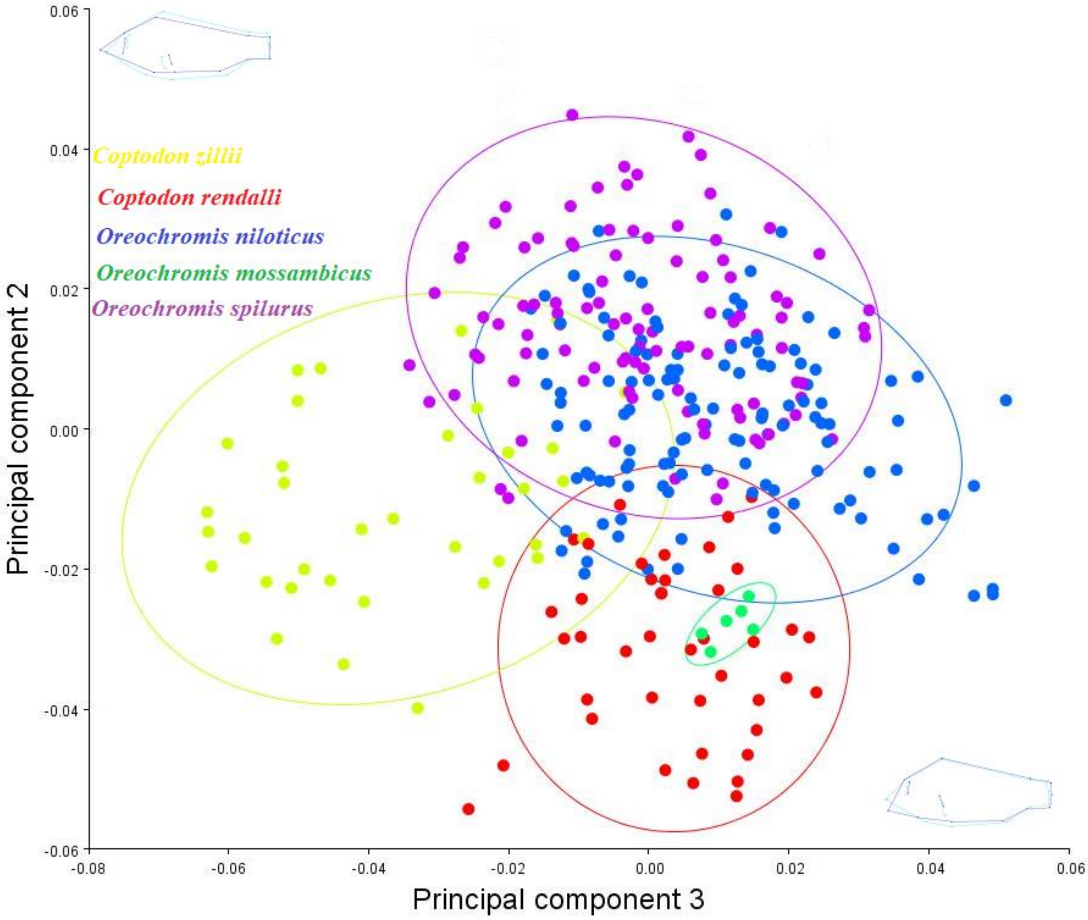

Figure 4: Shape variation among all tilapia species in all sampling sites with variations on each PC

ii. Shape variation between the genera *Coptodon and Oreochromis*

The findings of the Principal Component Analysis (PCA) carried out on 383 specimens from two genera, *Coptodon* and *Oreochromis* were differentiated using 2nd and 3rd principal components. The variation in PC2 and PC3 were 16% and 11% respectively with *Coptodon* aligned along PC3 and *Oreochromis* on PC2. The populations of *Coptodon* and *Oreochromis* were differentiated on PC3 with the larger population of *Oreochromis* having nearly a 25% overlap with the smaller *Coptodon* population. The variations were mainly attributed to body depth on PC2 and mouth position in relation to posterior insertions of dorsal fin on PC3 (Figure 4). The five species

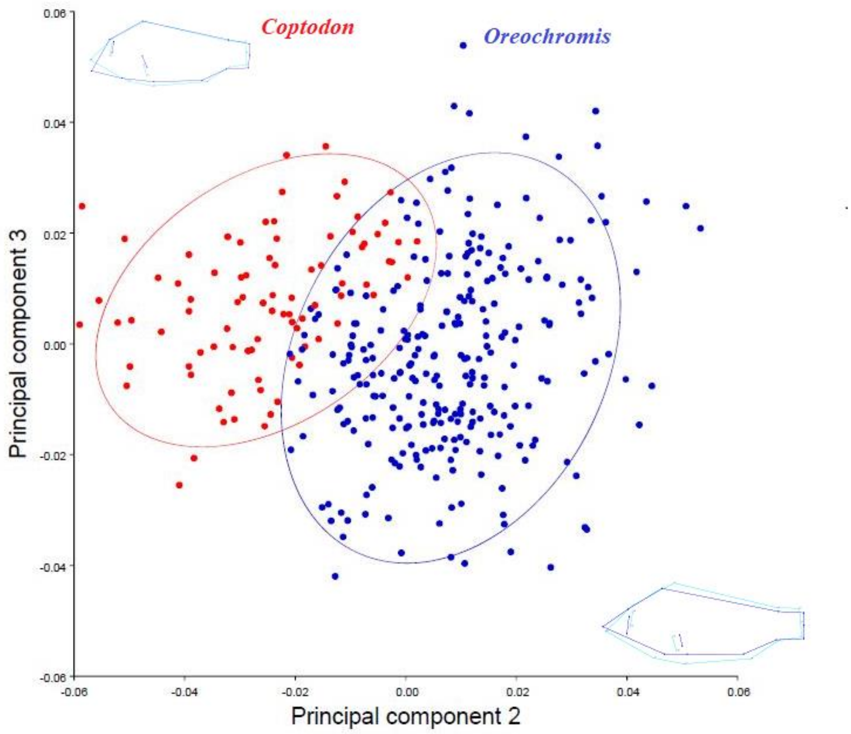

Figure 5: Shape variations and overlaps between genera Coptodon and Oreochromis with variations on each PC

iii. **Shape variation within the genus *Coptodon (C. rendalli and C. zillii)***

PCA was carried out on 73 specimens, which did not overlap (Figure 4), from various localities in upper Tana River basin. Redbreast tilapia and Redbelly tilapia were differentiated using 2nd and 3rd principal components (Figure 5). The variation in PC2 and PC3 were 16% and 11% respectively. There was no overlap between the two species of *Coptodon* at 95% confidence level. Redbreast tilapia were aligned along PC2 and *Redbelly tilapia* on PC3. The variations were linked to differences in head shape and dorsal posterior.

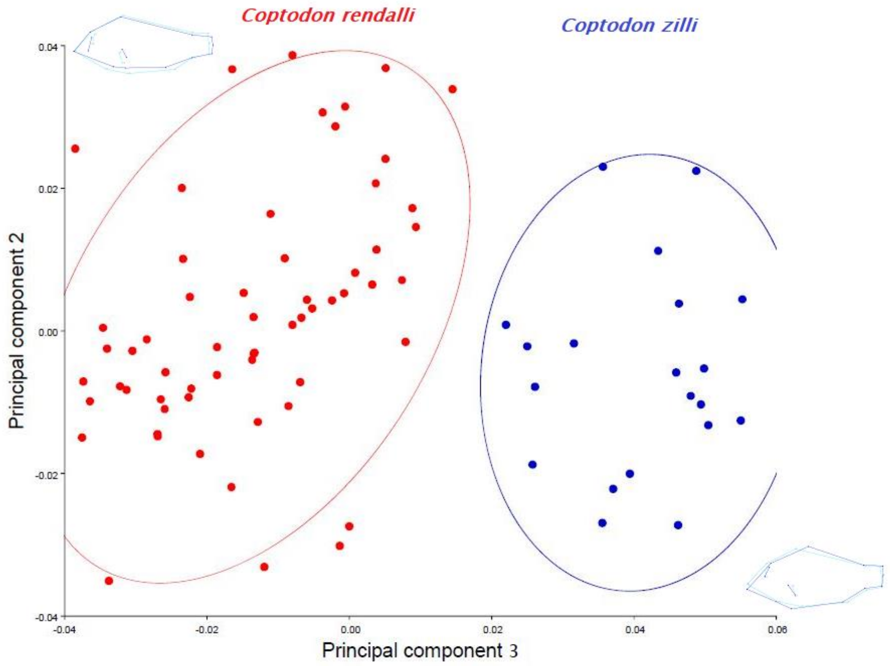

Figure 6: Shape variation between Redbelly tilapia (Coptodon zillii) and Redbreast tilpia (Coptodon rendalli) with variations on each PC

iv. Shape variation within the genus *Oreochromis (O. niloticus, O. spilurus, and O. mossambicus)*

PCA was carried out on 238 specimens picked from the samples used in shape variations between genera *Coptodon* and *Oreochromis* (Figure 4). The three tilapia species were differentiated using 2nd and 3rd principal components. The PC2 accounted for 15% of the variation, which was mainly related to the position of the mouth and eye diameter while PC3 accounted for 13% of the variations mostly associated with differences in the shape of caudal peduncle. There was significant overlap of about 40% between the Nile tilapia and Sabaki tilapia, with *Mozambique tilapia* appearing alone at 95% confidence level. Nile tilapia *and* Sabaki tilapia were aligned along PC2 and *Oreochromis mossambicus* on PC3. *Oreochromis mossambicus* was closer to Nile tilapia than Sabaki tilapia (Figure 6).

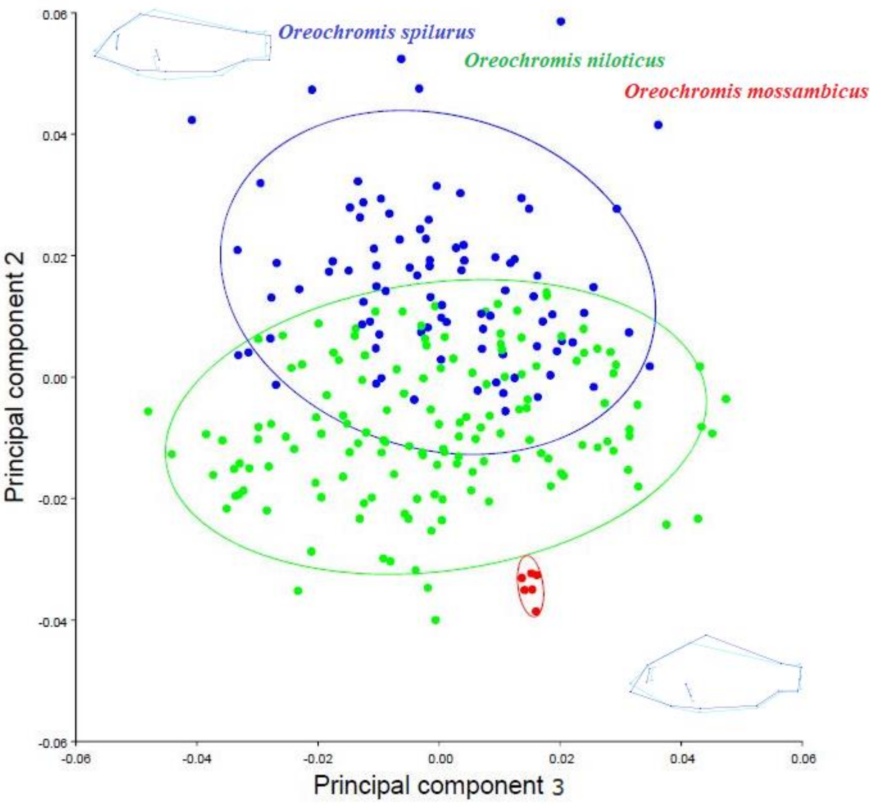

Figure 7: Shape variation among three Oreochromis species with variations on each PC

v. **Shape variation between the between subspecies of *Oreochromis spilurus spilurus* and *Oreochromis spilurus niger***

PCA was carried out on 99 specimens picked from the samples used in shape variation among three *Oreochromis* species (Figure 6). The two subspecies were differentiated using 2nd and 3rd principal components. The PC2 variations were mainly linked to the position of the mouth, pectoral fin accounting to 14% while PC3 variations were linked to the eye-dorsal fin posterior distance and accounted for 10%. There was an overlap of about 30% between the *Oreochromis spilurus spilurus* and *Oreochromis spilurus niger* (Figure 7).

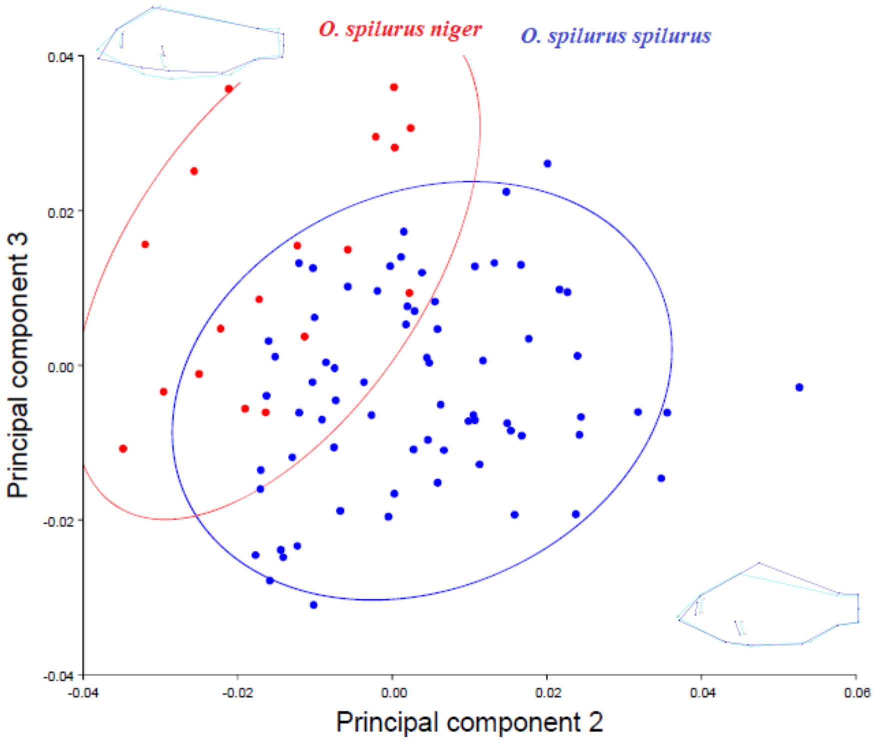

Figure 8: Shape variation between Oreochromis spilurus subspecies with variations on each PC

vi. **Shape variation among tilapia species in the fish farms**

PCA was carried out on 182 specimens drawn from five populations found in the artificial fish ponds in the study area. They were differentiated using 2nd and 3rd principal components (17% and 10%). Five tilapia species were recorded with a high overlap of about 50% between Sabaki tilapia and Nile tilapia. Redbreast tilapia and Redbelly tilapia had less than 5% overlap as opposed to the information on shape variation within the genus *Oreochromis* (Figure 6). The two *Coptodon* species were distinct from the three *Oreochromis* species in terms of shape. The variation in PC2 and PC3 were 17% and 10% respectively. Mozambique tilapia also had a small overlap with Nile tilapia wit total overlap with Redbreast tilapia (Figure 9). Most of the differences were observed in eye diameter, mouth-eye distance, and body depth.

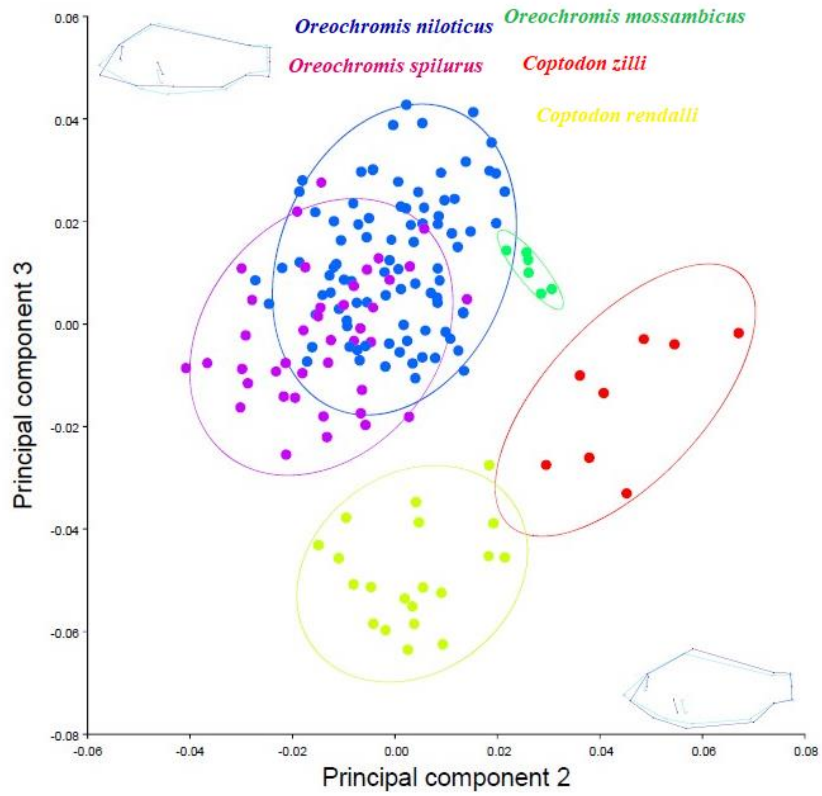

Figure 4: Shape variation among tilapia species in fish farms of upper Tana River basin

***vii.* Shape variation among tilapia species in the rivers**

PCA was carried out on 74 specimens of tilapia collected from the riverine habitats. They were differentiated using 2nd and 3rd principal components. Four tilapia species were recorded with overlap between Sabaki tilapia and Nile tilapia, Redbreast tilapia and Redbelly tilapia and *Coptodon zillii and Oreochromis niloticus.* The variation in PC2 and PC3 were 11% and 10% respectively. The results were interesting compared to the fish farms, with rampant overlap in rivers. The morphology of *Oreochromis niloticus* seems to be closer to *C, zillii* and *Oreochromis spilurus* as opposed to only closer to *Oreochromis spilurus* in the farms. The river also gave a higher overlap between *Coptodon zillii* and *Coptodon rendalli* (Figure 10) as opposed to the information on shape variation within the genus *Oreochromis* (Figure 6).

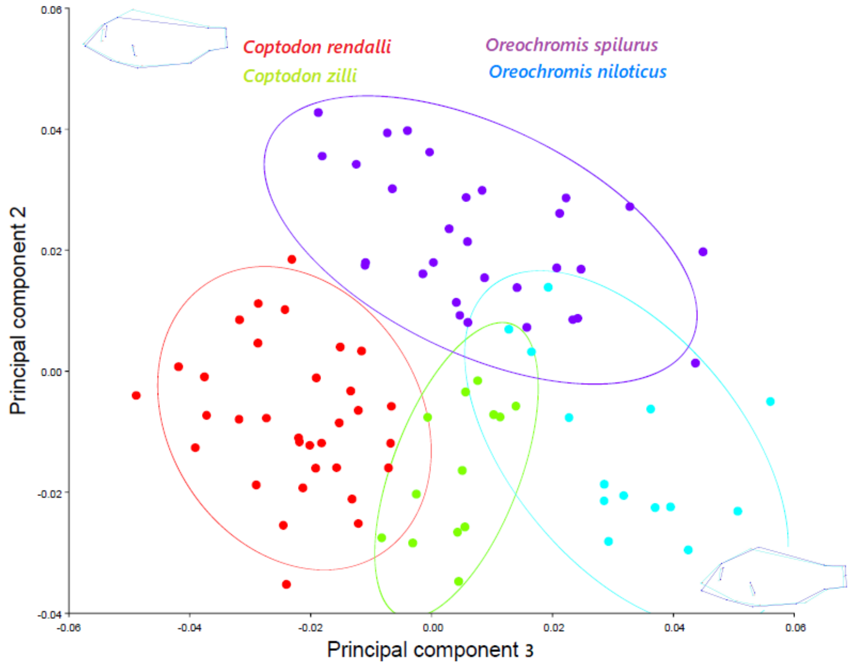

Figure 5: Shape variation among tilapia species in rivers of upper Tana basin

The findings on the overall showed that the Upper Tana basin habitats (ponds, dams, and rivers) support numerous fish's species with this study recording 16 species from 5 families with a bias on the tilapia species. The results showed that most of the tilapia species in upper Tana River were introduced. Key informants from the fisheries offices noted that most of the dams in the area were stocked with *Coptodon* species from Kiama's fish farm and others from unknown sources. Most of these introductions are undocumented therefore it is not easy to trace the sources of the fishes. In Embu County, for instance, fisheries officer noted that Masinga, Kiambere, and Gitaru dams were stocked without their knowledge hence no record of the stocked fishes.

Most of the fishes found in the farms were also recorded in the rivers and dams except for Mozambique tilapia. Only two families of fishes, namely *Clariidae*, and *Cichlidae*, were intentionally found in the farms, out of five families recorded. Similalrly, only 20% of the recorded tilapia species were native. The Upper Tana basin only has Sabaki tilapia as the native species yet there are four other tilapia species in the basin. Most of the non-native tilapia are as a result of aquaculture and restocking of the dams in the area (Balirwa *et. al*, 2003). There are few documented instances where fishes have been introduced directly into the river. Njeru, (2016), for instance, cited efforts by the County government to restore river fisheries by introducing thousands of tilapia fingerlings into the rivers in Tharaka Nithi County.

During this study five species of tilapia fishes from two genera were differentiated in the upper Tana basin. Two species of the genus *Coptodon* (Redbelly tilapia and Redbreast tilapia) had clear morphological distinction between them. This could have been attributed to the isolation because most of the species of Redbreast tilapia were found in the dams while Redbelly tilapia was mainly found in the fish farms and rivers. A mixture of the two species was only recorded in the NARDTC Fish Farm, Sagana. The three species of genus *Oreochromis* (Mozamnique tilapia, Sabaki tilapia and Nile tilapia) did not have a clear morphological distinction among them.

The native Sabaki tilapia showed possible hybridization with the non-native of Nile tilapia and Redbelly tilapia in the farms with a clear morphological differences with Redbreast tilapia (Figure 10). Turner, (2001) observed that cichlids are experiencing radiant speciation with very many possible undescribed species. Dieleman *et al.,* (2018) also reported that the tilapiines of Lake Challa had hybridized between the native *Oreochromis hunteri*, and the non-native *Oreochromis korogwe* as determined using phylogenetic analysis.

This study also established that the tilapia species had readily interbred in the Upper Tana. Previous work by Elder *et al.,* (1971) also showed hybridization in Mwea paddy fields, which is part of the upper Tana River basin. Other studies have noted hybridization between Nile tilapia and Redbelly tilapia (Elder *et al.,* 1971). Agnèse *et al.,* (2009) observed numerous natural hybridization and alluded to the unfinished phenomenon of speciation in the cichlids. They realized that the species integrity could only be maintained in the areas where they are the only ones occupying a certain ecological niche.

Competition and replacement of the species has been difficult to predict from previous studies such as the experiments using Mozamnique tilapia and Nile tilapia in Lake Itasy in Madagascar and Ihema in Rwanda which could not predict the more competitive species as both gave different results (Agnèse *et al.*, 2009). In Lake Victoria, there has been limited evidence of hybridization between the introduced and critically endangered tilapia species, namely *Oreochromis leucostictus* or Nile tilapia and *Oreochromis variabilis (*Wasonga *et al.,* 2017*;* Bradbeer *et al.,* 2019*).* Pinto (1982), recorded 100 percent hybridization between male *Oreochromis hornorum* and female Nile tilapia under experimental condition. The earlier studies have shown the possibility of tilapia fishes hybridizing either under experimental, confined, or natural conditions. In this study, there was hybridization evidence of under both confined, (aquaculture) and natural conditions.

The study established that there was a possible five species of tilapia in upper Tana River which were differentiated morphologically at 95% confidence level. Some species had overlapping morphological characteristics while others were distinct from each other. The overlaps could be attributed to the possible hybridization of the tilapia species, initial misidentification of the specimens or error in the land-marking of the specimens. Most of the variations were associated with head shape, position of the mouth in relation to posterior insertion of dorsal fin, eye-dorsal distance, and eye diameter.

4.3: Distribution of tilapia fishes in aquaculture and natural systems of upper Tana River basin

4.3.1: Tilapia fish occurrence in the aquaculture systems of upper Tana River basin

Eleven fish farms were sampled Nyeri (3), Kirinyaga (5) and Embu (3) (Figure 11). Out of these, ten fish farms had the Nile tilapia except Kariuki's fish farm which only had catfish (*Clarias gariepinus).* No fish farm had intentionally reared the Sabaki tilapia, although four of the farms contained the species. The genus *Coptodon* was only recorded in four fish farms in found Nyeri and Kirinyaga counties, although, only two farms had records of their sources. Similarly, Mozamnique tilapia was only recorded in two fish farms, namely, the Kiama Fish Farm and NARDTC Fish farm in Sagana, Kirinyaga County.

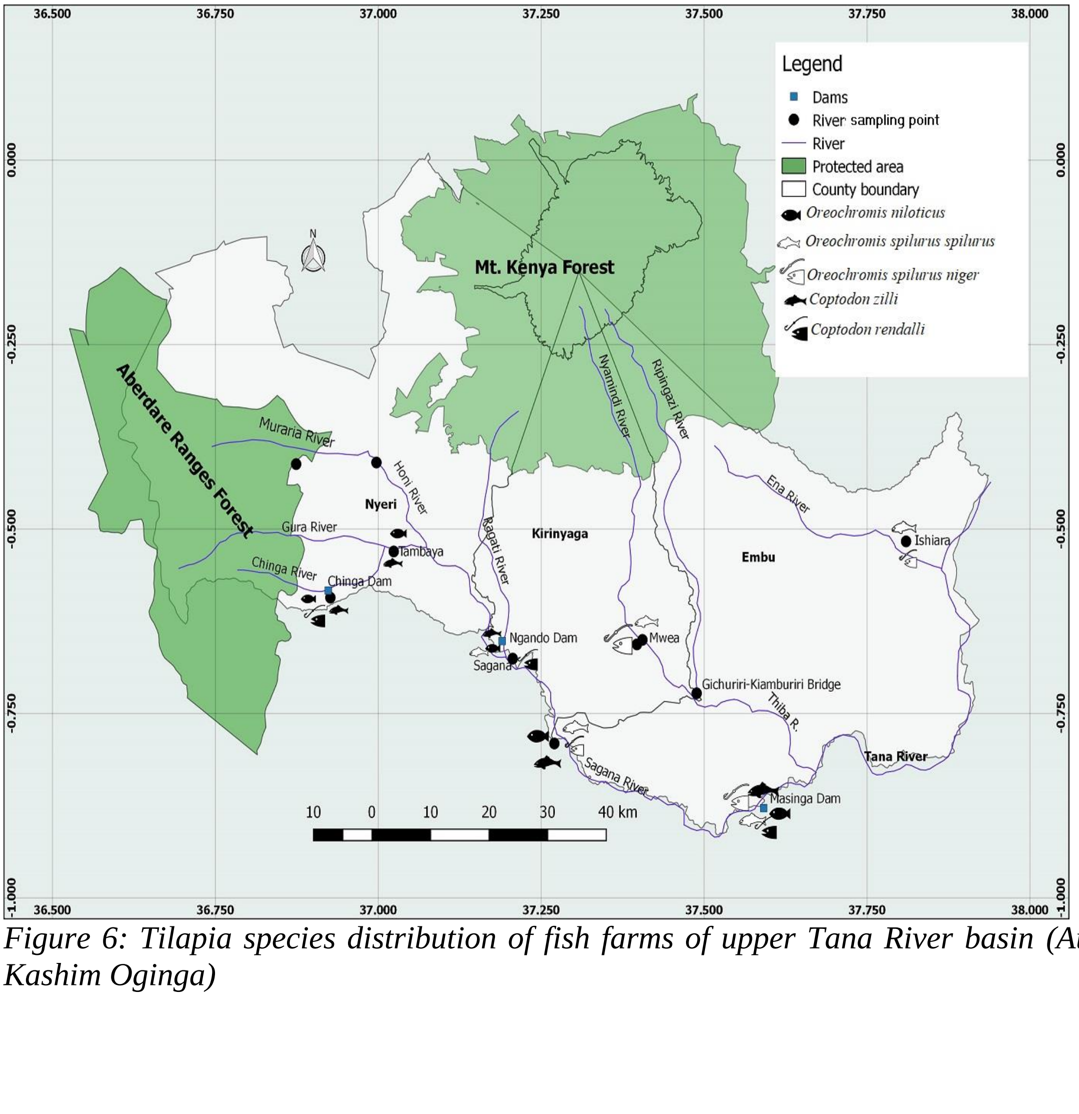

Figure 6: Tilapia species distribution of fish farms of upper Tana River basin (Author: Kashim Oginga)

4.3.2: Tilapia fish occurrence in natural systems of upper Tana River basin

The natural systems considered in this study comprised of rivers and dams (Figure 12) where four tilapia fish species have previously been recorded by (Nyingi, 2013) including Sabaki tilapia, Nile tilapia, Redbelly tilapia and Redbreast tilapia. The findings of this study shown three non-native species of tilapia species in the area, namely Nile tilapia, Redbelly tilapia and Redbreast tilapia. Masinga dam recorded all the four species of tilapia in the basin. However, Muraria River, Chinga River, Rupingazi River, Nyamindi River, and Honi River did not record any tilapia species. Most of these were rivers found at a higher altitude approximately 1650m above sea level, fast flowing and clear waters which are not suitable habitats for tilapia. Two species of tilapia were surprisingly recorded in Gura River at an altitude of 1615m above the sea level is also the fastest flowing river in Africa (Mathia, 2016), namely: Nile tilapia and Redbelly tilapia. A bigger population of genus *Coptodon* were recorded in the three dams (Masinga, Ngando, and Chinga). Only Mwea rice canals (Mainga-ini) and Ena River recorded considerably pure native sub-species of Sabaki tilapia *(Oreochromis spilurus spilurus* and *Oreochromis spilurus niger).*

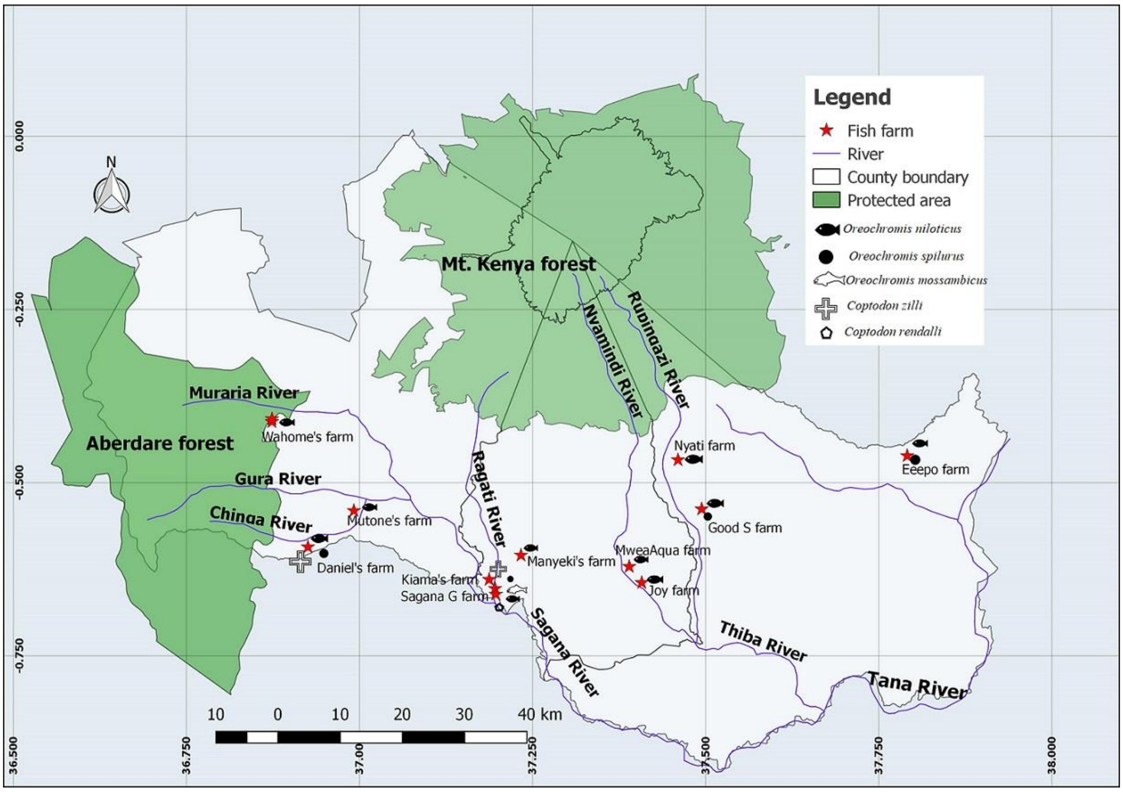

Figure 7: Tilapia distribution in natural systems of upper Tana River basin (Author: Kashim Oginga)

4.3.3: Tilapiamap Application

The TilapiaMap application has been used in Kenya since February 2018 by fish farmers, Fisheries Officers, university students and scientists for compiling tilapia species records and providing simple field guide for tilapia species identification (Tilapiamap.org, 2019). The application has 202 records from 7 catchments from Kenya. The Upper Tana River basin has highest number of records (146) recorded from 18 localities, and five application users (mainly researchers from National Museums of Kenya and university students). Lake Victoria basin has the least number of records followed by Ewaso Ng'iro basin and Lake Magadi. The TilapiaMap application have had 11 users in Kenya. The records from Athi River, Lake Victoria, and Pangani system have been only uploaded by one user.

Apart from Upper Tana, the Lower Tana River has had a higher number of TilapiaMap application coverage followed by Athi River, Ewaso Ng'iro, and Lake Victoria with three localities covered in each (Figure 13)

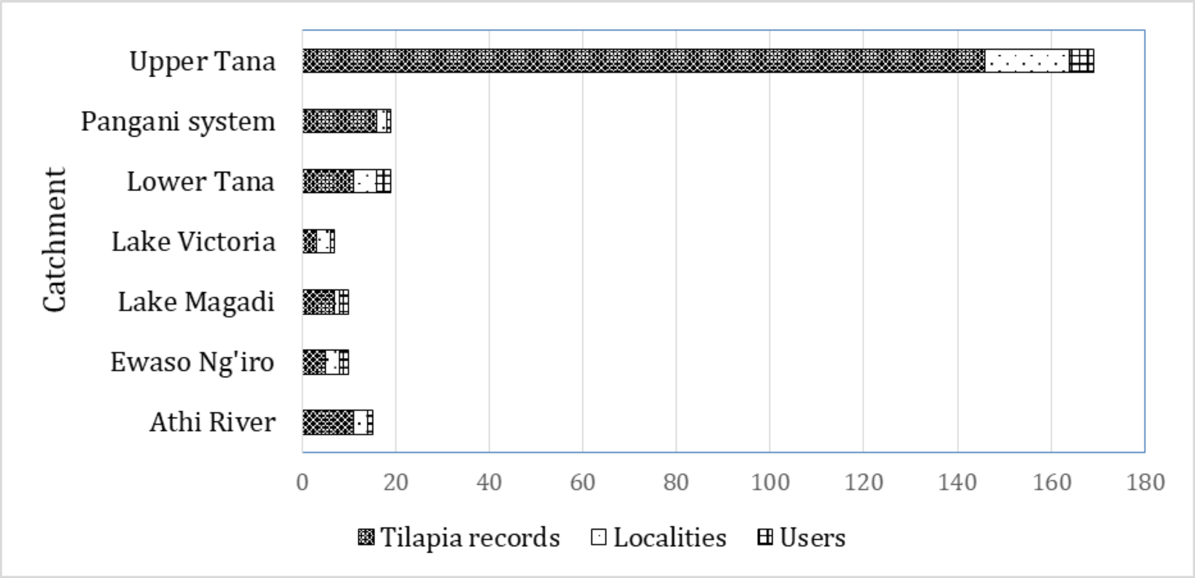

Figure 8: The TilapiaMap Application coverage, records, and users in Kenya

i. Tilapiamap application in species identification

TilapiaMap has an inbuilt tilapia species field guide for tilapia identification (TilapiaMap, 2017). The application so far has 202 tilapia records in Kenya which have been uploaded by six users. Nearly 87% of the records were correctly identified by the application users. 13% of the records were wrongly identified, of which most were closely related to Nile tilapia and Sabaki tilapia at 38% followed by the two *Coptodon* species at 16%. The TilapiaMap application identified three possible hybrids based on the physical features shared between or among tilapia species, namely body color and markings, body depth, tail markings and number of anal fins. Four records were not identified at all by the application users and one record remains unidentified (Table 8).

Table 8: The number of misidentified species by users of TilapiaMap

Misidentified species records	**Number of records**
Nile tilapia- Sabaki tilapia	10
Redbreast tilapia-Redbelly tilapia	4
Redbelly tilapia-Sabaki tilapia	3
Oreochromis esculentus- Nile tilapia	2
No Match to Match	4
Suspected hybrid	3
Unidentified record	1
Total	**27**

Source (tilapiamap.org)

ii. TilapiaMap application in species coverage

The TilapiaMap Application has been used to identify ten species and three subspecies of tilapia in Kenya since 2018 (TilapiaMap.org, 2019) but only species with at least five records have been plotted (Figure 14). Out of the ten, the Nile tilapia has the highest number of records (95) followed by Sabaki tilapia (56) and Redbreast tilapia (14). The Nile tilapia has been recorded in 71% of the catchments sampled while Sabaki tilapia has been recorded in 43% of the catchments. The remaining eight tilapia species have only been recorded in one catchment each.

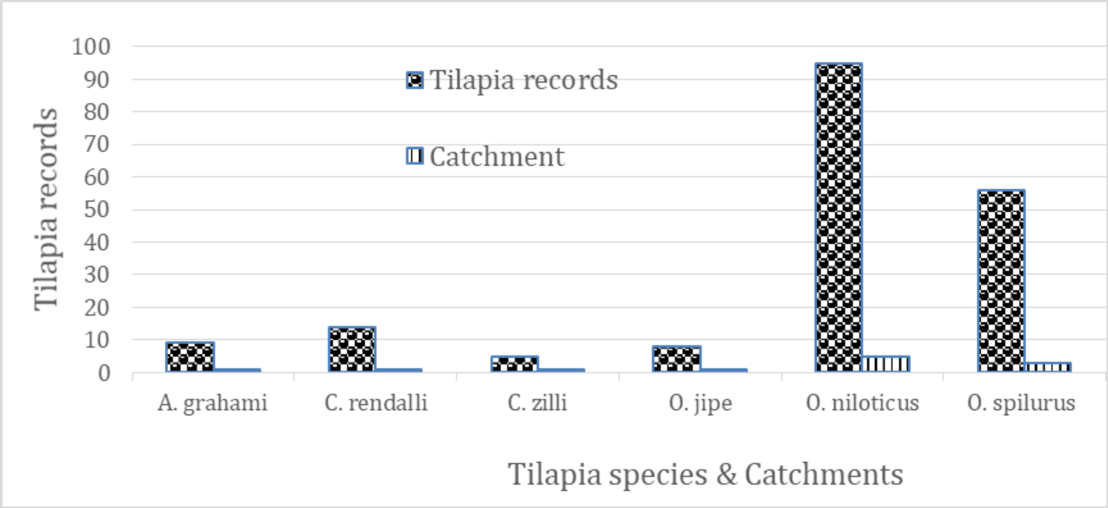

Figure 9: TilapiaMap Application species record distribution in Kenya

Citizen science is becoming a vital source of scientific information with the advancement of technology. Today, there are various mobile applications being used in the collection of the scientific information of different taxa (Sturm *et al*., 2018). Citizen science has helped in transmitting real-time data and wide coverage within a short period (Silvertown, 2009). The TilapiaMap mobile application has been used in this study to map the distribution of the tilapia fishes in upper Tana, including other basins in the country.

TilapiaMap Application is used in mapping the tilapia fish occurrence and display them on a map. The map shows the specific points where the fish has been recorded represented by a blue position mark. Annex 7 shows general distribution of the tilapia fishes in Kenya as recorded by the TilapiaMap application. Annex 8 shows TilapiaMap records of upper Tana River basin, study area. This is similar to use of the mobile application (CitiSci) in mapping invasive species in the continental US (Silvertown, 2009). The TilapiaMap application identification results supports the geometric morphometric analysis work. Both suggests the possible hybrids and close similarity between Sabaki tilapia and Nile tilapia. The citizen science aspects depends on the design of the tools involved (Schröter *et al.*, 2017).

4.4: The connectivity between natural river system and the fish ponds

4.4.1: Water quality assessment in rivers, dams and fish ponds in upper Tana River basin

Water quality assessment was done to establish a differences in the thresholds of the survival of tilapia fishes in different habitats of upper Tana River basin. An overview of the physic-chemical parameters obtained in the 96 sampling units in Nyeri County, Embu County and Kirinyaga County (Table 9). The analysis showed the highest temperature to occured in Ena River (30.1±1.6°C) in Embu County and the lowest temperature occurred in Muraria River in Nyeri County (17.73±0.35 ° C). The dissolved oxygen ranged from 1.48±1.01 to 24. 23 ±0.81mg/l in Nyamindi River and Kimbirwa dam respectively. Sites with lower temperatures recorded a higher dissolved oxygen compared to dry areas like Ena River in Embu County.

The highest pH range was 9.26 – 10 at the Mwea Aqua Fish Farm in Kirinyaga County while the lowest pH ranges was 7 – 7.4 in Chinga River in Nyeri County. The electrical conductivity ranged from 56.52 ±0.71 to 1158.5±11 from Daniel's Fish Farm and Ena River, respectively. The highest turbidity of water was recorded in Eeepo Fish Farm, Embu County at 240±0.98 NTU and the lowest in Kiama Mutone Fish Farm in Nyeri County at 8±0.06 NTU.

Analysis of variance of some of the physic-chemical parameters showed significant differences among the habitats (fish ponds, dams, and rivers): EC (one-way ANOVA, $F = 3.66$, df (2, 87), $p < 0.05$), Turbidity (one-way ANOVA, $F = 18.22$, df (2, 87), $p < 0.05$). Similarly, the water pH range also showed differences in values ranging between 7.01 and 10 (Table 9). Water temperature (one-way ANOVA, $F = 2.02$, df (2, 87), $p > 0.05$) and DO (one-way ANOVA, $F = 2.03$, df (2, 87), $p > 0.05$) did not vary significantly among the three habitats. The Tukey's HSD post hoc test showed differences for electrical conductivity and turbidity among the three habitats, (farm ponds, rivers and dams) ($p < 0.05$) and similarities among the other three physico-chemical variables (temperature, dissolved oxygen and pH) ($p > 0.05$).

The difference in the physic-chemical parameters between the fish ponds, dams, and rivers were assessed through multivariate analysis giving ($p < 0.001$) at 0.05 confidence level using the Pillai's trace approach. The level of significance for all the four multivariate tests was small ($p < 0.001$), (Pillai's $F (10,168) = 7.89$, $p < 0.001$). The null hypothesis that there is no significant difference in water quality parameters among the fish habitats was consequently not rejected.

Table 9: Mean values (with SE) of water quality parameters, altitudes of the sampling sites in Nyeri County, upper Tana River basin

					Physical parameters		Chemical parameters		
Main River	**Farm/River**	**Altitude (m) n=3**	**River-Farm Distances (m)**	**Water Depth (m) n=4**	**Turbidity (NTU) n=4**	**Temperature (°C) n=4**	**E.C (µS/cm) n=4**	**D.O (mg/l) n=4**	**pH**
Gura River	Daniel Aqua	1889.6±0.5	15	1.3±0.03	8±0.28	21.6±0.8	56.52±0.71	3.73±0.35	7.53-7.59
	Kiama Aqua	1692.3±0.7	10	1.6±0.09	8±0.06	21.33±0.9	173.28±2.6	1.89±0.02	7.01-7.06
	Gura R	1614±25.1	-	0.5±15.28	14.3±5.3	25.9±0.3	112.69±0.4	7.78±0.2	8-8.12
	Ichamara R	1688.5±23	-	0.3±5.57	19±0.01	24.83±0.5	186.53±2.6	3.26±0.58	7.4-7.8
Honi River	Wahome Aqua	1989±1.5	5	0.8±18.48	203±31.7	21.18±0.7	176.9±77.5	3.83±0.69	7.93-8.95
	Honi R	1767±15.2	-	0.3±10.58	52.3±4.31	18.37±0.8	362.3±0.32	6.52±0.06	8-8.5
	Muraria R	1989.5±11	-	0.3±5.13	46.6±6.07	17.73±0.5	246.5±2.4	6.75±0.1	7.73-7.85
Dams	Chinga Dam	1898±1.9	-	0.2±3.06	41.6±7.6	23.8±0.6	83.78±0.4	6.9±0.4	7-7.4

DO - Dissolved oxygen, E. C - Electrical Conductivity, NTU – Nephelometric Turbidity Units

					Physical parameters		Chemical parameters		
Main River	**Farm/River**	**Altitude**	**River-Farm**	**Water**	**Turbidity**	**Temper**	**E.C**	**D.O**	**pH**

		(m) n=3	Distances (m)	Depth (m) n=4	(NTU) n=4	ature (°C) n=4	(µS/cm) n=4	(mg/l) n=4	
Rupingazi R	Nyati Aqua	1589.6±1.8	200	88.00±2.59	120±0.98	25.76±0.42	94.89±2.18	12.2±0.52	7.6-8.6
	Shepard G Aqua	1393±0.1	9500	77.33±8.01	240±0.98	26.61±0.63	131.4±1.22	3.7±0.17	8-8.14
	Rupingazi R	1080.1±4.2	-	80.33±48.17	14±1.35	27.6±0.9	227.6±1	7.56±0.4	8.11-8.61
Ena R	Eeepo Aqua	854.8±0.2	950	51.83±4.48	240±0.49	26.13±0.84	105.84±7.78	3.92±0.38	7.83-8.34
	Ena R	705.3±1.8	-	21.67±8.5	50±3.64	30.1±1.6	1158.5±11	5.89±0.88	8-8.12
Dams	Masinga dam	1048.5±0.5	-	182.50±13.2	70±19.63	26±0.58	172.61±2.25	5.57±0.16	7.33-7.93

DO - Dissolved oxygen, E. Cg+- Electrical Conductivity, NTU - Nephelometric Turbidity Units

					Physical parameters		Chemical parameters		
Main River	**Farm/River**	**Altitude (m) n=3**	**River-Farm Distances (m)**	**Water Depth (m) n=4**	**Turbidity (NTU) n=4**	**Temperature (°C) n=4**	**E.C (µS/cm) n=4**	**D.O (mg/l) n=4**	**pH**
Sagana River	NARDTC Aqua	1246±1.3	150	103.8±19	57.6±32.5	22.8±0.5	354.4±5.7	6.6±0.4	7.27-8.07
	Emmi Aqua	1301.2±2.7	1300	75±21.7	51.6±12.5	27.8±1.6	65.5±5.2	7.3±1.5	8.54-8.72
	Kariuki Aqua	1256±1.3	520	85.1±7.2	152±87.5	27.3±2.2	98.9±0.2	12.8±0.4	9.1-9.25
	Sagana R	1057±43.5	-	59±12.4	28±3.4	25.8±0.4	134.1±0.2	5.7±0.3	7.78-8
	Ragati R	1206±5.3	-	61.6±12.5	21.6±4.6	25.7±0.7	185.8±1.2	5.3±0.4	8.31-8.56
Nyamindi R	Joy Aqua	1157.2±1.5	180	76.5±10.7	38.3±10.4	25.4±1.1	223.2±41.5	3.2±0.5	7.79-8.5
	Mwea Aqua	1191±0.9	100	109.4±13.1	88.3±20.2	32.8±1.2	232.5±10.2	17.2±0.6	9.26-10
	Nyamindi R	1155±31.3	-	30.6±7.1	28.6±7.1	23±0.4	345.3±0.8	1.4±1.1	7.58-7.84
Dams	Ngando dam	1236±1.7	-	113.3±11.5	10±3.4	27.8±0.9	262.7±0.5	24.4±0.8	8.12-8.76
	Mahigaini dam	1157±0.9	-	43.1±2.5	13.5±1.4	25.3±0.4	272.1±9.5	2.5±0.1	7.45-7.96

DO - Dissolved oxygen, E. C- Electrical Conductivity, NTU - Nephelometric Turbidity Units

A Pearson correlation test was conducted to determine the degree of association between water quality parameters and altitudes (Table 10). Altitude was negatively correlated with all the physic-chemical parameters. Altitude and water temperature had a statistically significant linear relationship ($r = -0.796$, $p < 0.05$), with a very strong negative overlap. The water temperatures decreases with increase in altitudes. Altitude and dissolved oxygen had a statistically significant linear correlation ($r = -0.698$, $p < 0.05$), with a strong negative correlation. The higher the altitude the lower the amount of dissolved oxygen in the fish habitats. The altitudes and pH had a statistically significant linear correlation ($r = 0.599$, p¸< 0.05), with a strong negative relationship. pH increases with decrease in altitudes and vice versa. Electrical conductivity had a very weak negative correlation and a statistically significant linear relationship with altitude ($r = 0.575$, $p < 0.05$). Turbidity and altitude a statistically significant relationship ($r = 0.1207$, $p < 0.05$). There is low turbidity in high altitudes.

Table 10: Correlation matrix between altitude and physic-chemical parameters studied

	Altitude	**Temp**	**D. O**	**pH**	**E. C**	**Turbidity**
Altitude	1					
Temp	-0.7958	1				
D. O	-0.0539	-0.69862	1			
pH	-0.599	0.54999	0.53112	1		
E. C	-0.5754	0.14523	-0.0323	0.04748	1	
Turbidity	-0.1207	0.11641	-0.0814	0.32427	-0.1027	1

DO - Dissolved oxygen, E. C- Electrical Conductivity

4.4.2: Comparisons of the fish habitats altitudinal gradients and distances (fish farms, rivers, and dams)

The altitudes of the dams, the fish ponds and rivers were measured using a hand held GPS gadget (Table 9). The altitudes of the farms ranged from 1889.65±0.59m (n=3) in Nyeri County to 854±0.25 (n=3) in Embu County. The highest measured river altitude was in Muraria River at 1989.92±11.02m (n=2) in Nyeri County while Ena River was the lowest at 705.36±1.85m. The dam's altitude measurement showed a range of 698.54±0.52m to 1898.14±1.98m in Gitaru and Chinga dam respectively.

A t-test was carried out to determine the significance of the altitudinal differences between the ponds and rivers, the ponds and dams and rivers and dams. The altitudes for ponds and rivers altitudes were strongly and negatively correlated ($r = -0.715$, $p = 0.001$). There was not significant average difference in altitude between ponds and rivers altitudes ($t_{29} = 0.431$, $p = 0.389$). The average altitude in the ponds were 43.8m higher than in the rivers (95% Cl {272.074, -184.541}). The altitudes in ponds and dams were weakly and negatively correlated ($r = -0.196$, $p = 0.3$). There was not significant average difference in altitude between ponds and dams altitudes ($t_{29} = 0.33$, $p = 0.44$). On average, pond altitudes were 30.2m higher than dams altitudes (95% Cl {-156.981, 217.381}). On the other hand, the altitudes for rivers and dams were weakly and negatively correlated ($r = -0.002$, $p = 0.991$). At the same time, there was a significant average difference between the altitudes for rivers and dams ($t_{29} = 0.75$, $p < 0.459$). On average, rivers altitudes were 73.967 higher than dams altitudes (95% Cl {-127.726, 275.66}). Based on this, the null hypothesis that there was no significant differences among the altitudinal gradients of the fish habitats was rejected and the alternative hypothesis that there was significant differences among the altitudinal gradients of the fish habitats accepted.

Most of the tilapia species caught in farms were also recorded in rivers and dams. The three habitats were interconnected using human intervention and topographical orientation. There was very little evidence of human intervention in the fish occurrences in the habitats while a lot was pegged on topography. Due to altitudinal differences, it is possible for the tilapia fishes in higher altitudes habitats to move down in the events of flash floods.

The fish farm-river distances were approximated to show the likelihood of introduction as a result of the flash floods in the area between the habitats (Table 9). Most of the fish farms in Nyeri County were nearer to the rivers with a mean distance of 24.44±28.29 m (n=5) followed by Kirinyaga and Embu with mean distances of 182.65±364.9 m (n=3) and 1262.22±224.7 m (n=3) respectively. In Nyeri county, though in the highest altitude, had tilapia fishes in the river (Gura River). Fish escapes can be attributed to the nearness between fish farms and rivers through uncontrolled pond outlets and inlets.

4.4.3: The flash floods frequency in upper Tana River basin

Findings from the social survey showed that most of the respondents acknowledged the occurrences of flash floods in the study area. Most respondents indicated that the fish farms experienced seasonal flooding with Nyeri County in the lead followed by Kirinyaga and Embu (Figure 15).

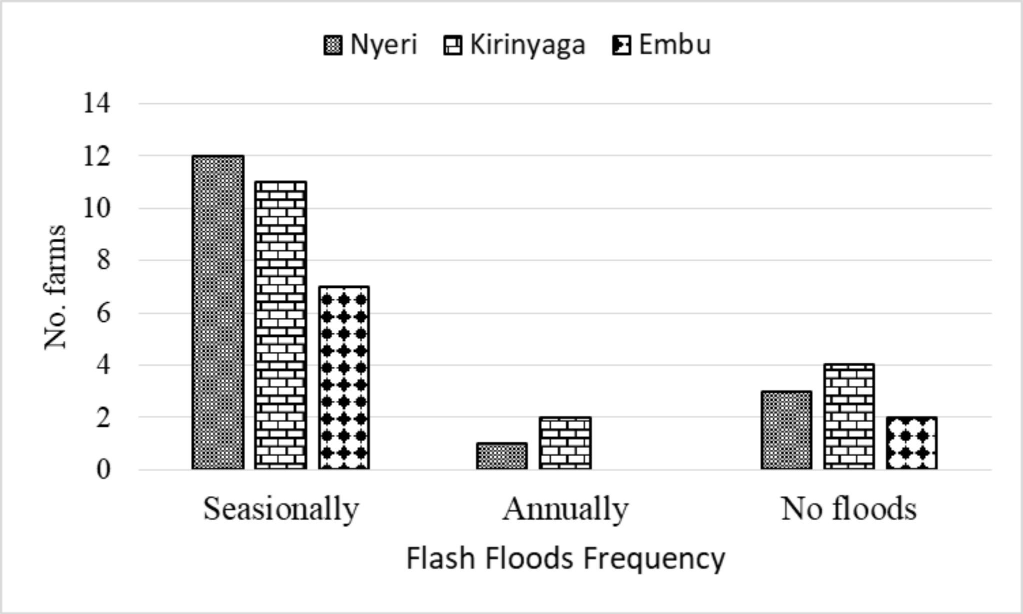

Figure 10: Flooding frequencies in the upper Tana River basin

The study assessed fish system connectivity in terms of water quality and altitude in order to establish their impact on tilapia fishes in upper Tana River basin. The water quality is essential to both aquaculture and natural systems for survival and optimum growth of the aquatic organisms. It is generally believed that the suitable range of water quality parameters leads to better performance of the aquatic ecosystems and its organisms including fish. Water temperature is one of the water quality parameters that influence the growth, food intake, among other biological activities of the fish. Swann (2019) stated that tilapia requires a temperature range of 28 to 35°C for optimum survival. In this study, the water temperature varied from 17 to 31°C, which is totally below the suitable range. The study was conducted during both the wet and dry seasons (from December to May) hence accommodating the impacts of seasonal variation.

The turbidity levels in the study area were in the range of 8 to 240NTU grossly indicates the presence or absence of natural food particles of the fish as well as the water body. Boyd, (1979) and FAO, (2012) noted that the transparency of water was affected by factors such as silt, microscopic organisms, suspended organic matter, the season, the area land use and rainfall. Turbidity between 13 to 90NTU is appropriate for the pond, and 19 to100NTU is recommended for natural water bodies. According to Mishra & Yadav, (1978) while doing a general comparative study of water quality parameters between lakes and rivers in India, observed the differences in turbidity and pH and resembles in temperature, dissolved oxygen, and electrical conductivity.

Setiadi *et al.* (2018) found out that fish farms are mainly situated on higher altitudes that the rivers. The study also found fish farms situated on higher altitudes than the rivers, 43.8m and 30.2m higher than the rivers and dams respectively.

4.5: Drivers of tilapia introductions in the upper Tana River basin

4.5.1: High tilapia fish preferences

The findings of the social survey in relation to fish preference are summarized in Figure 16. The respondents were asked which kind of fish grow faster, were more marketable, and preferred by consumers. Fishes were grouped according to the respondent capacity for identification and description of the fish they preferred. Many of the respondents preferred *Oreochromis*, which was commonly identified as tilapia by some and *Ngege* others. Some farmers referred specifically to Nile tilapia as the most preferred fish. Catfish were preferred by 12 respondents' consisting of three traders, three fishers, and six farmers. Only one farmer preferred *Coptodon* fish while three farmers and eight fishermen preferred a combination of the two fishes, *Coptodon* and *Oreochromis*. 77% of the respondents preferred *Oreochromis* fishes with a specification to Nile tilapia.

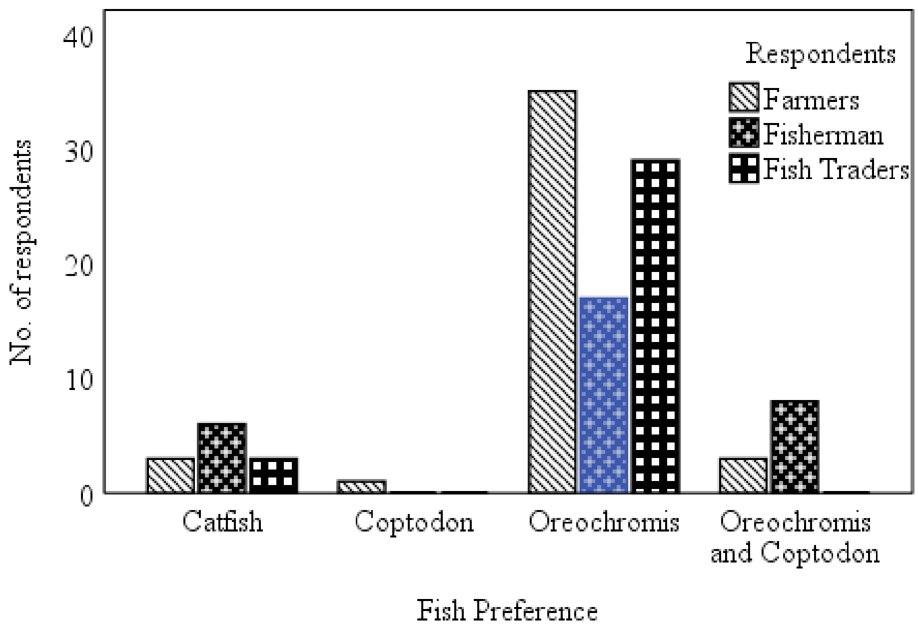

Figure 11: Fish preferences in upper Tana River basin

In the study, we demonstrated the possible drivers of tilapia introductions into the wild. The result also showed the use of non-native species of tilapia in aquaculture, which is in line with the findings of aquaculture in other regions of the world (Jean *et al.*, 2014). As an economic activity, aquaculture activities rely on the non-native tilapia species with known cultivation techniques (Canonico & Arthington, 2005). The study has established the presence of exotic species in the wild which could be closely linked the species in the fish farms. Generally, the act of fish farming stands out as the primary vector for non-native tilapia into the natural water bodies.

The findings on fish preference showed that the Nile tilapia is the most preferred table fish. This is consistent with (Wenaty *et al.*, 2018) study which listed Nile perch, Nile tilapia and Silver sardines as the most preferred fishes in Lake Victoria region. According Kioi, *et al.*, 2014, while considering the perceptions and preferences of farmed and wild fishes, the most preferred fish species in urban centers is Nile tilapia followed by Silver sardines. They also highlighted overall quality, nutritional value, and perception of the healthiness of the fillet as the main preference reason. Hinkes & Schulze-Ehlers of 2018 also tested the preferences between pangasius and tilapia in Germany and found that tilapia was the most preferred, the study also used the term tilapia referring to a group of fishes.

4.5.2: Tilapia market demand

The findings of the fish market demand showed a higher demand in Embu at 2130kg/month followed by Nyeri and Kirinyaga at 1950kg/month and 1770kg/month, respectively (Figure 17). The fish supply in relation to demand was low in all counties with Kirinyaga leading with 854kg followed by Nyeri and Embu counties at 561kg and 424kg respectively. The deficit was filled by fish from neighboring counties while some traders source from Lake Victoria.

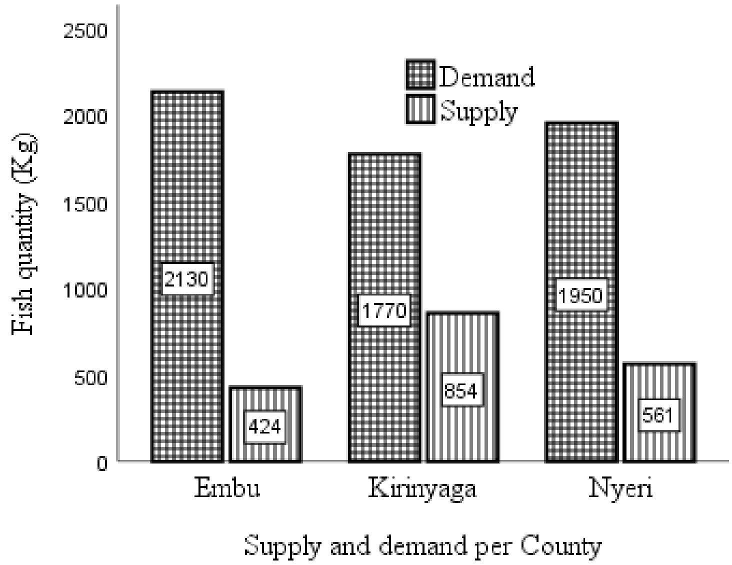

Figure 12: The supply and demand of tilapia fish for consumption per county

Mafupto of 2019, while investigating the tilapia market in Sub-Saharan Africa established that tilapia supplies from both culture and capture are not able to meet the demand, also giving a high preference for tilapia fishes. Most of the work done have grouped the demand and preferences as they go together. The higher the product preference, the higher the demand of the same product and the better the price.

4.5.3: Fisheries management policies and legal framework in Kenya

The study reviewed some laws and policies in Kenya concerning fish introduction, management, and aquaculture development against the findings in the field. Twenty laws were reviewed with only 35% touching on fish introductions (Figure 18, Table 12 & Table 13). Most legal frameworks are focused on fisheries management with less coverage on aquaculture issues. The current laws restrict fish introductions, except on the basis of scientific research. Likewise, the strategies and policies are also mainly dealing with the fisheries management aspects except for the National Oceans and Fisheries Policy, 2008, which also focuses on aquaculture development. The review of the fishery sector governance status showed that the existing laws on the regulation of aquaculture systems are elaborate from controlled waste handling to installation of filters to avoid introduction through pond outlet escapes.

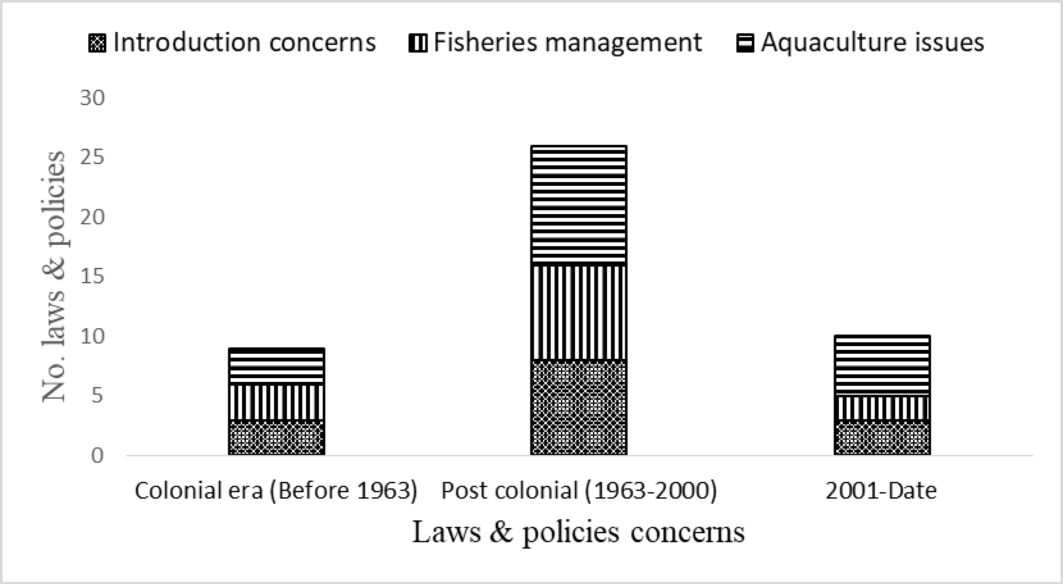

Figure 13: Laws and policies concerning fish introduction, management and aquaculture in Kenya

Table 11: Review of legislations on fisheries in Kenya since 1901 to 1999

No.	Year	Policy/regulation/ law	Introduction concerns	Fisheries management	Aquaculture issues
1	1901	Fish Order No. 9, 1901		Fisheries protection and management, Boat and fishermen registration	
2	1902	Fish Protection Act, 1902	Introduction of trout,	Fisheries protection and management, Boat and fishermen registration	Trout culture
3	1948	The Trout Ordinance (Cap 380) 1948		Restricted trout use by natives	Propagation of trout for introduction mountain ecosystems
4	1954	Fisheries Protection Act (Cap 379), Revised	Avoid invasive fish introductions	Creation of Fisheries department	Develop aquaculture, employment, and revenue creation, enhance food supply,
5	1966	The Statute Law (Miscellaneous Amendments) Act 1966		Fisheries protection	
6	1968	Fisheries Act	Regulation of fish caught	Registration of fishing vessels,	Regulation of fish cultivation
7	1979	The Science and Technology Act (CAP 250), 1979		Establishment of KMFRI for inland and marine fisheries research	
8	1991	Fisheries Act, 1991 (1989)	Introduction control	Net size measurements, catch size restriction (especially tilapia) and closed	
9	1991	Tana and Athi River Development Authority Act, 2012 (1991)		Natural resources study, advice on resource exploitation.	
10	1991	Fisheries (General) regulation, 1991	Live fish movement and permit	Vessels and fishermen registration,	Culturing aquarium fish
11	1999	Environmental Management and Co-ordination Act, 1999		Protection of aquatic systems, Conservation of biodiversity	

No.	Year	Laws	Introduction concerns	Fisheries management	Aquaculture issues
12	2008	Presidential circular No. 1, 2008		Establishment of Ministry of Fisheries Development	
13	2009	Wildlife Act		No trade on protected/endangered animals	
14	2010	Kenyan Constitution, 2010	conserve genetic resources and biodiversity	State Shall- ensure sustainable utilization, management, and conservation of natural resources,	Right to clean environment
15	2013	Agriculture, Fisheries and Food Authority Act, 2013	Stocking of fisheries		Promotion of ornamental fisheries
16	2013	Agriculture and Food Authority Act of 2013		Protection of aquatic systems, Conservation of biodiversity	
17	2016	Water Act, 2016		Protection of aquatic ecosystem	The water of discharged water
18	2016	Mining Act, 2016		Environmental restoration and water quality control	
19	2016	Forest Conservation and Management Act		Conservation of mangrove fisheries	
20	2016	Fisheries Management and Development Act, 2016	Stocking water with fish, Control of the fish introduction,	County government involvement, development of county fisheries management plans, Establishment of BMUs, closed seasons, better fishing methods, gear, and vessels limitations, Regulate trade on endangered fish,	The aquaculture development plan, Identification of suitable and unsuitable species for aquaculture, Requirement for water quality, wastes and escarpment, monitoring of non-commercial aquaculture, Restricted used of chemicals, Information on wild and GM species

Table 12: Fishery policies, regulations and strategies in Kenya

No.	Year	Policy/regulation	Introduction concerns	Fisheries management	Aquaculture issues
1	1940	Lake Victoria Nyanza Rules		Fishermen licensing, boat registration, net size measurements, catch size restriction (especially tilapia) and closed fish bans	
2	1947	Lake Victoria Fisheries Service	Reduce overcatch of juveniles and catch to support export market	Enforcement of fishermen licensing. Boat registration, net size measurements, catch size restriction (especially tilapia) and closed.	
3	1994	Fisheries Management strategies	Restocking of fisheries in inland lakes and rivers	Control of fishing methods, fish breeding grounds, monitoring pollution threats,	
4	2008	National Oceans and Fisheries Policy	Regulate fish stock off by foreign vessels	Conservation and management of fisheries resources	Development of the aquaculture sector
5	2008	National Economic Stimulus Programme (ESP)	Construction of fish ponds in every constituency		Construction of fish ponds in every constituency to boost aquaculture

The institutional framework for fisheries management in Kenya started back in 1901 by the issuance of Fish Order Number 9 by the colonial government followed closely by Fish Protection Act of 1902. These legal frameworks were associated with institutions like the Division of Fisheries in 1954 under the Game Department which later became the Department of Fisheries with the mandate to enforce various legislations in the Country. The first fisheries laws and regulations mainly focused on fisheries management. There was no much threat invasive species in Kenya therefore no effort to contain them. Species invasion is the second leading cause of biodiversity loss globally (Gichua *et al.*, 2013). Nile perch was introduced into Lake Victoria in 1954, it has caused a rapid drop in native fish stocks estimated to be extinction of more than 200 species of endemic fish species (Gichua *et al.*, 2013; Kerr & Grant, 2000). The threats are increasing due to minimal efforts to try understand invasive fishes biology in East Africa (Akinyi, 2018; Frank, 2007).

Currently, Fisheries Management and Development Act of 2016 encompasses the aspects of fish introduction, management, and aquaculture. The main concerns in the fisheries sector as established in the social survey is limited capacity and bureaucracy between National and County government in terms of devolved and National Government functions.

There have been attempts to introduce more fish species into the rivers and other waters bodies directly or indirectly. These efforts manifests through aquaculture practices, restocking programs, sharing fishing gears, dam restoration programs. These scenarios are critical in the conservation of the both the native and endemics fish species in Kenya. The aspect of food security also facilitate fish introduction in different parts of the country to boost economy. Most these introductions go unnoticed till the effects become apparent. Some of the effects of the fish introductions can be controlled by initial impact assessment.

CHAPTER FIVE: SUMMARY OF FINDINGS, CONCLUSION, AND RECOMMENDATIONS

5.1: Summary of findings

The five tilapia fish species identified in upper Tana River basin includes Nile tilapia, Sabaki tilapia, Mozamnique tilapia, Redbreast tilapia and Redbelly tilapia belonging to genera *Oreochromis* and *Coptodon*. They were identified using physical and morphological characteristics. The physical characteristics used includes the body shape, body colours, the markings on the caudal fin, number of anal spines and position of the mouth in relation to the dorsal fin posterior. Morphologically, body shape comparison analysis was done to understand body shape variations using 16 landmarks. The study found overlap in morphological characteristics among the species of tilapia in the area. The overlap is possibly as a result of hybridization between or among the species.

The geographic distribution of the tilapia species in Upper Tana River basin has changed from the single species Sabaki tilapia to a series of species sharing the same system. The study showed very little spaces left for native species compared to non-native species. Nile tilapia is widely distributed in the area followed by Sabaki tilapia, Redbelly tilapia, Redbreast tilapia and Mozamnique tilapia respectively. Tilapia species are found in all habitats of upper Tana River basin, namely, fish farms, dams and rivers. The tilapia fishes were recorded from the three habitats that is fish ponds, dams and rivers whereas higher population were from in fish ponds. The most abundant tilapia species were the non-native tilapia (Nile tilapia, Mozamnique tilapia, Redbreast tilapia and Redbelly tilapia) at 71.3% with Nile tilapia as the dominating species.

Tilapia fish introduction is contributed to in a number of ways through connection between the natural and aquaculture systems. The connections happens through: pond inlets and outlets channels, flash floods, wider ranges of water quality parameters, steep topographical gradients, intentional fish introduction into the rivers through restocking programmes and direct acquisition of fingerlings from the natural water bodies.

The drivers of tilapia introductions into the wild includes aquaculture practices which forms the basis for fish introduction into the wild; The frequent flash floods leading to fish species introductions in the area. The traditionally weak government policies and loss concerning fish introduction enabled earlier fish introduction in the study area.

5.2: Conclusion

This study set out to map the geographic distribution of tilapia fish species and model the pathways of aquaculture, and natural systems interact in upper Tana River basin covering Nyeri, Kirinyaga and Embu counties.

Five species of tilapia (Sabaki tilapia, Nile tilapia, Mozamnique tilapia, Redbelly tilapia, and Redbreast tilapia) were found in the area and identified using geometric morphometrics, TilapiaMap Application and field guides. Four out of five species recorded in upper Tana River are non-native (Nile tilapia, Mozamnique tilapia, Redbelly tilapia, and Redbreast tilapia). The non-native tilapia species had 71.3% relative abundance over native tilapia species. The study found the possible hybrids of tilapia species in the area between the native tilapia (Sabaki tilapia) and the non-native tilapia (Nile tilapia) and among the non-native species (Nile tilapia and Redbelly tilapia). The hybridization is attributed to the free interaction among the species.

There is alteration in the tilapia distribution in upper Tana, different from the known occurrences. The tilapia zones have changed from the known native ranges to complex and dynamic zones of both native and non-native with declining populations of native species. The study used TilapiaMap Application to map the distribution of tilapia in upper Tana River, from the records uploaded and accessed; the application can be more useful to researchers, educationist and farmers for real-time acquisition of information on both the farmed and wild tilapia species

The tilapia species connectivity pathways is enhanced by a wider water quality ranges. The tilapia fishes have expanded survival ranges from medium to higher altitudes with lower temperatures, wider pH ranges, higher conductivity and lower turbidity. The study confirmed the presences of tilapia at a low temperature of about 17°C at an altitude of 1600m above sea level. The tilapia fishes, especially Nile tilapia, are becoming more tolerant to a wider range of water quality parameters hence widening its geographical space. The steep altitudinal gradients and flash floods helps in connecting the aquaculture systems and the natural water system.

Tilapia fishes have been introduced mainly through aquaculture which is facilitated by high demand and preferences of tilapia fish for food over the other fishes. There is a high preference and demand of non-native, Nile tilapia, in the three counties than its production facilitating the establishment of more fish farms. The fisheries sector has adequate laws and policies to deal with sector benefits and challenges.

The introduction processes are now causing harm to the native tilapia species which are not desired for aquaculture activities making it possible to lose the native genetic materials through hybridization or competition.

5.3: Recommendations

In light of the findings from the study and to assist fisheries stakeholders in proper management and conservation of the native species, the following recommendation have been made. These recommendations are aimed at further research, management action and policy intervention.

5.3.1: Recommendations for further research

The study has been able to show the possible hybridization among tilapia species, widening in tilapia tolerance range of water quality parameters, aquaculture as the main driver to tilapia introduction facilitated by land gradient and flash floods, the use of citizen science in tilapia mapping and identification and the laws and policies for fisheries management in Kenya. Therefore, the following are suggested for further studies;

a) The genetic analysis of the tilapia tissue samples to confirm the hybridization extent in tilapia species in this area.
b) The role of cage culture in fish introductions
c) Ways of enhancing county and national governments' synergy on fisheries management
d) The role of climate change in fish introduction and change in tolerance range

5.3.2: Recommendation for management action

a) Proper pond management practice should be employed using the required architectural design of ponds recommended for different topography can help reduce unnecessary water overflow during flash floods to control fish mixing.
b) Proper implementation of the fisheries act requiring compliances with installation of fish pond inlet and outlets, patrol by fisheries extension officers and public education on the proper fish farming techniques.
c) There is a need for synthesis of the policies into the local dialects to promote understanding and enhance implementation.

5.3.3: Recommendation for policy intervention

Zonation of aquaculture activities: The national government through Kenya Fisheries Service should formulate a policy to restrict aquaculture activities in areas with native species. There is need for confirmation of the identified areas with pure native species of tilapia such as Ena River, Ishiara area in Embu County and Mahinga-ini rice field in Mwea, Kirinyaga County among others should be cordoned off from the exotic species to help preserve the native species.

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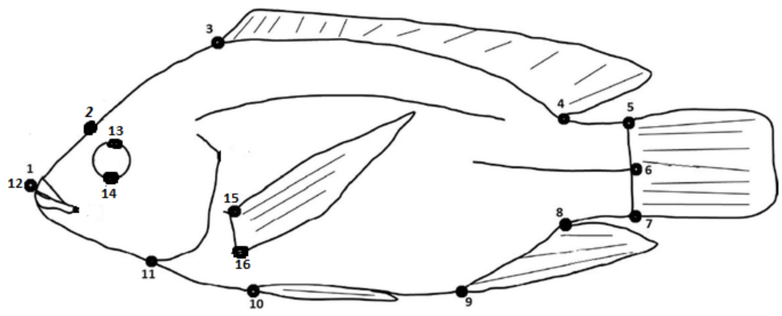
Annexes

Annex 1: Position of 16 landmarks used for Geometric morphometrics study



Annex 1: Position of 16 different landmarks used in the study: **(1 & 12)** anterior tip of the snout with mouth closed, **(2)** head above the eye, **(3 & 4)** posterior and anterior insertions of the dorsal fin, **(5)** dorsal origin of caudal fin, **(6)** halfway between caudal and ventral origin of caudal fin, **(7)** ventral origin of caudal fin, **(8)** posterior insertion of anal fin, **(9)** anterior origin of anal fin, **(10)** anterior origin of pelvic fin, **(11)** juncture of the ventral edge of operculum with the ventral outline, **(13 & 14)** eye diameter**, (15 & 16)** anterior and posterior of pectoral fin

Annex 2: List of collogued specimen at National Museums of Kenya used for the study

Catalogue No.	Species	Locality	Date	Collector	Latitude	Longitude
FW/4875/1-17	*Coptodon rendalli*	Masinga Dam, Spillway, Embu	23.III.2019	Gathua, Kashim, Ochong	0.52417 S	37.34888 E
FW/4871/1-4	*Coptodon zilli*	Daniel's fish farm, Othaya, Nyeri	25.III.2019	Gathua, Kashim, Ochong	0.34942 S	36.55322 E
FW/4874/1-17	*Coptodon zilli*	Chinga dam, Othaya, Nyeri	21.III.2019	Gathua, Kashim, Ochong	0.35001 S	36.55234 E
FW/4878/1-9	*Coptodon zilli*	Sagana river at Nyeri-Nairobi bridge	19.III.2019	Gathua, Kashim, Ochong	0.47264 S	37.16124 E
FW/4896/1-13	*Coptodon zilli*	Ngando Dam, Kirinyaga	18.III.2019	Gathua, Kashim, Ochong	0.38666 S	37.10839 E
FW/4908/1-51	*Coptodon zilli*	NARDTC fish farm, Kirinyaga	7.XII.2018	Kashim Oginga		
FW/4862/1-2	*Oreochromisniloticus*	Daniel's fish farm, Othaya	25.III.2019	Gathua, Kashim, Ochong		
FW/4869/1-13	*Oreochromis niloticus*	Nyati fish farm, Mukangu, Embu	21.III.2019	Gathua, Kashim, Ochong	0.28015 S	37.26966 E
FW/4870/1-11	*Oreochromis niloticus*	Emmi fish farm, Kiandai, Kirinyaga	19.III.2019	Gathua, Kashim, Ochong	0.36167 S	37.13601 E
FW/4872/1-11	*Oreochromis niloticus*	EEEPO fish farm, Ishiara, Embu	21.III.2019	Gathua, Kashim, Ochong	0.27402 S	37.46884 E
FW/4873/1-26	*Oreochromis niloticus*	Sagana river at Nyeri-Nairobi bridge	19.III.2019	Gathua, Kashim, Ochong	0.47264 S	37.16124 E
FW/4876/1-15	*Oreochromis niloticus*	Joy fish farm, Mwea, Kirinyaga	20.III.2019	Gathua, Kashim, Ochong	0.38392 S	37.23879 E
FW/4877/1-8	*Oreochromis niloticus*	Kiama Fish farm, Karima, Nyeri	26.III.2019	Gathua, Kashim, Ochong	0.31855 S	36.59311 E
FW/4880/1-2	*Oreochromis niloticus*	Chinga dam, Othaya, Nyeri	25.III.2019	Gathua, Kashim, Ochong	0.35001 S	36.55234 E
FW/4882/1-18	*Oreochromis niloticus*	Wahome Fish Farm, Njoguini, Nyeri	27.III.2019	Gathua, Kashim, Ochong	0.24433 S	36.52249 E
FW/4884/1-17	*Oreochromis niloticus*	Kiama Fish farm, Karima, Nyeri	26.III.2019	Gathua, Kashim, Ochong	0.31855 S	36.59311 E
FW/4886/1-10	*(Oreochromis niloticus*	Good Shepherd Fish Farm, Embu	22.III.2019	Gathua, Kashim, Ochong	0.31770 S	37.28996 E
FW/4891/1-14	*(Oreochromis niloticus*	Masinga Dam, Spillway, Embu	23.III.2019	Gathua, Kashim, Ochong	0.52417 S	37.34888 E

Annex 3: List of collogued specimen at National Museums of Kenya used for the study

Catalogue No.	Species	Locality	Date	Collector	Latitude	Longitude
FW/4893/1-3	*Oreochromis niloticus niloticus*	Gura River at Tambaya, Nyeri	26.III.2019	Gathua, Kashim, Ochong	0.31494 S	37.01205 E
FW/4894/1-2	*Oreochromis niloticus niloticus*	Daniel's fish farm, Othaya	25.III.2019	Gathua, Kashim, Ochong	0.34942 S	36.55322 E
FW/4897/1-10	*Oreochromis niloticus niloticus*	Wahome Fish Farm, Njoguini, Nyeri	27.III.2019	Gathua, Kashim, Ochong	0.24433 S	36.62249 E
FW/4898/1-11	*Oreochromis niloticus niloticus*	Good Shepherd Fish Farm, Embu	22.III.2019	Gathua, Kashim, Ochong	0.31770 S	37.28996 E
FW/4899/1-13	*Oreochromis niloticus niloticus*	Mwea Aqua Fish Farm, Kirinyaga	21.III.2019	Gathua, Kashim, Ochong	0.36758 S	37.22828 E
FW/4885/1-12	*Oreochromis spilurus niger*	Ena River, Karirima, Embu	22.III.2019	Gathua, Kashim, Ochong	0.31003 S	37.47952 E
FW/4887/1-11	*Oreochromis spilurus niger*	Mahigaini Mwea Rice, Kirinyaga	20.III.2019	Gathua, Kashim, Ochong	0.39228 S	37.23484 E
FW/4888/1-6	*Oreochromis spilurus niger*	Sagana river at Nyeri-Nairobi bridge	19.III.2019	Gathua, Kashim, Ochong	0.47264 S	37.16124 E
FW/4879/1-6	*Oreochromis spilurus spilurus*	Sagana river at Nyeri-Nairobi bridge	19.III.2019	Gathua, Kashim, Ochong	0.44264 S	37.16124 E
FW/4881/1-3	*Oreochromis spilurus spilurus*	Masinga Dam, Spillway, Embu	23.III.2019	Gathua, Kashim, Ochong	0.52417 S	37.34888 E
FW/4883/1-4	*Oreochromis spilurus spilurus*	Ngando Dam, Kirinyaga	18.III.2019	Gathua, Kashim, Ochong	0.38666 S	37.10839 E
FW/4889/1-51	*Oreochromis spilurus spilurus*	Ena River, Karirima, Embu	22.III.2019	Gathua, Kashim, Ochong	0.31003 S	37.47952 E
FW/4890/1-2	*Oreochromis spilurus spilurus*	Chinga dam, Othaya, Nyeri	25.III.2019	Gathua, Kashim, Ochong	0.35001 S	36.55234 E
FW/4892/1-10	*Oreochromis spilurus spilurus*	Mahigaini Mwea Rice, Kirinyaga	20.III.2019	Gathua, Kashim, Ochong	0.39228 S	37.23484 E
FW/4895/1-4	*Oreochromis spilurus spilurus*	EEEPO fish farm, Ishiara, Embu	21.III.2019	Gathua, Kashim, Ochong	0.27402 S	37.46884 E

Annex 4: Principal Component's loadings for PC1 to 15 for the data set analyzed using PCA

	Percentage Variance					
PC loadings	**Tilapia Genera**	**Coptodon species**	**Oreochromis species**	**Oreochromis subspecies**	**Farm tilapia**	**River tilapia**
PC1	19.73	26.08	21.59	20.33	22.09	22.87
PC2	15.68	16.97	15.21	14.42	17.41	11.33
PC3	10.68	11.88	12.76	10.31	10.48	10.54
PC4	8.46	9.45	8.91	9.25	8.56	9.46
PC5	7.86	7.18	7.86	9.02	7.65	7.65
PC6	7.1	6.11	6.73	5.2	6.61	7.25
PC7	4.05	4.02	4.88	4.58	3.97	4.3
PC8	3.44	2.8	3.17	3.33	3.23	3.47
PC9	2.6	2.46	2.58	2.82	2.34	3.12
PC10	2.36	2.02	2.06	2.59	2.25	2.55
PC11	1.96	1.93	1.66	2.33	1.84	2.16
PC12	1.69	1.35	1.59	1.9	1.63	2.06
PC13	1.55	1.23	1.33	1.66	1.53	1.84
PC14	1.17	1.08	1.1	1.34	1.2	1.52
PC15	1.04	0.9	0.96	1.27	1.02	1.3

Annex 5: Physic-chemical parameters and tilapia specimen field data Sheet

Date: …………………………………… Time: ………………..……..…………

River channel: ……………..………..………..…,…………………..…………………

Locality/sites:

…………………………………………………………………………..…………..

GPS Coordinates: Lat: ……………….Long:………..……… Alt: ………………

Water Chemistry: PH: ………...Temperature: ………..DO: …..………..

Turbidity………………… EC: …..………..

Approximate distance to natural water or fish pond (km)…………………………..

No.	Field ID	Species name	Total Length	Weight	Photo ID
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					

Annex 6: Socio-economic surveys

a. **Fish pond management practices in upper Tana River System for fish pond managers/owners**

This is an interview guide for a postgraduate research work from University of Nairobi conducting a research on mapping the geographic distribution and modeling pathways of interaction of tilapia fish species between natural and aquaculture systems in upper Tana River basin, Kenya. Please spare me a few minutes to answer the questions below. The information will be used for academic purposes only. Your assistance will be highly appreciated.

1. General Information

a. Name (optional)…..	Gender (male/ Female)
Duration of working in the farm 0-5yrs 5-10yrs 10yrs and above	Education Level- Primary, Secondary, Tartiary
County: Kirinyaga, Embu, Nyeri	

2. When did the aquaculture project start (year)

No.	**Years**	kciT
1	0-5	
2	5-10	
3	10- Above	

3. The type of pond the farmer uses for aquaculture

No.	**Years**	kciT
1	Earthen Ponds	
2	Concrete ponds	
3	Liner ponds	

4. The sources of fingerlings used in the farm

No.	**Sources**	**Tick**
1	Private fish Hatcheries	
2	* NARDTC hatcheries (Sagana)	
2	Other Fish farmers ponds	
3	River sources	

4	Dam sources	
6	Other sources (……………………)	

5. The species of Tilapia fishes reared in the farm

No.	Species	✓
1	*Coptodon*	
2	*Oreochromis*	
5	Others	

6. Where is the source of pond water used?

No.	Sources	✓
1	Borehole	
2	River	
3	Dams	
4	Water pan	
5	Others	

7. Is there direct connection between inlet and outlet of the pond to the natural river system?

No.	Answer	Tick
1	Yes	
2	No	

If yes, How……………………………

8. Do the pond has screens/filters in the inlets or outlets

No.	Answer	Tick
1	Yes	
2	No	

9. How is the wastes water from the pond handled?

No.	Waste water	✓
1	Directed to farms	
2	Back to the river	
3	Directed to other ponds	
4	Others	

10. Has there been incidence of flooding leading to the connection between the pond and the river?

No.	Answer	Tick
1	Yes	
2	No	

If yes, what is the frequency ……………

No.	Frequency	✓
1	Seasonally	
2	Yearly	
3	Every 5years	
4	Over every 5years	

11. Are there river fishing activities?

No.	Answer	Tick
1	Yes	
2	No	

12. If yes, where (which River)………………..

Which fishing method do they use?

No.	Fishing method	•
1	Hook and line	
2	Spears	
3	Seining	
4	Gill netting	
5	Combination	

13. How is the fish harvesting done?

No.	Way of harvesting	•
1	Contractual	
2	Individual	
3	Other	

14. Is the fishing gears shared among fish farms?

No.	Fishing gears sharing	•
1	Yes	
2	No	

15. Are the fishing gears shared between fish farms and the rivers?

No.	Fishing gears sharing	•
1	Yes	
2	No	

16. When is the river fishing common?

No.	River fishing	•
1	Though out the year	
2	Rainy season	
3	Dry season	

17. Where do the farmer sale the produce?

No.	Market	Tick
1	Local traders	
2	Up country	
3	Export	
4	Subsistence	

18. Where is the source of fish feeds?

No.	Sources	•
1	Fisheries department	
2	Market direct	
3	Locally made	

19. What are the types of fish feeds used?

No.	Feeds type	Tick
1	Plant materials	
2	Manufactured	

3	Both	

20. What is the average fish price per piece or per Kg?

No.	Price	Tick
1	>100	
2	100-250	
3	250-400	
4	400<	

22. How long to fingerlings take to mature?

No.	Time (months)	Tick
1	3-6	
2	6-9	
3	9 and above	

b. River fishing practices in upper Tana River System, Questionnaire for fisherforks

This is an interview guide for a postgraduate research work from University of Nairobi conducting a research on mapping the geographic distribution and modeling pathways of interaction of tilapia fish species between natural and aquaculture systems in upper Tana River basin, Kenya. Please spare me a few minutes to answer the questions below. The information will be used for academic purposes only. Your assistance will be highly appreciated.

1. General Information

Name (optional) …………	Gender (male/ Female)
County: Kirinyaga, Embu, Nyeri	Educational Level- Primary, Secondary, Tartiary
Name of the fishery………………………	

2. When did you start fishing (year)

No.	Years	•
1	0-5	
2	5-10	
3	10 and above	

3. Where (Fishery) do you normally fish?

No.	Places	T
1	River	
2	Dams	

3	Others specify……………..	

4. Which kind of tilapia do you normally get (*interpret from the his/her explanation*)?

No.	Species	
1	*Coptodon*	
2	*Oreochromis*	
3	Sarotherodon	
5	Others	

6. Where is the source of fishery?

No.	Sources	
1	Mt. Kenya	
2	Arberdares	
3	Arbadares and Mt. Kenya	
4	Others ……………………..	

8. Are there fish farms around?

No.	Answer	
1	Yes	
2	No	

9. Is there possibility of fish escaping from the farm to the river where you fish?

No.	Opinion	
1	Yes	
2	No	

10. Has there been incidence of flooding in the area?

No.	Answer	'
1	Yes	
2	No	

1. If yes, what is the frequency………

No.	Frequency	' '
1	Seasonally	
2	Yearly	
4	Not periodical	

2. Which fishing method do you use?

No.	Fishing method	' '
1	Hook and line	
2	Spears	
3	Seining	
4	Gill netting	
5	Traditional fish traps	
6	Combination	

14. Is the fishing gears shared among fishermen?

No.	Fishing gears sharing	'
1	Yes	
2	No	

15. Are the fishing gears shared between fish farms and the rivers?

No.	Fishing gears sharing	·
1	Yes	
2	No	

16. When is the river fishing common?

No.	River fishing	·
1	Though out the year	
2	Rainy season	
3	Dry season	

17. Where do you sale the catch?

No.	Market	· ·
1	Local traders	
2	Up country	
3	Export	
4	Subsistence	
5	Others	

20. What is the average fish price per kg?

No.	Price	·
1	>100	
2	100-250	
3	250-400	
4	200-300	
5	300-500	
6	500<	

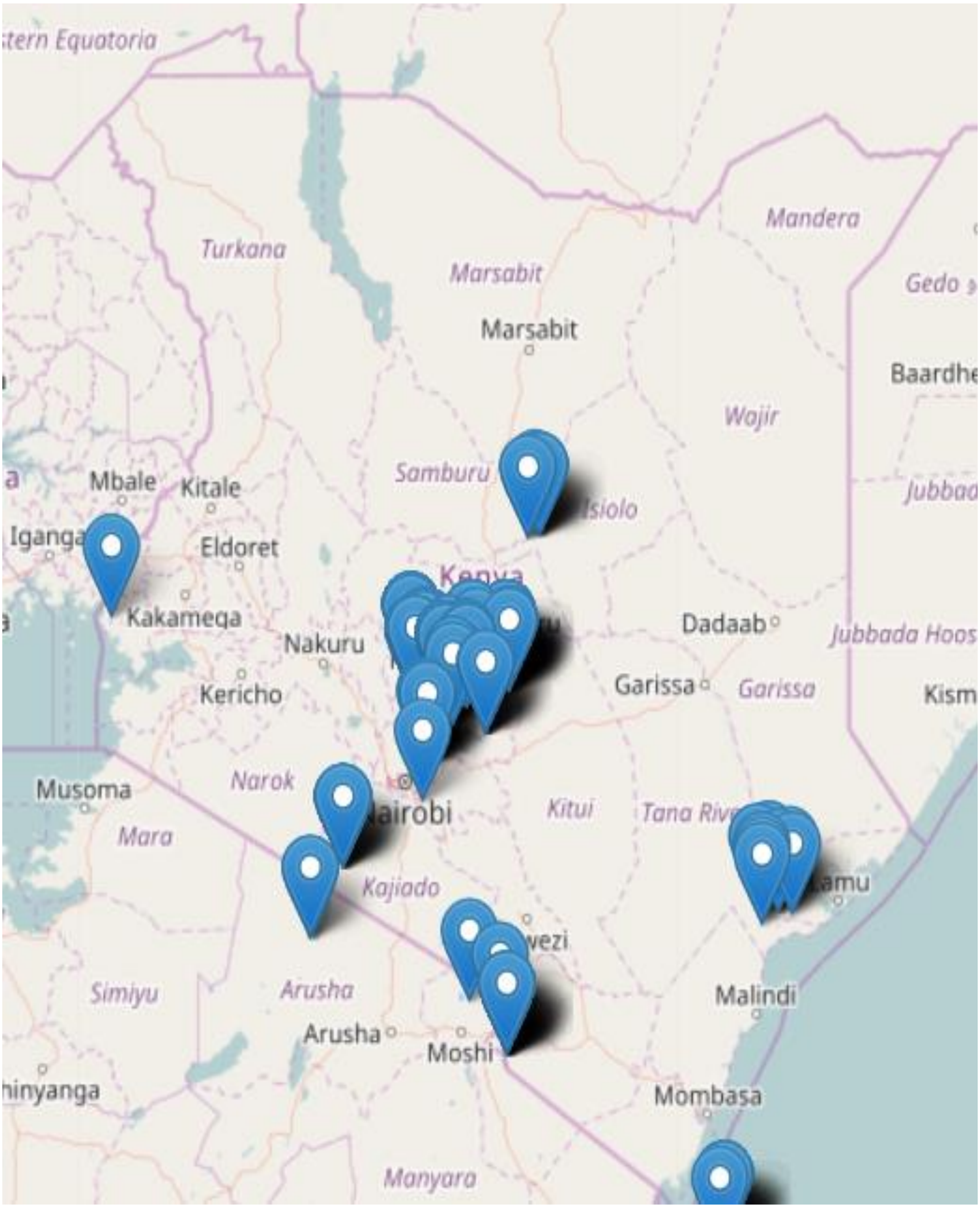
21. What is the area fishing season?

No.	Seasons	·
1	Dry	
2	Wet	

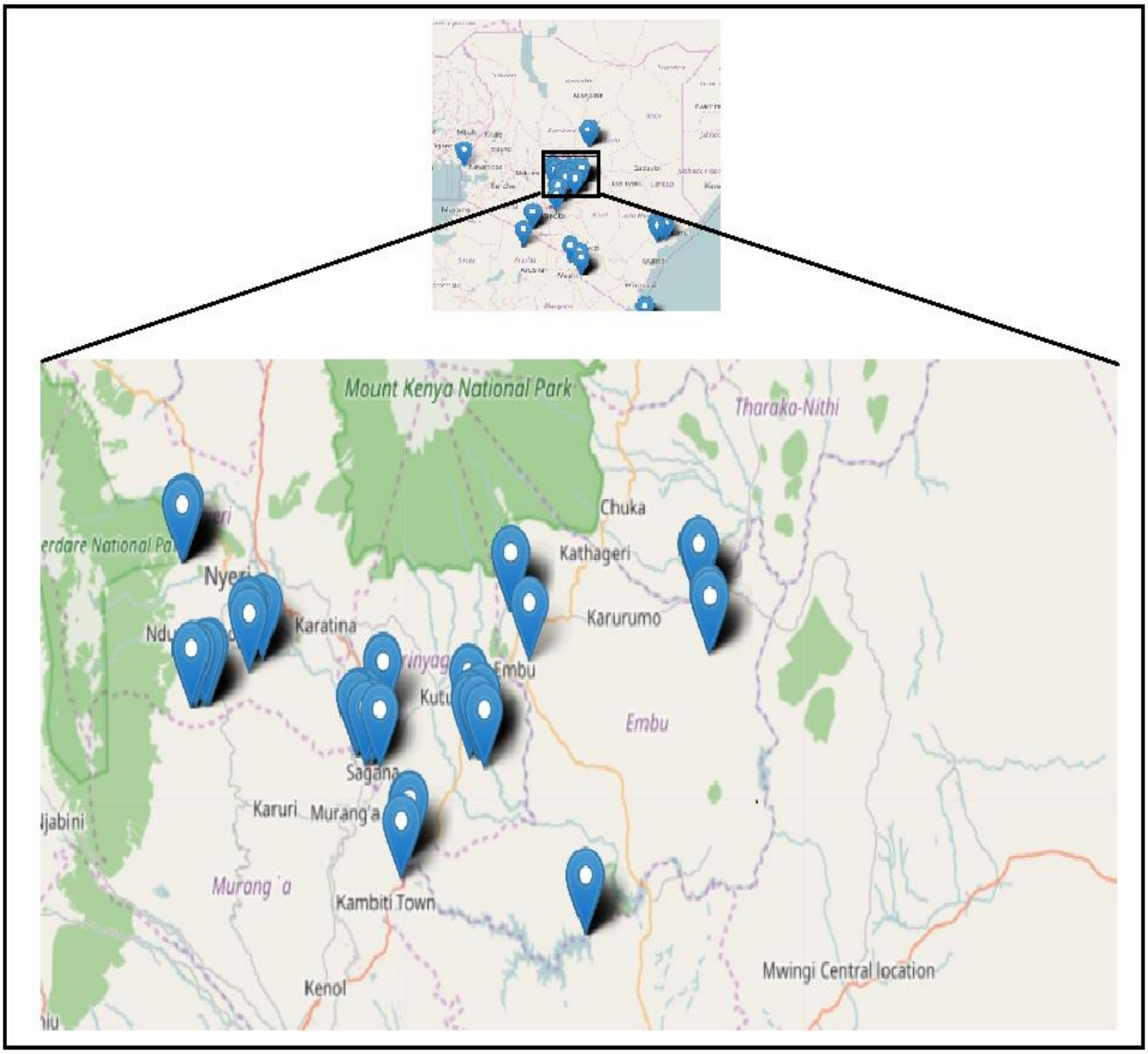
22. Area fisher men licensed in the area?

No.	Opinion	Tick
1	Yes	
2	No	

Annex 7: TilapiaMap Extract of tilapia species records in Kenya (2018-2019) (Map pinpoint shows single species record)



Annex 8: TilapiaMap Application tilapia species records in upper Tana River basin



Annex 9: Field Work Photographs

- **Plate 5: Sampling in Good S fish pond, seining with gillnet Plate 6: Sampling in Masinga Dam, using rented boat and gillnet**

Plate 7: Sampling in River Ena at Karima area, using seine net