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The development and use of a GIS model to map Mozambique tilapia pond aquaculture site suitability for the Limpopo province of South Africa

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The development and use of a GIS model to map Mozambique tilapia pond aquaculture site suitability for the Limpopo province of South Africa

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A Dissertation submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science

Main Supervisor: Dr Mary-Jane Thaela-Chimuka: Agricultural Research Council – Animal production (ARC-AP)

Core Supervisor: Prof Mulala Danny Simatele: University of the Witwatersrand, Faculty of Science, School of Geography, Archaeology & Environmental Studies, The Global Change Institute

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Acknowledgements

To God, the Creator:

Genesis 1:20-22 NKJV:

“[20] Then God said, “**Let the waters abound with an abundance of living creatures**, and let birds fly above the earth across the face of the firmament of the heavens.” [21] **So God created great sea creatures** and **every living thing that moves, with which the waters abounded, according to their kind**, and every winged bird according to its kind. And God saw that it was good. [22] And God blessed them, saying, “**Be fruitful and multiply, and fill the waters** in the seas, and let birds multiply on the earth.”” (https://bible.com/bible/114/gen.1.20-22.NKJV)

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“Give a man a fish, and you feed him for a day.

Teach a man to fish, and you feed him for a lifetime.”

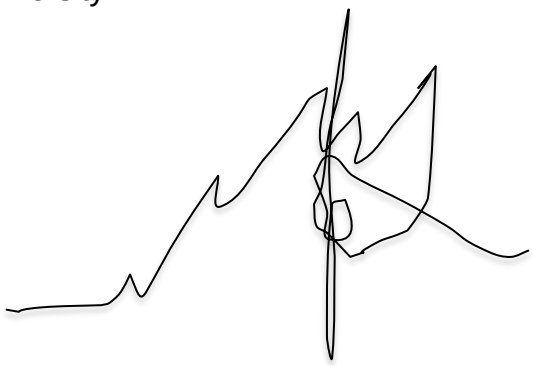
- Chinese philosopher, Lao Tzu -

“Inspire a man, or woman, to see themselves as resourceful, capable of learning to fish, farm or forage, grow, harvest, and create. Capable even of providing for and teaching others. Then you impact a community”.

- Anika van den Berg – 27 July 2024 -

Declaration

I, Celéste Dekker, declare that this Thesis is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



_____

(Signature of candidate)

____13th _____day of June _____2025_____in_Pretoria___

Abstract

The fast-growing population, globally, in Africa, Sub-Saharan Africa and South Africa, could lead to food insecurity. One solution to this challenge is that aquaculture can provide alternative sources of food and protein and increase job-creation and income to especially small-scale rural pond aquaculture farmers to ultimately improve food security in South Africa. Pond aquaculture could offer an alternative solution to overfishing of the dwindling wild fish stocks. The South African government has established numerous aquaculture funding initiatives, like Operation Phakisa and the National Development Plan (NDP) 2030 in place but requires information as to where to spend and allocate their resources effectively and optimally.

The main aim of this study was to create a Mozambique tilapia *(Oreochromis mossambicus)* pond aquaculture site suitability model for the pilot study area, the Limpopo province of South Africa. The model should however be a general model which could be used for the whole of South Africa. The model was designed in a Geographic Information Systems (GIS) which could be used to create suitability maps. The importance of this study is that it could indicate to Government where to focus their funding and other support. By focussing their funding only on new or current enterprises and farmers in highly suitable areas, funders could be sure that only the more efficient producers and areas were supported. This could ensure that their financial aid would lead to increased return on investment, accelerating aquaculture and increasing food security in South Africa. The choice of this fish species and pilot study area, the Limpopo province of South Africa, is since the Mozambique tilapia is a warm-water, palatable fish, suitable to pond aquaculture. Pond aquaculture is relatively simple and cheap to start-up and maintain. The Mozambique tilapia is endemic to the Limpopo province of South Africa.

The suitability products and -maps were also used to score and rank 48 existing tilapia farmers, to showcase that top-scoring farmers in the highly suitable areas could be identified so that fiscal and other support could be focussed on them.

The research findings indicated that the GIS site suitability model, which was created in a Multi-criteria Evaluation (MCE) environment, had generated many sub-model intermediate suitability products which fed into the two final suitability products for the Limpopo province of South Africa. The final suitability products were the Weighted

Overlay (WO) suitability integer raster and the Weighted Sum Overlay (WSO) suitability floating-point raster. These rasters were classified to produce suitability maps which could indicate to Government, other stakeholders and funders where to sustainably invest limited resources on only highly suitable areas, from provincial- to farm-scale.

From the results of the WO suitability product, the Limpopo province suitability was tabulated to indicate the area and percentages of every suitability class, namely Highly suitable (16%), Moderately suitable (31%), Marginally suitable (13%), and unsuitable or restricted/ constraint areas (39%).

The 48 existing farmers' GPS locations were used to score and rank them according to their suitability using the floating-point WSO product. This was done to identify the farmers that were ranked the highest suitability to justify the distribution of limited funding.

The results from extracting the Weighted Sum Overlay (WSO) of the GPS locations of the existing 48 farmers, were encouraging; as 50 percent of the farmers were already located in Moderately suitable areas, 35 percent of farmers were situated in Highly suitable areas and only 15 percent in Marginally Suitable areas. From the Weighted Overlay (WO) extraction, most farmers (56 percent) found themselves in Moderately suitable areas, 27 percent in Highly suitable areas and 17 percent in Marginally suitable areas.

It was investigated whether using a GIS for Mozambique tilapia pond aquaculture site suitability allocation was faster and cheaper than other methods. It was established that farmers in highly suitable areas produced more efficiently, and that these farmers produced more fish more sustainability. Funding these mostly small-scale farmers could increase their livelihoods, and increase household income, of which many are female-headed, and increase production of fish via roll-out of the model to other provinces. This would accelerate aquaculture in South Africa and assist in increasing food security for its growing population.

Recommendations from this research include research findings that are very clear that the government of South Africa and funders should ensure that their investments were optimised by annually, (not once-off) adding the following to the chosen farmers or pond tilapia enterprise owners: Consistent training (by government also via extension

officers) as well as credit facilitation and funding and the encouragement of private-public cooperation.

Recommendations for further study include the use of the AQUASUIT Suitability App for querying suitability of points and areas, the roll-out of the use of the model to other provinces, the insertion of climate change Global Circulation Models' data into the model to provide future-suitability maps and to delineate Mozambique tilapia sanctuaries and breeding sites.

Key words: Geographic Information System (GIS), Mozambique tilapia, *(Oreochromis mossambicus)*, pond aquaculture, site suitability, Multi-Criteria Evaluation (MCE), Analytical Hierarchy Process (AHP), Pairwise Comparison Matrix (PCM), South Africa, Limpopo province.

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List of Acronyms

AHP Analytical Hierarchy Process

ARC Agricultural Research Council

CI Consistency Index

CR Consistency Ratio

DEM Digital Elevation Model

ESRI Environmental Systems Research Institute, Inc.

GIS Geographic Information System

MCE Multi Criteria Evaluation

PCM Pairwise Comparison Matrix

WO Weighted Overlay

WSO Weighted Sum Overlay

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Chapter 1

Frames of Reference

1.1 Introduction

The world population has grown massively post-World War II (Kaba, 2020), and continued growth is projected, but after the 1950s, the growth rate will be slower (UNDESA, 2019a, UNDESA, 2022). Africa has the fastest population growth rate in the world and its growth rate is expected to increase by an estimated 50% between 2017 and 2035 (UNDESA, 2019b, UNDESA, 2015). Sub-Saharan Africa's population growth rate is predicted at 99%, thus the total population is estimated to double by 2050 (UNDESA, 2019c). More than half of the world's population growth between 2019 and 2050 could be attributed to the population growth in Sub-Saharan Africa (SSA). Projections up to the year 2100, might still see SSA's continued population growth (UNDESA, 2019a; UNDESA, 2019b; UNDESA, 2019c). Sub-Saharan Africa, with the highest population growth rate in the world, holds the largest proportion of food-insecure people, with one in four people undernourished (PAI, 2011).

High population growth rates could lead to increased poverty in Sub-Saharan Africa (Schünemann, et al, 2017). South Africa's population growth rate is expected to increase until 2082 (WPR, 2022). The link between population growth and possible food insecurity is well known (UNDESA, 2017; PAI, 2011; FAO, 1991; FAO, et. al, 2019). To address hunger and malnutrition for the growing populations, food from aquatic sources is playing an increasing role in the improvement of food security and nutrition (FAO, 2022b).

Aquaculture can be defined as the farming of aquatic organisms (FAO, 2006). Quantitative evidence from the Blue Transformation (FAO, 2022a) initiative indicates that fisheries and aquaculture can contribute to the Sustainable Development Goals (SDGs) by positively contributing to food, nutrition, and employment (FAO, 2020). The year 2020 marked the year of the highest annual global fisheries and aquaculture production. Aquatic animal production was more than 60 % higher in 2020 than the average in the 1960s and higher than the growth in world population at that stage. This was mostly because of the increase in aquaculture production (FAO, 2022b). The global aquaculture sector has become the fastest growing agri-food sector in the past

3 decades. Up to the year 2030, a further 14% increase in the growth rate of fisheries and aquaculture in production, consumption, and trade, was predicted, but the growth rate will be lower than the periods prior to that (FAO, 2022b).

When compared globally with the five other main animal protein sources for humans, aquaculture contributes 7% which is more than bovine (at 4%), and the same percentages for poultry (7%). The portion of aquaculture making up the protein intake of a human diet, is increasing globally, depending in context on the differences in rates of increase amongst different regions, countries, and income status of the different countries (FAO, 2022b). The significant increase in aquatic food consumption was due to the significant rise in aquaculture production in the presence of capture fisheries showing relatively no growth, remaining stagnant since the 1990's (FAO, 2022b).

Billions of people worldwide rely on fish for protein, but natural fisheries are close to their biological limit (FAO et. al., 2019, WWF, 2015). People are globally consuming increasing amounts of aquatic foods than in previous years (20.2 kg per capita) from aquaculture, which is more than double their consumption 50 years ago (FAO, 2022b). While wild fish stocks are dwindling, freshwater inland aquaculture could help alleviate food insecurity and poverty (Bondad-Reantaso and Subasinghe, 2013). Aquaculture is playing an increasing role in protein supply, economic growth and the fight against hunger and malnutrition (FAO, 2018; FAO et. al, 2019). Aquatic foods contributed to a greater share of animal protein intake in low-income countries than in high–income countries (FAO, 2022b).

Africa's share in the total contribution to world aquaculture is low, at about 2.7 percent of world aquaculture production (FAO, 2020; Halwart, 2020). The increase in aquaculture production in South Africa from 2000 to 2020 was 7.46 %, which was higher than the world growth rate of 5.38 % during that period, but lower than the regional and sub-regional averages (FAO, 2022). Despite government initiatives to increase aquaculture production, Africa and South Africa still have a relatively slower growth-rate in the freshwater aquaculture sector than the rest of the world (FAO, 2020; Halwart, 2020). South African aquaculture is still mostly in the infant stage of development, despite many initiatives of the South African Government to grow the industry (Britz and Venter, 2016). However, the aquaculture sector was identified by government as a sector with a high growth potential (Britz and Venter, 2016). The

South African government is focussing their initiatives to address unemployment, poverty, and inequality via Operation Phakisa (Operation Phakisa, 2021). Operation "Phakisa," which translates to "hurry up" in Sesotho, was launched in 2014 by President Jacob Zuma to help stimulate the growth of The Blue Economy via implementation of the National Development Plan (NDP) to 2030, which has as its mission to boost economic growth and create jobs, alleviate poverty and address inequality within a very short time (Britz and Venter, 2016; DFFE, 2019, DFFE, 2021). The NDP governs every sector's plans, policies and operations (DFFE, 2019). The Department of Planning, Monitoring and Evaluation leads Operation Phakisa, while the Department of Environment, Forestry and Fisheries established the Oceans Economy Secretariat, which mainly focuses on marine fisheries and -aquaculture development. (DFFE, 2019); DFFE, 2024a). Most of Operation Phakisa's initial projects were based in the marine fisheries and -aquaculture sectors (DFFE, 2015) This was mainly done via the implementation of the Aquaculture Development Zones (ADZ) initiative along the coastal regions and some were inland (Initiative E9 of Operation Phakisa) (Operation Phakisa, 2021, DFFE, 2019).The first priority of Operation Phakisa was unlocking the potential of the oceans via the Oceans Economy Programme (DFFE, 2019).

There is thus scope to investigate the potential of inland aquaculture to fulfil the mandate of growing aquaculture in Southern and South Africa (Britz and Venter, 2016; FAO, 2011; FAO, 2022). There are many freshwater fish species that are suitable for aquaculture and quite palatable, but the main freshwater fish species in South Africa are the Sharptooth catfish (*Clarias gariepinus)*, the Common carp *(Cyprinus carpio)*, the freshwater trout *(Oncorhynchus mykiss)* and two tilapia species, of which one is the Nile tilapia *(Oreochromis niloticus)*, but which is an invader species in South Africa (Aquaculture Innovations, 2010; Urban Econ, 2018, Zengeya et al, 2012,). The other Tilapia species that is palatable and is suitable to aquaculture is the Mozambique tilapia *(Oreochromis mossambicus),* a warm-water, fresh-water aquaculture fish, with a white fleshed meat, hight in protein and suitable to local and wholesale markets (Mchunu, Lagerwall and Senzanje, 2017). The Mozambique tilapia is indigenous to many areas in South Africa, especially the Limpopo province, where it is endemic and thrives due to Limpopo's climate which matches the fish's own temperature preferences (Urban Econ, 2018, Zengeya et al, 2012). The reason for choosing the

Mozambique tilapia and the Limpopo Province for this research is because the largest part of the Limpopo province forms part of the native range of Mozambique tilapia according to the International Union for Conservation of Nature (IUCN) in Southern Africa (IUCN, 2021; Urban-Econ, 2018).

There are many aquaculture farming systems available to farm Mozambique tilapia in inland freshwater areas (Aquaculture Innovations, 2010, Pillay and Kutty, 2005; Urban Econ, 2018), of which pond aquaculture requires relatively low start-up capital, is the more cost-effective and easier to start-up and manage (Aquaculture Innovations, 2010). Unlike aquaponics, which can basically be farmed anywhere, but is a complicated system (Mchunu, Lagerwall and Senzanje, 2017), pond aquaculture needs to take place in areas that conform to many different environmental and economic criteria related to the geographical location of the pond production system (Francisco, et. al, 2019; Pillay and Kutty, 2005; Salam et. al., 2003; Ssegane, et. al, 2012). The tilapia fish also has a specific range of temperature preferences and tolerances for growth and survival which needs to be accounted for (Mchunu, Lagerwall and Senzanje, 2017). To select a suitable site for pond aquaculture for Mozambique tilapia, one will have to take all these factors into account. One way of carrying out site suitability, is via Geographic Information Systems (GIS) in which one can overlay many environmental and economic layers (or variables) and define their thresholds as well as for that of the chosen fish species in pond aquaculture (Falconer et al, 2020).

The selection of suitable sites for aquaculture activities, using species-specific environmental and economic criteria and -constraints, must take place prior to site development, to ensure more effective application of scarce resources by funders (Francisco, et. al, 2019; Salam et. al., 2003; Ssegane, et. al, 2012).

Suitable sites can be pre-selected using spatial environments to produce site suitability maps in which the suitability of an area like the Limpopo province can be determined in a Geographic Information System (GIS). To produce such site suitability maps for the Limpopo province, an array of species-specific suitability criteria is required. These criteria or variables, incorporated into a Geographic Information System (GIS) can produce site-suitability maps specific for the Mozambique tilapia using specific variables and their thresholds (Aguilar-Manjarrez and Nath, 1998).

Spatial environmental software can be used in the Geographic Information Systems (GIS) to produce site suitability maps from these criteria or variables (Aguilar-Manjarrez and Nath, 1998). By incorporating the Multi Criteria Evaluation (MCE) (Eastman, 1999) methodology into the GIS, a Pairwise Comparison Matrix (PCM) (Saaty, 1977) can be used to calculate the relative importance of each variable concerning the site suitability utilising the Analytical Hierarchy Process (AHP) (Saaty, 1977) (Francisco, et. al, 2019; Salam et. al., 2003; Ssegane, et. al, 2012). This facilitates the rating and weighting of the different suitability criteria (Radiarta, et al, 2011; Falconer et al., 2018; FAO, 2013).

Some variables are more important in terms of weighting than others when site suitability for inland pond aquaculture species are determined (Aguilar-Manjarrez and Nath, 1998; Aquaculture Innovations, 2010). One of these variables is water temperature (Aguilar-Manjarrez and Nath, 1998; Handisyde, 2015; Urban-Econ, 2018). Water temperature is one of the major factors influencing Mozambique tilapia growth, reproduction, and survival (Aguilar-Manjarrez and Nath, 1998; Handisyde, 2015; Urban-Econ, 2018). Air temperature values are used as a good proxy for pond water temperatures (Mohseni, et al, 1999; Boyd and Tucker, 1998; Morrissy, 1976; Klemetson and Rogers, 1985; Wax and Pote, 1990).

Due to climate change, however, air temperatures are constantly changing over short- and over longer time periods (FAO, 2022b). A regional climate model (RCM) together with other Global Circulation Models (GCM) predicted a rise in Africa's annual average temperatures of approximately 1.5 times that of the rest of the global rate of temperature increase in the subtropics and at bit lower rate in rise in the tropics (Engelbrecht, et.al, 2015). Research of rising temperatures over the Limpopo Province (Tshiala, et. al, 2011) further strengthen the notion that only producing current suitability maps, may not be adequate to address the impacts of future air- (and thus water-) temperature changes on future suitability in the Limpopo province. This will require future research in terms of its effects on aquaculture suitability and necessitate that a site selection suitability model produced in a GIS environment must be able to incorporate data from RCMs and GCMs.

Although this research focuses on the Limpopo Province, the design of the site suitability model from this research will be able to create site suitability maps which

could help facilitate the assessment of the suitability for inland earthen-pond aquaculture of the Mozambique tilapia *(Oreochromis mossambicus)* for any province in South Africa and could be applied at farm level up to national scale. The design of the site suitability model will enable easy duplication of the model. An additional aspect of the model will be its compatibility with spatial GIS layers of climate data in spatial format from different climate change models. By exchanging current climate data layers with future climate data layers, future site suitability maps could be produced.

The use of current as well as future site suitability maps could help guide stakeholders to more efficiently focus their resource funding efforts validate expenditure on existing tilapia farmers but also guide government as to which of these enterprises might be viable in future, and which geographical areas should be delineated for inland Mozambique tilapia pond aquaculture as well as the delineation of fish sanctuaries for future generations.

1.2 Thematic considerations

Food security can be increased, and malnutrition addressed for Sub Saharan Africa's (SSA)'s and South Africa's growing population by increasing protein production and household income via inland fresh-water aquaculture (Muringai et al, 2022). The National Development Plan (NDP) in South Africa has identified aquaculture as a tool to assist in alleviating food insecurity and contributing positively to SA's Gross Domestic Production (GDP) by creating jobs and improving rural livelihoods via Operation Phakisa (DFFE, 2021; Operation Phakisa, 2021).

Despite efforts by government to grow aquaculture enterprises, South-African aquaculture has been in its infant stage for many years, and it still is (Adeleke et al., 2021). However, South Africa's aquaculture sector shows much potential to increase fish production and rural development amidst the increasing global demand for fish and declining wild fish stocks (DFFE, 2021).

There are several types of inland freshwater aquaculture production systems (Aquaculture Innovations, 2010). One of the more affordable and more simplistic of these systems is the use earthen ponds to cultivate freshwater inland fish species (Aquaculture Innovations, 2010). These extensive systems are amongst other

variables, highly dependent on the temperature ranges that this fish species can tolerate (Aquaculture Innovations, 2010).

The Mozambique tilapia *(Oreochromis mossambicus)* is indigenous to South Africa (IUCN, 2021). The Mozambique tilapia *(Oreochromis mossambicus)* is native to most of the Limpopo Province in South Africa (IUCN, 2021). Its congeneric, the Nile tilapia *(Oreochromis niloticus),* has a similar geographic distribution and temperature tolerance range. However, Nile tilapia are exotic to many areas in South Africa and require permits in the Limpopo-, Gauteng- and KZN provinces for aquaculture in recirculating aquaculture systems (RAS). With reference to total tilapia production, most of South Africa's Mozambique tilapia *(Oreochromis mossambicus)* are produced in the Limpopo Province (Urban-Econ, 2018).

The selection of a suitable site for the planned aquaculture enterprise is a vital exercise (Aquaculture Innovations, 2010; Hossain et. al., 2007). A suitable site will increase the chances of the enterprise being successful, sustainable, viable and profitable in the current physical and economic environment (Aquaculture Innovations, 2010; Hossain et. al., 2007). There are many geographically based site suitability variables that need to be considered in the aquaculture enterprise planning phase (Meaden and Kapetsky, 1991).

Aquaculture pond site suitability can be determined spatially with Geographic Information Systems (GIS) instead of traditional methods like word of mouth and speculation trial and error (Steer, 2006). Geographic Information Systems (GIS) are ideal tools for conducting pond aquaculture site suitability analysis (Aguilar-Manjarrez and Nath, 1998; Assefa and Abebe, 2018; Ssegane, et. al, 2012; Hossain, et. al, 2007). Making wise decisions in selecting suitable sites beforehand via Geographic Information Systems (GIS) and not traditional methods, can improve the economic and ecological return on investment by decision makers (Falconer, et al, 2018; Luo, et al, 2018; Meaden and Kapetsky, 1991; Steer, 2006). GIS models can combine several environmental, economic, social, and other types of spatial information layers required to fulfil the requirements of a suitable environment for an inland pond fish farm (Salam, et. al., 2003). Many types of GIS models exist that can be utilised in GIS software to delineate suitable aquaculture sites (Salam, et.al., 2003). One such type of GIS model

is the use of Multi Criteria Evaluation (MCE) to score, weigh, and rank variables that have an influence on the suitability of a site for aquaculture, in a spatial environment, (Aguilar-Manjarrez and Nath, 1998). Multi Criteria Evaluation (MCE) (Eastman, 1999) combined with the Pairwise Comparison Matrix (PCM) (Saaty, 1977) can be used to calculate the relative importance of each variable concerning the site suitability with the Analytical Hierarchy Process (AHP) (Saaty, 1977) (Francisco, et. al, 2019; Salam et. al., 2003; Ssegane, et. al, 2012).

Two of the most important variables in pond aquaculture site selection are the distance to the water source and pond water temperature (Aguilar-Manjarrez and Nath, 1998; Verster, 2017). Water temperature has an influence on the rate of the Mozambique tilapia production, mortality, reproduction and growth (Aquaculture Innovations, 2010).

Other variables like slope percentage and soil clay percentage play a role in the economic suitability of a site and such as pond construction costs, and therefore need consideration as well (Aguilar-Manjarrez and Nath, 1998).

Air temperature is a good proxy for pond water temperature (Mohseni et. al., 1999). A drastic increase was observed in African annual-average near-surface temperatures over the last five decades. Over parts of the sub-tropics and central tropical Africa, the rate of temperature increase was twice that of the rest of the globe (Engelbrecht et al, 2015). Further warming is projected up to the year 2100 using Global Circulation Models (GCM) over the tropics and sub-tropics of Africa. This projected increase is 1.5 times that of the global rate of temperature increase (Engelbrecht et al, 2015). Research findings of the Working Group II (WGII) to the Sixth Assessment Report) (AR6) of the Intergovernmental Panel on Climate Change (IPCC) assessed the risk associated with possible future global warming (IPCC, 2022). Therefore, in this research, the pond aquaculture site suitability model will be designed so that Climate Change Models' air temperature data and calculated water temperature can be incorporated into the model when required to produce future site suitability maps for Mozambique tilapia pond aquaculture.

In view of the above discussion, this study will create a Mozambique tilapia specific pond aquaculture site suitability GIS model. This model will be used to create site suitability maps. These maps will be used to evaluate the suitability of the entire surface area of the Limpopo province of South Africa for Mozambique tilapia

(Oreochromis mossambicus) pond aquaculture. Using these suitability maps, specific existing tilapia farmers will be scored and ranked using their GPS positions on the suitability maps. These suitability maps will be produced by overlaying the required variables using the Weighted Overlay (WO) and Weighted Sum Overlay (WSO) functions in Environmental Systems Research Institute, Inc. (ESRI) Esri ArcMap 10 (Esri, 2016). This model will be able to accommodate climatic data from future Global Circulation Models (GCMs) to delineate the future site suitability of any chosen fish species for pond aquaculture and the delineation of future fish sanctuaries.

1.3 Research questions

In the light of the above considerations, the following questions will guide the research process:

i. How can a Mozambique tilapia *(Oreochromis mossambicus)* pond aquaculture site suitability model be designed, which should contain only some of the most crucial variables and their respective thresholds in a Multi Criteria Evaluation (MCE) Geographic Information System (GIS) environment?
ii. How can the designed suitability model be used to produce a Mozambique tilapia pond aquaculture site suitability map for the entire surface area of the Limpopo Province?
iii. How can the created suitability outputs be used to score and rank specific existing tilapia farmers' suitability using their current GPS locations?

1.4 Research aim and objectives

This section defines the research aim and objectives pertaining to the thematic considerations communicated in section 1.2.

The aim of this study is to produce a Mozambique tilapia *(Oreochromis mossambicus)* pond aquaculture Site Suitability Model in a Geographic Information System (GIS) environment and to use this model to create a Mozambique tilapia pond aquaculture site suitability map for the entire surface area of the Limpopo Province. The suitability map will be used to classify, score, and rank specific existing aquaculture farmers based on their current GPS locations in terms of the Mozambique tilapia pond aquaculture site suitability map. This model should also be designed to be easily

duplicated and expandable to other eight South African provinces and as well as other regions or countries. The desired outcome and reason for this research, was the hope that through the creation of the model; to produce the suitability products and maps, these suitability outputs would be used by government and other funding stakeholders. These suitability outputs were envisioned to provide information to funders on where to concentrate their investment efforts more effectively, for instance on the more suitable areas. This could help to avoid wasting funding on unsuitable areas and ultimately to grow aquaculture in South Africa.

In view of the above Aim, the following Research Objectives will guide my research:

i. To design a Mozambique tilapia *(Oreochromis mossambicus)* pond aquaculture site suitability model, based in a Geographic Information System (GIS) Multi- Criteria Evaluation (MCE) environment using only some of the most crucial variables and their respective thresholds pertaining to site suitability.
ii. To use the designed model to produce a Mozambique tilapia pond aquaculture site suitability map for the entire surface area of the Limpopo Province.
iii. To use the created Mozambique tilapia pond aquaculture site suitability map to score and rank specific existing tilapia aquaculture farmers in the Limpopo Province based on their current GPS locations.

1.5 Theoretical considerations and Literature Review

Global human population growth-rate projections estimate that from 7.7 billion people in 2019, there will be an increase to 8.5 billion humans on earth by 2030. Projections estimate a further rise to 10 billion people by the year 2050. By 2100, there will be an estimated 11.2 billion people on earth (UNDESA, 2015; UNDESA, 2019b). Some factors linked to population growth are; “sustainable food consumption”,” sustainable food production”, and ”food insecurity” (UNDESA, 2021).

Many definitions of food insecurity often include indicators such as “hunger” or undernourishment” (FAO et.al., 2019). A new indicator, Indicator 2.1.2 of the Sustainable Development Goals (SDG), is based on the Food Insecurity Experience Scale (FIES) (FAO et. al., 2019). This new indicator addresses the concept of “the prevalence of moderate to severe food insecurity”. This indicator of global food

insecurity is relevant to all countries (FAO et. al., 2019). The goal is to ensure access to nutritious and sufficient food for all (FAO et. al., 2019).

One way to improve the access to nutritious and sufficient food is to increase the intake of fish in the human diet (Berg, et al, 2021; FAO, 2018; Österblom, et al, 2016b; Perschbacher, 2014). Fish is a source of complete protein (contains all nine (9) types of essential amino acids) (WebMD, 2021b). Fish provides a range of micronutrients and essential fatty acids (Berg et al, 2021; FAO, 2018). One such type of nutritious fish is the Tilapia, which is a warm-water fish, native to the Middle East and Africa. Two of the main species of Tilapia in Africa are the Mozambique tilapia *(Oreochromis mossambicus*) and the Nile tilapia *(Oreochromis Niloticus)* (Zengeya et. al., 2012). The health benefits associated with eating Tilapia fish can be attributed to the high amounts of nutrients it contains. These nutrients include vitamins and minerals like choline, niacin, vitamin B12, vitamin D, selenium, and phosphorus as well as omega-3 fatty acids, which are healthy fats (WebMD, 2020). Compared to beef, pork, chicken and turkey, Tilapia contains more omega-3 fats (WebMD, 2021a)

World fish consumption and the percentage of fish in the human diet has increased and will keep increasing (FAO, 2018; FAO et. al., 2019). Per capita fish consumption in Africa and South Africa are also on the increase (FAO, 2018; FAO et. al., 2019).

An increasing demand for fish from a growing world population as well as other factors such as climate change have placed a huge demand on wild caught fish (Österblom, et. al., 2016a). This has created overfishing. Wild capture fish stocks have been declining since 1996 (Österblom et. al., 2016a). Aquaculture is the farming of aquatic organisms (Österblom, et al, 2016b). The trend of stagnating wild captured fish volumes has created an opportunity for aquaculture to supply fish to the growing world population (Berg et. al, 2021). On a global scale, aquaculture percentage production has increased faster than other sources of animal protein, such as poultry, beef and dairy products (Österblom, et al, 2016b). Aquaculture Provides employment and contributes to the growth of GDP (Troell, et al, 2014). In terms of aquaculture for human consumption, aquaculture production exceeded capture fisheries production for human consumption by 2016 (FAO, 2020a) In 2018, aquaculture production for

human consumption contributed 52% of the total harvest weight of aquatic animals (FAO, 2020a, FAO, 2020b).

Aquaculture has significant potential to contribute to the Sustainable Development Goals (SDGs), such as reduced hunger, reduced poverty, and improved human health and wellbeing (Berg et. al, 2021). Aquaculture has the potential to increase food security, improve rural livelihoods and increase income, especially for resource poor female farmers in rural communities and for low-income food-deficit countries (LIFDCs), (HLPE, 2014). Is South Africa, the increase of inland freshwater aquaculture was indicated for the improvement of food security (Meaden and Kapetsky, 1991).

South Africa has had a positive human population growth rate from 1960 to 2022 (Worlddata.info, 2022), and an increase from 2022 to 2023 of 0.87% (Stats SA, 2022) South Africa's total population is projected to grow steadily from 2024 to 2029, increasing by approximately 4.9 million people (7.75%). By 2029, the population is expected to reach a peak of 68.06 million, marking the tenth consecutive year of growth. This trend reflects a consistent population increase in recent years (Statista, 2025).

There is the prevalence of poverty, unemployment, and food insecurity, especially amongst small-scale, subsistence rural households of which many are female headed (Statistics SA, 2019). Not only can aquaculture contribute to food security, but also an increase in employment and the improvement of rural livelihoods, leading to economic and social development (Meaden and Kapetsky, 1991; Berg et. al, 2021).

Aquaculture production in Africa is low compared to the other regions of the world and contributed to only 2.5% of the global aquaculture production in 2016 (Berg et al, 2021). The progress of aquaculture development in Africa remains relatively slow (Berg et al, 2021). Africa lagged in aquaculture development compared to the rest of the world, contributing only 2.7% to global production in 2018 (Adeleke et al., 2021). Despite extensive research and investments by governments and donors in the past five decades, aquaculture development in Sub-Saharan Africa (SSA) has had only limited success and is still not fully realising its high potential (Berg et al, 2021). By 2014, aquaculture in Sub Saharan Africa was undergoing a more promising phase of growth, after numerous failed starts (Berg et al, 2021).

Fish currently provides 19% of the animal protein intake of people in Africa (Berg et al, 2021; FAO, 2018: Perschbacher, 2014). South Africa's contribution to Africa's aquaculture production was 0.28% in 2018 and 0.01% of the global share (Adeleke, et al., 2021). In South Africa, the Department of Trade and Industry (the DTI) and the Department of Agriculture, Forestry and Fisheries (DAFF) guidelines for the Aquaculture Development and Enhancement Programme (ADEP) as well as Operation Phakisa's goal E7C, is strengthening the emerging aquaculture producers through increasing value chain ownership and the establishment of an Aquaculture Development Fund (ADF) (Operation Phakisa, 2021).

In South Africa, the farmed fish species are marine and freshwater (Operation Phakisa, 2021). Freshwater species mostly used in aquaculture are tilapia and trout (Operation Phakisa, 2021). Tilapia is a palatable, inland, fresh- warm-water fish species used for aquaculture in many countries (Perschbacher, 2014). Worldwide tilapia is the second most farmed species (Perschbacher, 2014). Tilapia is referred to as the aquatic chicken (Perschbacher, 2014). In South Africa, two types of tilapias are produced. The first is the exotic, Nile tilapia *(Oreochromis niloticus)*, for which a special permit, in RAS systems only, is required in six of the nine provinces in South Africa. The exempted provinces are Limpopo, Mpumalanga and Kwa-Zulu Natal. The second type of tilapia produced is the indigenous Mozambique tilapia *(Oreochromis mossambicus)*. The Nile tilapia is a faster grower and more robust and many farmers prefer to utilize it for aquaculture activities (Zengeya et al, 2012). Most tilapia farmers in South Africa are small-scale farmers and they employ recirculation and pond culture systems (Urban-Econ, 2018). The production of fish in earth ponds are relatively affordable aquaculture production systems, relatively simple to construct and easier to maintain than some of the other aquaculture production system types (Aquaculture Innovations, 2010).

Mozambique tilapia aquaculture is already practiced in the Limpopo province, and permits are required to farm with its congeneric, the invasive Nile tilapia *(Oreochromis niloticus)* (Zengeya et al, 2012). This invasive fish species is alien to the Limpopo province (IUCN, 2021, Zengeya et al, 2012). It is a threat to the survival of the Mozambique tilapia, as it inhabits similar physical environments due to its niche overlap similarities (Zengya et al, 2012). In terms of tilapia production volumes, the Limpopo province accounts for the highest share (37%) of South Africa's tilapia

production, followed by the Northwest (26%) and the Gauteng Province (18%) respectively. The remaining five provinces (Eastern Cape, KwaZulu-Natal, Mpumalanga, Northern Cape, and the Western Cape) collectively account for 19% of the total Tilapia production in South Africa (DFFE, 2022; Urban-Econ, 2018). The Limpopo Department of Agriculture (LDA) indicated that the Mozambique tilapia *(Oreochromis mossambicus)* was an ideal inland, freshwater aquaculture species for the Limpopo Province (DEA, 2012; Phoza, 2018). The Mozambique is indigenous to the Limpopo province (IUCN, 2021; Urban-Econ, 2018). The Limpopo Province is situated in the North-eastern part of South Africa on the borders with Botswana and Mozambique. The Limpopo province is an ideal pilot study area due to the large area of habitat of the Limpopo Province that contains the native range of the indigenous Mozambique tilapia *(Oreochromis mossambicus)* (IUCN, 2021; Urban-Econ, 2018).

The South African government has given priority to aquaculture via its National Development Plan (NDP) up to 2030. This creates an opportunity for aquaculture to alleviate poverty and unemployment as well as address inequality. By government investing in the growth of aquaculture, enhanced food security can be achieved when striving for these targets. The goals of the NDP are also supported by the National Aquaculture Policy Framework plan, which is focussed on targeting growth in the aquaculture sector. These growth targets are supported by another initiative, the National Aquaculture Strategy and Action Plan, which amongst others, was aimed at doubling aquaculture production by 2020 (Britz and Venter, 2016).

Operation Phakisa is one of the mechanisms that the South African government has put in place to facilitate the goals of the National Development Plan (NDP) (Ginindza, 2021). Government, organised business, labour, and citizens are encouraged to co-operate to improve economic growth, leading to the alleviation of unemployment, poverty, and inequality. The Aquaculture Development Zones (ADZ) are part of one of the initiatives of Operation Phakisa (Operation Phakisa, 2021). These and many other initiatives by the South African government to develop aquaculture, also on a commercial scale (via the Industrial Policy Action Plan, support by the Department of Trade and Industry (DTI) under the Aquaculture Development Enhancement Programme (ADEP) (Britz and Venter, 2016; WAS, 2017). Government and other decision makers like funders, require information regarding where to focus and invest

their attention, assistance, and fiscal resources sustainably and effectively (Bandira, et al, 2021).

Site suitability pertains to the identification of the most suitable areas for a pond aquaculture farm making use of different variables that determine the suitability of that site for a specific type of fish species. The site suitability exercise should be done in advance to increase the chances of a pond aquaculture enterprises' success, its sustainability and profitability (Meaden and Kapetsky, 1991). Many variables could determine the economic, geographic or socio-economic suitability of a site for pond aquaculture. (Falconer, et al, 2020; Aquaculture Innovations, 2010; Francisco, et. al, 2019; Hossain et. al., 2007; Meaden and Kapetsky, 1991; Steer, 2006). Geographic Information Systems (GIS) can be used to collect, analyse, model and display these variables spatially and create site suitability maps (Falconer, et al, 2020; Aquaculture Innovations, 2010; Francisco, et. al, 2019; Hossain et. al., 2007; Meaden and Kapetsky, 1991; Steer, 2006). Combining the Multi Criteria Evaluation (MCE) (Saaty, 1977) method with site suitability modelling in a GIS is an effective way of assigning appropriate weights to the different variables (Bandira, et al, 2021; Nayak et al, 2018; Hossain et al., 2007).

Water temperature is one of the most important variables in determining aquaculture site suitability as it affects fish growth and -survival (Aguilar-Manjarrez and Nath, 1998; Aquaculture Innovations, 2010). The use of surface air temperatures as proxies for water temperatures in suitability modelling and to calculate water temperatures are well-documented (Aguilar-Manjarrez and Nath, 1998; Kapetsky, 1994; Morrissy, 1976). Stream water temperatures for the entire United States were estimated from regressions between water temperatures and air temperatures at nearby weather stations. This method is described as easy and practical (Mohseni et. al., 1999). In addition, these methods are preferred for climate change studies as only one input variable, air temperature, is used in General Circulation Models (GCSs) (Mohseni and Stefan, 1999). Amongst regression models, linear models are easier to use and more common (Mohseni, et. al., 1999). Air temperature is often used to estimate pond water temperature ([Klemetson and Rogers, 1985; Wax and Pote, 1990)] In: Boyd and Tucker, 1998). Researchers indicated that a change in air temperature associated with climate change could cause changes in water temperature (Carpenter et. al. 1992;

Singh et al, 2021; Mohseni and Stefan, 1999). Air-temperature changes could influence fish growth, reproduction, and survival (Nath, 1996).

The global average (land and ocean) surface temperature shows an average warming of 0.85 °C in the period 1880 to 2012, based on multiple independently produced datasets (IPCC, 2013). For the period 1901 to 2012, almost the entire globe has experienced surface warming (IPCC, 2013). It is predicted that surface temperatures are likely to exceed a rise of 2°C during the 21st century under all assessed emission scenarios (IPCC, 2014). Warming will continue beyond 2100 under most scenarios. Global warming will continue to exhibit inter-annual-to-decadal variability and will not be regionally uniform (IPCC, 2013). There was a rapid rise in observed annual average near-surface temperatures over Africa (˚C) from 1961 to 2010 (Engelbrecht et.al, 2015).

Global warming and climate change are fundamental threats to food security across the globe (FAO, 2016). Mitigation and adaptation to climate change should be on every country's agenda (FAO, 2016). Without future policies to limit greenhouse gas emissions, climate change models predict an increase of between 1°C to 4.5°C from the late 20th to the middle 21st century over South Africa (Carbon Brief, 2018; Collins et al, 2013). Temperature increases that were predicted under low mitigation, range from 1 ˚C to 2 ˚C (2021-2050) to up to 4 ˚C to 7 ˚C for the interior of South Africa (Engelbrecht, 2019). Studies of livelihoods in the Limpopo Province in South Africa, used temperature changes as proxies to estimate that Southern African households were susceptible to climate variability and drought (Tshiala, et. al., 2011). Evidence of rising temperatures over the Limpopo province and potential links to the hydrological cycle, impacts on agriculture and water resources, need to be explored in future research (Tshiala, et. al, 2011).

Research published in 2015 on the suitability of aquaculture, was conducted on a global scale and produced suitability maps for tilapia in general (Handisyde, 2015). Pond aquaculture suitability maps for Africa were produced in 1998 during a strategic reassessment of fish farming potential in Africa on a continental scale. This research focused on three warm water fish species collectively: The Nile tilapia *(Oreochromis niloticus)*, Sharptooth catfish *(Clarias Gariepinus)* and the Common carp *(Cyprinus carpio)*. These suitability maps had a spatial resolution of 5 km x 5 km grid cells

(Aguilar-Manjarrez and Nath, 1998). There is thus a gap in knowledge due to the absence of known Mozambique tilapia-specific, inland, fresh-water pond–based aquaculture site suitability maps, applicable on farm to regional scale, for South Africa specifically, using in-house soil-, economic- and climate data (with a 1 km by 1km spatial resolution). The research for this dissertation is thus crucial in directing fiscal and other support in an effective way to farmers as well as the province in general and on a broader scale.

In this research a Mozambique tilapia *(Oreochromis mossambicus)* specific, freshwater pond aquaculture GIS site suitability model was developed. This model was used to create Mozambique tilapia pond aquaculture site suitability maps. These suitability maps were used to score and rank the site suitability of several current tilapia aquaculture farmers based on their GPS locations in the Limpopo province, which were collected during fieldwork for this research. This suitability was designed to be simple, robust, easily duplicable for easy transfer to other users in a GIS, expandable to any of the other eight provinces of South Africa and be applicable from farm scale to country level. The model will also be designed to accommodate spatial climate-change air- or water-temperature data in order to create future Mozambique tilapia pond aquaculture and -sanctuary site suitability maps.

1.6 Delimitation

Site suitability modelling executed in a GIS environment encompasses a vast array of possible variables and methods which could be used to determine the suitability of a chosen location or area (Falconer, et al, 2020; Aquaculture Innovations, 2010; Francisco, et. al, 2019; Hossain et. al., 2007; Meaden and Kapetsky, 1991; Steer, 2006). Only the most crucial variables which determine site suitability were chosen and incorporated into the model produced in this research. In Chapter 6, Conclusions and Recommendations, additional suitability variables are suggested to add to the model to make it more oriented towards commercialisation of the aquaculture enterprises.

As explained in Section 1.2, this research focussed on the pilot study area, which was the Limpopo Province of South Africa. This is due to the fact that most of the province’s surface area is home to the indigenous Mozambique tilapia (Bills, 2019). However, the

variables and their thresholds included in the model, which specifically pertain to freshwater earth-pond aquaculture for Mozambique tilapia suitability, can be changed or modified in the suitability model, to incorporate other fish species' temperature thresholds. If a GIS user has the required input data layers for any or all of the other eight provinces, and /or other fish species, the model variable thresholds can be changed. In this way the model can be populated with the new layers to produce suitability maps for other areas and / or different fish species.

The suitability maps that were created from the suitability model by weighted Sum Overlay (WSO) as well as Weighted Overlay (WO), were used to score and then rank the current suitability of the known, existing tilapia farmers according to their GPS positions on the maps. There may be other existing farmers which might be more deserving of aid due to their location being more favourable, but if their existence is not known, only the farmers provided on the list on record from the Limpopo Department of Agriculture (LDA, 2018) at the time of the field work (2018) could thus be scored and rated.

The original suitability model was later divided into eight steps. The fact that the model was split up into different, smaller components, facilitated easier recognition of map production phases as well as improved model stability and shortened execution run-time. The insertion of alternative layers is easier and simplified due to the splitting the model. However, the user must be in possession of these spatial layers pertaining to the other provinces. Collecting spatial data from scratch may take considerable time.

The suitability model was designed to be able to incorporate and process climate change data from General Circulation Models (GCMs). Ultimately, predicting future suitability based on future air- or water temperature data, is dependent on the accuracy of the GCM's predictions. Additionally, as with all spatial models and maps, these are all representations of reality, and not reality itself. Models are thus limited to the quality of the input data and the reliability of the source data.

Environmental Systems Research Institute, Inc. (Esri) had announced that their ArcMap 10 software (Esri, 2018), in which the model for this research was created using its Model Builder environment (Esri, 2018), will be migrated (or no longer be for sale) from 31 March 2024. However, the suitability model created in this research was generated firstly by using the Pairwise Comparison Matrix (PCM) (Saaty, 1977)

method on the Multi-Criteria Evaluation (MCE) scale of one to nine (Eastman, et.al, 1995), which is computed independent of spatial software. The overlay process that was used in ArcMap 10, for overlaying the relative weights of the variables, Weighted Linear Combination (WLC), as used by Ssegane et.al, (2012), can be selected in the Esri ArcGIS-Pro (Esri, 2023c) software package's functionality as well (De Munnik, R., 2023: Personal communication) making use of the Weighted Overlay (WO) and Weighted Sum Overlay (WSO) tools in ArcGIS-Pro (Esri, 2023c) as in ArcMap 10 (Esri, 2018) versions. Furthermore, the model in the ArcMap 10 Model Builder environment, can be seamlessly transferred into the Model building environment of ArcGIS-Pro without any prior configuration required (De Munnik, R., 2023: Personal communication).

The model and its products will be accessible to three types of users. Firstly, the GIS user, to change and populate the model for other provinces or species of fish and to generate the suitability maps. Secondly, the map user, for decision making by funders and other stakeholders. Thirdly, by farmers or potential farmers and aquaculture extension officers and other officials requiring suitability values in-field or at the office on an Application (App) platform, hosted by the software developing company, Esri. Having three tiers of users has pros and cons, in that the lower tier users will not be able to create the maps from the shared model, but users on all tiers will be able to use the AQUASUIT App to determine the suitability of a GPS location or an area. The middle tier user will not be able to query the map in the software in-office like the GIS user, but that is where their use of the App functionality is applicable. To operate the ArcMap 10 or ArcGIS-Pro software, a licence is required, but at the same time, also guarantees professional user support from the software vendor. The choice of the software company, Esri, hosting the App platform, always ensures quality and availability of the suitability products for usability and accessibility, both online and offline (De Munnik, R., 2023: Personal communication), If the software vendor hosts and maintains the App, this will need to be financed.

This GIS research was done to, amongst others, illustrate the capabilities and strengths of using a GIS for pond aquaculture site selection, rather than other more traditional methods, such as word of mouth or trial and error (Steer, 2006). Utilising a GIS for the purpose of site selection, will save time and assist in avoiding the funding of unsuitable sites or areas (Steer, 2006). However, as with all models and software

functionalities, no GIS is perfect, and is not reality, but a model of reality. The choice of fuzzy- or crisp overlay as well as other overlay methods, could yield slightly different suitability results (Malczewski, 2000; Ssegane, et, al, 2012).

1.7 Ethical considerations

In-field farm visits for the purpose of collecting additional information on each farmer's situational analyses, from the 48 available aquaculture farmers at the time (2018) yielded much information, amongst others, their GPS locations, and some form of identifying them for later use in the assistance phase (but which does not form part of this research). However, for this study and research, only the GPS locations collected from the known existing aquaculture farmers were utilized and no situational analyses information that were recorded, were utilised, or displayed or made known in any way, shape, or form. These situational analyses data collected in the form of filling in questionnaires, might be useful for future research. Like the selecting process of candidates suitable for assistance or additional suitability analyses. However, only numerical identifiers in the form of numerical order of visitation was utilised and disclosed in this research for suitability rating and scoring from their GPS locations. This research thus encompasses a desktop GIS study only to draw suitability conclusions from suitability products. The identities of the farmers and their contact details were not disclosed in the thesis document or any publications or oral communications pertaining to the obtained results from the research contained in this thesis document. The information will be stored for the later stages of a larger funding project of which this research is part. Kindly refer Appendixes A, B, C and D for the situational analyses forms and the ethical clearance obtained to visit the then known farmers in Limpopo.

1.8 Structure of dissertation

This dissertation starts off with Chapter 1, Frames of Reference, which encompasses a condensed description of the entire thesis document. Chapter 2, Theoretical Considerations and Literature review, describes the literature reviewed on the topics of human population growth and its link to food insecurity, human fish consumption, how to achieve food security through aquaculture, the biological and geographical and physical environment specifically required by the aquaculture fish species chosen for

this research, the indigenous Mozambique tilapia *(Oreochromis mossambicus)*. Further literature reviewed focussed on the use of a Geographic Information System (GIS) in a Multi Criteria Evaluation (MCE) model environment to determine aquaculture pond site suitability. The literature review continued with global warming and climate change. It then concludes on how the existing South African government initiatives on aquaculture development could benefit from accurate site suitability models and maps to improve their investment initiatives to grow aquaculture in South Africa. Following Chapter 2 is Chapter 3, Methodology, which describes the researcher's philosophical standpoint which influenced the approach of the research design as well as the design of the suitability model in a GIS. Chapter 3 further describes the research site, the methodology applied in designing and execution of the model and the classification of the produced suitability maps. Chapter 3 concludes by describing the method of the scoring and ranking of the known existing aquaculture farmers. Chapter 4, Results, addresses the findings from the outputs achieved by executing the methodology applied to the model, the production of the suitability maps and the scoring and ranking of the farmers. Chapter 5, Discussion, explains the reasoning for the findings in Chapter 4. The dissertation ends with Chapter 6, Conclusions and Recommendations. Chapter 6 is a synthesis chapter containing conclusions on the achievement of the aim and objectives and suggestions on the utilisation of the model and suitability products. The importance of this research, which was ultimately to assist with aquaculture funding decision making, to help grow aquaculture in South Africa, is followed by recommendations on the application of the model and products as well as further suggestions for future research.

Chapter 2

Theoretical Considerations and Literature Review

2.1 Introduction

This chapter contains the review of literature with regards to various aspects of this research. These aspects include the challenge of food insecurity and the role that aquaculture could play in possible alleviation thereof. Mozambique tilapia *(Oreochromis mossambicus)* pond aquaculture site suitability is investigated, utilising the GIS modelling environment. Possible ways in which investing in the most suitable locations by funders, could lead to aquaculture growth, is explored. The chapter concludes with the identification of a possible gap in knowledge pertaining to pond aquaculture site suitability.

2.2 Human population growth

Global human population growth-rate projections estimate that the figure of 7.7 billion people in 2019, will increase to 8.5 billion humans on earth by 2030. Projections estimate a further rise to 10 billion people by the year 2050. By 2100, there will be an estimated 11.2 billion people on earth (UNDESA, 2015; UNDESA, 2019b).

Africa exceeds the global human population growth rate of 1.1 %, with a figure of 2.5%. Sub-Saharan Africa could account for more than half of the growth of the world's population between 2019 and 2050, and the region's population is projected to continue growing through the end of the century (UNDESA, 2019a; UNDESA, 2019b; UNDESA, 2019c). South Africa's current population is 58.8 million, with a growth rate of 1.4% (UNDESA, 2019a, World Bank, 2019, Stats SA, 2019).

As the South African human population continues to grow, there exists poverty, unemployment, and food insecurity, especially amongst small-scale, subsistence rural households of which many are female headed (Statistics SA, 2019).

2.3 Food insecurity

There exists a link between population growth and food insecurity (UNDESA, 2021; PAI, 2011; FAO, 1991; FAO, et. al, 2019). Many definitions of food insecurity often

include indicators such as “hunger” or undernourishment” (FAO et.al, 2019). A new indicator, Indicator 2.1.2 of the Sustainable Development Goals (SDG), is based on the Food Insecurity Experience Scale (FIES) (FAO et. al., 2019). This new indicator addresses the concept of “the prevalence of moderate to severe food insecurity”. This indicator of global food insecurity is relevant to all countries (FAO et. al., 2019). The goal is to ensure access to nutritious and sufficient food for all (FAO et. al., 2019).

Sub-Saharan Africa, with the highest population growth rate in the world, holds the largest proportion of food-insecure people, with one in four people undernourished (PAI, 2011).

2.4 Access to nutritious and sufficient food

One way to improve the access to nutritious and sufficient food is to increase the intake of fish in the human diet (Berg, et al, 2021; FAO, 2018b; Österblom, et al, 2016b; Perschbacher, 2014). Billions of people worldwide rely on fish for protein, but fisheries are close to their biological limit (FAO et al, 2019, WWF, 2015). Fish is a source of complete protein, as it contains all nine of the essential amino acids (WebMD, 2021b). Fish provide a range of micronutrients and essential fatty acids (Berg et al, 2021; FAO, 2018b).

The health benefits associated with eating Tilapia fish can be attributed to the high amounts of nutrients it contains. These nutrients include vitamins and minerals like choline, niacin, vitamin B12, vitamin D, selenium, and phosphorus as well as omega-3 fatty acids, which are healthy fats (WebMD, 2020). Compared to beef, pork, chicken and turkey, Tilapia contains more omega-3 fats (WebMD, 2021a).

2.5 Fish consumption

World fish consumption and the percentage of fish consumed by humans have increased, and both will keep increasing (FAO, 2018b; FAO et. al., 2019). Fish currently provides 19% of the animal protein intake to people in Africa (Berg et al, 2021; FAO, 2018: Perschbacher, 2014).

2.6 Per capita fish consumption

World annual per capita fish consumption has increased from 5.2 kg in 1961 to 17.8 kg in 2010 and a continued increase was projected (FAO, 2014). By 2016 this figure rose to above 20 kg per year for the first time due to greater aquaculture supply and a higher demand for it (FAO, 2016). In 2022 the per capita fish consumption was at 20.2 kg per capita per year (FAO, 2022).

Per capita fish consumption in Africa and South Africa were also on the increase (FAO, 2018; FAO, 2019b). However, by 2022 it was reported that the varying per capita fish consumption across Africa, was mostly quite low in comparison to the world average (except for eleven African countries with a higher per capita fish consumption than the world average) (FAO, 2022). The low fish consumption in the remainder of Africa was expected to decline even further in the next 10 years. This was predicted due to, amongst others, the high population growth rate (which was higher than the growth rate of capture fisheries) and the relatively small aquaculture sector. If this decline were to take place as predicted up to 2032, it could threaten food security, due to the high existence of undernourishment in the region. Aquatic food can contribute to the intake of animal proteins in these African countries (FAO, 2022).

2.7 Aquaculture as a solution to food insecurity and unemployment

Food insecurity can be addressed by modifying coping responses to food insecurity, the regaining of food security is possible (Peng and Berry, 2019). Aquaculture is one such a solution by producing more food, in the form of fish, which can reduce food insecurity, create income and improve rural livelihoods. Investment in aquaculture, particularly in the small-scale farming sector, is considered vital as it forms the backbone of Africa's rural economy (Wambua, 2018). Despite half a century of support from external funders, these efforts have largely been unsuccessful, often due to aquaculture being promoted in unsuitable regions with unfavourable climates, insufficient infrastructure, or limited market access (Wambua, 2018). Yet, aquaculture holds substantial potential to enhance food security, create employment, and generate income for vulnerable small-scale rural households (Bosma and Verdegem, 2011; Shava and Gunhidzirai, 2017).

Aquaculture is the farming of aquatic organisms (Österblom, et al, 2016b). Aquaculture is playing an increasing role in protein supply, economic growth and the fight against hunger and malnutrition (FAO, 2018b; FAO, 2019a). Aquaculture provides employment and contributes to the growth of GDP (Troell, et al, 2014).

Aquaculture has significant potential to contribute to the Sustainable Development Goals (SDGs), such as reduced hunger, reduced poverty, and improved human health and wellbeing (Berg et. al, 2021). Aquaculture has the potential to increase food security, improve rural livelihoods and increase income, especially for resource poor female farmers in rural communities and for low-income food-deficit countries (LIFDCs), (HLPE, 2014). In South Africa, the increase of inland freshwater aquaculture was indicated for the improvement of food security (Meaden and Kapetsky, 1991).

Aquaculture has grown faster than any other agricultural produce over the last few decades. In 2013 aquaculture was still the fastest growing agri-food industry in the world, and was predicted to continue to grow globally, although at a reduced growth rate from 2000 to 2030 (World Bank, 2013). Aquaculture is still enjoying one of the highest growth rates in the agri-food industry and is still achieving double-digit growth rates in Africa (FAO, 2018a; FAO et al, 2019).

Compared to other sources of animal protein, globally, aquaculture has grown faster percentage wise than poultry, beef and dairy products (Österblom, et al, 2016b).

Aquaculture was providing more fish for human consumption than wild captured fish (Troell, et al, 2014). Aquaculture contributed 9% of global fish production for human consumption in 1980 compared to 47% in 2010 (Isaacs and Hara, 2015) and rose to approximately 50% in 2012 (FAO, 2014).

Africa has lagged behind in aquaculture development, contributing only 1.5% to global production by 2012. South Africa's contribution to Africa's production was less than 1% in 2012 (Isaacs and Hara, 2015). Later data relating to aquaculture development in Africa, state that Africa only contributed 2.7% to global aquaculture production in 2018 (Adeleke et al., 2021). Aquaculture production in Africa is low compared to the other regions of the world and contributed 2.5% of the global aquaculture production in 2016, and the progress of aquaculture development in Africa remains relatively slow (Berg et al, 2021).

However, South African, as the rest of African aquaculture production, is growing at an increasing rate (FAO, 2014). There was an 8.7 percent overall sector growth rate from 2005 to 2013. Aquaculture contribution to total SA fish production in 2012 was 0.8 percent. Aquaculture's contribution to the South African GDP was 0.2 percent in 2016 (Britz and Venter, 2016). South Africa's contribution to Africa's aquaculture production was 0.28% in 2018 and 0.01% of the global share (Adeleke, et al., 2021).

Despite extensive research and investments by governments and donors in the past five decades, aquaculture development in Sub-Saharan Africa (SSA) has had only limited success and is still not fully realising its high potential (Berg et al, 2021). By 2014, aquaculture in Sub Saharan Africa was undergoing a more promising phase of growth, after numerous failed starts (Berg et al, 2021).

For example, implementing fish farming in drought-prone areas of Zimbabwe has been shown to improve food security, dietary diversity, and household income, while also mitigating poverty among communities affected by climate change (Shava and Gunhidzirai, 2017). Fish production provides a valuable protein source, complementing the limited availability from overexploited fisheries (Bosma and Verdegem, 2011). However, while aquaculture has shown robust growth in suitable regions globally, it has not experienced similar success in most of Sub-Saharan Africa (Njagi and Huka, 2013).

Aquaculture can significantly alleviate food insecurity by providing protein, sustainable livelihoods, and income, particularly for South Africa's growing population (Shava & Gunhidzirai, 2017). Despite high potential, tilapia production remains low in most Southern African countries, with government and donor programmes having limited success in the past four decades (Moyo & Rapatsa, 2021). Zambia has recently experienced growth in tilapia production, Moyo and Rapatsa (2021).

In other Southern African countries namely, South Africa, Namibia, Botswana, Mozambique, Malawi, and Eswatini, tilapia production has remained low (Moyo and Rapatsa, 2021). In their study, Moyo and Rapatsa, (2021) physical, biological, and socio-economic factors that have affected tilapia production in the region were identified, but only after these farmers were funded without any mention of suitability studies with a GIS. Economic factors, the choice of the tilapia species and the production system to be used were identified as the key factors affecting tilapia

production in the region. However, their counterargument against seeing pond tilapia as a solution to food security, is that the overriding factor affecting tilapia aquaculture production in Southern Africa is the lack of profitability. They argue that Tilapia culture is not profitable because of the cheaper wild caught tilapia and the Chinese imported tilapia. They suggest a paradigm shift in the way aquaculture is viewed, being instead of looking at aquaculture as a poverty alleviation tool it must be viewed as a business. A new approach in the training of fish farmers at a regional level is also suggested (Moyo and Rapatsa, 2021).

In South Africa, the farmed species are marine and freshwater (Operation Phakisa, 2021). Freshwater species are tilapia and trout (Operation Phakisa, 2021). Tilapia is a palatable, inland, fresh- warm-water fish used for aquaculture in many countries (Perschbacher, 2014). Most tilapia farmers in South Africa are small-scale farmers and they employ recirculation and pond culture systems. The production of fish in earth ponds are relatively affordable aquaculture production systems, simple to construct and easy to maintain (Aquaculture Innovations, 2010).

The Limpopo Department of Agriculture (LDA) indicated that the Mozambique tilapia *(Oreochromis mossambicus)* was an ideal inland, freshwater aquaculture species for the Limpopo Province of South Africa (DEA, 2012; Phoza, 2018) (as Mozambique tilapia aquaculture is allowed in Limpopo).

2.8 Fish production

An increasing demand for fish from a growing world population as well as other factors such as climate change have placed a huge demand on wild caught fish (Österblom, et. al., 2016a). This has created overfishing. Wild capture fish stocks have been declining since 1996 (Österblom et. al., 2016a). The trend of stagnating wild captured fish volumes has created an opportunity for aquaculture to supply fish to the growing world population (Berg et. al, 2021). Global fish production has grown steadily in the last five decades, with food fish supply increasing at an average annual rate of 3.2 percent, outpacing world population growth which was estimated at 1.6 percent (FAO, 2014).

Improved food security is listed in the second of the seventeen United Nations Sustainable Development Goals (SDGs), the 2030 Agenda for Sustainable

Development and the FAO Code of Conduct for Responsible Fisheries [(FAO, 1995) In FAO, 2018a]. By increasing inland, freshwater aquaculture, food security could be increased in South Africa (Meaden and Kapetsky, 1991; Britz and Venter, 2016).

Not only can aquaculture contribute to food security, but also an increase in employment and the improvement of rural livelihoods, leading to economic and social development (Meaden and Kapetsky, 1991; Berg et. al, 2021).

2.9 Mozambique tilapia

The Tilapia is one of the nutritious fish species. It is a warm-water fish, native to the Middle East and Africa. Worldwide tilapia is the second most farmed species (Perschbacher, 2014). Tilapia is referred to as the aquatic chicken (Perschbacher, 2014). Two of the main species of Tilapia farmed and present in Africa are the Mozambique tilapia *(Oreochromis mossambicus*) and the Nile tilapia *(Oreochromis Niloticus)* (Zengeya et. al., 2012). In South Africa, these two types of tilapias are also produced. The first is the exotic, Nile tilapia, for which a special permit, in RAS systems only, is required in 6 provinces, except Limpopo, Mpumalanga and Kwa-Zulu Natal. The second type of tilapia is the indigenous Mozambique tilapia *(Oreochromis mossambicus*). The Nile tilapia is a faster grower and more robust and farmers prefer to use it for aquaculture activities (Zengeya et al, 2012).

Many types of freshwater fish are suitable to aquaculture in South Africa, but of the many types of edible, inland, freshwater fish permitted by the South African government, the Mozambique tilapia *(Oreochromis mossambicus)* is the most suitable due to its palatability, marketability and conservational- and legal status (Urban-Econ, 2018).

The Mozambique tilapia can tolerate temperatures from 4.4 °C to 40 °C and it is also very resilient to organic waste, low oxygen levels, and many types of pollution (Tilapia Website, 2016). The most optimal water temperature range for Mozambique tilapia is 28°C to 30°C. South Africa has nine provinces, of which some suitable for Mozambique tilapia production. These are the Eastern Cape (except for the escarpment bordering Lesotho), Kwa-Zulu Natal (specifically Northern KZN and along the coastline), Mpumalanga, Northern Gauteng, and the Limpopo Province (Urban-Econ, 2018).

Most of the registered Mozambique tilapia farms are located in Gauteng, Limpopo, Mpumalanga, and the Northwest provinces respectively (Urban-Econ, 2018). In terms of production volumes, the Limpopo province accounts for the highest share (37%) of South Africa's tilapia production, followed by the North-West (26%) and the Gauteng Province (18%) respectively. The remaining five provinces (Eastern Cape, KwaZulu Natal, Mpumalanga, Northern Cape and Western Cape) collectively account for 19% of the total Tilapia production in South Africa (Urban-Econ, 2018).

The Limpopo province contains a large part of the native range of Mozambique tilapia according to the International Union for Conservation of Nature (IUCN) in southern Africa (Adapted from IUCN data in: Urban-Econ, 2018). The survival of the indigenous Mozambique tilapia in South Africa is however threatened by the presence of the invasive Nile tilapia *(Oreochromis niloticus).* The Nile tilapia was introduced into Lake Victoria for aquaculture in the 1950's from where it spread into South Africa. It is a faster growing, larger and more robust, invasive species with a similar niche habitat as that of *Mozambique tilapia* and is already present in some river systems of South Africa (Aquaculture Innovations, 2010; Zengeya, et.al, 2013; Zengeya, et.al, 2015).

The reported ranges of the Nile tilapia and the natural distribution of the Mozambique tilapia, overlap in many areas across South Africa (IUCN data in: Urban-Econ, 2018, and data from SAIAB data in: Van der Waal, 2014). The Nile tilapia poses an unacceptable risk to its congenerics, like the Mozambique tilapia, through the risk of extinction via hybridization and competition exclusion (Zengeya, 2013; Zengeya, 2015). The lack of effective protective measures has left the Mozambique tilapia vulnerable, and it needs to be protected as it is considered an ideal food aquaculture species and was approved for aquaculture activities in the South Africa by the then Limpopo Department of Agriculture (Van der Waal, 2014). In Limpopo, permits are required to farm with Nile tilapia in RAS systems, which at least presents some form of protection to Mozambique tilapia in this province (Aquaculture Innovations, 2010; Van der Waal, 2014). Mozambique tilapia aquaculture is already practised in the Limpopo province, and permits are required to farm with its congeneric, the invasive Nile tilapia *(Oreochromis niloticus)* (Zengeya et al, 2012). This invasive fish species is alien to the Limpopo province (IUCN, 2021, Zengeya et al, 2012). It is a threat to the survival of the Mozambique tilapia, as it inhabits similar physical environments due to its niche overlap similarities (Zengeya et al, 2012).

The Limpopo Province is situated in the North-eastern part of South Africa on the borders with Botswana and Mozambique. A large part of the Limpopo Province currently includes the native range of the indigenous Mozambique tilapia *(Oreochromis mossambicus)* (IUCN, 2021; Urban-Econ, 2018).

In terms of tilapia production volumes, the Limpopo province accounts for the highest share (37%) of South Africa's tilapia production, followed by the Northwest (26%) and the Gauteng Province (18%) respectively. The remaining five provinces (Eastern Cape, KwaZulu-Natal, Mpumalanga, Northern Cape and Western Cape) collectively account for 19% of the total Tilapia production in South Africa (Urban-Econ, 2018)

2.10 Site suitability

Site suitability pertains to the identification of the most suitable areas for a pond aquaculture farm making use of different variables that determine the suitability of that site for a specific type of fish species. The site suitability exercise should be done in advance to increase the chances of a pond aquaculture enterprises' success, its sustainability and profitability (Meaden and Kapetsky, 1991). Many variables determine the economic and geographic suitability of a site for pond aquaculture.

Instead of choosing an aquaculture site by word of mouth, trial and error or establishing fish farms at inappropriate sites, the most suitable areas could be delineated in advance using several spatial information layers in a Geographical Information System (GIS) (Francisco, et. al, 2019; Steer, 2006). This is a relatively cheaper and faster method than the traditional methods and could eliminate visits to potentially unsuitable sites (Steer, 2006).

Site selection is a vital factor in any aquaculture operation (Aquaculture Innovations, 2010; Hossain et. al., 2008). A suitable site will increase the chances of the enterprise being successful, sustainable, viable and profitable in the current physical and economic environment (Aquaculture Innovations, 2010; Hossain et. al., 2007).

2.11 Site suitability analysis using GIS

Geographic Information Systems (GIS) can be used to collect, analyse, model and display the variables, that pertain to suitability of a site, spatially and create site

suitability maps (Falconer, et al, 2020; Aquaculture Innovations, 2010; Francisco, et. al, 2019; Hossain et. al., 2007; Meaden and Kapetsky, 1991; Steer, 2006).

Geographic Information Systems (GIS) are ideal tools for conducting pond aquaculture site suitability analysis (Aguilar-Manjarrez and Nath, 1998; Assefa and Abebe, 2018; Ssegane, et. al, 2012; Hosain, et. al, 2007). GIS models can combine several environmental, economic, social, and other types of spatial information layers required to fulfil the requirements of a suitable environment for an inland pond fish farm (Salam, et. al, 2003).

Several types of spatial models exist that can be utilised in the GIS environment to delineate suitable aquaculture sites (Salam et.al. 2003). Multi Criteria Evaluation (MCE) can be used to score, weigh and rank factors in the spatial environment which have an influence on the suitability of a site for aquaculture as well as its yield potential (Aguilar-Manjarrez and Nath, 1998).

Combining the Multi Criteria Evaluation (MCE) (Saaty, 1977) method with site suitability modelling in a GIS is an effective way of assigning appropriate weights to the different variables (Bandira, et al, 2021; Nayak et al, 2018; Hossain et al., 2007).

A powerful suitability model can be developed by combining Multi Criteria Evaluation (MCE), using a Pairwise Comparison Matrix (PCM) (Saaty, 1977) to calculate the relative importance of each factor concerning the site suitability with the Analytical Hierarchy Process (AHP) (Saaty, 1977) (Francisco, et. al, 2019; Salam et.al., 2003; Ssegane, et. al, 2012).

Research on the suitability of aquaculture on a global scale, produced a suitability model and maps for tilapia in general (Handisyde, 2015). Pond aquaculture suitability maps for Africa were produced in previous research during a strategic reassessment of fish farming potential in Africa. This research focused on three warm water fish collectively: The Nile tilapia *(Oreochromis niloticus)*, Sharptooth catfish *(Clarias Gariepinus)* and the Common carp *(Cyprinus carpio)* on a continental scale, containing 5 km x 5 km grid cells (Aguilar-Manjarrez and Nath, 1998). There is no known Mozambique tilapia specific, inland, pond–based aquaculture suitability maps, on a regional scale, for South Africa, using in-house soil, economic and climate data. There is a need for this type of map produced in a GIS using MCE from an academically defendable, peer reviewed GIS model, which can be used at any scale.

2.12 Water temperature

Water temperature is one of the most important variables in determining aquaculture site suitability as it affects fish growth and -survival (Aguilar-Manjarrez and Nath, 1998; Aquaculture Innovations, 2010). The use of surface air temperatures as proxies for water temperatures in suitability modelling and to calculate water temperatures are well-documented (Aguilar-Manjarrez and Nath, 1998; Kapetsky, 1994; Morrissy, 1976). Stream water temperatures for the entire United States were estimated from regressions between water temperatures and air temperatures at nearby weather stations. This method is described as easy and practical (Mohseni et. al., 1999). In addition, these methods are preferred for climate change studies as only one input variable, air temperature, is used in General Circulation Models (GCSs) (Mohseni and Stefan, 1999). Among regression models, linear models are easier to use and more common (Mohseni, et. al., 1999). Air temperature is often used to estimate pond water temperature ([Klemetson and Rogers, 1985; Wax and Pote, 1990)] In: Boyd and Tucker, 1998).

2.13 Global warming and climate change

Researchers indicated that a change in air temperature associated with climate change could cause changes in water temperature (Carpenter et. al. 1992; Singh et al, 2021; Mohseni and Stefan, 1999). Air-temperature changes could influence fish growth, reproduction, and survival (Nath, 1996).

The global average (land and ocean) surface temperature shows an average warming of 0.85 °C in the period 1880 to 2012, based on multiple independently produced datasets (IPCC, 2013). For the period 1901 to 2012, almost the entire globe has experienced surface warming (IPCC, 2013). It is predicted that surface temperatures are likely to exceed a rise of 2°C during the course of the 21st century under all assessed emission scenarios (IPCC, 2014). Warming will continue beyond 2100 under most scenarios. Global warming will continue to exhibit inter-annual-to-decadal variability and will not be regionally uniform (IPCC, 2013).

Global warming and climate change are fundamental threats to food security across the globe (FAO, 2016). Mitigation and adaptation to climate change should be on every

country's agenda (FAO, 2016). There was a rapid rise in observed annual average near-surface temperatures over Africa (˚C) from 1961 to 2010 (Engelbrecht et.al, 2015). Without future policies to limit greenhouse gas emissions, climate change models predict an increase of between 1°C to 4.5°C from the late 20th to the middle 21st century over South Africa (Carbon Brief, 2018; Collins et al, 2013). Temperature increases predicted under low mitigation range from 1 ˚C to 2 ˚C (2021-2050) to up to 4 ˚C to 7 ˚C in the interior of South Africa (Engelbrecht, 2019).

Studies of livelihoods in the Limpopo Province in South Africa, used temperature changes as proxies to estimate that Southern African households were susceptible to climate variability and drought (Tshiala, et. al., 2011). Evidence of rising temperatures over the Limpopo province and potential links to the hydrological cycle, and impacts on agriculture and water resources, need to be explored in future research (Tshiala, et. al, 2011). For these reasons, a GIS site suitability model, which can incorporate climate change variables such as air temperature, is required. Such a model could produce future scenario pond aquaculture site suitability maps. These products could be used to delineate sites for preservation of future production and Mozambique tilapia sanctuaries.

2.14 Governmental initiatives for aquaculture growth

The development of aquaculture in many African countries, requires sector-specific development policies and plans (Jamu and Ayinla, 2003). In South Africa, the Department of Trade and Industry (the DTI) and the Department of Agriculture, Forestry and Fisheries (DAFF) guidelines for the Aquaculture Development and Enhancement Programme (ADEP) as well as Operation Phakisa goal E7C, is strengthening the emerging aquaculture producers through increasing value chain ownership and the establishment of an Aquaculture Development Fund (ADF) (Operation Phakisa, 2021).

The South African government has given priority to aquaculture via its National Development Plan (NDP) to 2030 as a sector with high growth potential and a route to alleviating poverty, unemployment and inequality through enhanced food security. By government investing in the growth of aquaculture, enhanced food security can achieve these targets. The goals of the NDP are also supported by the National

Aquaculture Policy Framework plan, which is focussed on targeting growth in the aquaculture sector. These growth targets are supported by another initiative, the National Aquaculture Strategy and Action Plan, which amongst others, was aimed at doubling aquaculture production by 2020 (Britz and Venter, 2016).

Operation Phakisa is one of the mechanisms that the South African government has put in place to facilitate the goals of the National Development Plan (Ginindza, 2021). Government, organised business, labour, and citizens are encouraged to co-operate to improve economic growth, leading to the alleviation of unemployment, poverty, and inequality.

The Aquaculture Development Zones (ADZ) are part of one of the initiatives of Operation Phakisa (Operation Phakisa, 2021). These and many other initiatives by the South African government to develop aquaculture, also on a commercial scale (via the Industrial Policy Action Plan, support by the Department of Trade and Industry (DTI) under the Aquaculture Development Enhancement Programme (ADEP) are in place (Britz and Venter, 2016; WAS, 2021). Government and other decision makers, like funders, require information regarding where to focus and invest their attention, assistance and fiscal resources sustainably and effectively (Bandira, et al, 2021).

The use of site suitability maps to geographically inform funders on where to focus their resources, is required. That is because areas of higher suitability and farmers in higher suitability areas, are likely to produce more efficiently.

GIS enables the integration of key environmental and economic variables—such as soil clay content, temperature, slope, proximity to water sources, and road access. These variables are vital for site the suitability and sustainability of aquaculture operations. Funding should be channelled at the more sustainable enterprises (Wambua, 2018). Sites identified as highly suitable support more efficient production than marginal or unsuitable sites (Njagi and Huka, 2013; Meaden and Kapetsky, 1991; Chentouf, 2023). Each variable selected in this study's model significantly impacts aquaculture efficiency (Aguilar-Manjarrez and Nath, 1998, Moyo and Rapatsa, 2021; Bosma and Verdegem, 2011; Njagi and Huka, 2013).

The outputs presented here highlights sites with greater investment potential. Highly suitable sites comply with essential requirements, promoting operational sustainability and economic viability (Fynn, 2015). Fynn's (2015) research on "pond aquaculture

spatial distribution, production and productivity determinants in Ghana" emphasises that site selection critically affects an enterprise's economic success, influencing initial capital, production costs, yield, and market access (Fynn, 2015; Chentouf, et, al, 2023).

Empirical evidence supports that efficient sites located in more suitable areas produce more fish per unit of investment, increasing profitability and contributing to food security (Aguilar-Manjarrez and Nath, 1998; Bosma and Verdegem, 2011; Fynn, 2014: Steer, 2006; Handisyde, 2015; Stander, 2023; Urban-Econ, 2018; Wambua, 2018).

Farming efficiency and increased fish growth rate could also be affected by preferable temperature conditions and improved disease- and feed management. (Wambua, 2018; Shava and Gunhidzirai, 2017; Fynn, 2015; Bosma, and Verdegem, 2011). Government support in infrastructure, training, and resource allocation is critical to maintaining efficiency in aquaculture operations (Fynn, 2015).

Farmers' management skills and knowledge of fish farming significantly affect efficiency, even in optimally suitable areas (Wambua, 2018; Shava and Gunhidzirai, 2017; Fynn, 2015; Bosma, and Verdegem, 2011, Njagi and Huka, 2013). Thus, ongoing training is essential to maximise farm performance post-investment (Wambua, 2018; Shava and Gunhidzirai, 2017; Njagi and Huka, 2013, Bosma and Verdegem, 2011).

Increased production from more suitable sites, due to their increased efficiency, can be expected if supportive measures are implemented (Wambua, 2018). An example of this conclusion was from an economic analysis of a project implemented in Meru County in Kenya (Wambua, 2018). In this Fish Farming Enterprise and Productivity Program (FFEPP), government support led to high productivity levels of 270 kg/pond/cycle. But as soon as funding ceased, productivity levels dropped to 188 kg. The empirical evidence exists for these observations and a sensitivity analysis projected that increasing the production in line with this expectation would increase the Net Present Value (NPV) by an astounding 347%, assuming other parameters remain the same. This would also bring the Internal Rate of Return (IRR) up to 17.1% and the Benefit-Cost Ratio (BCR) to 1.2 and greatly boost the returns of the project (Wambua, 2018).

The Net Present Value (NPV) measures the present value of the net benefits of the development project. The NPV, rather than the Benefit-Cost Ratio (BCR), is suggested as a more reliable metric for comparing site efficiency (Wambua, 2018).

More suitable sites, with ideal temperature ranges, promote rapid fish growth, shorter production cycles, and increased yield, resulting in higher returns on investment (Wambua, 2018). Increases in average pond production proportionally raise NPV. NPV becomes zero at an average pond production of 164.6 kg and subsequently becomes negative with further reduction in average production. The NPV is inversely proportional to the dropout rate of fish farmers (Wambua, 2018).

The FFEPP project aimed for increased economic return, a reduction in unemployment and improved food quality. It could benefit South Africa to learn from this programme, which highlighted the need for government to invest in infrastructure (amongst others, pond construction) and farmer support. It also provides factors to calculate a farmer's efficiency.

Another factor that is used to see whether a project is desirable as a financial investment, is the Internal Rate of Return (IRR). The IRR is the rate of discount that equates the present value of benefits with the present value of costs. The IRR appears as the 'unknown' in its equation, meaning there is no closed-form solution for the rate itself. Consequently, it must be determined using numerical methods. The IRR is typically used to compare the internal financial productivity of a project with the official interest rate or cost of funds, to see whether the project is desirable as a financial investment. The IRR should not be used to rank mutually exclusive options, as it can also result in a ranking that is inconsistent with a ranking based on NPV. A distinction is sometimes drawn between an economic IRR and financial IRR. The difference is that for an economic IRR, all values for benefits and costs comprise economic rather than financial values (James and Predo, 2015).

Recommendations were made based on the outcome of the cost-benefit analysis. The cost-benefit analysis was based on calculation of NPV, Benefit-Cost Ratio (BCR), and IRR (Wambua, 2018). Ranking based on NPV instead of CBR or IRR was recommended (Wambua, 2018). This is the case if the NPV is positive. If there are

options and alternative choices available, the BCR should not be used to rank mutually exclusive options, as it can lead to rankings that are inconsistent with those obtained using NPV as the ranking criterion (Wambua, 2018).

The Benefit–Cost Ratio (BCR), is the ratio of the present value of benefits to the present value of costs. The ratio makes it possible to determine the return per every unit of investment made (Wambua, 2018).

A BCR of a project that exceeds 1, means that the present value of benefits is greater than the present value of costs. A project with a BCR greater than 1 is acceptable in terms of economic efficiency. If the BCR is less than 1, the project is not economically viable. This conclusion is conditional to the NPV being positive. The BCR should not be used to rank mutually exclusive options, as this could lead to inconsistent rankings to those obtained using NPV as the ranking criterion (Wambua, 2018).

In the Benefit-Cost Analysis (BCA) of any governmental policy, an implicit assumption is that the policy should enhance overall societal welfare. To evaluate this, the total costs and benefits must be measured across society and compared. Projects or policies where total benefits exceed total costs are deemed worthy of support (Denne et al., 2007; Wambua, 2018).

In conclusion, the efficiency of production can be measured by many factors. One of the preferred methods is by comparing the NPV of farmers. However, other factors such the farmer's management capabilities, institutional support, the scale of production, and the risks of crop failure (due to diseases, water quality problems and theft) also contribute to a farmer’s efficiency (Bosma and Verdegem, 2011).

2.15 Conclusion

High population growth rates are linked to food insecurity. One solution to alleviating food insecurity is through the increased production and consumption of fish. Instead of sourcing fish from dwindling wild stock, another option is to produce fish in inland ponds, via aquaculture. The pre-selection of a suitable site for an aquaculture enterprise is crucial and can be accomplished with the use of Multi-Criteria Evaluation (MCE) in a GIS environment. This methodology has been widely used to guide

stakeholders as to where to focus their funding to ensure sustainable resource allocation and aid the development of new inland aquaculture sites, but also to assist existing fish farmers. However, from the literature reviewed, this research found no known work on the production of a Mozambique tilapia specific, pond aquaculture site suitability spatial model and the use of this model for the creation of subsequent site suitability maps. Using the Multi-Criteria Evaluation (MCE) approach in a GIS is advisable due to its powerful ability to combine multiple layers of the variables that determine the suitability of a site for pond aquaculture production.

There is a need for a simple and robust GIS site suitability model which can easily be duplicated. It is recommended that the model should contain only the most relevant (or crucial) variables and sub-models and be suited for the indication of all earth-pond Mozambique tilapia aquaculture enterprises. It should be suitable for small-scale, subsistence pond aquaculture, without necessary alterations. It should also be usable as a simple and robust method to indicate suitability for commercial pond aquaculture. Small-scale, subsistence farmers can become more than self-sufficient, and their enterprises can migrate to becoming small scale-commercial or large-scale commercial farms. A model that can cater for this transition is needed. For a more comprehensive model (containing more suitability variables) or for a more commercial aquaculture pond- suitability model, some of the following influential factors could be added to the model: Distance to markets, distance to fish processors, distance to feed producers and market size (market availability) by adding population density statistics (Aguilar-Manjarrez and Nath, 1998, Assefa and Abebe, 2018).

A model that can produce Mozambique tilapia pond aquaculture site suitability layers and maps usable on farm scale up to regional scale and that can also incorporate data from climate change General Circulation Models (GCMs) to produce future suitability maps, was found lacking in the literature. It is recommended that currently existing aquaculture farms be evaluated by being scored and ranked according to their positions on the site suitability maps produced from this model. This model and suitability maps could provide vital information to Government and Non-Governmental Organisations (NGOs) on where to focus the allocation of their funds and other aid more effectively.

Chapter 3

Methodology

3.1 Introduction

This chapter describes the philosophical and methodological ideologies and patterns of thought chosen by the researcher and goes on to explain the reasons for these choices within the realm of the Geographic Information Systems (GIS) research domain.

This chapter explains the chosen research philosophy from the different schools of thought. This chapter then explains the chosen research design describing the different research steps. A section offering insight into the research site follows. The process of following the research methodology is described.

The conclusion captures the essence of the researcher's thought patterns and the way the researcher views the world to answer the research questions. This section articulates the reasons for the researcher's choice in school of philosophical thought. The chosen philosophy guided the selected methodology and subsequent actions followed to deduct answers from the sourced data.

From the literature reviewed in Chapter 2, the main variables and their thresholds that determine the growth and survival of the Mozambique tilapia were applied to the model. Some additional research to explain the choice of variables and their respective thresholds is included in this section. Existing methods of site suitability modelling that were researched in the literature reviewed in Chapter 2, are elaborated on to defend the choice of the model. The design of the site suitability model is explained, including details of how the model was transferred to the GIS environment. From the sourcing of the data to the analysis's steps are explained. The production of the intermediate suitability products in the sub-models received much attention in this chapter. The chapter ends with the conclusions about the possible limitations of the chosen methodology as well as methodology.

3.2 Research philosophy / approach

The methodological approach of this research was guided by the specific idea that the researcher harbours regarding reality and the nature of knowledge (Collis and Hussey, 2014). Firstly, this was based on the researcher's chosen research philosophy as discussed in section 3.2.1. This section describes how the researcher sees the world as well as the reasons for this choice.

Secondly, the chosen research approach, also termed research strategy (Creswell, 2009), is explained in section 3.2.2.

These two steps translate to how section 3.3, the research design (Creswell, 2009) was developed and executed.

3.2.1 Research philosophy

Philosophical worldviews are people's beliefs that in turn determine what they do or how they act (Creswell, 2009). Philosophical worldviews are also known as philosophical perspectives, "a system of generalized views of the world, which form beliefs that guide action" (Moon and Blackman, 2014). In geographical research, philosophy paradigms deal with the "source, nature and development of knowledge" (Sapkota and Paudyal, 2021).

Philosophical perspectives stem from ontology "(what exists for people to know about)" (Moon and Blackman, 2014) or the nature of reality (Dudovskiy, 2022) and epistemology "(how knowledge is created and what is possible to know)" (Moon and Blackman, 2014). Ontology and epistemology are two different ways of viewing the research philosophy. Ontology is a system of belief that reflects an interpretation of an individual about what constitutes a fact (Dudovskiy, 2022). Ontology, also referred to as the 'study of being', deals with what really exists in the world about which humans can acquire knowledge (Moon and Blackman, 2014).

Ontology is a branch of metaphysics. Metaphysics is the philosophy about the overall nature of what things are (Berryman, 2019). While ontology is concerned with the identification of the kinds of things that "exist in reality" (what is true), epistemology on

the other hand, is about the methods used for “figuring out those truths” (Berryman, 2019).

The two types of ontology that exist are objectivism and subjectivism (Hamati-Ataya, 2014; Trivedi, 2020). This research relies on seeing reality objectively, thus “Objective ontology” or “Objectivism” was pursued (Jakubczak, F., 1968; Trivedi, 2020). Objectivism reflects upon reality as existing independent of knowledge, being extramental (existing outside the researcher’s mind) and anybody should be able to unbiasedly verify it with their five senses (Baise, 2020; Trivedi, 2020).

The philosophical perspectives in this research stem from the researcher’s Ontology perspective. Ontology describes what exists for people to gain knowledge about and understand their reality of a subject (Moon and Blackman, 2014) or the nature of reality (Dudovskiy, 2022). Epistemology has to do with how this knowledge about a subject can be created or collected so that it is possible to know more about the ontological reality (Moon and Blackman, 2014).

One of the pillars of philosophy is Theoretical Philosophy, of which one is Metaphysics. Metaphysics studies the fundamental nature of reality (Dudovskiy, 2022; Leverage Edu, 2021). The research done for this study is metaphysical in nature. Metaphysics lays out a complete, coherent ontology, encompassing all the required information to capture the correct amount of the world in any of the specific enquiries, which can be empirical, mathematical, modal or of a moral nature (Lowe, 2011).

The essence of this research is geographical in nature. The philosophy of geography thus entails the many aspects of metaphysics, the researcher’s perception of reality as well as the spatial representation of the location of entities (Tambassi and Tanca, 2021). In the case of this research the key philosophical assumptions chosen and the research methods flowing from them in the field of geography, determined each stage in this research process (Sapkota and Paudyal, 2021).

In this research, the worldview of Postpositivism was adopted by the researcher. Postpositivism is sometimes called the scientific method for doing science research (Creswell, 2009). Positivist research is known for being highly structured in terms of its research methodology to facilitate the duplication of this research study by others after its completion. Science is described as a fundamental in positivism research philosophy (Dudovskiy,2022). Postpositivism can be deterministic in its philosophical

view (Creswell, 2009). Deterministic research means that in this research the causes that affect the outcomes were researched (Creswell, 2009). This applies to the determination of which variables contribute to the farmers' and areas' suitability for Mozambique tilapia farming. Postpositivist research for the purpose of this geographical research is also reductionistic in that the variables which were used to create an outcome were used to answer research questions (Creswell, 2009). The knowledge generated via this research was thus based on observation and measurement of the objective reality that exists "out there" in the world (Creswell, 2009).

A post-positivism approach was used to predict the suitability of the Limpopo province for pond aquaculture. This is because multiple methods are required to solve the research questions (Moon and Blackman, 2014). In this research, Creswell's (2009) formulation of the research process was chosen, which flows from the philosophical assumptions to the strategies of inquiry, and these ultimately lead to the specific research methods that were used (Creswell, 2009). This process was applied from literature reviewed, the choice of model design methodology, the collection of the input data and the choice of quantitative and qualitative (thus, mixed) methods of strategies of enquiry (Creswell, 2009; Saunders, Lewis and Thornhill, 2012). The research approach (or reasoning) followed is Inductive of nature, meaning it started by making specific observations, to recognising general patterns to drawing general conclusions (Dudovskiy, 2022; Sheppard, 2020). The Inductive reasoning process followed during this research, contributed at the end of the research process to new generalisations about the suitability status of the entire area of the Limpopo province for Mozambique tilapia pond aquaculture (Dudovskiy, 2022).

Choosing the key philosophical assumptions and thus research methods in the field of geography, determined each stage in the research process (Sapkota and Paudyal, 2021). For this GIS research, ontology is an ideal philosophical approach. This is since ontology is applicable to all the aspects of science and information systems (Mark et al, 2004). Ontology is specifically applicable in practice to the aspects of modelling and representation that pertaining to geographic information science (Mark et al, 2004). In this research, the site suitability model designed is used for map visualisation of the suitability classes for Mozambique tilapia pond aquaculture for the Limpopo province.

One way of visualising the different stages or layers in philosophical thinking leading to the choice of research methodology, is by using the well-known “Research onion model” displayed in Figure 3.1 (Saunders, Lewis and Thornhill, 2012). The time horizon for this research is longitudinal. After the philosophical thinking stage, the following stages are the research approach/strategy. Another layout of the philosophical process, which leads from thinking to planning, can be seen in Figure 3.2, by Moon and Blackman, (2014).

Being aware of the beliefs and assumptions made in this research about GIS and geographical suitability studies, constitutes the outside layer of the “research onion” in Figure 3.1 (Sapkota and Paudyal, 2021).

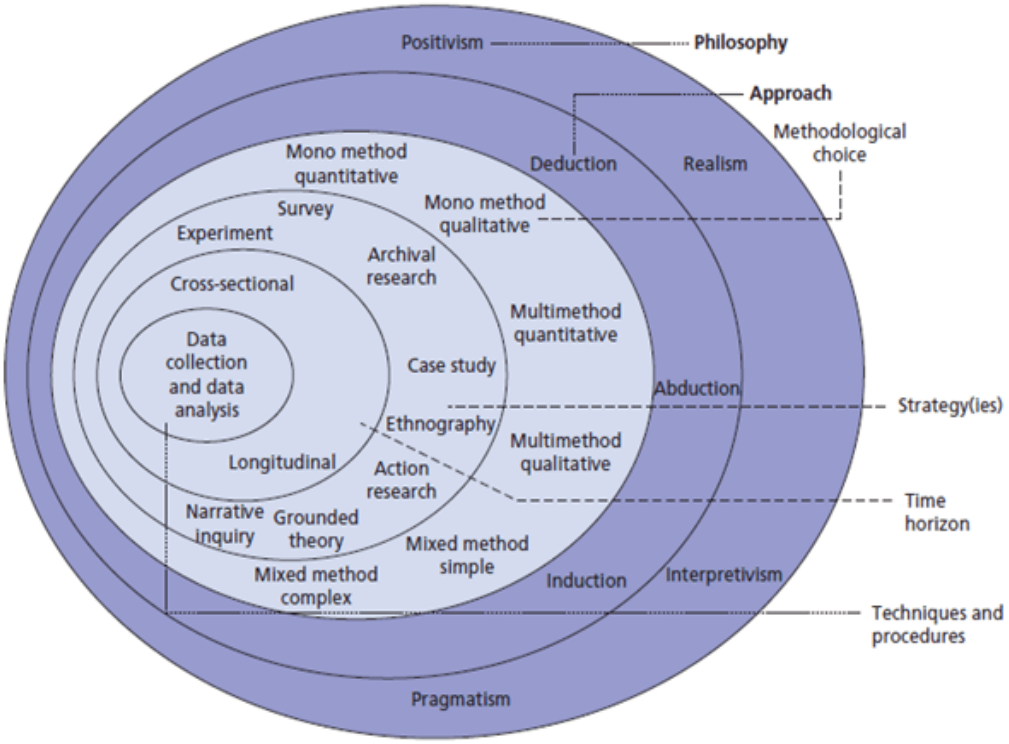


Figure 3.1The research onion model (Saunders, Lewis and Thornhill, (2016).

In Figure 3.1, Saunders, Lewis and Thornhill, (2016), compare the research philosophy and the processes following the chosen philosophy, to a “research onion”. In the case of this research, it explains the timelines of the chosen process from ontology, epistemology and the resultant research methods and design, pertaining to the data collection and data analysis. The outside layers reflect the choice of

philosophy, then the approach was followed by the research design, which was applied in the case if this research as well.

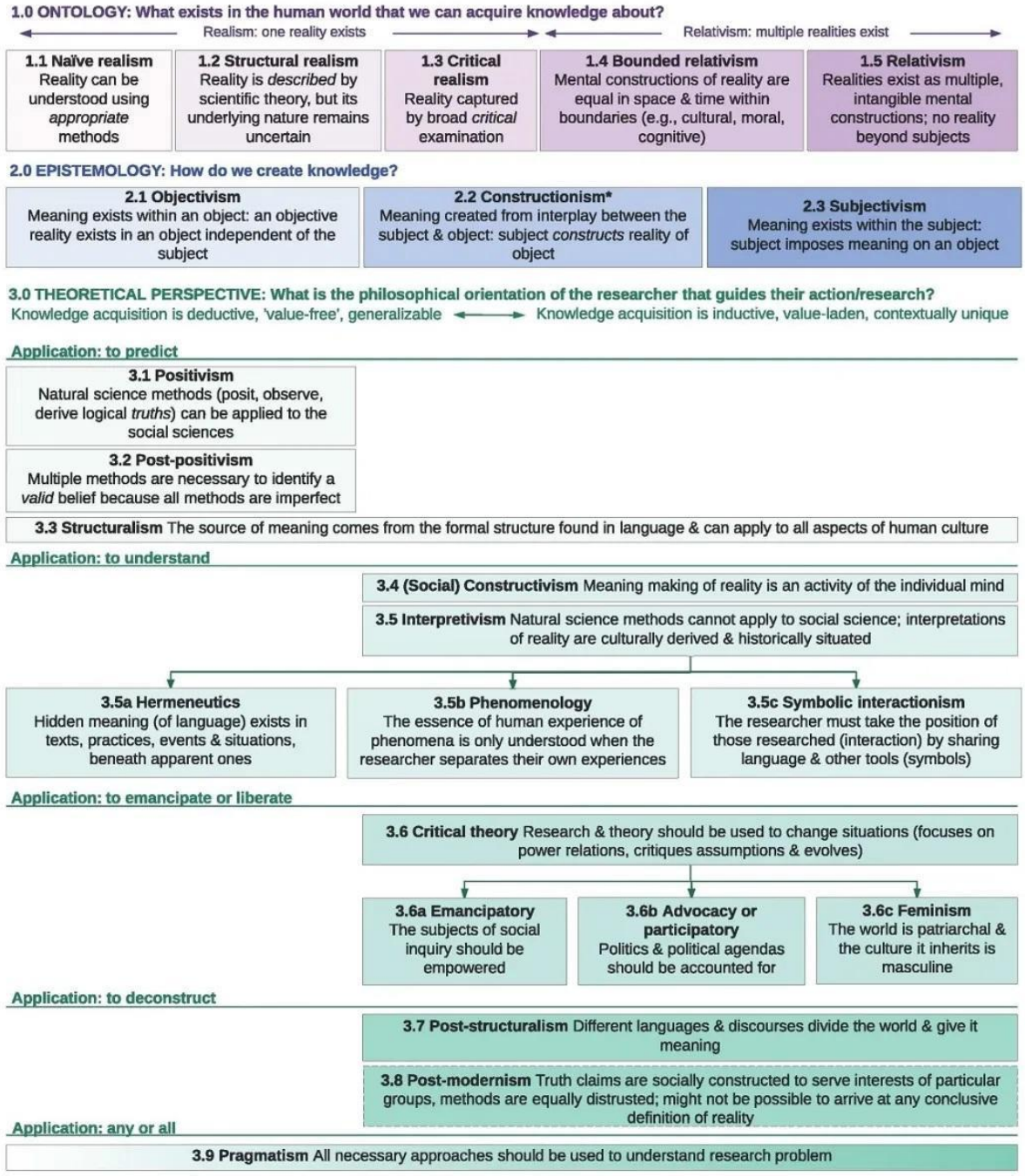


Figure 3.2 Different ideas of reality (Moon and Blackman, 2014).

According to the diagram in Figure 3.2 by Moon and Blackman, (2014), ontology is about what exists out there to know about, and epistemology is the methods used to find out about these realities and how one can create knowledge about it, according to the researcher. The diagram further describes that the theoretical perspective of the researcher will guide the action taken by the researcher. The subsequent knowledge

acquisition of this research was deductive, meaning the research contains value in a unique context. The diagram (Moon and Blackman, 2014) further illustrates five levels of applying these chosen theoretical perspectives to solve the problem; in the case of this research: Postpositivism was used to predict the suitability of the Limpopo province for pond aquaculture. This is because multiple methods are required to solve the question (Moon and Blackman, 2014).

The intellectual and philosophical position of this suitability study can be described in terms of “Ontological Reductionism” (Doniger, 1999; Kricheldorf, 2016; Ruse, 2005). This is because in this research the chosen philosophical idea is that the phenomena of the final suitability can be broken down into- and understood by the many different simpler, more fundamental components that make up the reasons behind the suitability grading of the Limpopo area and the existing farmers. The whole of reality of the final, complex suitability map can be explained and interpreted by the minimal sum of its parts (Doniger, 1999; Kricheldorf, 2016; Ruse, 2005). However, the knowledge created in this research was done by collecting secondary and primary data and analysing these data to answer the suitability research questions and thereby create new knowledge (Sapkota and Paudyal, 2021). Thus, a desktop GIS study was implemented to answer the research questions, by overlaying many economical and geophysical layers, to ultimately gain insight into the suitability of - and to produce site suitability maps for the Limpopo province.

The purpose of this section was to identify the chosen research philosophy for this GIS site suitability research question of where in the Limpopo province the most suitable areas for Mozambique tilapia pond aquaculture are. This philosophical worldview influenced the research design. In the next section the data collection methods associated with the chosen research philosophy, are discussed. This influenced not only the choice of the methods by which data were collected, but the data analysis methods as well (Dudovskiy, 2022).

3.2.2 Research strategies of enquiry

A Geographic Information System (GIS) can be described as a system that can be utilised for the management, analysis, and mapping of many types of data (Saylor Academy, 2012). This definition of a GIS helps to determine the stance of this research

in terms of the utilisation of a GIS and thus the strategies of enquiry to be followed. As is the case in this research, GIS connected the data used in this research, to the maps created from the model, making it possible to integrate where things are located, with their respective associated descriptive (or attribute) information (Saylor Academy, 2012).

In addition to the many definitions that exist about what a GIS is, there are three basic approaches to a GIS (Saylor Academy 2012). In this research it was found that these three approaches overlapped. It was useful to identify which of these three approaches applied to this research, as they have an influence on the thought pattern and planning of the strategies of enquiry (Saylor Academy, 2012). These three basic approaches to a GIS are termed the application approach, the developer approach and the science approach (Saylor Academy, 2012). Although many GIS users identify with one approach more than another, they are not necessarily mutually exclusive (Saylor Academy, 2012).

In the application approach, GIS is primarily considered as being a tool. In this research, GIS was also used and applied as a tool. A tool to collect and maintain data and the database, answer suitability questions, support the decisions making process and visualise the information on maps. All these applications were used to solve the question of the spatial suitability of the Limpopo Province for Mozambique tilapia pond aquaculture as well as how the known existing farmers ranked in terms of this suitability (Saylor Academy, 2010).

The second approach to GIS is the developer approach. To a lesser extent this approach was implemented in this research, as it focuses more on the development of the GIS as a software or technology platform. To this extent, the development of the suitability model in the Esri ArcGIS Model builder interface (Esri, 2018), could be viewed partly as falling in this category (Saylor Academy, 2012).

Lastly, the science approach to GIS, also termed geographic information science (GIS science), investigates more complex issues like geospatial thinking and gathering accurate information from maps. The GIS science approach used in this research, could have social consequences and there could be implications for decision makers from the use and distribution of the knowledge generated hereby (Longley et al. 2005; Saylor Academy, 2012).

Ultimately, this research integrates all three these approaches as there are social consequences of this GIS suitability exercise for the future of the aquaculture role players and stakeholders.

After the research philosophy was established in section 3.2.1, all the beliefs about how the GIS site suitability model data should be collected, analysed and applied, were based on those philosophical assumptions (Creswell, 2009; Dudovskiy, 2022; Sapkota and Paudyal, 2021). The reason for this is that every stage in this research process was based on these chosen philosophical assumptions and these determined how the sources of the input data and the generated knowledge, were approached. These decisions served as the basis for the chosen research strategy (Sapkota and Paudyal, 2021).

In this research, Creswell's (2009) formulation of the research process was chosen, which flows from the philosophical assumptions to the strategies of inquiry, and these ultimately lead to the specific research methods used (Creswell, 2009). This was applied from the literature reviewed, the choice of model design methodology, the collection of the input data and choice of quantitative and qualitative (thus, mixed) methods of strategies of enquiry. The three common approaches to conducting research are quantitative, qualitative, and mixed methods. In this geographic research, it was anticipated that all these types of data would be required to answer the research question (Dudovskiy, 2022; Sapkota and Paudyal, 2021).

Not only are geographic data and generated knowledge qualitative as well as quantitative, but it is also known as "the mixed method, and is complex (Saunders, Lewis and Thornhill, 2012). The time horizon is longitudinal, also known as time series data (Saunders et al, 2007). The farmers were interviewed once to get their GPS points and other production data, and that type of data is cross-sectional (Saunders, Lewis and Thornhill, 2016). However, the production data were not utilised.

The strategy of enquiry is also termed the research approach, and it stemmed from the chosen philosophical worldview in section 3.2.1. The research approach (or reasoning) followed, could be described as being inductive in nature, meaning it started by making specific observations, to recognising general patterns to drawing general conclusions (Dudovskiy, 2022; Sheppard, 2020). The inductive reasoning in this research contributed at the end of the research process to new generalisations

about the suitability status of the entire area of the Limpopo province for Mozambique tilapia pond aquaculture (Dudovskiy, 2022).

Aspects of the strategies of enquiry (also termed the methods of approach) that provided specific direction for the research procedures, were followed. These aspects were described by the types of data or models collected and analysed for use in this research (Creswell, 2009). A mixed method of approach of data handling was followed. This means the data that were utilised contained qualitative as well as quantitative attributes (Creswell, 2009). Furthermore, the mixed method of enquiry is termed “concurrent mixed methods” (Creswell, 2009). In these types of procedures used for this research, the quantitative and qualitative data were collected and used at the same time, merged and converged to create a comprehensive analysis of the research problem. The information created from and during the analysis process were integrated in the interpretation of the overall results (Creswell, 2009).

However, in “Hybrid-Geography”, the philosophical poststructuralist assessment of GIS and the GIS scientists’ view of which type of data should and could be used in the strategies of enquiry process, are philosophically very different. The critical-theoretic epistemological view and the ontological metaphysics view of qualitative- or quantitative data in the strategies of enquiry process, pose a philosophical divide about seamless hybridization of the two types of data in the GIS research process (Hannah and Strohmayer, 2001; Leszczynski, 2009).

Because the design for this research and data collection generated findings that could practically be used for decision-making, the research design is conclusive rather than exploratory (which only aims to explore specific aspects of the research area). Exploratory research does not aim to provide final and conclusive answers to research questions (Dudovskiy, 2022).

The intellectual and philosophical position of this suitability study can be described in terms of “Ontological Reductionism”. This is because in this research the chosen philosophical idea is that the phenomena of the final suitability can be broken down into- and understood by the many different simpler, more fundamental components that make up the reasons behind the suitability grading of the Limpopo area and the existing farmers. The whole of reality of the final, complex suitability map can be explained and interpreted by the minimal sum of its parts (Doniger, 1999; Kricheldorf,

2016; Ruse, 2005). However, the knowledge created in this research was done by collecting secondary and primary data and analyse this data to answer the suitability research questions and thereby create new knowledge (Sapkota and Paudyal, 2021).

3.3 Research design

For the purposes of this research, it was decided to adopt the definition of research design as being the choice and design of a specific master plan (or framework) and procedure of conducting this research project, that will be used for data collection and analysis to answer the research questions (Dudovskiy, 2022; Saunders, Lewis and Thornhill, 2016; Creswell, 2009). These include tasks like the literature review, the data collection, the data preparation, the Multi-Criteria Evaluation (MCE) model design, the analysis of the data, data visualisation, the extraction of the site suitability information and the presentation of the results.

All research efforts require a well-defined methodology to enable the researcher to achieve the aim and objectives of the research (Creswell, 2009; Garg, 2016). This approach to research contains and stems from the philosophical assumptions made before embarking on the research endeavour (Creswell, 2009; Khanday and Khanam, 2023). The distinct methods and procedures chosen are also known as the “plan or proposal to conduct research” or the “research design” (Creswell, 2009; Panya and Nyarwath, 2022). During research design, the chosen philosophy, the chosen strategies of enquiry and the chosen specific methods are combined since they are related to the philosophical worldview assumptions. The research design’s “specific methods” or “procedures of research” are developed to practically enable the research process to deliver answers to the research questions (Creswell, 2009; Khan et al., 2023). Assumptions about the nature of truth and knowledge thus determine the way that knowledge is developed in a research study (Dudovskiy, 2022).

The choice between qualitative and quantitative research methods are sometimes referred to as the research design. The choice of specific methods of data collection and data analysis are often used to describe research design. From the many existing definitions used to describe research design, the definition chosen for this research is that research design can also be referred to as “the master plan for conducting a research project” (Dudovskiy, 2022).

There are two different groups that research design can be divided into: exploratory and conclusive (Dudovskiy, 2022). For the purposes of this research design, conclusive research design was chosen over exploratory research design. This is since exploratory research only explores specific aspects of the research topic, and its aim is different from that of conclusive research design. Exploratory research does not aim to provide final and conclusive answers to research questions as required for this research. Conclusive research generates findings for practical application, for decision making and for answering research questions"" (Dudovskiy, 2022).

Section 3.4 elaborates on the details of the steps followed to achieve the results that will answer the three research questions (research design) (Creswell, 2009; Dudovskiy, 2022). It describes how the main sources of data for the study were determined during a thorough and extensive literature review of the many known variables that have an influence on the economic, geographical and social aspects of inland freshwater pond aquaculture farming. From this literature review, the most critical variables that are required for Mozambique tilapia pond aquaculture site suitability were distinguished, together with their suitability threshold values. The data acquisition, data preparation and data analyses followed another literature review in search of the most appropriate spatial modelling method for this specific pond aquaculture site suitability. The data sources that were utilised included spatial and non-spatial data. The data contained economic-, geographic, and environmental variables from various sources.

A desktop Geographic Information System (GIS) study followed. For this GIS desktop study, the site suitability model was developed in a Multi-Criteria Evaluation (MCE) (Eastman et al, 1995) environment and utilised the Analytical Hierarchy Process (AHP) (Saaty, 1977) to score and weigh the suitability variables. The pilot study area is the entire surface area of the Limpopo province of South Africa. The site suitability maps were produced from this Multi-Criteria Evaluation (MCE) modelling process as described by Eastman et al, 1995; Eastman, 1999; and Voogd, 1983. The MCE model was designed as a technical diagram flow chart in MS Word. This flow chart was recreated in the ArcGIS 10 (Esri, 2018) Model-Builder environment, where it was executed. The created suitability maps created are qualitative as well as quantitative in nature.

The analyses of the findings were transferred from the spatial environment to MS Excel where the calculations took place. The calculations produced tables containing the areas (in square meters, square kilometres, and percentages) of every suitability class as well as the restricted areas of the Limpopo province for pond aquaculture. Existing known tilapia farmers were scored and ranked according to their GPS locations on the suitability maps. These results were also tabulated. These tabulated research results are quantitative as it measures the areas ($m^{2,}$ km^2 and %'s) pertaining to every suitability class as well as the ranks and scores of the farmers.

The model was developed containing only the most crucial variables to make it robust, easily executable-, easily understandable and easily transferable to other users. This could simplify the creation of suitability maps for the other eight provinces in South Africa.

The suitability maps produced by this research could be used to guide decision makers in identifying the most suitable areas for optimal allocation of funds and to support the existing aquaculture farmers that are in more suitable locations than others. These maps could also be utilised to develop new Mozambique tilapia pond aquaculture farming sites in the Limpopo province. The South African Government has prioritised many existing local, provincial, and national growth initiatives in the aquaculture sector, with special emphasis on small-scale subsistence- and female farmers (Britz and Venter, 2016).

The use and transfer of the model, suitability maps and layers developed during this research could aid in the alleviation of poverty, the increase of sustainable livelihoods, economic growth, and the optimisation of governmental food security initiatives. These products from this research could also aid in contributing to the nutritional and socio-economic development needs which were identified as priority areas for South Africa (Britz and Venter, 2016).

3.3.1 Description of the research site

This study is focused on the entire surface area of the Limpopo Province of South Africa, which served as a pilot study area. The Limpopo Province is the most northern province of the nine provinces of South Africa, as depicted in Figure 3.3. It is situated between 22 to 32 ° South and 27 to 32 ° East (Tshiala et. al, 2011). The total area of

the Limpopo Province is 125 754 km² or 125 754 0000 m^2 (as calculated in Esri ArcMap 10) (Esri, 2016) and agrees with the area stated as 125 754 km^2 by the South African Government (STATSSA, 2012; Limpopo Province of South Africa, 2023). The total estimated population of the Limpopo province was 5 982 584 people, which was 10.2% of the total population of South Africa in 2019 (STATSSA, 2019) and 6 015 000 in 2020 (STATSSA, 2020). However, it is estimated that this figure could have unofficially risen to 6 429 332 in 2023 (at the same growth-rate as for 2011 to 2015 (+1.46%/year) (Population City South Africa, 2023).

The main economic activities include agriculture (livestock, fruits, vegetables, cereals, and tea) and tourism (Limpopo Department of Agriculture, 2023). The province boasts a vast biodiversity and many national parks which support the tourism industry (Limpopo Department of Agriculture, 2023).

The province comprises of three climatic regions: Semi-arid Lowveld, Middle- and Highveld regions that are considered semi-arid, and the Escarpment, which is sub-humid (Limpopo Department of Agriculture, 2023; Tshiala et.al, 2011). The average rainfall per annum is 400–600 mm, with an average annual temperature of 20°C in winter and 27°C in summer (Tshiala et.al, 2011).

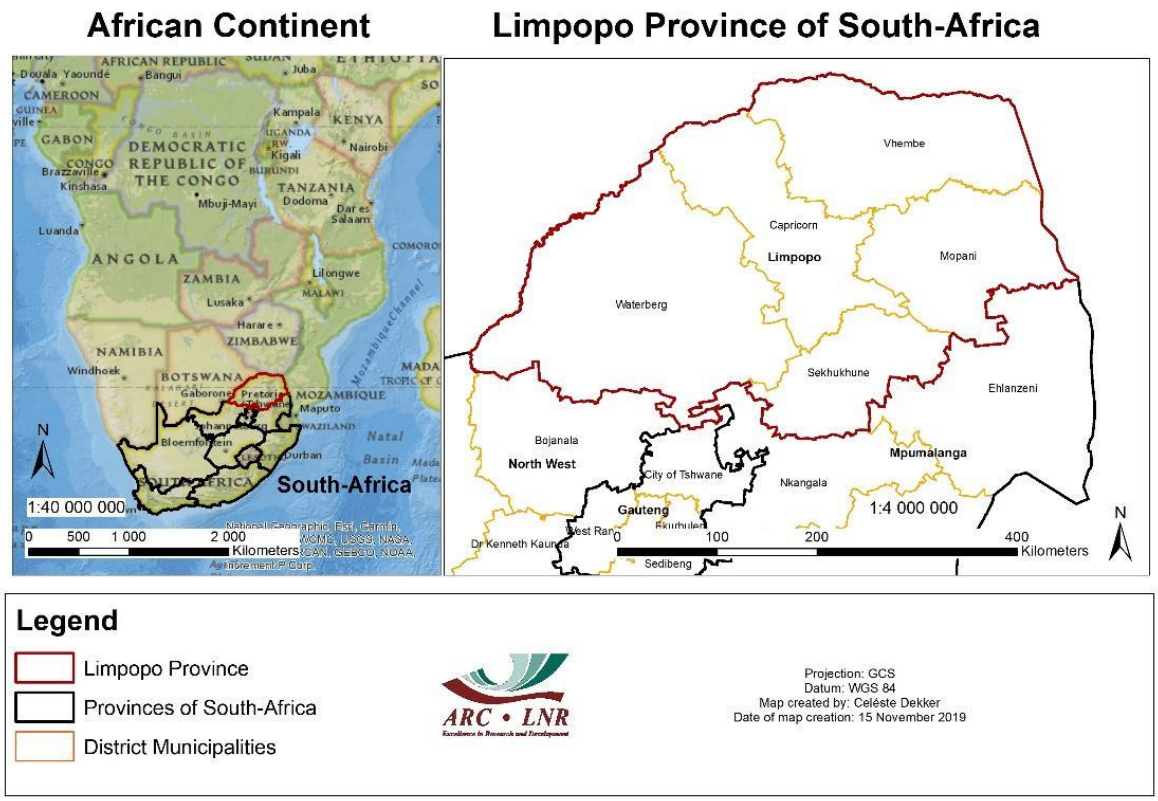


Figure 3.3 Study area: The Limpopo Province of South Africa.

The Limpopo Province was chosen as the pilot study area for this site suitability research pertaining to pond aquaculture of the Mozambique tilapia. For this research, the fish species chosen had to be a nutritious, edible, fresh-water, warm-water inland fish species. The Mozambique tilapia is one such a species (Urban Econ, 2015; Urban Econ 2018; Zengeya et al, 2012). The Mozambique tilapia is native to the Middle East and Africa (Zengeya et al, 2012). The Mozambique tilapia is indigenous to certain areas in South Africa. The Limpopo province is currently home to the indigenous Mozambique tilapia, and it contains the largest area which forms part of the native range of the Mozambique tilapia in South Africa, according to the International Union for Conservation of Nature (IUCN, 2021; Urban-Econ, 2018). This can be seen in Figure 3.4 which depicts the natural distribution of Mozambique tilapia in southern Africa on the IUCN Red List of Threatened Species map (Version 2021-1. (Bills, 2019; IUCN, 2019; IUCN, 2021).

The Mozambique tilapia can tolerate temperatures from 4.4 °C to 40 °C and it is also very resilient to organic waste, low oxygen levels, and many types of pollution (Tilapia

Web Site, 2016). The most optimal water temperature range for Mozambique tilapia is 28°C to 30°C (Urban-Econ, 2018). Most tilapia farmers in South Africa are small-scale farmers, and they employ recirculation and pond aquaculture systems. In terms of production volumes, the Limpopo province accounts for the highest share (37%) of South Africa's total tilapia production (Urban-Econ, 2018).

However, another fresh-water, inland, warm-water aquaculture fish species of tilapia, which is also present in South Africa, is the Nile tilapia *(Oreochromis Niloticus)* (Zengeya et. al., 2012). Although the Nile tilapia is an invasive fish species in South Africa, it is already present in parts of South Africa, (Figure 3.5) due to introduction in the eastern to northern parts of the Limpopo province (Urban-Econ, 2015; Zengeya et al, 2012).

The invasive Nile tilapia is a threat to the Mozambique tilapia in South Africa. This is due to the niche overlap in the environmental conditions under which these congenerics can both occur (Zengeya et al., 2012). In Figure 3.5, the red areas (picture on the right) and purple areas (picture on the left) indicate the introduced range of the Nile tilapia, although not all introductions were successful. Also, the Incomati River was reported to contain introduced Nile tilapia, which is not indicated on the figure on the right (Picker and Griffiths, 2011). In Figure 3.6, the native range of the Mozambique tilapia is visible as the boundary area containing the potential distribution by Zengeya et al., (2015).

The Mozambique tilapia species is also threatened through hybridisation with the Nile tilapia (DFFE, 2022). Farming with Nile tilapia is allowed in six (6) of the nine (9) provinces in Recirculating Aquaculture Systems (RAS), although it requires a permit for production in the Limpopo-, Gauteng- and KwaZulu-Natal provinces) (Urban-Econ, 2015).

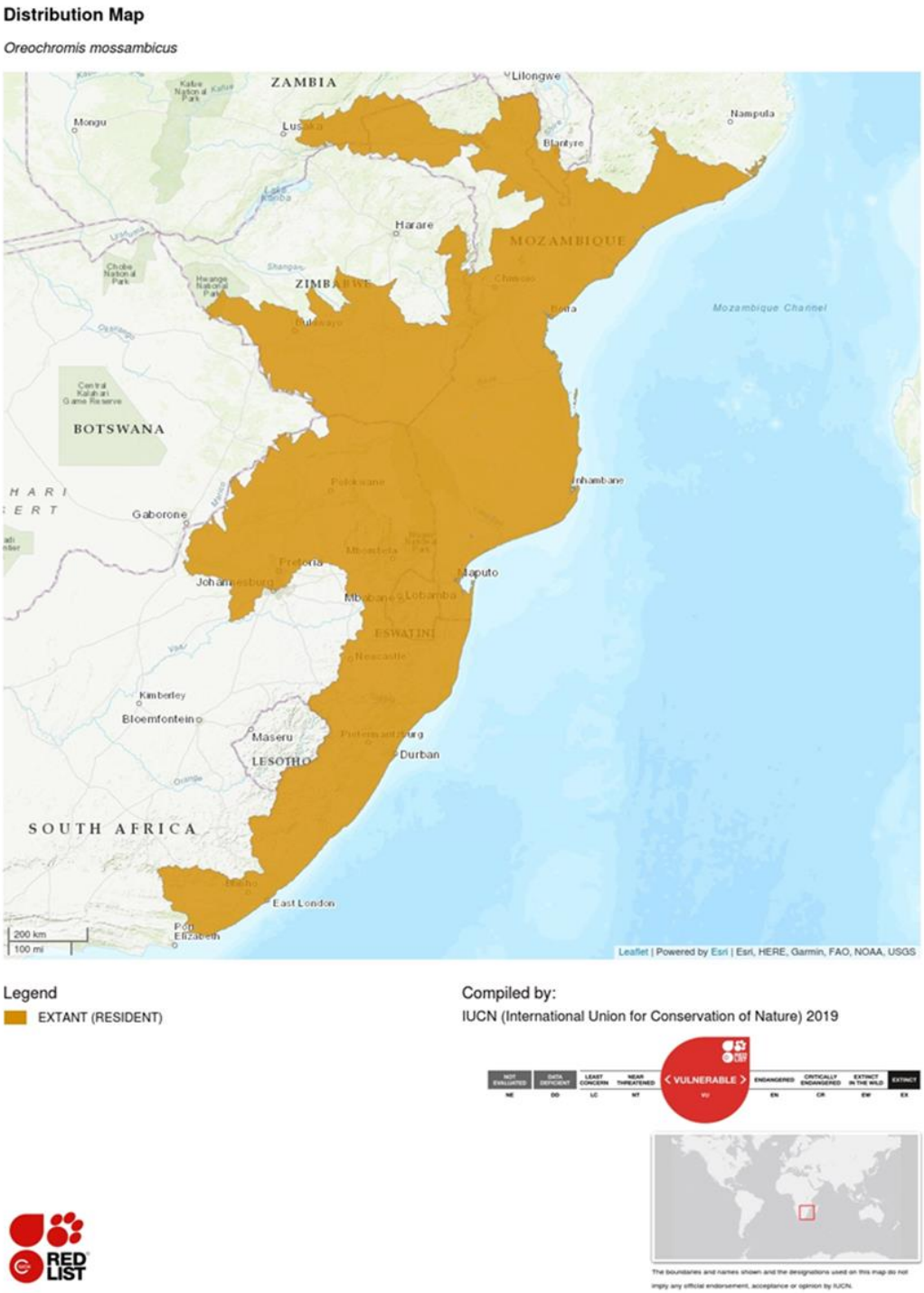


Figure 3.4 Natural distribution of Mozambique tilapia in southern Africa (Bills, 2019; IUCN, 2019; IUCN, 2021; Urban-Econ, 2018).

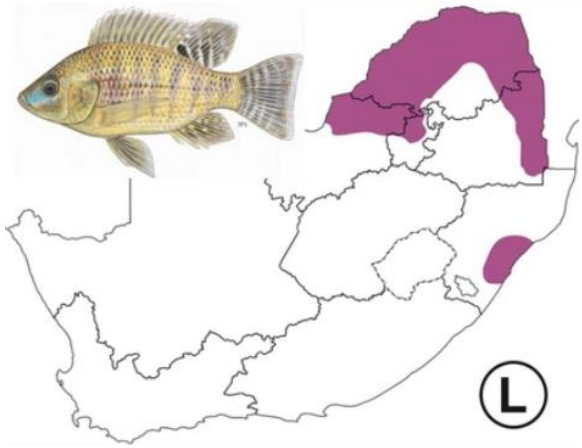
 Alian freshwater fauna in South Africa: *Oreochromis Niloticus* (adapted from Skelton and Weyl 2011; Marr et al. 2018; Khosa et al. 2019).	 The introduced range of Nile tilapia *(Oreochromis Niloticus)* (areas in red) in South Africa (Picker and Griffiths, 2011; Found in Urban-Econ, 2018).

Figure 3.5 The introduced range of Nile tilapia *(Oreochromis Niloticus)* (areas in purple (left) and red (right) in South Africa from different sources.

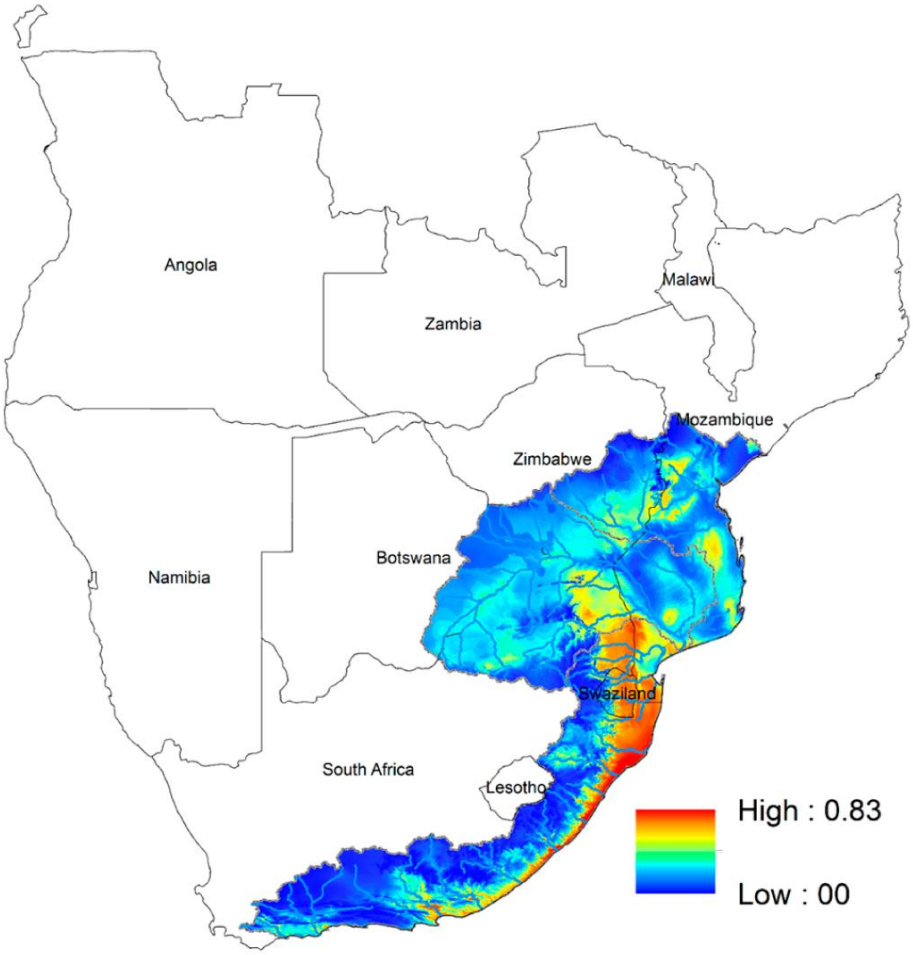


Figure 3.6 Potential distribution of Mozambique tilapia within its native range (Zengeya et al., 2015).

This research promotes the Mozambique tilapia for use as an aquaculture species, due to its protected status, even though the Nile tilapia is a more robust fish, a faster grower and preferred by many for aquaculture purposes (Urban-Econ, 2015).

3.3.2 Suitability variables and model design

The purpose of this section is to describe the choice of the main variables applicable to specifically Mozambique tilapia pond aquaculture suitability. To produce site suitability maps for the Limpopo province, an array of species-specific suitability criteria is required. These criteria or variables incorporated into a Geographic Information System (GIS) can produce suite suitability maps specific for the

Mozambique tilapia using specific variables and their thresholds (Aguilar-Manjarrez and Nath, 1998).

The selection of a suitable site for the planned aquaculture enterprise is a vital exercise (Aquaculture Innovations, 2010; Hossain et. al., 2007). A suitable site will increase the chances of the enterprise being successful, sustainable, viable and profitable in the current geographical and economic environment (Aquaculture Innovations, 2010; Hossain et. al., 2007). There are many geographically based site suitability variables that need to be considered in the aquaculture enterprise planning phase (Meaden and Kapetsky, 1991).

Apart from the physical factors, there are other factors that influence the success of the economic activities required for the pond aquaculture enterprise. These factors are called production functions. The combination of these production functions necessary for instance for pond aquaculture activity, will vary. Production functions can include economic factors, physical factors, and social factors. All production functions will exhibit varying degrees of importance in spatial and temporal terms (Meaden and Kapetsky, 1991).

Some variables are viewed as more important than others when described for pond aquaculture site suitability (Aguilar-Manjarrez and Nath, 1998; Aquaculture Innovations, 2010). Thus, a thorough literature review was done to identify these more critical environmental- and economic variables that determine the suitability of a site for earthen-pond aquaculture.

After choosing only the most crucial variables, the availability of data pertaining to each of these variables were determined. After that, the availability of data pertaining to these chosen variables (in a suitable spatial or translatable to spatial data format) was established.

The model was designed to produce pond aquaculture site suitability products with the focus on empowering small-scale farmers, which often are female-headed households. The model can be modified to include more variables. Some of these variables could enable the model to be more useful for farmers migrating from subsistence and farm-gate sales to a larger scale: I.E.: When they transition to becoming commercial producers.

The thresholds that apply specifically to the Mozambique tilapia *(Oreochromis mossambicus)* species, for each variable, were then determined from another literature review. These species-specific requirements in terms of these variables and their thresholds were then classified into the categories of suitability for pond aquaculture.

The reason for choosing only a limited number of variables and only the most crucial variables was to keep the GIS suitability model simple and robust and to pertain to mostly subsistence pond aquaculture enterprises of any size at any special resolution.

3.3.2.1 Variables and their thresholds

The variables and their thresholds were selected while doing an extensive literature review. The many factors that could affect pond aquaculture site suitability for specifically the Mozambique tilapia were researched. Many variables could potentially be included in an inland pond aquaculture site suitability model. There is no exhaustive list of variables that could be considered. The variables that were included were selected due to the importance of the variable for inland pond aquaculture site suitability, data availability, keeping the model simple to populate and share, the type of model (quantitative) and the technical environment that the model was designed to function in (Hossain et al, 2007). Rarely do these models contain an exhaustive, thorough assessment of all man-made and environmental characteristics (Fegan, 1994).

Some of the variables that were not included were some physical- or environmental variables, economic variables, social variables, socio-economic variables and individual management -and financial capabilities of farmers in the areas. The said categories of variables could range from water balance models for pre-determined pond volumes, physio-chemical conditions, existing land-use patterns, theft in the area, distance to poultry and other farm inputs, the occurrence of natural disasters, the exclusion of flood zones, aspect of the terrain, farm-gate sales including population statistics and governmental considerations (Handisyde, 2015; Hossain et al., 2007; Ssegane et.al, 2012). In Chapters 5 and 6, some recommendations of variables which might be added in the case of commercialization of the small-scale farmers, are suggested.

The GIS model created in this research made use of several of these input data sets, but not all. These chosen data sets originated from different sources and were generated at different spatial resolutions, as displayed in Table 3.1.

Table 3.1 List of some of the selected data variables containing their data sources, -resolution, -format, -creation date and justification for use in pond aquaculture site suitability.

Data	Data Source	Spatial Resolution	Creation Date	Data Format	Justification
Surface-air temperature	Generated by the interpolation of the Agricultural Research Council: Soil Climate and Water ARC-NRE (ARC-SCW, 2019) and the South African Weather service (SAWS, 2019) weather station data.	1 kilometre (km)	2021	Raster (Tiff)	Proxy for pond water temperature. Suitable for use at farm level up to national scale.
Digital Elevation Model (DEM	In-house (ARC-SCW) improved gap-filled Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Farr, et.al, 2007) (ARC-SCW, 2018a).	30 metres (m)	2018	Raster (Tiff)	To calculate slope Percentage rise (%) of the surface. Suitable to be utilised at farm level up to national scale.
Slope percentage (%) rise of the surface	Created from the in-house corrected SRTM DEM Tiff (Farr, et.al, 2007) (ARC-SCW, 2018a) and snapped to the DEM in ArcMap 10 Spatial Analyst Model Builder (Esri, 2018).	30 metres (m)	2022	Raster (Tiff).	Percentage rise (%) of the surface to establish drainage and ease of construction. Suitable to be utilised at farm level up

					to national scale.
Restricted areas (Masks /Constraints)	Created in the constraints sub-model according to guidelines provided by Francisco et al., (2019). DEA, (2012) and Roets, (2016).	30 metres (m)	2022	Raster (Tiff)	To define areas that are restricted for pond aquaculture. Suitable to be utilised at farm level up to national scale.

3.3.2.1.1 Distance to water source

Location variables such as the pond's distance to a water source, was determined from literature to be one of the most important determining factors in the spatial suitability of a pond aquaculture enterprise (Aguilar-Manjarrez and Nath, 1998; Verster, 2017).

South-Africa is a water scarce country (Damkjaer and Taylor, 2017; Rijsberman, 2006). Water scarcity in the Limpopo River Basin (LRB) is the result of the basin's highly variable climate, with frequent extreme seasonality, intense El Niño-Southern Oscillation (ENSO) events, and interactions with oceanic climates from both the Atlantic- and Indian Oceans. These factors make rainfall and runoff unreliable in the basin (Mosase and Ahiablame, 2018; Jury, 2016; Moeletsi et.al. 2011; Schulze, 2001). Water availability is a very important consideration when wanting to establish if an area is suitable for earth-pond aquaculture and is considered a key-factor in determining where aquaculture might be established (Aguilar-Manjarrez and Nath, 1998; Aquaculture Innovations, 2010; Nayak et. al., 2014.)

The suitability model develop in this research consists of five sub-models. These sub-models contain variables that were grouped according to the way they influence site suitability. The Water Availability sub-model consists of distance to water sources such as boreholes, springs, rivers, and dams. There are many guidelines in literature concerning the suitability classification according to the distance from a water source.

The number of suitability classes recommended for use also differ amongst authors (Nayak, 2014; Hadipour, Vafaie an Hadipour, 2015). In this research, the suitability classification consists of four classes: Highly suitable, moderately suitable, marginally suitable, and unsuitable. These suitability classes' threshold values were determined after considering the information in the literature reviewed of many authors. Spatial data sets of water bodies such as rivers, dams, springs and boreholes, were sourced from the Department of Water and Sanitation (DWS, 2019) and the National Geospatial Institute (NGI, 2019). These input data were overlaid using the Weighted Overlay (WO) method in ArcMap Model Builder (Esri, 2016). The map that was created by the Weighted Overlay (WO) process during the execution of the distance to a water source sub-model, is displayed in Figure 3.7.

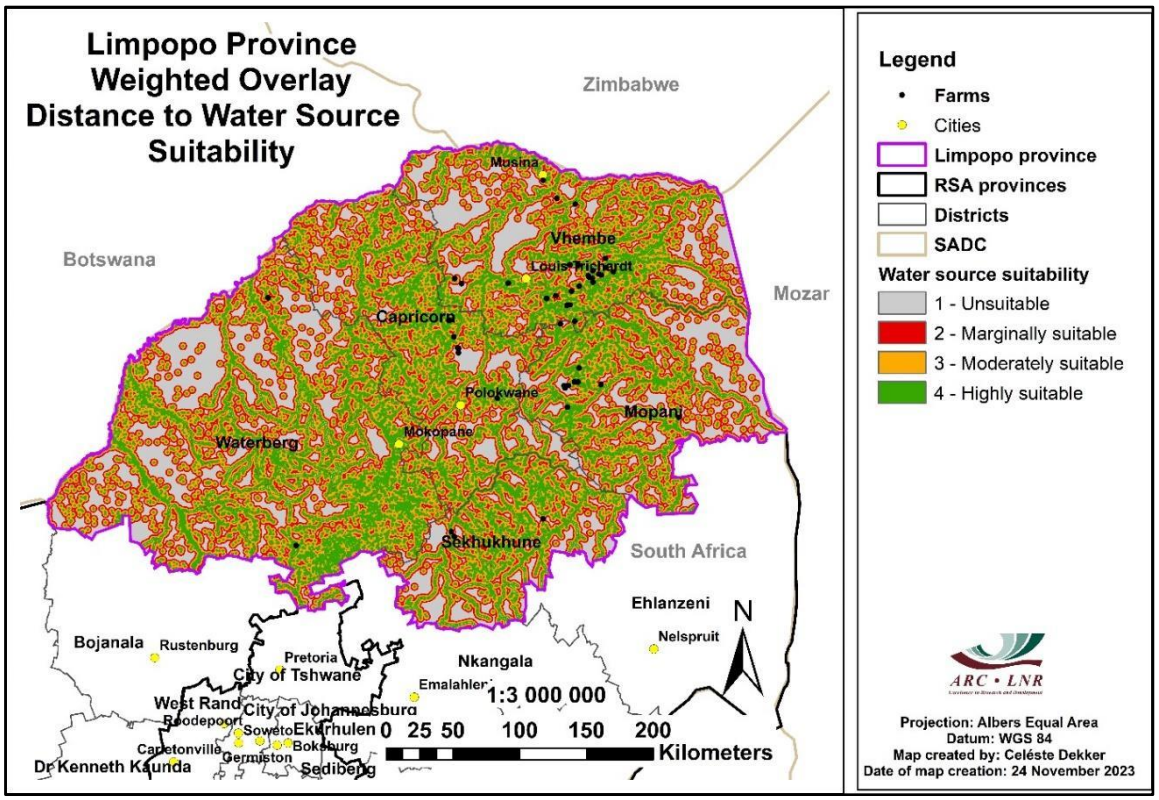


Figure 3.7 Map of the distance to a water source suitability sub-model created via Weighted Overlay (WO).

3.3.2.1.2 Temperature variable

Water temperature is viewed as one of the major factors in aquaculture earth pond site selection and thus was chosen as one of the variables in the site suitability analysis for inland pond aquaculture in this research (Aguilar-Manjarrez and Nath, 1998; Handisyde, 2015; Urban-Econ, 2018; Verster, 2017). This is due to the fact that water temperature is one of the most critical factors that influence fish growth, reproduction, survival, and mortality rate (Aguilar-Manjarrez and Nath, 1998; Aquaculture Innovations, 2010; Handisyde, 2015; Urban-Econ, 2018).

Water temperature also has a profound effect on the fishes' distribution and length of breeding season and is therefore considered by some as the primary suitability factor (Hutchison, Sarac and Norris, 2011). Unusually low or high temperatures can negatively influence reproduction, survival, and growth of fish in both natural ecosystems and aquaculture facilities (Boyd and Tucker, 1998). A study of the potential range of the Mozambique tilapia in the Murray-Darling basin in Australia, stated that the factor that most affects Mozambique tilapia *(Oreochromis mossambicus)* occurrence and distribution, is its vulnerability to cold temperatures (Hutchison, Sarac and Norris, 2011). The Mozambique Tilapia is a tropical to warm water temperate fish species native to certain parts of Africa (Pullin and Lowe-McConnel, 1980).

During the literature research conducted to determine the thresholds of water temperature for the Mozambique tilapia, much variability was found. This was the case for optimal water temperature, as well as upper and lower thermal tolerances (Hutchison, Sarac and Norris, 2011; Webb and Maughan, 2007). Warm-water species grow best around 24-36 º C according to Stander, (2023). The fastest growth takes place from 28 ˚C to 32 ˚C (Boyd and Tucker, 1998). The optimal temperature range throughout the year should be 28 ˚C to 30 °C (Aquaculture Innovations, 2010); while others stated that the optimum temperature range should be from 24 ˚C to 32 ˚C (Stander, 2023), and 18 ˚C to 34 ˚C (Boyd and Tucker, 1998). According to Webb and Maughan, (2007), the Mozambique tilapia is described as a poikilothermic (Boyd and Tucker, 1998), warmwater, stenothermal species, with habitat distribution only restricted to its limited tolerance of somewhat lower temperatures (Hickling, 1963). The Mozambique tilapia can survive low temperatures of between 8°C and 15°C (Smit et al., 1981; Philippart and Ruwet, 1982).

Others claim that the Mozambique tilapia's thermal tolerance ranges between 15°C and 37°C, and in the higher temperature ranges between 39°C and 40°C, where mortality will set in between 41°C to 42°C (Philippart & Ruwet 1982; Stauffer 1986). Being multiple spawners throughout the year, the number of spawning is also dependent upon temperature and thus latitude and altitude (Philippart and Ruwet 1982). In laboratories, the optimal temperature range of the Mozambique tilapia, where more than 90% of development occurred, was 24°C and 34.5°C, (Webb and Maughan, 2007).

Stander, (2023) refers to the Mozambique tilapia 's characteristic range of tolerance to water temperatures as being between 11˚C to 37˚C. Other lower critical ranges have been reported as being between 10˚C to 14˚C, optimal ranges of 18 ˚C to 34 ˚C and 28 ˚C to 32˚C, and the upper critical range of 36˚C to 42˚C (Boyd and Tucker, 1998) or between 15°C to 42°C (Aquaculture Innovations, 2010). At 20˚C the feeding rate of tilapia decreases and stops at 16˚C (Balarin and Haller, 1982). Upper thermal tolerances in which tilapia can survive have been reported to range between 38ºC and 42ºC (Wohlfarth and Hulata, 1983; Allanson and Noble, 1964; Kirk, 1972). Water temperature could thus have a major effect on aquaculture productivity (Boyd and Tucker, 1998). Thus, the geographic area where the pilot study site was chosen, was the province in South Africa with the most preferential temperature range, i.e., the Limpopo province.

The Limpopo Province has a minimum average air temperature of 8ºC in the south to 20ºC in the east of the Limpopo River Basin (LRB). The maximum average air temperatures are 23ºC in the south of the basin to 32ºC in the east of the Limpopo River Basin (Mosase and Ahiablame, 2018). In this research, surface-air temperature was used as a proxy for water temperature (Mohseni et. al., 1999), as limited pond water temperature data were available.

Air temperature values are widely used as a good proxy for pond water temperatures (Mohseni, et al, 1999; Boyd and Tucker, 1998; Morrissy, 1976; Klemetson and Rogers, 1985; Wax and Pote, 1990). The relationship between air temperature and water temperature has been documented since the 1960's according to Boyd and Tucker, (1998). Water temperatures in ponds closely follow and resemble air temperature values (Boyd and Tucker, 1998; Morrissy, 1976; [Klemetson and Rogers, 1985; Wax

and Pote, 1990)] In: Boyd and Tucker, 1998). In a study that took place in Pemberton, Western Australia, average monthly air temperatures were used to correlate with average monthly water temperatures (Morrissy, 1976). The monthly air temperatures were about 0.5°C to 2.0°C higher than monthly water temperatures, but the trends of increase and decrease over the year were alike (Morrissy, 1976) The Average monthly air- and water temperatures at Pemberton, Western Australia were obtained by averaging minimum and maximum temperature data. (Morrissy, 1976). More recent research confirmed that air temperature is a good proxy for pond water temperature (Fahy, et al., 2024; Li, et al., 2025; Staples et al., 2023).

In “A strategic reassessment of fish farming potential in Africa” by Aguilar-Manjarrez and Nath, (1998), the same method to determine water temperatures from air temperatures was implemented as described in Kapetsky, (1994). However, wind velocity was added to the equation (Aguilar-Manjarrez and Nath, 1998). A study conducted in Zimbabwe was used as the primary water temperature verification site in their study. It provided a more comprehensive dataset than the other sites in Africa (Aguilar-Manjarrez and Nath (1998). Their verification exercise was conducted using data collected from three ponds at a research station in Zimbabwe. Minimum and maximum daytime air temperatures (in °C) were converted to dekadal (ten-daily) and then to mean monthly daytime air temperatures (MMDT). MMDT were then converted to mean monthly water temperatures (MMWT). The conversion of MMDT to MMWT was executed using a model developed through regression of water temperatures from the three ponds (Aguilar-Manjarrez and Nath, 1998).

Regression results of MMWT from MMDT for each of the three ponds were significant and provided coefficients of determination of 0.88, 0.85 and 0.67 respectively. Because of an overlap of the 95% confidence limits, both on the slopes and on the intercepts, it was assumed that there were no significant differences among the air temperature-water temperature relationships of the three ponds. Therefore, the monthly data were pooled and a regression analysis on the pooled data provided the air temperature to water temperature model (Aguilar-Manjarrez and Nath, 1998).

When expressed as a linear function, the coefficient of determination of MMWT as a function of MMDT over 51 Months was 0.82 (Aguilar-Manjarrez and Nath, 1998;

Kapetsky, 1994). Equation 3.1 indicates the relationship found between MMWT and MMDT.

Equation 3.1 Equation for Mean Monthly Water temperature (MMWT) from Mean Monthly Daytime Temperature (MMDT).

$$MMWT = -6.35 + 1.3\ (MMDT)$$

(Aguilar-Manjarrez and Nath, 1998; Kapetsky, 1994).

A study by Mohseni et.al, (1999) estimated stream temperatures for the entire United States from regressions between water temperatures at individual stream gaging stations and air temperatures at nearby weather stations. This method was described as being easy and practical (Mohseni et. al., 1999). This type of method is also attractive for climate change studies because only one input variable, air temperature, is used. General Circulation Models (GMSs) simulate the air temperature variable better than they simulate other variables ([Lau et. al., 1996] in Mohseni and Stefan, 1999). Among regression models, linear models are easier to use and more commonly used. But stream temperature starts levelling off as air temperature exceeds 20°C. In that case the overall stream temperature-air temperature relationship often resembles an S-shaped function (Mohseni, et. al., 1999).

The Air-Temperature data used in the Temperature Sub-Model in this research, were created using the same aggregation methodology as described by Aguilar-Manjarrez and Nath, (1998), Kapetsky, (1994) and Ssegane, et. al., (2012). The 30-year long-term average air-temperature data sets were created from weather station data. These data were sourced from The South African Weather Service (SAWS, 2019) and from the Agricultural Research Council Institute for Soil, Climate and Water (ARC-ISCW, 2019).

The weather stations' 30-year data sets consisted of the 1988 to 2018 hourly maximum and minimum near-surface air temperature data, that were aggregated to average daily temperatures by addition and then dividing by the number of hours.

The SAWS data were converted to 24-hour period data from 00:00 am to 24:00 pm. Its original collation is from 12:00 pm to 12:00 pm the following day according to Dall'Amico and Horsteiner, (2006). The ARC-ISCW data were collected from hourly weather station data and aggregated to 24-hour period averages by adding all minimum hourly data and dividing it by 24, then adding all maximum hourly data and dividing them by 24. The average daily minimum and -maximum temperatures were added and divided by 2. All average daily temperatures were then added for each month and divided by the number of days in each month. Finally, all thirty January months' data were added and divided by thirty (30). The same was done for each of the other 12 months.

This methodology of calculating the mean monthly daytime temperature is prescribed by the World Meteorological Organisation (WMO, 2017) and was used by Arguez and Vose, (2011). In this research, Equation 3.2 describes how the 30-year long-term mean monthly surface air temperatures ($MMDT_{Mean}$) were created by adding the 30-year long-term maximum monthly temperature ($MMDT_{Max}$) to the 30-year long-term minimum monthly temperature ($MMDT_{Min}$) and dividing it by two (2). The product of these calculations were rasters in the Tagged Image File Format (TIFF) format (ARC-SCW, 2019; SAWS, 2019; Ssegane, et. al, (2012).

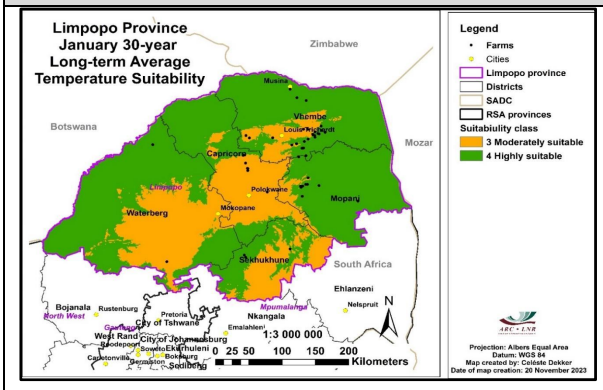
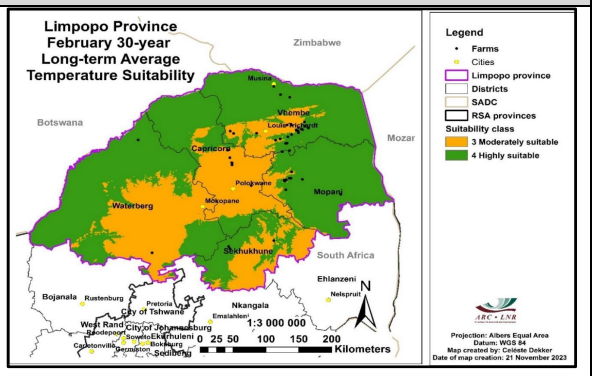
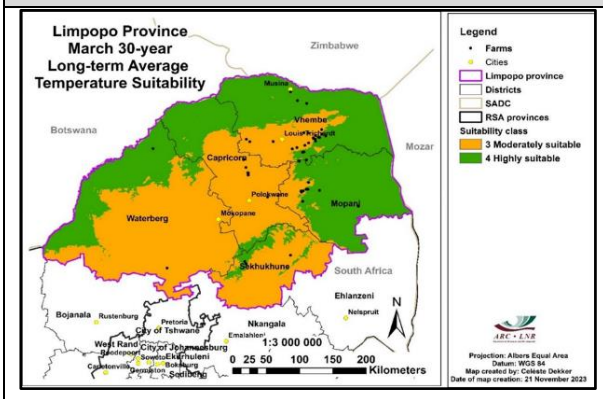
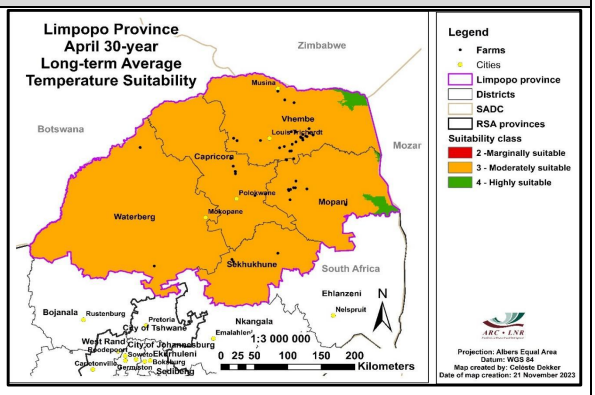
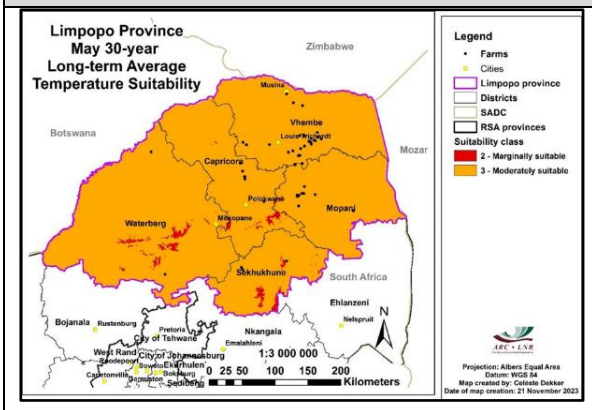
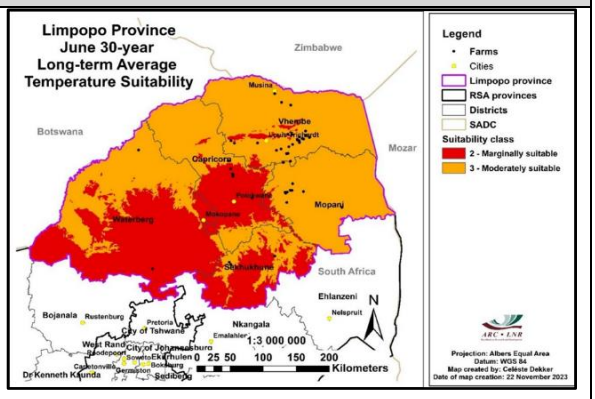
Equation 3.2 Calculation of the 30-year long-term average air-temperature data sets:

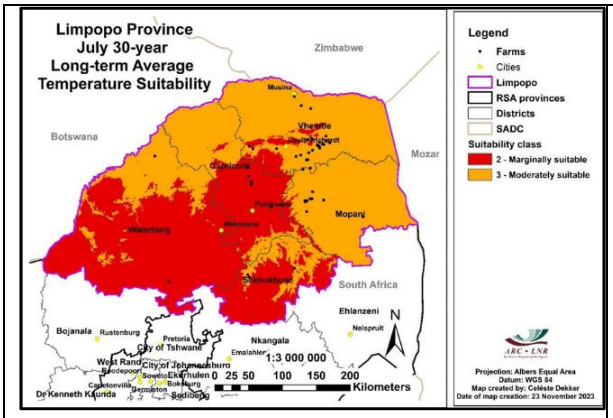
$((MMDT_{Max}) + (MMDT_{Min})) /2 = (MMDT_{Mean})$

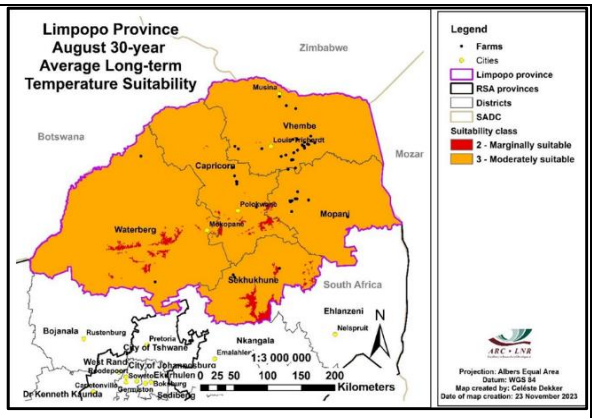
The temperature data that were used in the Temperature suitability sub-model in this research, thus consisted of 30-year long-term historical surface air temperature data. This consists of a 30-year period, the prescribed number of years for a long-term period by the WMO, (2017). These data were used as a proxy for pond water temperature (Mohseni et al, 1999) in the model. The input data were 12 Tiffs, one for each of the 12 months of the year.

The outputs of the temperature sub-model were 12 temperature site suitability Tiffs and their maps, one for each of the 12 months of the year. For ease of comparison, these 12 suitability maps are first displayed together in Table 3.2. Thereafter, each temperature suitability map is presented separately for viewing (Figure 3.8 to Figure 3.19). These maps contain the locations of the 48 known farmers in on the temperature suitability maps of each month.

Table 3.2 Long-term (30-year) monthly average historical near-surface air temperature suitability maps for Mozambique tilapia of the Limpopo province.

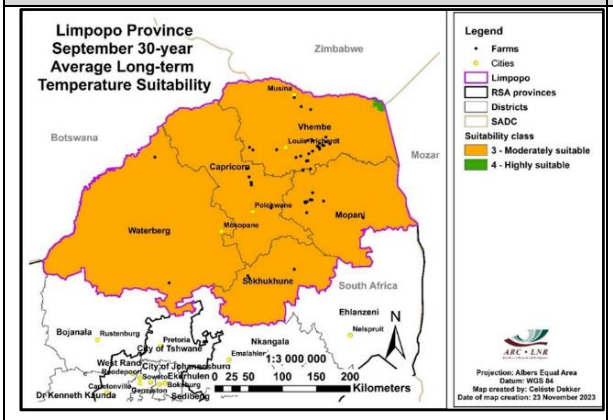
January	February
	
March	**April**
	
May	**June**
	
July	**August**

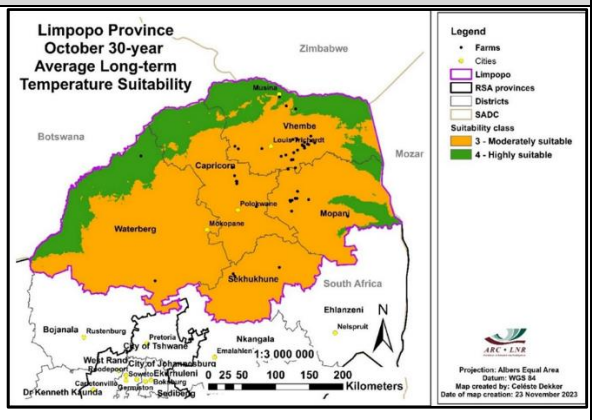




September

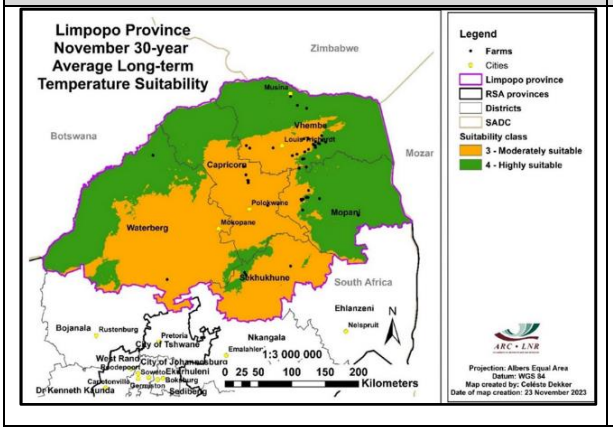
October

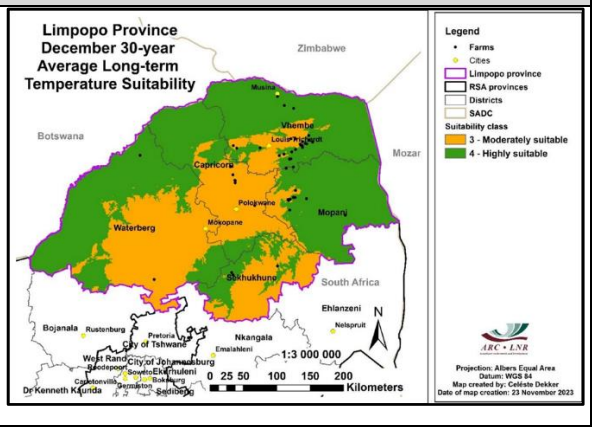




November

December





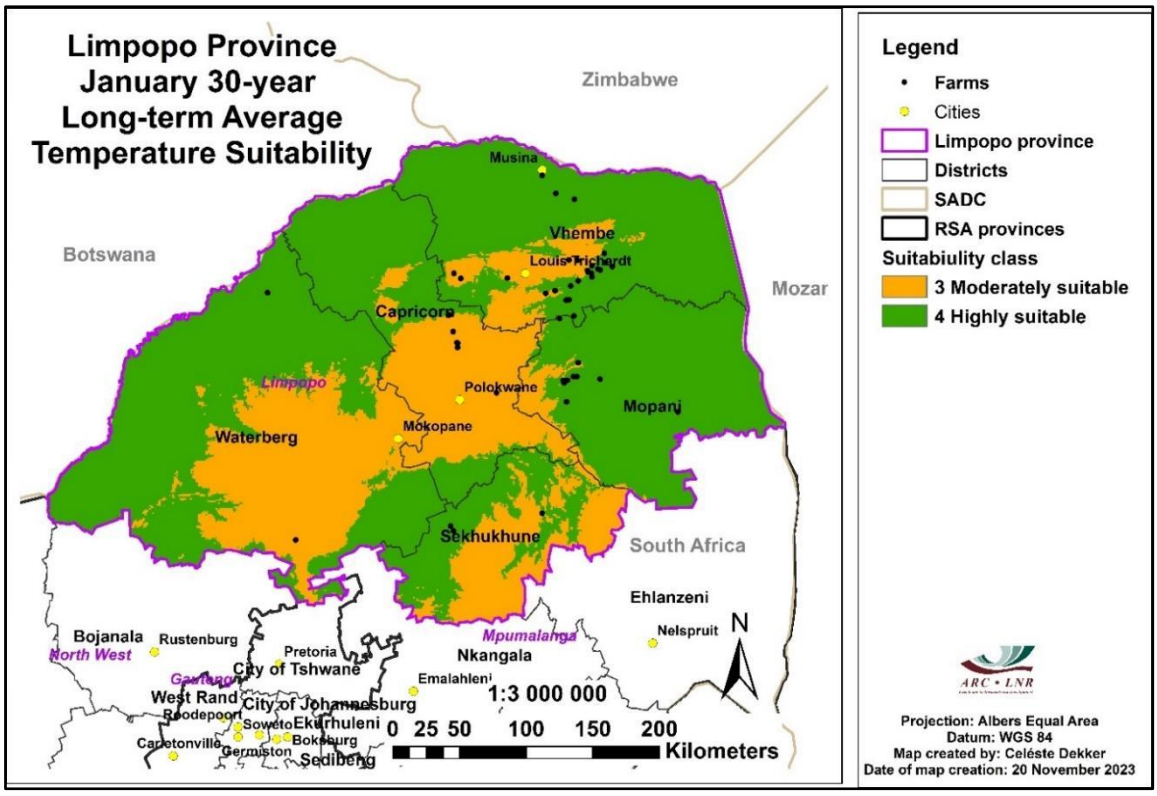


Figure 3.8 January temperature site suitability map for Mozambique tilapia of the Limpopo Province.

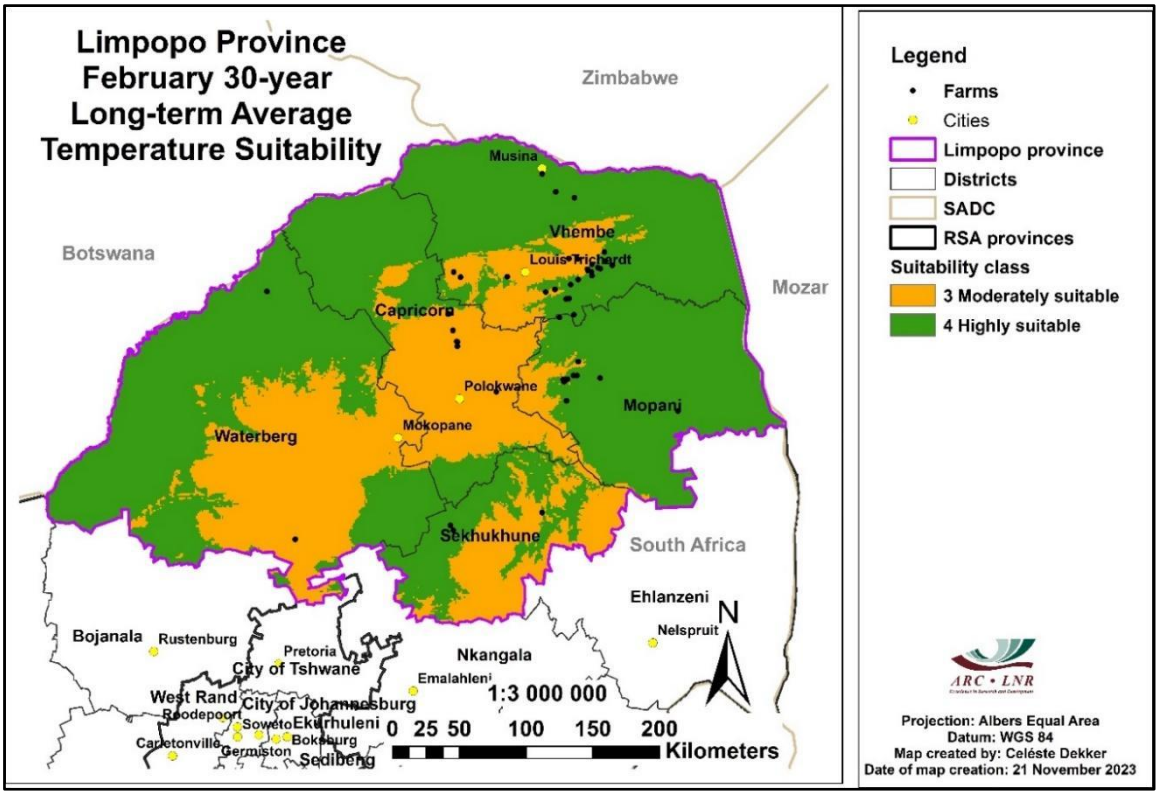


Figure 3.9 February temperature site suitability map for Mozambique tilapia of the Limpopo Province.

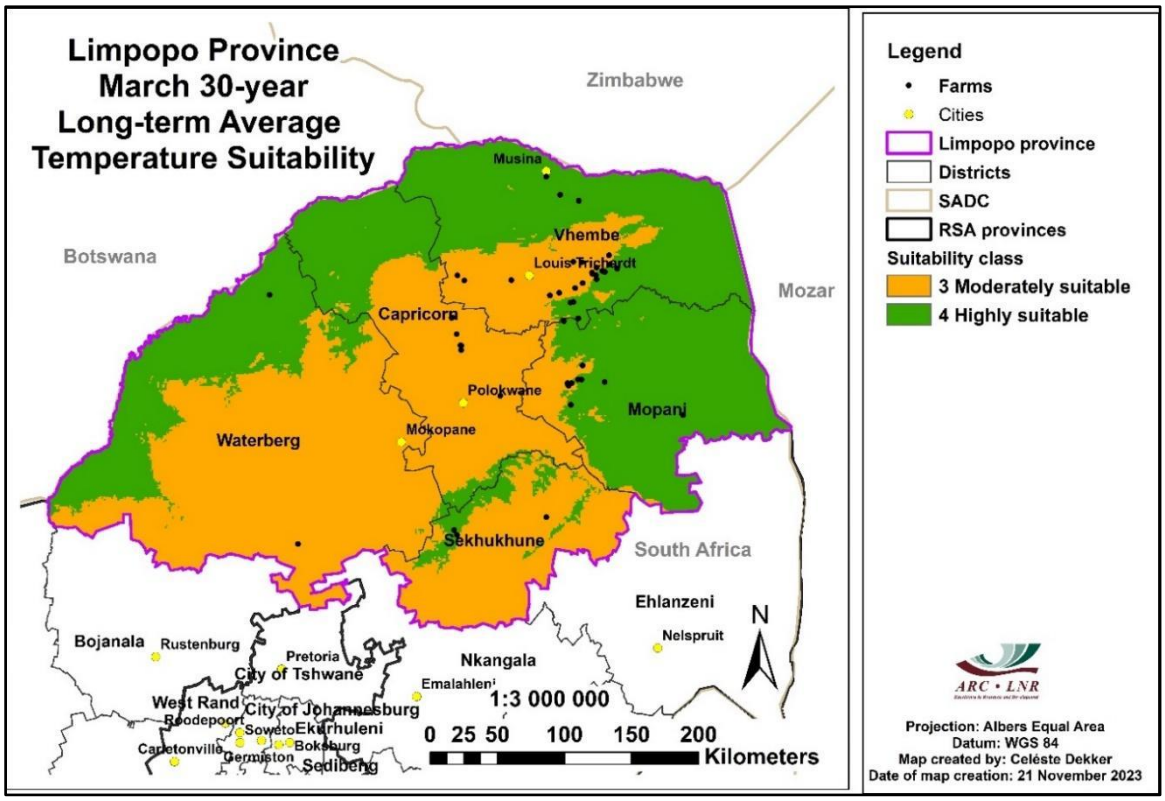


Figure 3.10 March temperature site suitability map for Mozambique tilapia of the Limpopo Province.

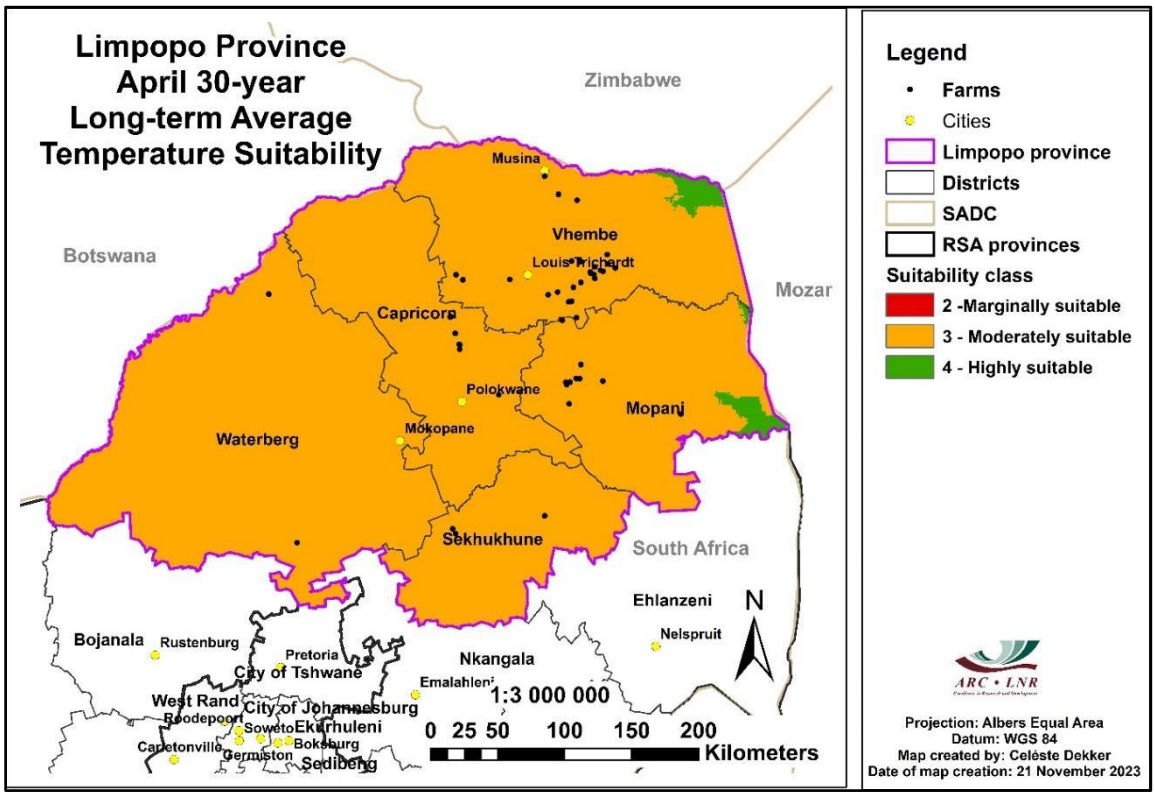


Figure 3.11 April temperature site suitability map for Mozambique tilapia of the Limpopo Province.

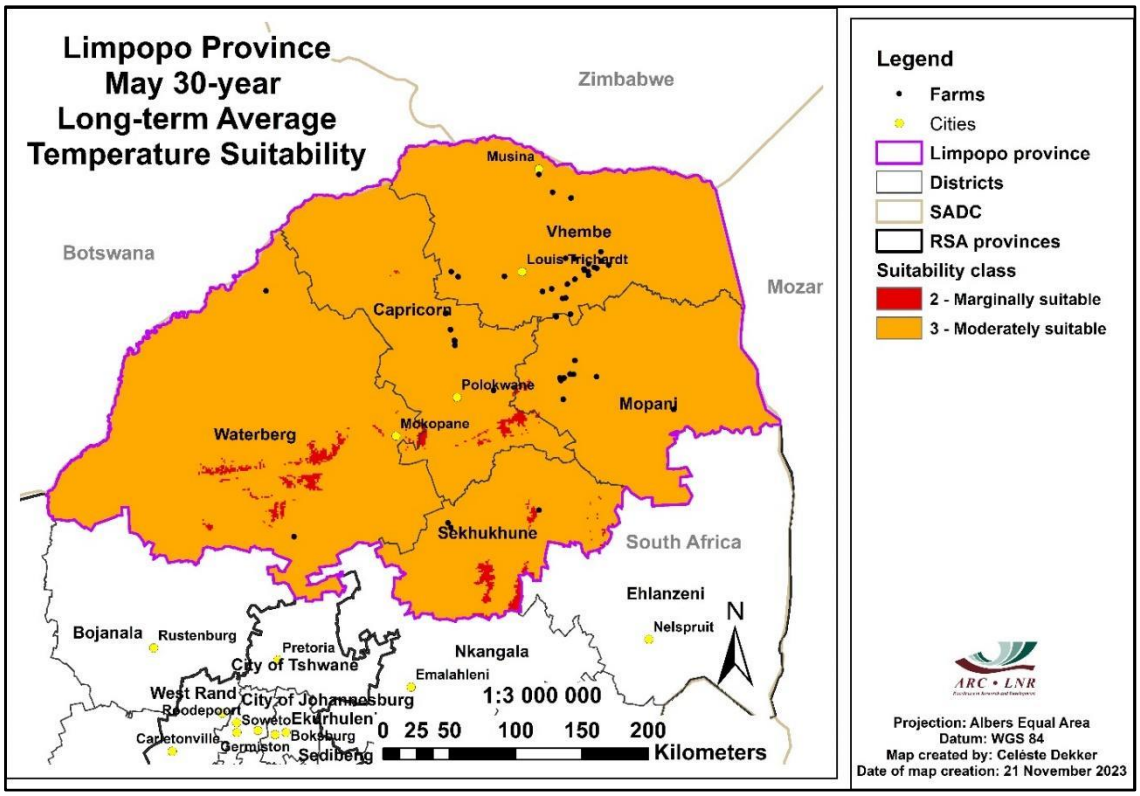


Figure 3.12 May temperature site suitability map for Mozambique tilapia of the Limpopo Province.

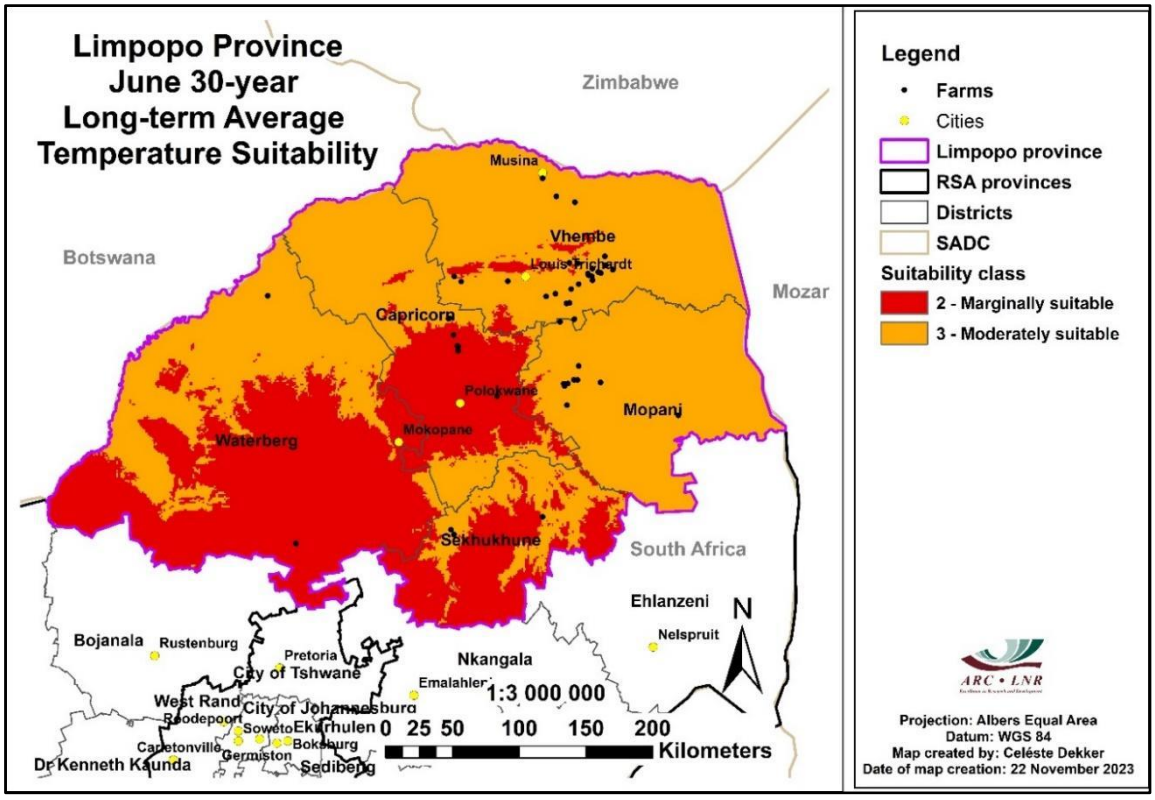


Figure 3.13 June temperature site suitability map for Mozambique tilapia of the Limpopo Province.

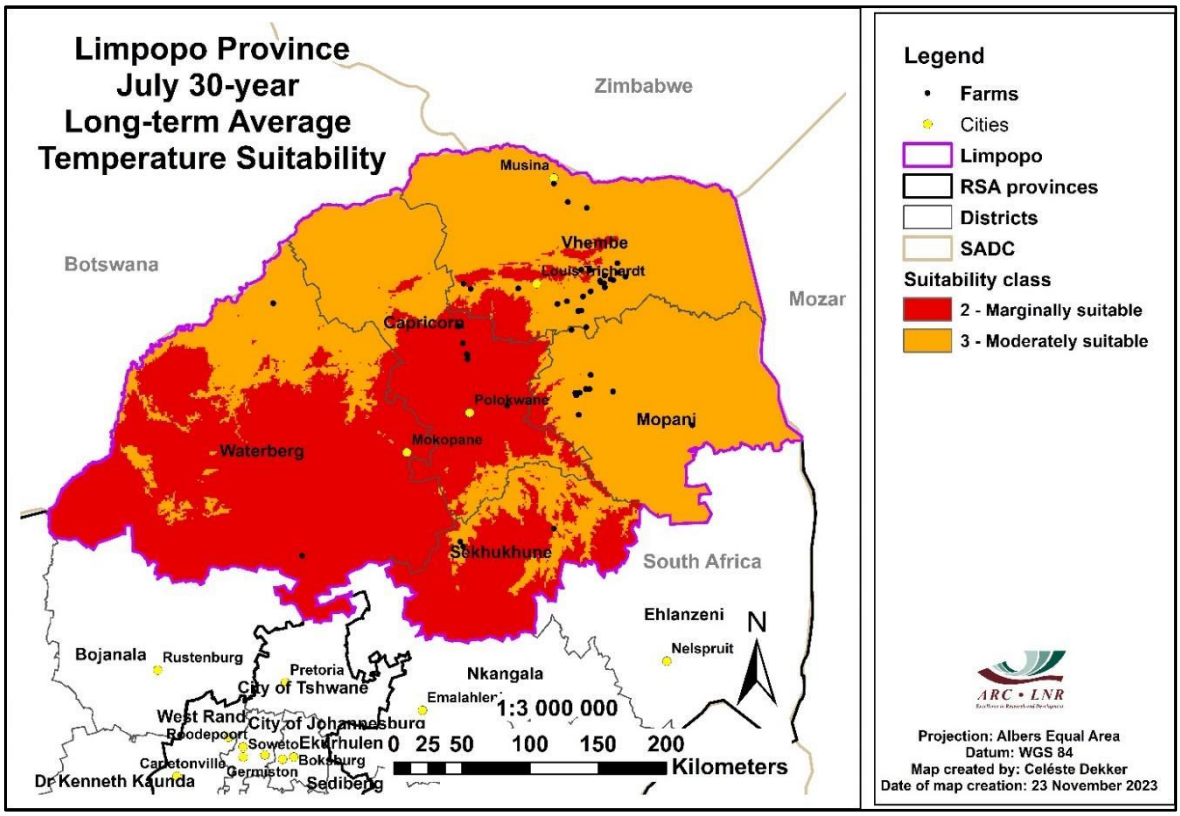


Figure 3.14 July temperature site suitability map for Mozambique tilapia of the Limpopo Province.

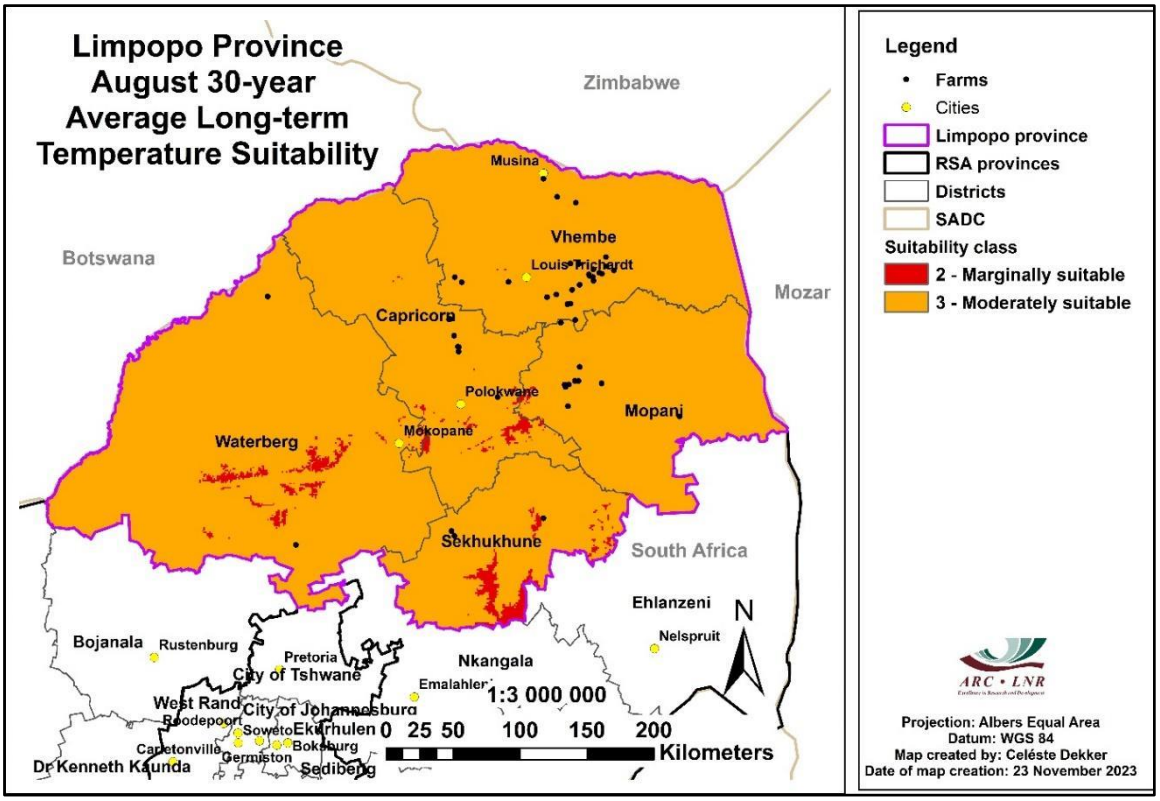


Figure 3.15 August temperature site suitability map for Mozambique tilapia of the Limpopo Province.

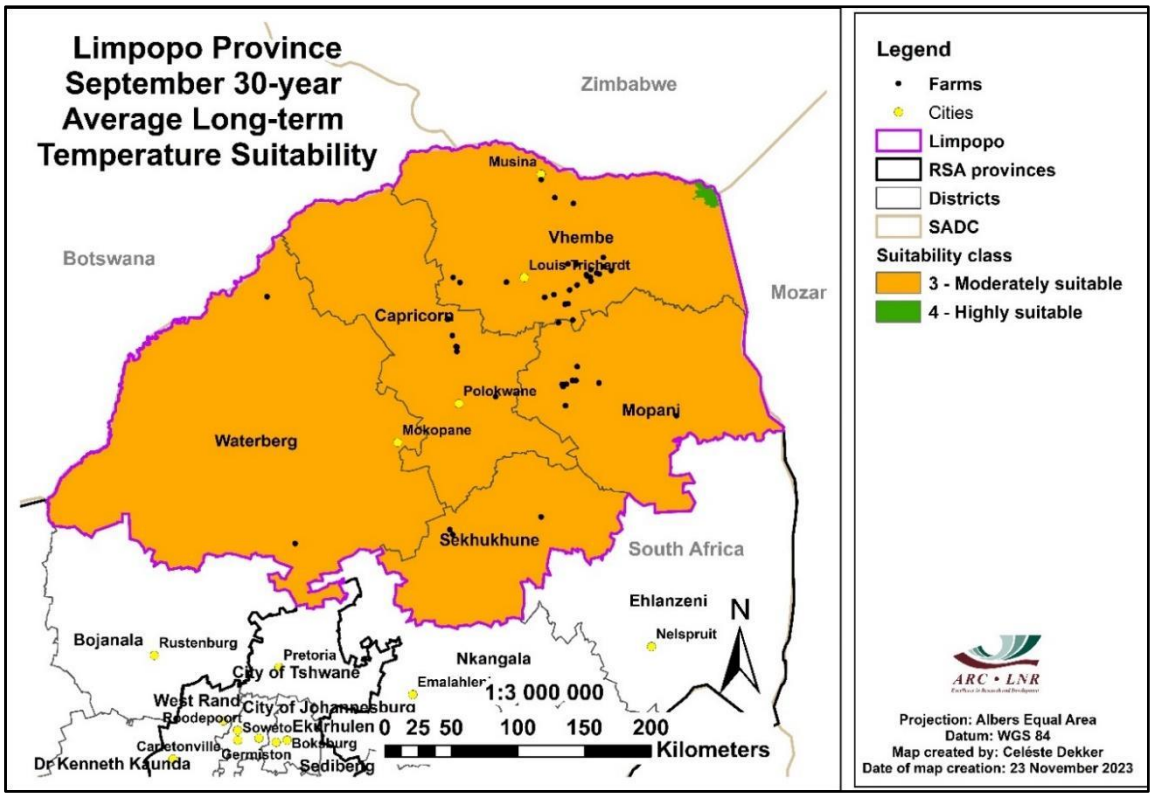


Figure 3.16 September temperature site suitability map for Mozambique tilapia of the Limpopo Province.

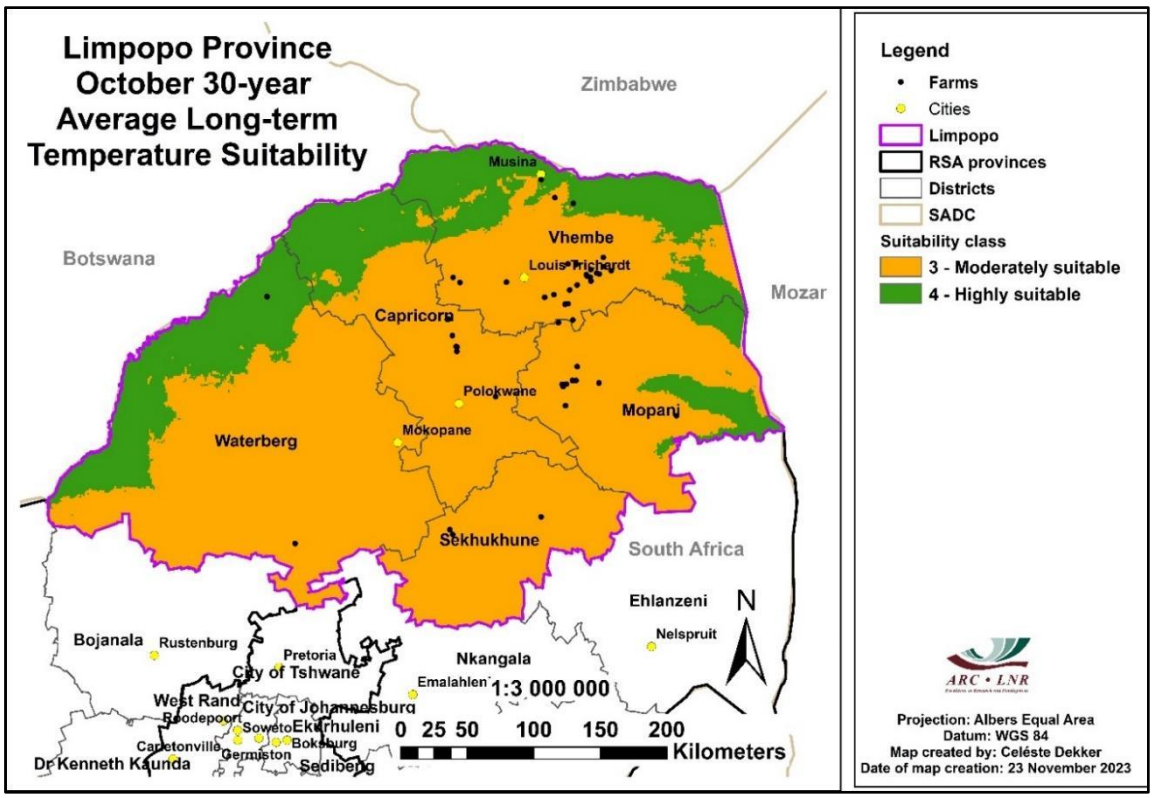


Figure 3.17 October temperature site suitability map for Mozambique tilapia of the Limpopo Province.

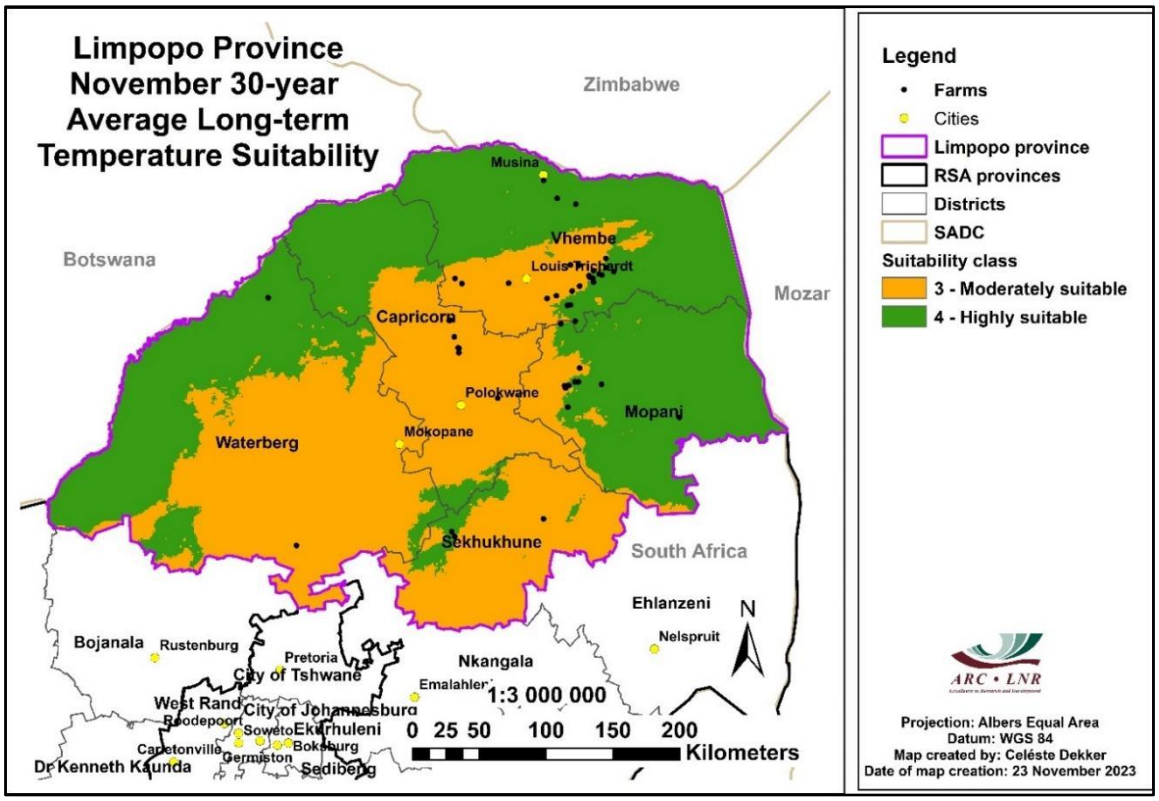


Figure 3.18 November temperature site suitability map for Mozambique tilapia of the Limpopo Province.

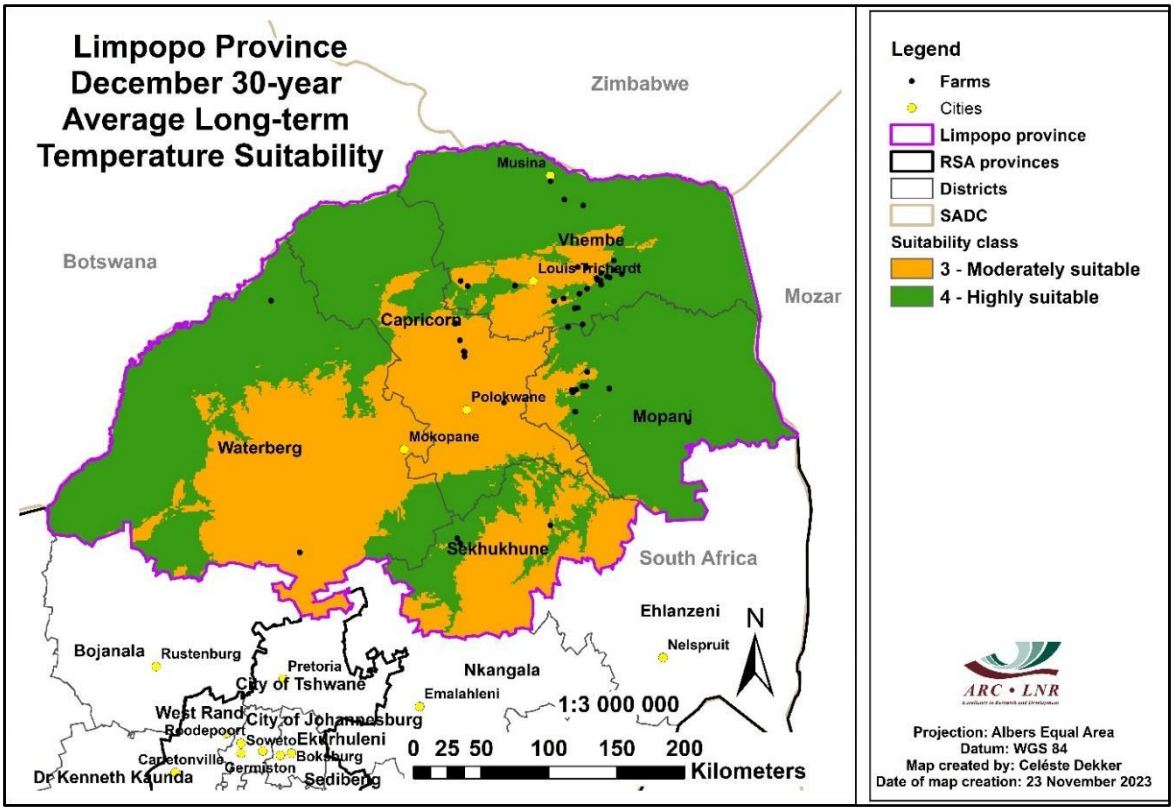


Figure 3.19 December temperature site suitability map for Mozambique tilapia of the Limpopo Province.

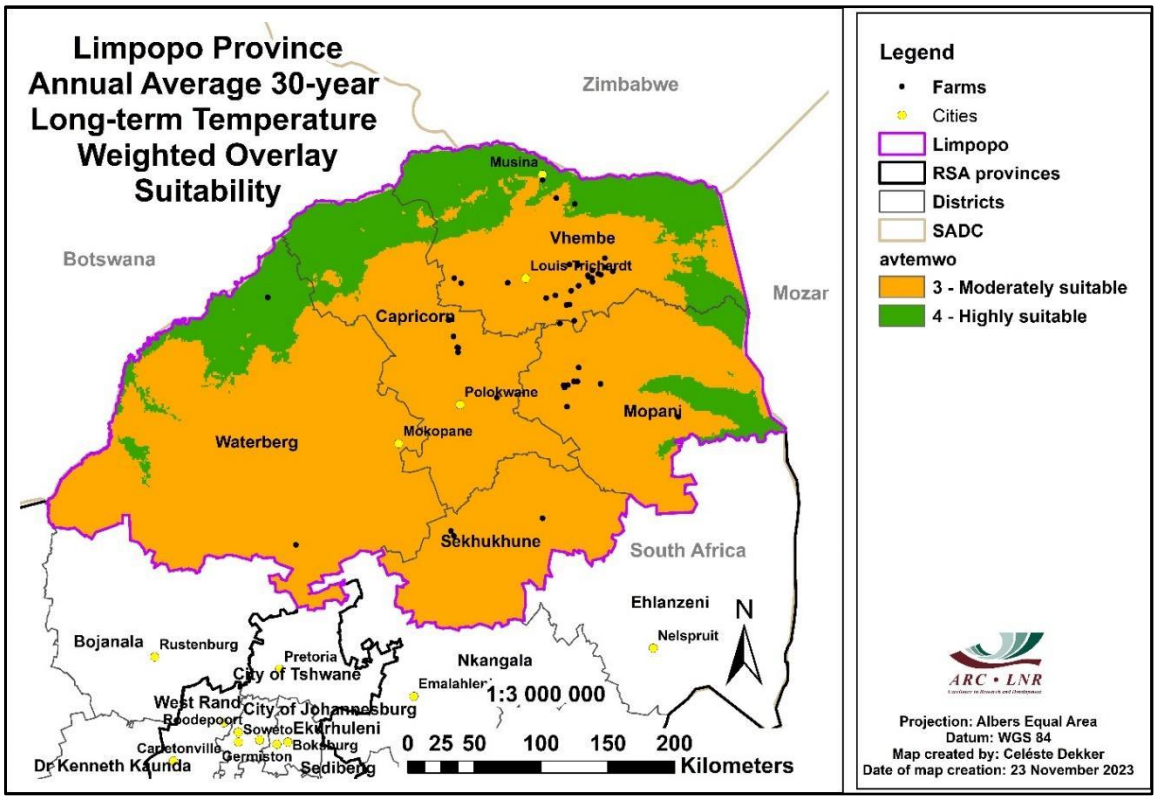


Figure 3.20 Annual average 30-year long-term temperature suitability map of the twelve months combined via Weighted Overlay (WO) for Mozambique tilapia of the Limpopo Province.

The 12 annual average 30-year long-term temperature suitability maps, one for each month of the year, were overlaid via the Weighted Overlay (WO) technique. The result is seen in Figure 3.20.

A drastic increase was observed in African annual-average near-surface temperatures over the last five decades. Over parts of the sub-tropics and central tropical Africa, the rate of temperature increase was twice that of the rest of the globe (Engelbrecht et al, 2015). Further warming is projected up to the year 2100 using Global Circulation Models (GCM) over the tropics and sub-tropics of Africa. This projected increase is 1.5 times that of the global rate of temperature increase (Engelbrecht et al, 2015). Research findings of the Working Group II (WGII) to the Sixth Assessment Report) (AR6) of the Intergovernmental Panel on Climate Change (IPCC) assessed the risk associated with possible future global warming (IPCC, 2022). Therefore, the model was designed to accommodate climate change input data sets like temperature data, to produce future suitability maps.

The pond aquaculture site suitability model was designed so that Climate Change Models' air temperature data or water temperature data could be incorporated into for instance the Temperature sub-model stage. Data from Global Circulation Models (GCMs) can be imported into the model to delineate future site suitability for pond aquaculture. This could also be useful for the selection of fish sanctuaries for the preservation of the Mozambique tilapia for future generations. The temperature thresholds can be adjusted in the model to calculate suitability for any other fish species' water temperature suitability ranges.

The ease with which other data can be imported into the model was tested. Air temperature data from a climate change dataset, known as the CORDEX (Co-Ordinated Regional Downscaling EXperiment)-CORE (COmmon Regional Experiment), The CORDEX-CORE initiative provides Regional Climate Model (RCM) projections over domains worldwide, one of which is Africa (Teichmann et al. 2020). These temperature data were used in the model to produce future Mozambique tilapia pond aquaculture site suitability maps.

3.3.2.1.3 Soil Suitability variables

Variables such as slope and soil clay percentage play a role in the economic suitability of a site in terms of pond construction, and therefore need to be considered as important (Aguilar-Manjarrez and Nath, 1998).

According to Ssegane et.al., (2012), soil texture is more important than slope in terms of rating in a suitability exercise. Various suitability threshold recommendations were found in literature regarding soil clay and slope percentage (Aquaculture Innovations, 2010; Aguilar-Manjarrez and Nath, 1998; Boyd, Wood and Thunjai, 2002; Hajek and Boyd, 1990; Yoo and Boyd, 1993; Handisyde, 2015; Ssegane et.al, 2012; Nayak, et. al, 2014; Richard et.al, 2016). A clay percentage of 20% to 40% was stated as highly suitable (Handisyde, 2015); a clay content of 5% to 10% is more desirable than a high clay content (Boyd, Wood and Thunjai, 2002). A clay percentage greater than 60% or less than 10% is not suitable, while the range between 10% and 60% could be classified into the other remaining categories (Handisyde, 2015).

In terms of slope percentage rise (%) suitability, a slope of less than 2% (or 1% to 2% for 1 ha to 5 ha ponds) is most favourable, while a slope of between 2% and 5% is

moderately suitable, 5% to 8 % is marginally suitable and all terrain with slopes greater than 8% were classified as unsuitable (Aguilar-Manjarrez and Nath, 1998; Hajek and Boyd, 1990). Slope percentage rise suitability threshold classifications by Ssegane et al., 2012), classified all slopes of less than 2% as highly suitable. Slopes from 2% to 5% were classified as Moderately suitable, while slopes of 5% to 15% were classified as Marginally suitable. All slopes greater than 15% were classified as Unsuitable (Ssegane et al., 2012). The ideal site should be flat or almost flat with a slope of 0.5% to 1%, up to a maximum of 2.5% (Thaela-Chimuka, M-J., 2019: Personal communication) in Dekker et al., (2019).

Slopes of up to 5% are suitable for 0.01ha to 0.05 ha ponds (ICLARM and GTZ, (1991). While Hossain et. al., (2007) classified slopes of 0% to 5% as the most suitable. Slopes that range from 5% to 15% were classified as moderately suitable, while slopes of greater than 15% were classified as not suitable (Hossain et. al., 2007).

Thresholds for soil clay % (Table 3.5 and Table 3.6) and slope % rise (Table 3.3 and

Table 3.4) for this research were adapted from the various author's classifications. Topsoil clay percentage, the soil depth range, and the spatial component information were used for each soil entry from the digital Land type information (Land type survey staff, 1972-2009). A weighted average was calculated for each Land type unit. These were combined with the available in-house (ARC-ISCW) soil inventory databases containing soil clay percentage profile descriptions (Soil Survey Staff, 2006).

An in-house improved 30-meter Digital Elevation Model (DEM) data set (Figure 3.21) (ARC-SCW, 2018a) created from The Shuttle Radar Topography Mission (SRTM) (Farr, et.al, 2007) was used to create the slope percentage raster (Figure 3.22) in ArcGIS 10 (Esri, 2018) Spatial Analyst.

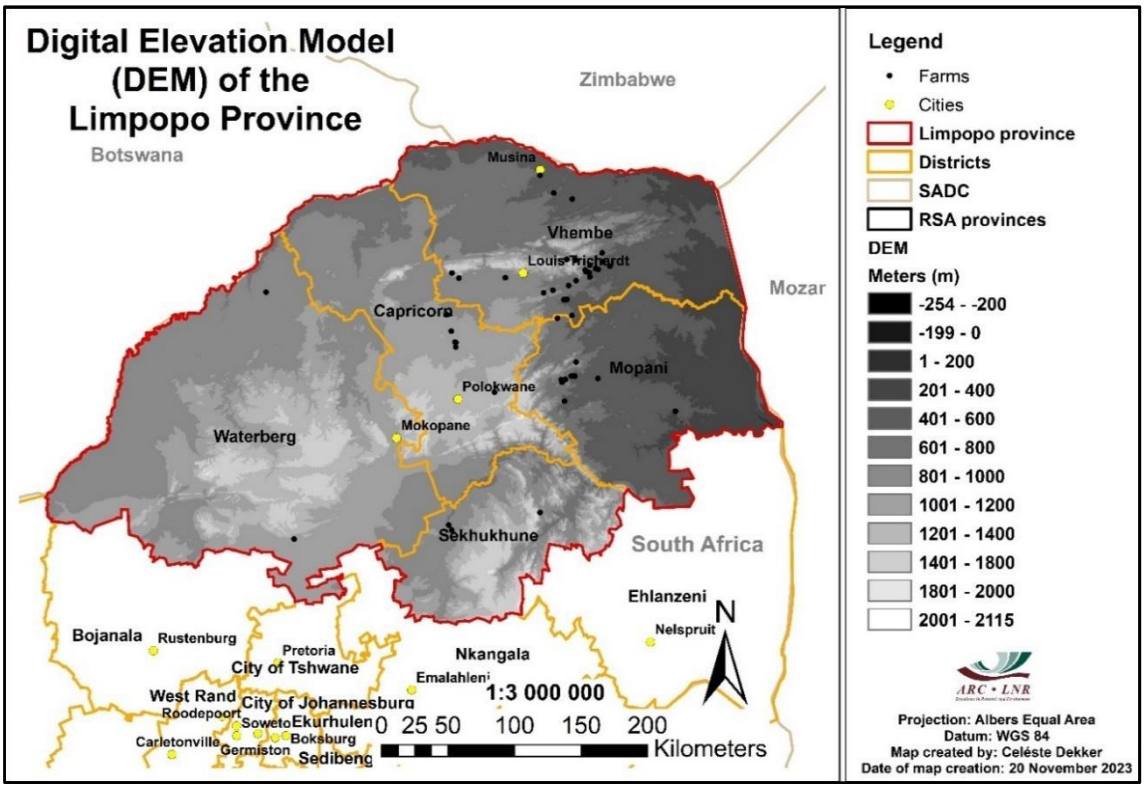


Figure 3.21 The Digital Elevation Model (DEM) map of the Limpopo province.

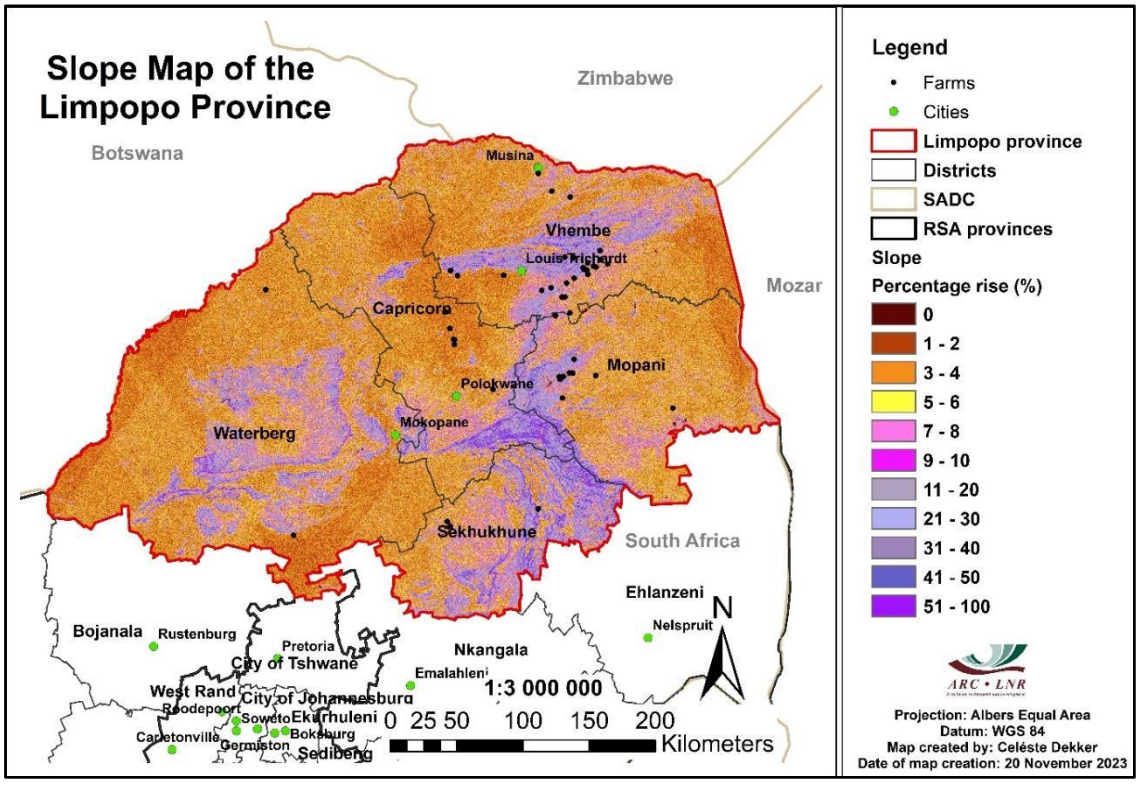


Figure 3.22 The slope percentage rise map of the Limpopo province.

The soil clay percentage Tiff and the slope percentage rise Tiff were the two inputs used to create the soil suitability Tiff in the soil suitability sub-model.

The capability of the model to be modified by a GIS user, was tested. This was done by changing the threshold values for the slope percentage rise from Table 3.3 to the values in Table 3.4. The slope suitability map created from the threshold values in

Table 3.4 is displayed in Figure 3.24.

Table 3.3 Initial slope suitability thresholds.

Criteria	Highly Suitable (4)	Moderately Suitable (3)	Marginally Suitable (2)	Not Suitable /Restricted (1)	References (Combined authors' statements and thresholds adapted from authors)
Soil Suitability					
Slope %	0.5 to 2 %	2 to 5 %	5 to10 %	>10 %; <0.5%	Aguilar-Manjarrez and Nath, 1998; Handisyde, 2015; Aquaculture Innovations, 2010; Hadipour, Vafaie and Hadipour, 2015; Richard et.al, 2016; Hossain et al., 2007; Falconer et. al., 2016; Ssegane et.al, 2012; Yoo and Boyd, 1993.

Table 3.4 Slope suitability thresholds used for the final slope suitability map.

Criteria	Highly Suitable (4)	Moderately Suitable (3)	Marginally Suitable (2)	Not Suitable /Restricted (1)	References (Combined authors' statements and thresholds adapted from authors)
Soil Suitability					
Slope %	≤2%	>2% to ≤5%	>5% to ≤10%	>10%	Aguilar-Manjarrez and Nath, 1998; Handisyde, 2015; Aquaculture Innovations, 2010; Hadipour, Vafaie and Hadipour, 2015; Richard et.al, 2016; Hossain et al., 2007; Falconer et. al., 2016; Ssegane et.al, 2012; Yoo and Boyd, 1993.

Figure 3.23 depicts the spatial Model Builder window user interphase containing the thresholds from

Table 3.4. These thresholds were used to classify the slope Tiff to produce the final slope suitability Tiff (Figure 3.24).

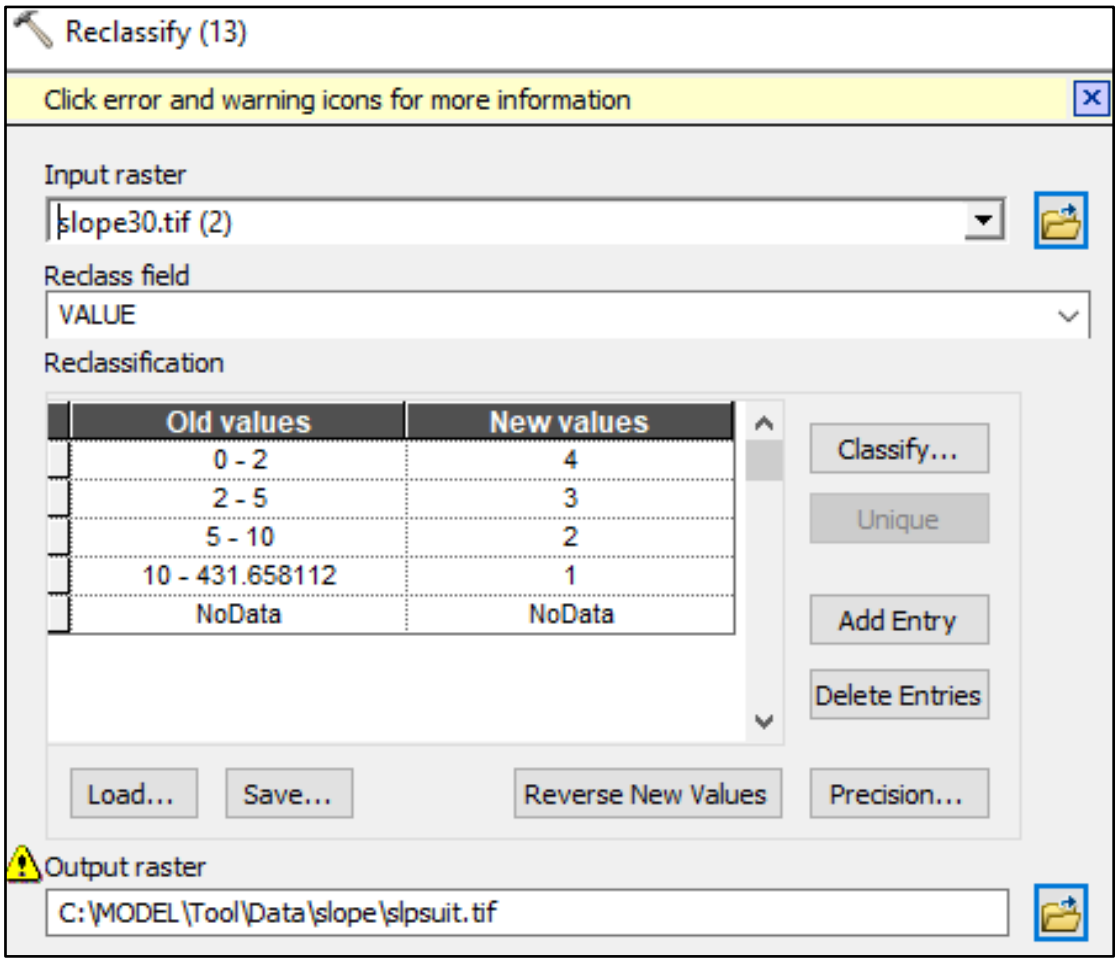


Figure 3.23 Model Builder interphase of the slope suitability thresholds.

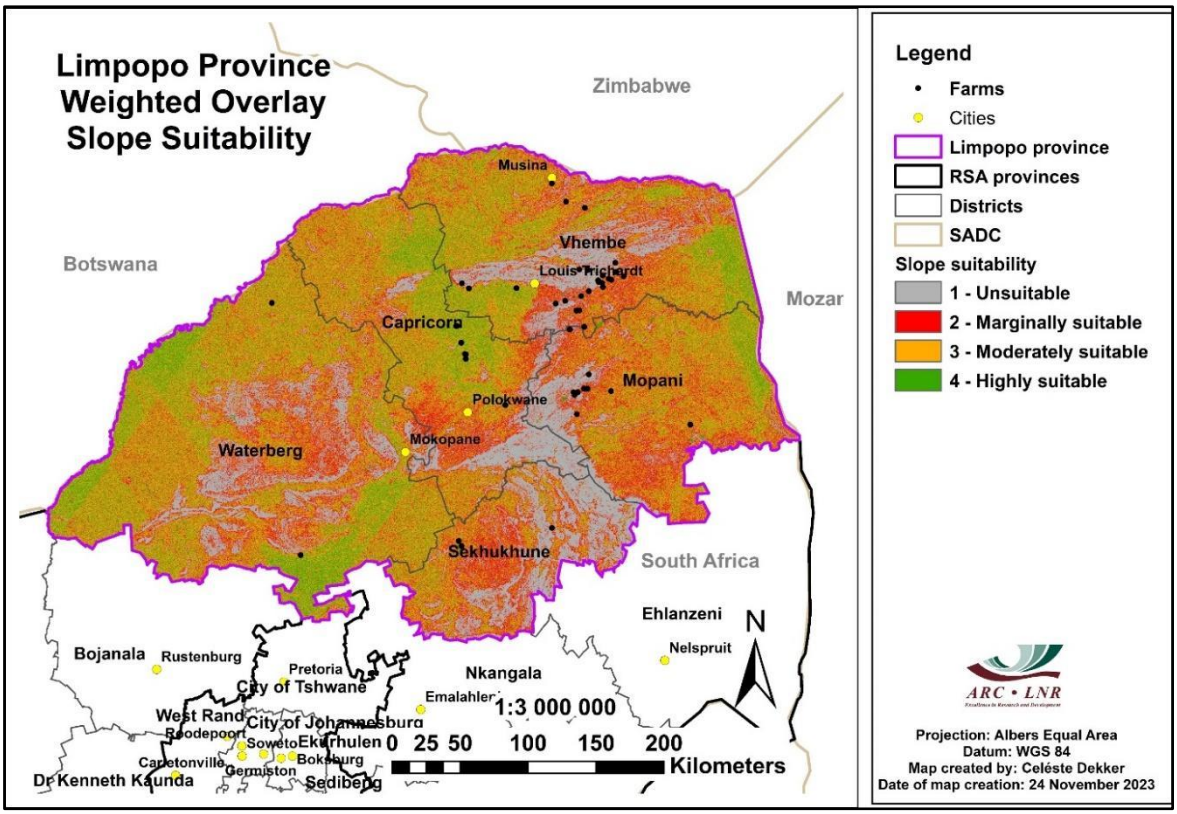


Figure 3.24 Final slope suitability map of the Limpopo Province.

Following the creation of the final slope suitability product, was the creation of the two clay suitability maps (Figure 3.27 and Figure 3.28). These two clay % suitability maps were created from the two different sets of thresholds depicted in Table 3.5 and Table 3.6. The second set of thresholds for classifying clay % suitability (Table 3.6) was used in the rest of the soil suitability mapping process.

Two soil suitability maps were initially created using the two different clay suitability Tiffs as inputs. The first soil suitability map made use of the thresholds in iteration one (Figure 3.30) while the second soil suitability map (Figure 3.31) was created from the thresholds described in iteration two ((Table 3.6).

The process of changing the threshold values in the model, within the Model Builder interphase, as described above, was relatively simple. The threshold values used in these steps in the Model Builder tool for iteration one and two, are depicted in Figure 3.25 and Figure 3.26.

After the entire suitability model was executed with iteration one used for creating the clay percentage suitability map, the entire suitability model was also executed using

iteration two's threshold values (Table 3.8). The last column, column six, depicts the references consulted for determining the variables and their respective thresholds to use in the suitability model.

The GIS user with technical GIS skills in ArcMap or ArcGIS Pro, can easily change the threshold values in Model Builder. The model can be shared to a GIS user via email for instance, and it can be opened by the GIS user after receiving it. The receiver can alter the threshold values as required. Suitability threshold value ranges for any variable can be altered and the output used throughout the rest of the execution process.

Table 3.5 Clay percentage: Iteration one. First set of thresholds used for classification.

Criteria	Highly Suitable (4)	Moderately Suitable (3)	Marginally Suitable (2)	Not Suitable /Restricted (1)	References (Combined authors' statements and thresholds adapted from authors)
Soil Suitability					
Clay (%)	≥20% to ≤40%	≥10% to <20%	<40 % to ≥60%	≥0% to <10% and >60% to ≤100%	Aquaculture Innovations, 2010; Aguilar-Manjarrez and Nath, 1998; Boyd, Wood and Thunjai, 2002; Hajek and Boyd, 1990; Handisyde, 2015; Ssegane et.al, 2012; Nayak, et. al, 2014; Richard and Ogba, 2016; Falconer et. al., 2016. Igaz, et.al, 2021.

Table 3.6 Clay percentage: Iteration two. Second set of thresholds used for classification.

Criteria	Highly Suitable (4)	Moderately Suitable (3)	Marginally Suitable (2)	Not Suitable /Restricted (1)	References (Combined authors' statements and thresholds adapted from authors)
Soil Suitability					
Clay (%)	≥20% to ≤40%	≥5% to <20% and >40% to ≤50%	>50 % to ≤60%	<5% or >60%	Aquaculture Innovations, 2010; Aguilar-Manjarrez and Nath, 1998; Boyd, Wood and Thunjai, 2002; Hajek and Boyd, 1990; Handisyde, 2015; Ssegane et.al, 2012; Nayak, et. al, 2014;

					Richard and Ogba, 2016; Falconer et. al., 2016. Igaz, et.al, 2021.

The suitability classification in the Model Builder environment tools using the threshold values from iteration one and iteration two are depicted in Figure 3.25 and Figure 3.26 below.

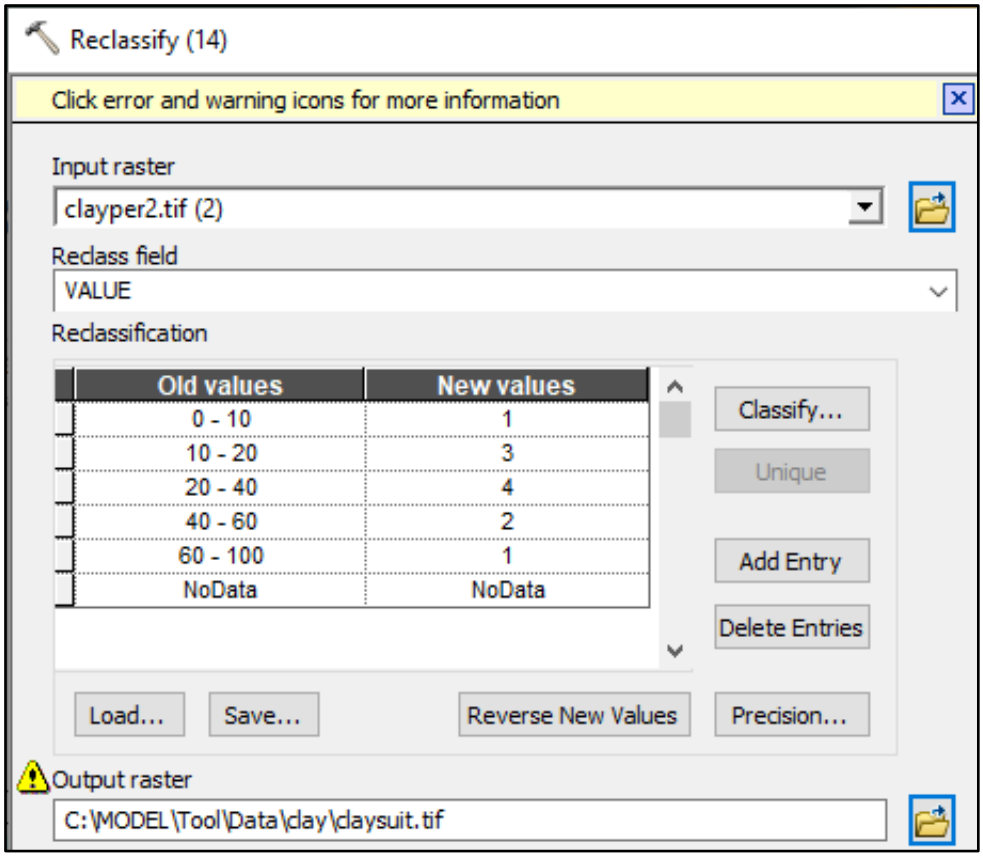


Figure 3.25 First iteration thresholds used to classify the clay percentage Tiff in Model Builder.

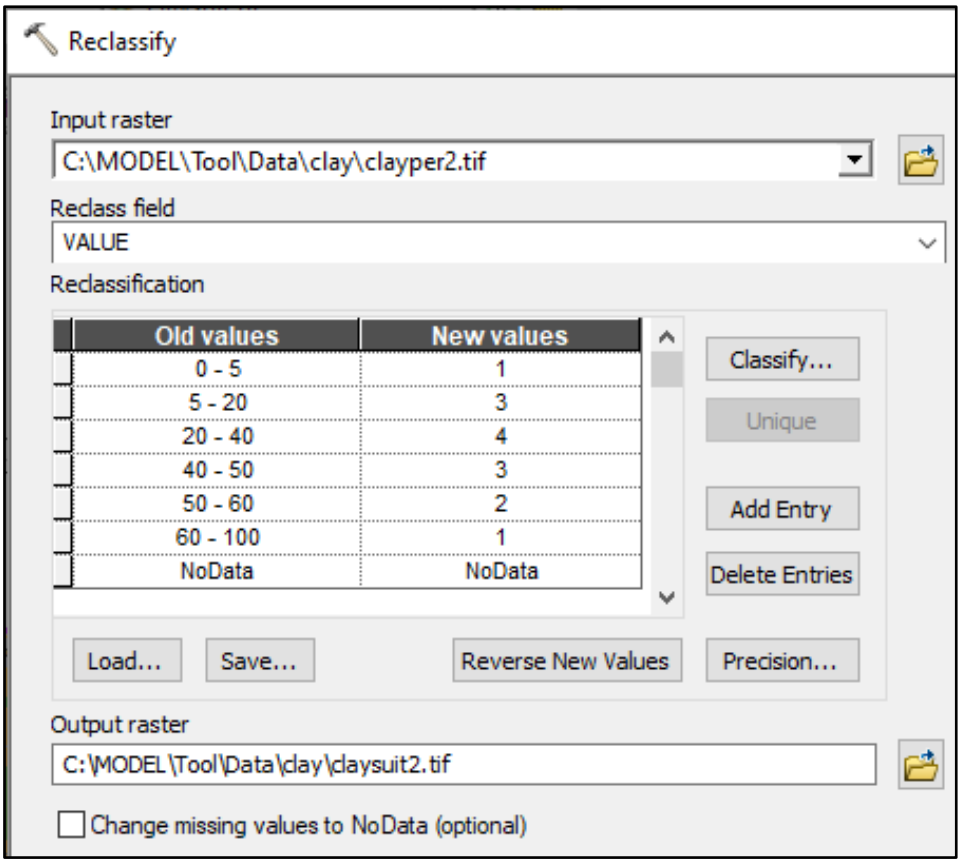


Figure 3.26 Second iteration thresholds used to classify the second clay percentage Tiff in Model Builder.

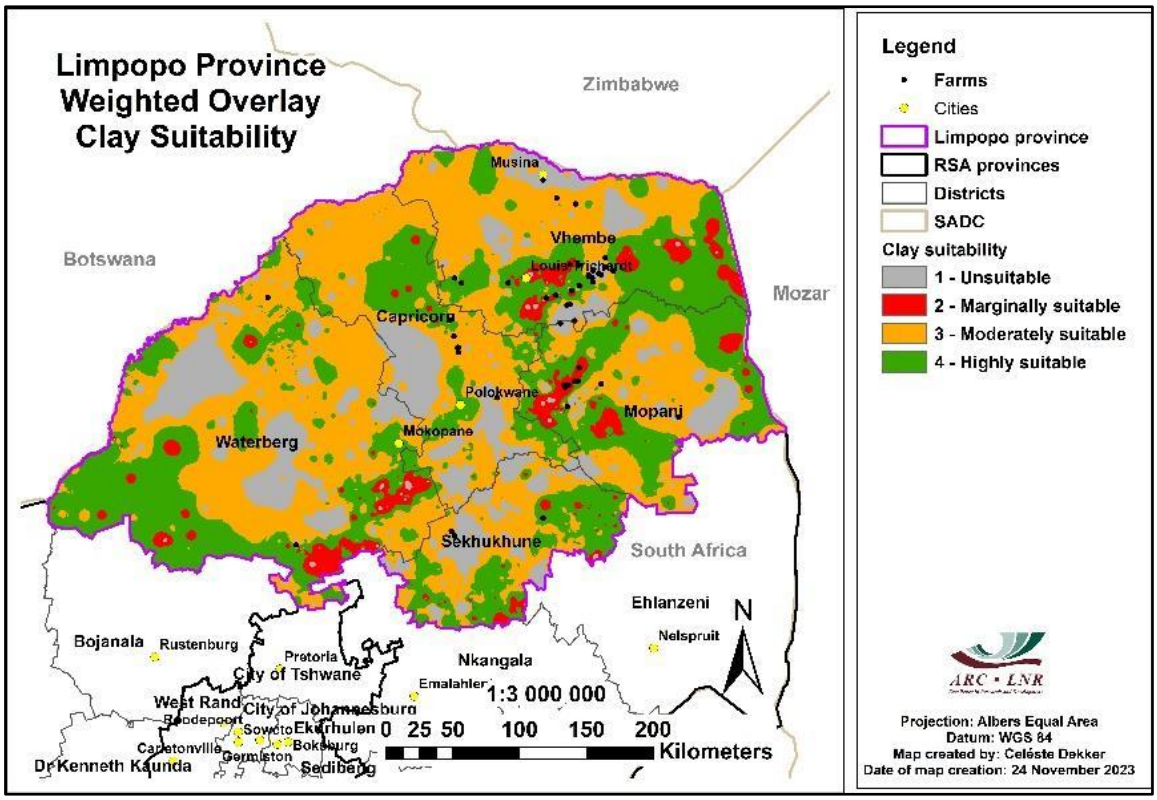


Figure 3.27 Clay suitability map produced from the threshold values of iteration one.

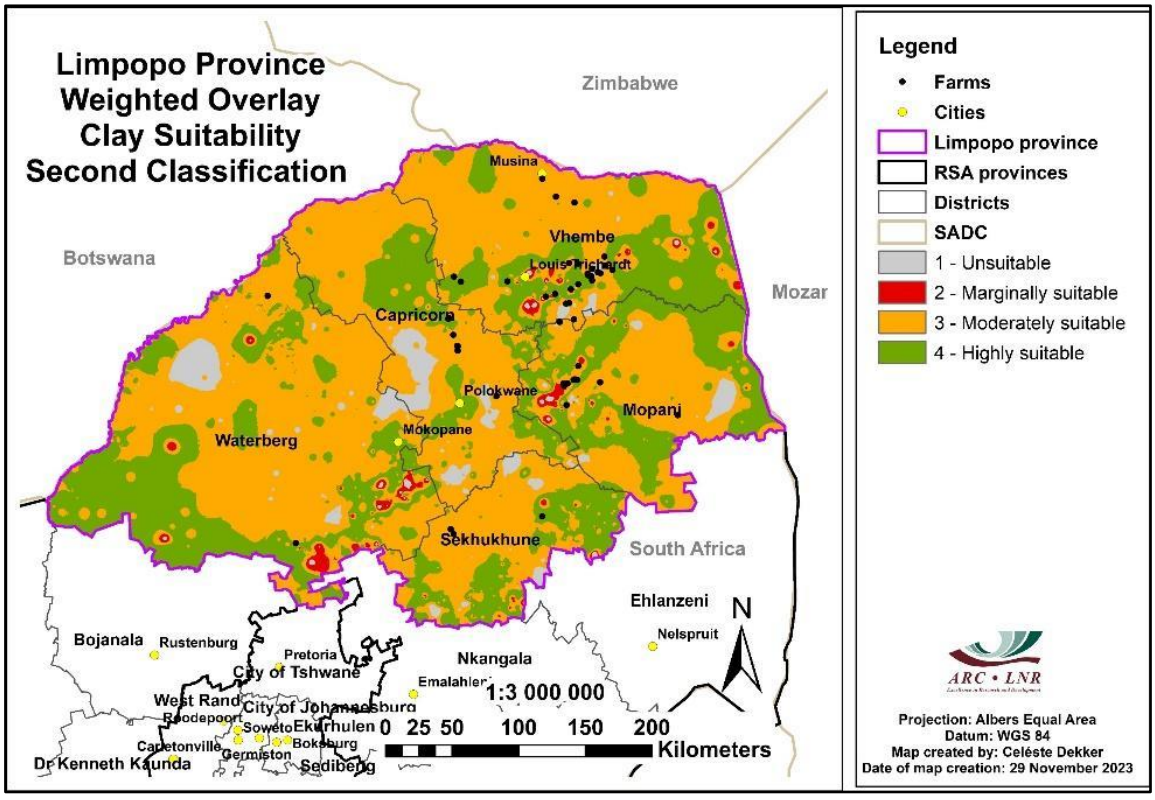


Figure 3.28 Clay suitability map produced from the threshold values of iteration two.

The slope percentage-rise suitability map and the soil clay percentage suitability map were combined in the soil suitability sub-model using the Weighted Overlay (WO) method. The result was the final soil suitability map depicted in Figure 3.31.

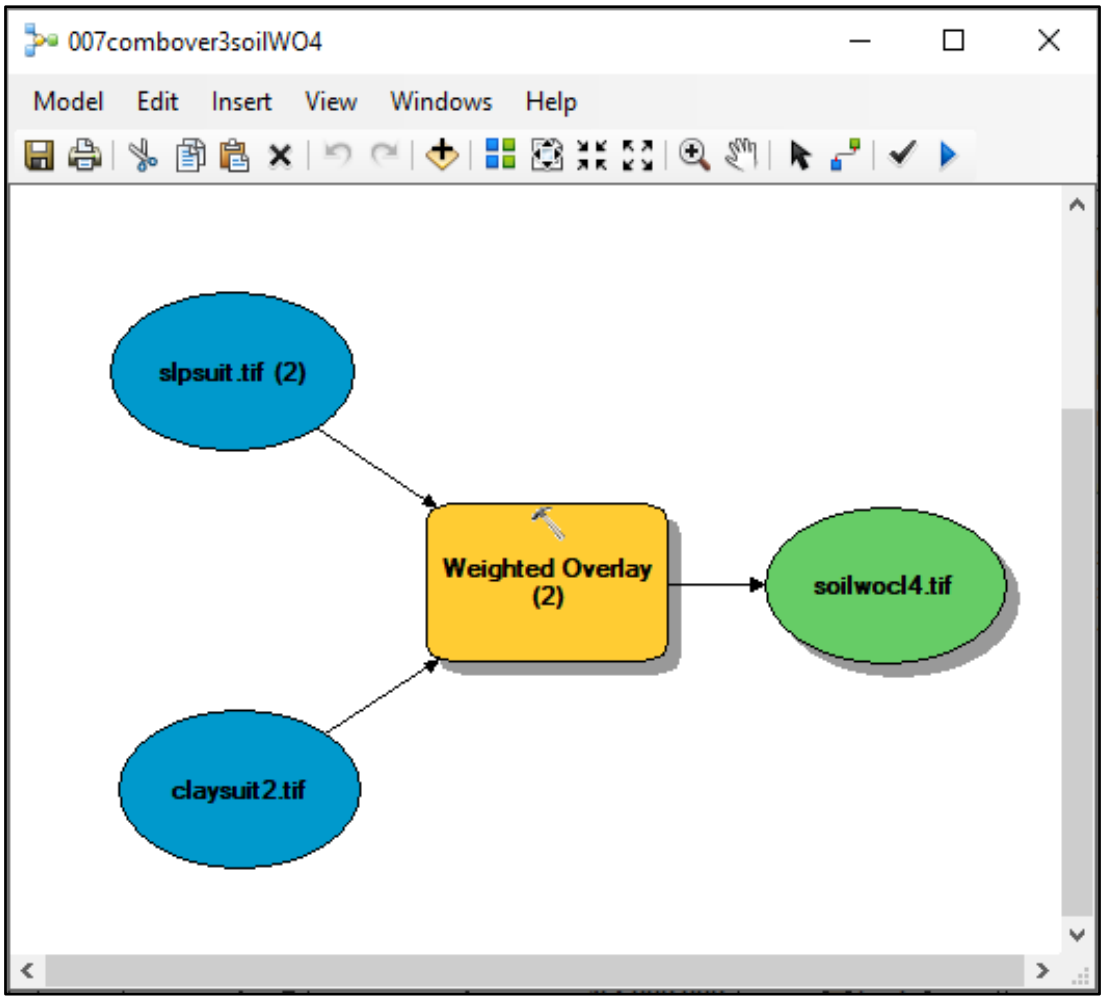


Figure 3.29 Model Builder view of the soil suitability Weighted Overlay (WO) process.

The Weighted Overlay (WO) process executed in Model builder is depicted in Figure 3.29. The WO process delivered integer numbers for soil suitability classes of one, two, three or four, as depicted in Figure 3.30 and Figure 3.31. Iteration one of clay suitability and the original slope suitability was combined to create the first soil suitability map (Figure 3.30). The second soil suitability map (Figure 3.31) was produced using iteration two of clay suitability and the original slope suitability classification thresholds. In the rest of the suitability modelling process, the threshold values that produced Figure 3.31 were used, together with the Tiff that Figure 3.31 was created from.

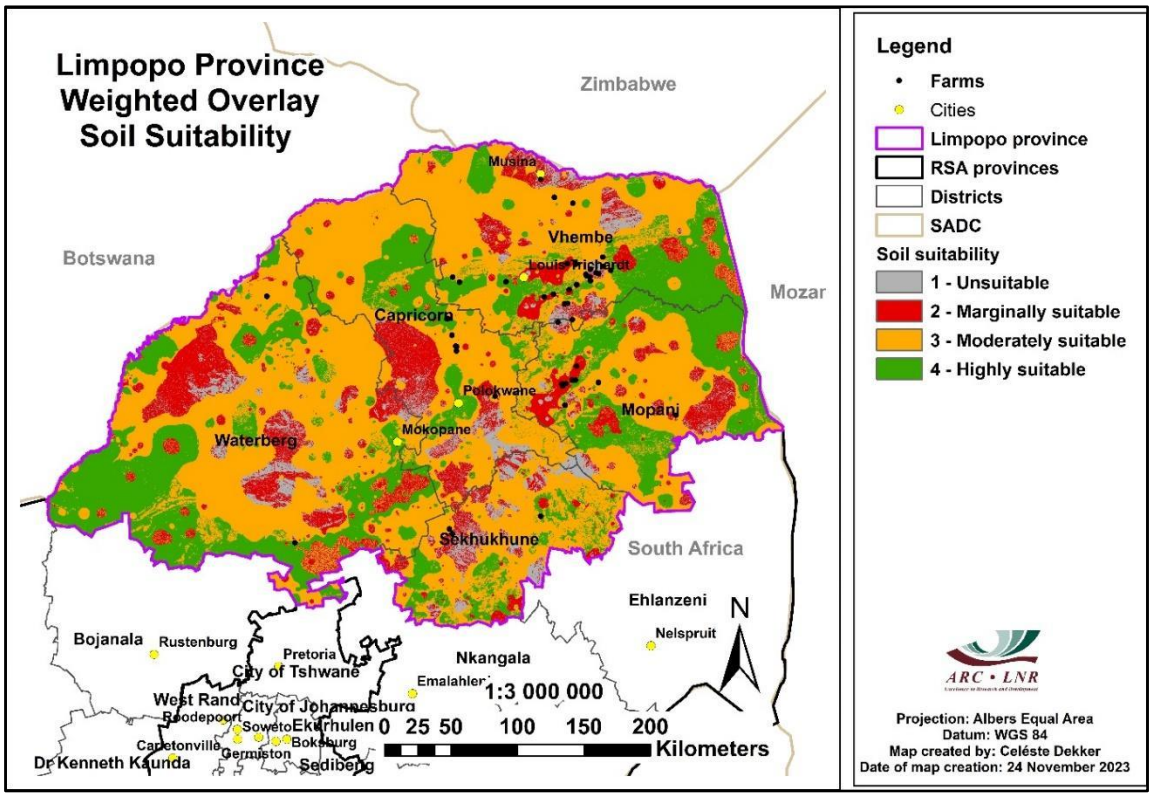


Figure 3.30 Soil suitability map produced from the first iteration of clay percentage and the original slope percentage.

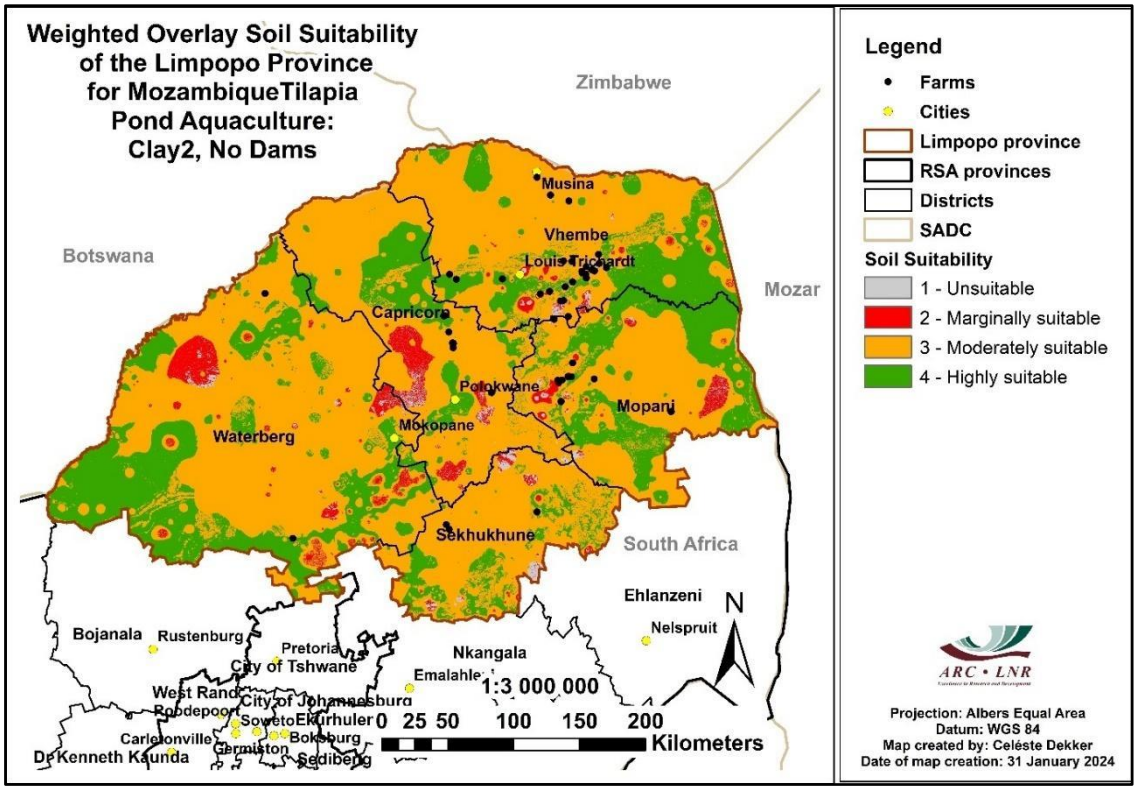


Figure 3.31 Soil suitability map produced from the second iteration of clay percentage and the original slope percentage.

3.3.2.1.4 The distance to substantial roads

It is vital for an aquaculture site that vehicles such as 1-ton trucks have access to the premises. The reason for this is to deliver fingerlings and fish-feed and collect the live fish for the market (Steer, 2006; Nayak et.al, 2014). Roads that can support the weight and passage of such vehicles, were referred to as substantial roads in this study. The classification thresholds of distances to a substantial road, vary in literature (Nayak, et. al, 2014; Hadipour, Vafaie and Hadipour, 2015; Hossain et. al, 2007; Falconer et. al., 2016).

The threshold distances of suitability classification to a substantial road are described as less than 500 meters for highly suitable areas, between 500 meters and 1000 meters for moderately suitable areas, and more than 1000 meters for unsuitable areas (Hossain et. al, 2007; Nayak, et. al, 2014). Falconer et. al., (2016) stated that the distance to a road should be less than 500 m to be most suitable, while further than 2000 meters is highly unsuitable. Hadipour, Vafaie and Hadipour, (2015), stated that if a road is less than 2km away, it is highly suitable, but more than 5 km away is unsuitable.

For the purposes of this research, the distance to substantial roads' sub-model thresholds were adapted from the above authors and is summarised in Table 3.8.

Spatial datasets containing the roads of South Africa were sourced from the Chief Directorate National Geospatial Information (NGI, 2019). The substantial roads were selected from this dataset, comprising all roads except footpaths and dirt roads. This equation (Equation 3.3) was executed in ArcMap 10 (Esri, 2016), where the exceptions were selected and inversed to create the Substantial roads shape file:

Equation 3.3: Substantial Road Selection:

"FEAT_TYPE = 'Arterial Road' OR FEAT_TYPE = 'Main Road' OR FEAT_TYPE = 'National Freeway' OR FEAT_TYPE = 'National Road' OR FEAT_TYPE = 'On/OffRamp' OR FEAT_TYPE = 'Other Road' OR FEAT_TYPE = OR FEAT_TYPE = 'Slipway' OR FEAT_TYPE = 'Street' OR FEAT_TYPE = 'Track'"

The Euclidian distance function was performed in Model Builder on the Distance to roads shapefile. From this process a Tiff was created, with the same spatial resolution, projection, datum and boundary as the slope Tiff. The distance to roads Tiff was

reclassified according to the thresholds displayed in Table 3.8 and Figure 3.32 below. The output of this process was the Distance to substantial roads suitability Tiff. The distance to substantial roads suitability map created from this Tiff is displayed in Figure 3.33.

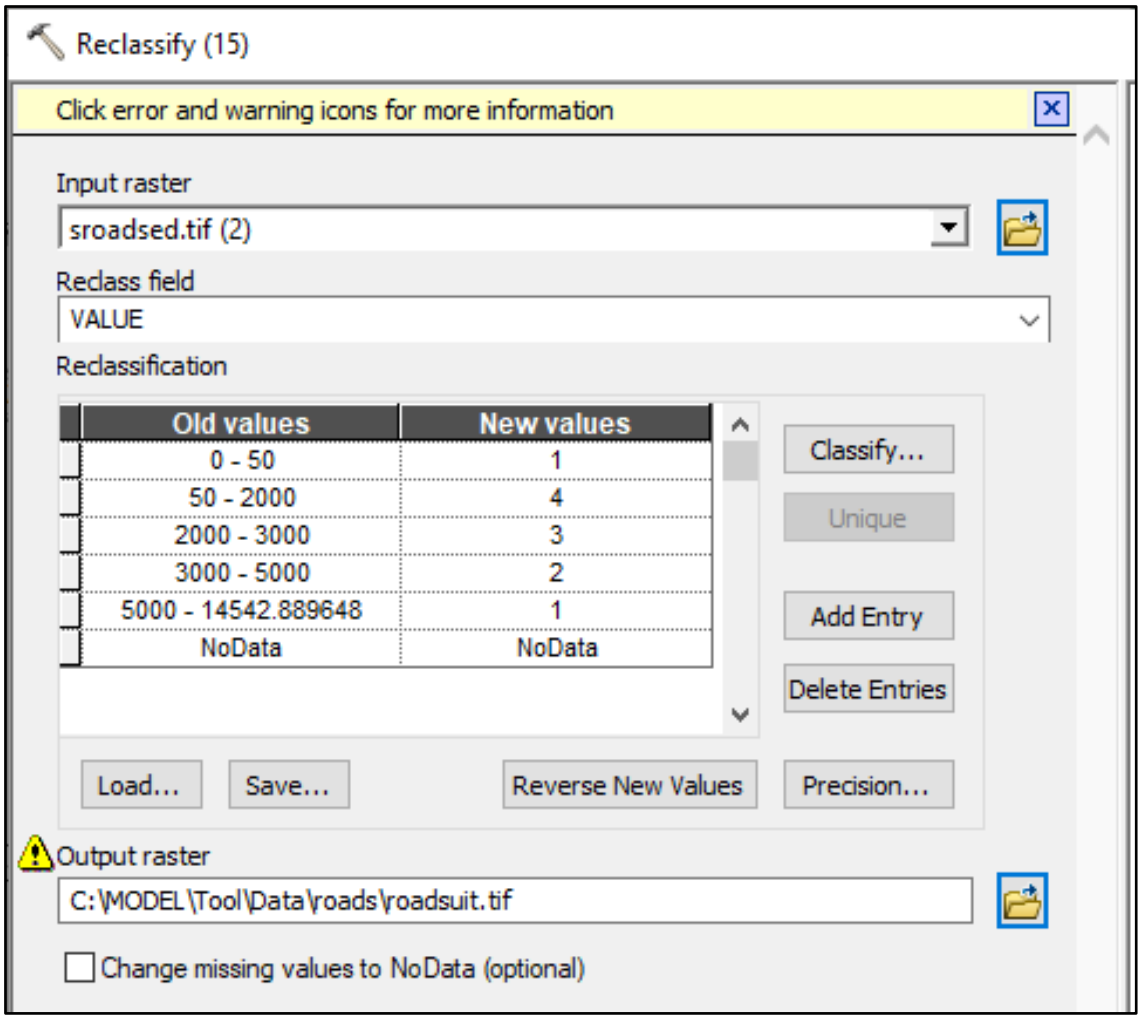


Figure 3.32 Reclassification thresholds of the Distance to substantial roads Tiff.

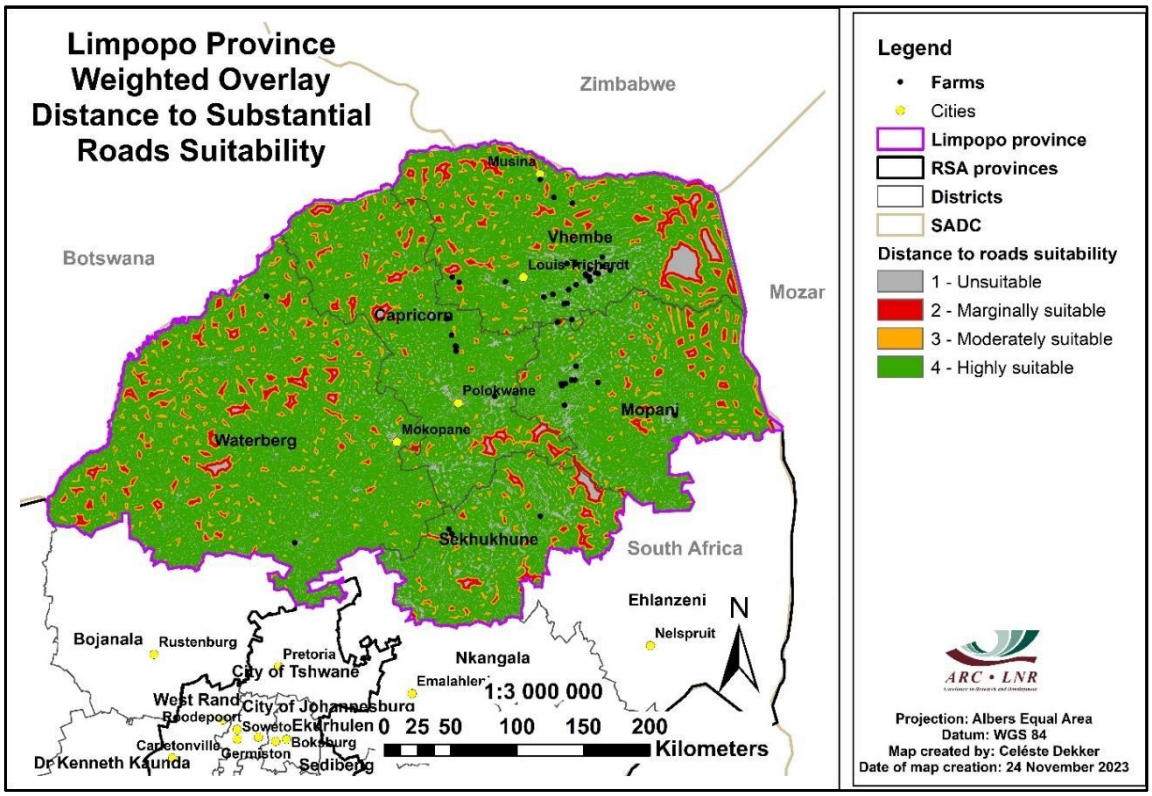


Figure 3.33 The distance to substantial roads suitability map of the Limpopo Province.

The distance to substantial roads suitability Tiff was overlayed in the model with the suitability layers from the three other sub-models. Both the WO and Weighted Sum Overlay (WSO) processes were followed in the subsequent steps. The four Tiffs from the suitability sub-models were overlaid to produce integer values from the WO process and floating-point values from the WSO process. In the final step of the suitability model, the WO and WSO products were extracted to the 48 GPS points of the available farmers at the time.

3.3.2.1.5 Masks or Restricted Areas (Constraints)

There are certain areas that should be avoided when considering the establishment of a pond aquaculture enterprise. Restricted areas (also referred to as masked out areas, masks or constraints) are areas where pond aquaculture could not or should not take place. This could be according to the rules of good aquaculture practice or due to restrictions set by authorities (Aquaculture Innovations, 2010; Aguilar-Manjarrez and Nath, 1998; Francisco, et al., 2019). Substantial roads, perennial rivers, springs, boreholes, dams, and protected areas were buffered according to their

respective restriction distances as depicted in Table 3.8. Pond aquaculture is not permitted in any formal or informal protected areas. The data for the protected areas and parks were sourced from The South African National Botanical Institute (SANBI, 2018) and The South African Protected Area Database (SAPAD, 2019) and included the following:

- National parks
- Formal protected areas
- RAMSAR sites (RAMSAR Convention Secretariat, 2010).
- Informal protected areas
- Nature reserves

Wetlands are also protected from aquaculture activity by South African Law (DEA, 2012). It was observed that existing pond aquaculture activities were however already present in some wetland areas in the Limpopo Province at the time of the farmer location collection (2018). Some of the farmers were granted permits by local authorities to practice pond aquaculture in certain wetland areas. Due to this situation, additional aquaculture enterprise establishment in wetlands could be discouraged, but not necessarily denied. All wetlands and their surrounding areas at a radius of 500 meters are protected by the National Environmental Management Act (NEMA Act No 107 of 1998) (SA GOV, 1998) (DEA, 2012).

The wetland areas were buffered by 500 meters. The results from scoring and ranking the farmer's according to their suitability in Table 4.6, indicated that some farmers were situated in wetlands or were located too close to wetlands. In Figure 3.34, the wetlands are mapped in green. The positions of the 48 farmers are displayed as black points on the map.

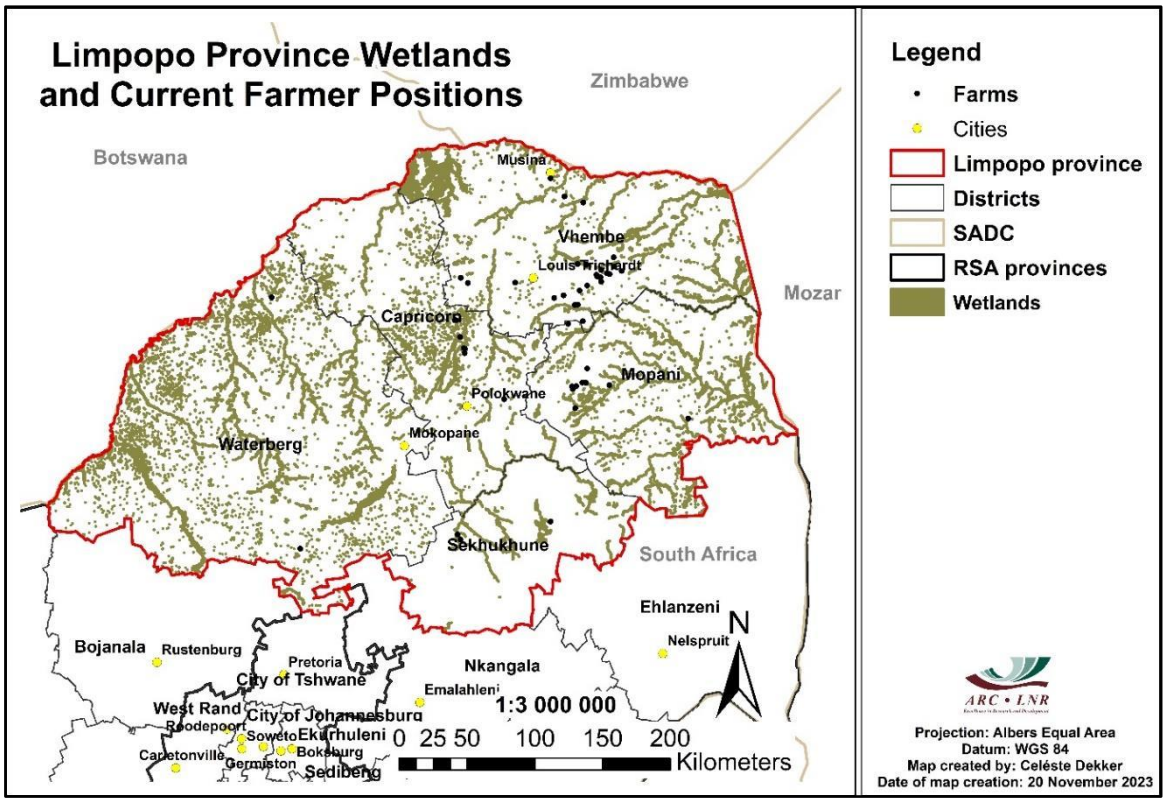


Figure 3.34 Map depicting the positions of the wetlands in the Limpopo province including the positions of the then known aquaculture farms.

The areas too close to water sources and substantial roads were buffered in step 4 of the modelling process (Figure 3.41). The thresholds used for each restricted variable, are displayed in Table 3.8. The restricted areas Tiff was created by merging the masks of all restricted areas into one shapefile and then executing the Euclidean distance function on the combined shapefile.

In step 5 of the model (Figure 3.42), the Euclidian distances around the combined masked areas Tiff, were reclassified. The resultant map was created depicting the restricted areas in grey and the rest of the areas of the Limpopo province in the apricot colour (Figure 3.35). At the end of the modelling process, this Tiff was used to mask out the restricted areas from the final pond aquaculture site suitability product.

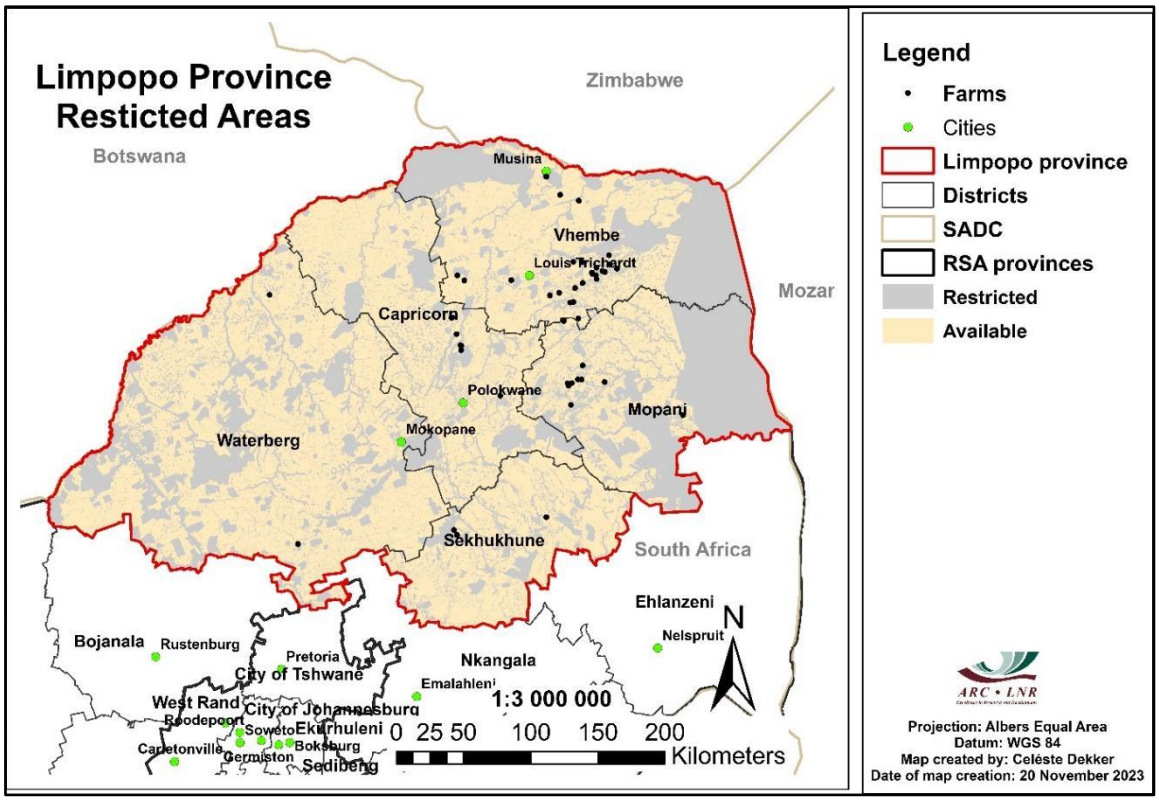


Figure 3.35 Map of restricted and available areas for pond suitability analyses of the Limpopo province.

The apricot-coloured areas in Figure 3.35 represent the available areas for pond aquaculture analyses. The grey areas represent the restricted areas, buffered by the distances depicted in Table 3.8.

It should be noted that the distance from a wetland is subject to the Conservation of Agricultural Resources Act (CARA, 1983), National Environmental Management Act (NEMA) and the National Water Act (NWA, 1988) as well as its relevance to Multilateral Environmental agreements (Grundling, A., 2023: Personal communication). The regulatory area in terms of NEMA is 32m from a wetland. In terms of the NWA, it is 100m from the edge of a watercourse/river and a 500m radius from a delineated wetland. The buffering distances chosen in the Restricted areas shapefile, were based on these regulation distances. The landowner must apply for a water use license (WUL) from the Department of Water and Sanitation (DWS) (Grundling, A., 2023: Personal communication). Each individual case needs to be considered in terms of the geology, topography and source of water of the area, which

are some of the preliminary guidelines for the determination of buffer zones for rivers, wetlands and estuaries, according to Macfarlane, et.al., (2014).

Ponds should not be constructed in zones prone to flooding (Kövári, 1984). But data for the 10-, 20-, 50- and 100-year flooding zones, were not available for the whole of Limpopo at the time of this research. It can be sourced by each farmer or situational analyst from the relevant municipality.

3.3.2.2 Suitability Classification

The selected suitability variables were classified into four classes as illustrated in Table 3.7 and Table 3.8. These classes are: Highly Suitable (4), Moderately Suitable (3), Marginally Suitable (2) and Unsuitable (1). A distinction between the Unsuitable class and the Restricted areas (Or Constraints) Sub-model, which includes restricted areas (Also referred to as masks or Constraints) (0). These four classes were adapted from the classification methodology used by Assefa and Abebe, (2018).

Amongst the many opinions and statements of all the authors, also those listed in Table 3.8, much literature regarding the use of dams, lakes, and perennial pans for inland pond aquaculture, might not be directly applicable to all dams, lakes and pans in South-Africa. South-Africa's lakes, pans and dams' spatial data was sourced from the Department of Water and Sanitation (DWS), (2019) These spatial source data of all natural and manmade dams of all sizes, do delineate between dams, pans, lakes, and artificial manmade water bodies. However, the water quality and quantities available are outside the scope of this study and therefore two sets of variables and thresholds were initially created. The first set contains the addition of dams to the inland pond aquaculture site suitability model (Table 3.7). The second set of variables and their thresholds pertaining to inland pond aquaculture for the Mozambique tilapia, does not include water bodies such as dams, lakes and pans for the above stated reasons. This second set of variables and their thresholds are found in Table 3.8.

Table 3.7 Set one: Mozambique tilapia pond aquaculture suitability thresholds. Includes dams as a water source.

Criteria	Highly Suitable (4)	Moderately Suitable (3)	Marginally Suitable (2)	Unsuitable (1)	References (Combined authors' statements and thresholds adapted from authors)
Distance to Water Source					
Distance to springs/ boreholes (km)	< 1 km	1 km - 2 km	2 km - 3 km	>3 km	Hadipour, Vafaie and Hadipour, 2015. Nayak, et al 2014.
Distance to Perineal rivers (km)	< 1 km	1 km – 2 km	2 km - 3 km	>3 km	Hadipour, Vafaie and Hadipour, 2015. Nayak, et al, 2014
Distance to dams (km)	< 1 km	1 km - 2 km	2 km - 3 km	> 3 km	Hadipour, Vafaie and Hadipour, 2015. Nayak, et al, 2014
Air Temperature					
30-year Long-term monthly average air temperature	25 °C – 31 °C	18 °C – 25 °C & 31 °C to 34 °C	13 °C – 18 °C & 34 °C to 38 °C	< 13 °C & > 38 °C	Handisyde, 2015; Hossain et al., 2007; Hutchison, Sarac and Norris, 2011; Boyd and Tucker, 1998; Aquaculture Innovations, 2010; Balarin and Haller, 1982; Wohlfarth and Hulata, 1983; Allanson and Noble, 1964; Kirk, 1972.
Soil Suitability					
Clay (%)	20 % – 40 %	10 % - 20 and 40 - 50 %	5 % - 10 % 50 % to 60%	< 5% and > 60 %	Aquaculture Innovations, 2010; Aguilar-Manjarrez and Nath, 1998; Boyd, Wood and Thunjai, 2002; Hajek and Boyd, 1990; Handisyde, 2015; Ssegane et.al, 2012; Nayak, et. al, 2014; Richard et.al, 2016; Falconer et. al., 2016. Igaz, et.al, 2021.
Slope %	≤2%	>2% to ≤5%	>5% to ≤10%	>10%	Aguilar-Manjarrez and Nath, 1998; Handisyde, 2015; Aquaculture Innovations, 2010; Hadipour, Vafaie and Hadipour, 2015; Richard et.al, 2016; Hossain et al., 2007; Falconer et. al., 2016; Ssegane et.al, 2012; Yoo and Boyd, 1993.

Distance to Substantial Roads					
Distance to Substantial Roads (km)	0.5 – 1.5 km	1.5 – 2.5 km	2.5 km – 3.5 km	0 - 0.5 km and > 3.5 km	Nayak, et. al, 2014; Hossain et. al, 2007; Hadipour, Vafaie and Hadipour, 2015; Hossain et al, 2007; Falconer et al, 2016.
Restricted Areas (Added Buffers)					
Distance from boreholes, and springs (m)				50 m	Francisco et al., 2019.
Distance from all rivers (m)				100 m	Francisco et al., 2019.
Distance from all dams (m)				500 m (used 50 m due to ponds included)	Adapted from Francisco et al., 2019.
Distance from all roads (m)				50 m	Adapted from Francisco et al., 2019.
All protected areas and parks (m)				500 m	Adapted from DEA, 2012.
Distance from all wetlands (m)				500 m	Adapted from DEA, 2012; Roets, 2016.

The variables and their thresholds, summarised in Table 3.7, were used in the first Model Design process. The last column depicts the references consulted on the variables and their respective thresholds to reach a conclusion on the threshold values to program into the model. The suitability maps that were created that do contain dams, are discussed, but not used for display in Chapter 4.

After creating maps of all suitability surfaces that include dams as sources of water, the variables and their thresholds in Table 3.8, were used to create a second set of suitability maps. These maps are creations of the raster data generated by running the

model without dams as a water source. The resulting suitability raster images and maps are displayed in the section after that in Chapter 4.

Table 3.3 was created after using the same references but displaying how the model can be modified according to the users' and experts' application of the values suggested by these different authors. It was simple and fast to insert different thresholds into the model and to remove the dams to re-run the model without the dams as displayed by the screenshots of the ArcGIS Model Builder in Chapter 4.

Table 3.8 Set two: Mozambique tilapia pond aquaculture suitability thresholds. Excludes dams, pans and lakes as water sources.

Criteria	Highly Suitable (4)	Moderately Suitable (3)	Marginally Suitable (2)	Unsuitable (1)	References (Combined authors' statements and thresholds adapted from authors)
Distance to Water Source					
Distance to springs/ boreholes (meters) (m)	≥50 m to ≤1000 m	>1000 m to ≤2000 m	>2000 m to ≤3000 m	<50 m or >3000 m	Hadipour, Vafaie and Hadipour, 2015; Nayak, et al 2014.
Distance to Perineal rivers (meters) (m)	≥ 100 m to ≤1 km	>1000 m to ≤2000 m	>2000 m to ≤ 3000 m	<100 m or >3000 m	Hadipour, Vafaie and Hadipour, 2015; Nayak, et al, 2014.
Distance to dams (meters) (m)	N/A	N/A	N/A	-	Assefa and Abebe, 2018; Ssegane et, al, 2012.
Air Temperature 1					
30-year (1993 to 2022) Long-term monthly average air temperature	≥24°C to ≤35°C	≥14°C to <24°C or >35°C to ≤38°C	≥8°C to <14°C or >38°C to ≤40°C	< 8°C or >40°C	Handisyde, 2015; Hossain et al., 2007; Hutchison, Sarac and Norris, 2011; Boyd and Tucker, 1998; Aquaculture Innovations, 2010; Balarin and Haller, 1982; Wohlfarth and Hulata, 1983; Allanson and Noble, 1964; Kirk, 1972.
Soil Suitability					

Clay (%) **First iteration**	≥20% to ≤40% Used ≥20% to ≤40%	≥10% to <20% and >40% to ≤50% Used 10% t0 to 20%	≥5% - <10% and >50 % to ≤60% Used 40% to 60%	<5% or >60% Used >60% to ≤100% or 0% to ≤10%	Aquaculture Innovations, 2010; Aguilar-Manjarrez and Nath, 1998; Boyd, Wood and Thunjai, 2002; Hajek and Boyd, 1990; Handisyde, 2015; Ssegane et.al, 2012; Nayak, et. al, 2014; Richard et.al, 2016; Falconer et. al., 2016. Igaz, et.al, 2021.
Slope %rise **First iteration**	≥0.5% to ≤2 % Used: ≤2%	>2% to ≤5% Or >0% to <0.5% Used: >2% to ≤5%	>5 to ≤10 % Used: >5% to ≤10%	>10 % or <0.5% Used: >10%	Aguilar-Manjarrez and Nath, 1998; Handisyde, 2015; Aquaculture Innovations, 2010; Hadipour, Vafaie and Hadipour, 2015; Richard et.al, 2016; Hossain et al., 2007; Falconer et. al., 2016; Ssegane et.al, 2012; Yoo and Boyd, 1993.
Distance to Substantial Roads					
Distance to Substantial Roads (meters) (m)	≥50m to ≤2000m	>2000m to ≤3000m	>3000m to ≤5000m	<50m or >5000m	Nayak, et. al, 2014; Hossain et. al, 2007; Hadipour, Vafaie and Hadipour, 2015; Hossain et al, 2007; Falconer et al, 2016.
Restricted Areas (Added Buffers)					
Distance from boreholes, and springs (meters) (m)				≤50 m = 0	Francisco et al., 2019.
Distance from all rivers (meters) (m)				≤100 m = 0	Francisco et al., 2019.
Distance from all dams (meters) (m)				≤50 m = 0	Adapted from Francisco et al., 2019.
Distance from all roads (meters) (m)				≤50 m = 0	Adapted from Francisco et al., 2019.

All protected areas and parks (meters) (m)				≤500 m = 0	Adapted from DEA, 2012.
Distance from all wetlands (meters) (m)				≤500 m = 0	Adapted from DEA, 2012; Roets, 2016.

In set one, the Inverse Distance Weighting used 10 points for interpolation while in set two, 9 points were used.

In set one, masks were not included in the equations of the thresholds. While in set two, the minimum and maximum threshold values per variable, were added to the equations to create a class = 1: Unsuitable.

In Table 3.8, clay percentage ranges are interpreted according to different guidelines given by different authors (Boyd, Wood and Thunjai, 2002; Handisyde, 2015) and many others in the last column of Table 3.8. These guidelines differ between authors, and how the suitability model is programmed, will give a different clay percentage suitability outcome if the class values are changed. This can be changed in the model itself.

3.3.2.3 Model design

After the choice of the five most crucial variables and after determining their data availability and respective thresholds, another thorough literature review explored the many options for the choice of a suitability model type to use in a Geographic Information System (GIS). Aquaculture pond site suitability can be determined spatially with Geographic Information Systems (GIS) instead of traditional methods like word of mouth and speculation (Steer, 2006). Geographic Information Systems (GIS) are excellent tools to determine site suitability for inland aquaculture freshwater enterprises (Nath et al, 2000). Geographic Information Systems (GIS) are also ideal tools for conducting inland pond aquaculture site suitability analysis (Aguilar-Manjarrez and Nath, 1998; Assefa and Abebe, 2018; Ssegane, et. al, 2012; Hosain, et. al, 2017). Making wise decisions in selecting suitable sites beforehand via a

Geographic Information System (GIS) and not traditional methods, can improve the economic and ecological return on investment by decision makers (Falconer, et al, 2020; Luo, et al, 2018; Meaden and Kapetsky, 1991; Steer, 2006).

GIS models can combine several environmental, economic, social, and other types of spatial information layers required to fulfil the requirements of a suitable environment for an inland pond fish farm (Salam, et. al., 2003). Several types of GIS models exist that can be utilised in GIS software to delineate suitable aquaculture sites (Salam, et.al., 2003). One such type of GIS model is the use of Multi Criteria Evaluation (MCE) (Eastman et al., 1993) to score, weigh, and rank variables that have an influence on the suitability of a site for aquaculture, in a spatial environment, (Aguilar-Manjarrez and Nath, 1998). Multi Criteria Evaluation (MCE) (Eastman et al., 1993) combined with the Pairwise Comparison Matrix (PCM) (Saaty, 1977) can be used to calculate the relative importance of each variable concerning the site suitability with the Analytical Hierarchy Process (AHP) (Saaty, 1977) (Francisco, et. al, 2019; Salam et. al., 2003; Ssegane, et. al, 2012).

It was decided that the type of model to use in the Geographic Information Systems (GIS) environment to produce site suitability maps from suitability variables, is the Multi-Criteria Evaluation (MCE) (Eastman et al., 1993) approach in conjunction with a Pairwise Comparison Matrix (PCM) (Saaty, 1977) and the Analytical Hierarchy Process (AHP) (Saaty, 1977) to rate and weigh the different criteria (Radiarta, et al, 2011; Falconer et al., 2020). Each of the five chosen suitability variables were translated into sub-models that feed into the main suitability mode. Only five of the most crucial variables were chosen as to keep the number of influencing factors limited so that the model is simple to populate, reproduce and execute.

3.3.2.3.1 Multi-Criteria Evaluation (MCE) Model

The method used in this research for comprising the suitability model, made use of Multi Criteria Evaluation (MCE) in a GIS (Eastman et al., 1993). The variables were weighted and scored according to relative importance decision-making using the Pairwise Comparison Matrix (PCM) method according to the Analytical Hierarchy Process (AHP) developed by Saaty, (1977). This method makes the scores of the criteria compatible (Malczewski, 2000). The relevant input variables were then grouped into Sub-models, which were also weighted and scored where applicable

(Hossain et al., 2009; Aguilar-Manjarrez and Nath, 1998; Nayak et al., 2014, Store and Kangas, 2001). On a scale of relative importance, ratings are systematically scored on a 17-point continuous scale from 1/9 (least important) to 9 (most important) as in Table 3.9, adapted from (Saaty, 1977) as in in Aguilar-Manjarrez and Nath, (1998).

Table 3.9 The scale of relative importance of criteria.

1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Extremely		Very strongly		Strongly		Moderately		Equally	Moderately		Strongly		Very strongly		Extremely	
Less Important									More Important							

The spatial site suitability model was developed incorporating the five chosen site suitability variables in a Geographic Information System (GIS) using Esri ArcMap 10 Model Builder platform (Esri, 2018) (Francisco, et. al, 2019; Salam et.al., 2003; Ssegane, et. al, 2012). The model was designed using the Multi-Criteria Evaluation (MCE) method (Eastman et al, 1995; Eastman, 1999; Voogd, 1983), in conjunction with the Analytical Hierarchy Process (AHP) (Saaty, 1977) and a Pairwise Comparison Matrix (PCM) (Saaty, 1977).

The five chosen main suitability variables were translated to the five Sub-Models of the MCE Suitability Model. Between the two soil suitability variables (Figure 3.37), soil texture (as soil clay percentage) is seen as more important than slope, according to Ssegane et.al, (2012). The different sub-models were combined via MCE to determine the model weights (Falconer, et al., 2016), as seen in Figure 3.37.

3.3.2.3.2 The five Sub-Models

i. Distance to water source. This sub-model measures the distance from water sources required for the aquaculture ponds (Aguilar-Manjarrez and Nath, 1998; Aquaculture Innovations, 2010; Meaden and Kapetsky, 1991; Hadipour, Vafaie and Hadipour, 2015; Nayak et. al., 2014).

ii. Temperature. Many authors refer to pond water temperature as one of the most important variables in the determination of pond aquaculture site suitability (Aquaculture Innovations, 2010; Hutchison, Sarac and Norris, 2011; Ssegane et. al., 2012; Viljoen, 2001; Boyd and Tucker, 1998; Aguilar Manjarrez and Nath, 1998; Meaden and Kapetsky, 1991). Air temperature is widely used as a proxy for pond water temperature, which is determined mainly by surface air temperature, but also by some other climatic factors (Meaden and Kapetsky 1991; Aguilar-Manjarrez and Nath, 1998; Kapetsky,

1994; [Lau et. al., 1996] in Mohseni and Stefan, 1999). ([Klemetson and Rogers, 1985; Wax and Pote, 1990)] In: Boyd and Tucker, 1998.

iii. Soil Suitability. This sub-model consists of the soil clay percentage (%) as well as the slope percentage (%) variables (Aquaculture Innovations, 2010; Viljoen, 2001; Boyd, Wood and Thunjai, 2002; Meaden and Kapetsky, 1991; Ragbirsingh and Da Souza, 2005; Aguilar-Manjarrez and Nath, 1998; Ssegane et.al, 2012).

iv. Distance to Substantial Roads. This sub-model measures the suitability of a potential or existing aquaculture enterprise, based on the distance from roads that are suitable to carry delivery vehicles. These roads are called substantial roads, as they enable delivery trucks and vehicles to reach the farms to deliver fingerlings and fish-feed and collect the live fish for delivery to the different offset points or market types (Steer, 2006; Nayak et.al, 2014; Meaden and Kapetsky, 1991; Hossain et al., 2009).

v. Constraints. This sub-model's function is to eliminate (or mask out) all the constrained areas in the Limpopo province from the final suitability map. These are areas that are not suitable for pond aquaculture activities or where aquaculture is not permitted to take place (Aquaculture Innovations, 2010; Aguilar-Manjarrez and Nath, 1998; Francisco, et al., 2019; Ragbirsingh and Da Souza, 2005).

3.3.2.3.3 Pairwise Comparison Matrix

A Pairwise Comparison Matrix (PCM) Saaty, (1977) was used to compute the relative weights of each criterion (group of variables). Each cell in the PCM indicates a relative importance of the row factor as compared to the column factor on a scale from one to nine as in Eastman et. al, (1995). The relative importance of the values was assigned so that the Consistency Ratio (CR) was less than 0.1 (which is a standard). This implies that there was a low probability that the matrix cell values were assigned randomly. In Equation 3.4, *Lambda max* is the maximum eigenvalue of the matrix and *n* is the total number of factors, and the relative weights were calculated as the relative values of the eigenvector corresponding to the maximum eigenvalue.

Equation 3.4: The Consistency Ratio

$CR = (\lambda max^{-n})/ (n - 1) \geq 0$

Table 3.10 Pairwise Comparison Matrix (PCM) Un-Normalised.

		DWS	WT	SS	DR
Distance from Water Source Sub-Model	**DWS**	1	2	4	8
Water Temperature Sub-Model	**WT**	1/2	1	6/3	7/3
Soil Suitability Sub-Model	**SS**	1/4	3/6	1	7/2
Distance to Road Sub-Model	**DR**	1/8	3/7	2/7	1
Sum of Columns					

Table 3.11 Pairwise Comparison Matrix (PCM) Un-Normalised: Decimal Values.

		DWS	WT	SS	DR
Distance from Water Source Sub-Model	**DWS**	1,0000	2,0000	4,0000	8,0000
Water Temperature Sub-Model	**WT**	0,5000	1,0000	2,0000	2,3333
Soil Suitability Sub-Model	**SS**	0,2500	0,5000	1,0000	3,5000
Distance to Road Sub-Model	**DR**	0,1250	0,4286	0,2857	1,0000
Sum of Columns		**1,8750**	**3,9286**	**7,2857**	**14,8333**

All the elements of each column were divided by the sum of the column to get the values as depicted in Table 3.12.

Table 3.12 Pairwise Comparison Matrix (PCM) Normalised: Decimal Values.

		DWS	WT	SS	DR	Criteria Weights
Distance from Water Source Sub-Model	**DWS**	0,5333	0,5091	0,5490	0,5393	0,5327
Water Temperature Sub-Model	**WT**	0,2667	0,2545	0,2745	0,1573	0,2383
Soil Suitability Sub-Model	**SS**	0,1333	0,1273	0,1373	0,2360	0,1585
Distance to Road Sub-Model	**DR**	0,0667	0,1091	0,0392	0,0674	0,0706
Sum of Columns		**1,0000**	**1,0000**	**1,0000**	**1,0000**	**1,0000**

In

Table 3.13 depicts an intermediate step. In this table, each Un-normalised PCM value is multiplied with each column which contains the Citeria Weight, to calculate the weighted Sum Values and the WSV divided by the Criteria Weight.

Table 3.13 Intermediate step: Un-normalised PCM values multiplied each column with the Criteria Weights.

		DWS	WT	SS	DR	Criteria Weights (CW)	Weighted Sum Value (WSV)	WSV/ CW
Distance from Water Source Sub-Model	**DWS**	0,5327	0,4765	0,6338	0,5648	**0,5327**	2,2078	4,1446
Water Temperature Sub-Model	**WT**	0,2663	0,2383	0,3169	0,1647	**0,2383**	0,9862	4,1394
Soil Suitability Sub-Model	**SS**	0,1332	0,1191	0,1585	0,2471	**0,1585**	0,6578	4,1517
Distance to Road Sub-Model	**DR**	0,0666	0,1021	0,0453	0,0706	**0,0706**	0,2846	4,0308
Sum of Columns		**0,9988**	**0,9360**	**1,1545**	**1,0472**	**1,0000**	**4,1364**	**16,4665**

Next, Equation 3.5 was calculated, namely the Lambda max ($\lambda_{max)}$ (Saaty, 1977):

Equation 3.5: Lambda Max (λ_{max})

λ_{max} = Sum (WSV /CW) / *n*

= 4,116622826

Next the Consistency Index (CI) (Saaty, 1980) was calculated in Equation 3.6:

Equation 3.6: Consistency Index (CI)

Consistency Index (CI) = (λ_{max} – *n*) / (*n* – 1)

= (4,116622826 - 4) / (4 - 1)

= 0,038874275

After calculating the CI, the next step was to calculate the Consistency Ratio (CR) (Saaty, 1980) visible in Equation 3.7.

Equation 3.7: Consistency Ratio (CR)

Consistency Ratio (CR) = CI / 0,9

= 0,043193639

The CR must be less than 0,10 (Saaty, 1980).

Table 3.14 The Random Index Table (RI).

n	**2**	3	4	5	6	7	8	9	10
RI	**0**	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,51

As there are four variables, the number 0.9 from

Table 3.14 (Saaty, 1980), is used. The Consistency Ratio (CR) of the tables should be equal to or less than 0.10, to satisfy a small probability that the weights were developed by chance (Saaty, 1977). The calculated CR is less than 0.10, which is recommended by Saaty, (1977). Thus, the possibility that the weights were chosen by chance, is small enough.

Using the four factors, the criteria weights in percentage were calculated in

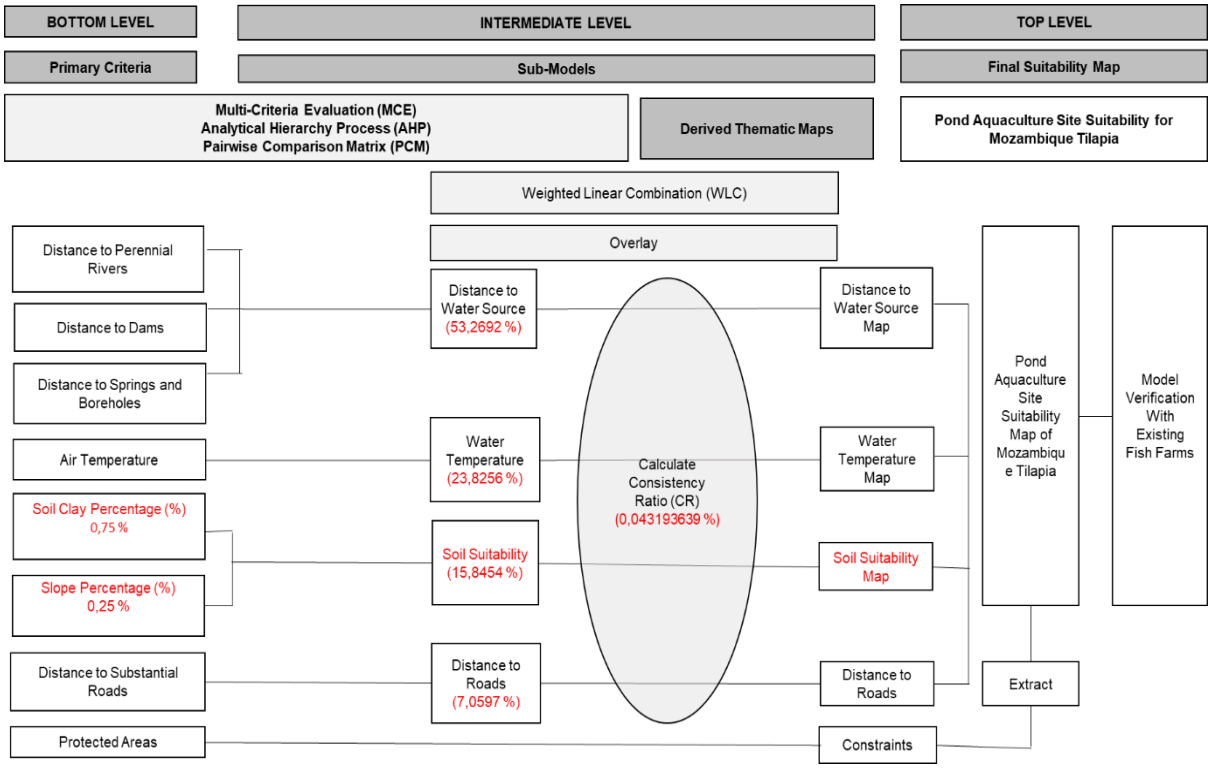
Table 3.15.

Table 3.15 Criteria weights.

Variable	**Criteria Weights:**	**Criteria Weights (%)**
Distance from Water Source Sub-Model	0,5327	53,2692
Water Temperature Sub-Model	0,2383	23,8256
Soil Suitability Sub-Model	0,1585	15,8454
Distance to Road Sub-Model	0,0706	7,0597
Sum of Columns	1,0000	100,0000

As in Ssegane, (2012), a schematic diagram was used to illustrate the flow chart of the geospatial modelling process. In Figure 3.36, the flow chart contains each of the four sub-models as well as the constraints (also called restrictions) element in a schematic diagram of the geospatial suitability model.

In Figure 3.36 there are three levels in the modelling process. From the bottom level in the left of the figure to the top level in the right, the variables (or sub-models) are listed and overlain to produce the five maps that will be discussed in Chapter 4, Results. The five suitability maps (models) comprise of the inputs to the final suitability map, that contains the final suitability product.


BOTTOM LEVEL
INTERMEDIATE LEVEL
TOP LEVEL
Primary Criteria
Sub-Models
Final Suitability Map
Multi-Criteria Evaluation (MCE)
Analytical Hierarchy Process (AHP)
Pairwise Comparison Matrix (PCM)
Derived Thematic Maps
Pond Aquaculture Site Suitability for Mozambique Tilapia
Weighted Linear Combination (WLC)
Overlay
Distance to Perennial Rivers
Distance to Dams
Distance to Springs and Boreholes
Air Temperature
Soil Clay Percentage (%)
0,75 %
Slope Percentage (%)
0,25 %
Distance to Substantial Roads
Protected Areas
Distance to Water Source (53,2692 %)
Water Temperature (23,8256 %)
Soil Suitability (15,8454 %)
Distance to Roads (7,0597 %)
Calculate Consistency Ratio (CR) (0,043193639 %)
Distance to Water Source Map
Water Temperature Map
Soil Suitability Map
Distance to Roads
Constraints
Pond Aquaculture Site Suitability Map of Mozambique Tilapia
Extract
Model Verification With Existing Fish Farms

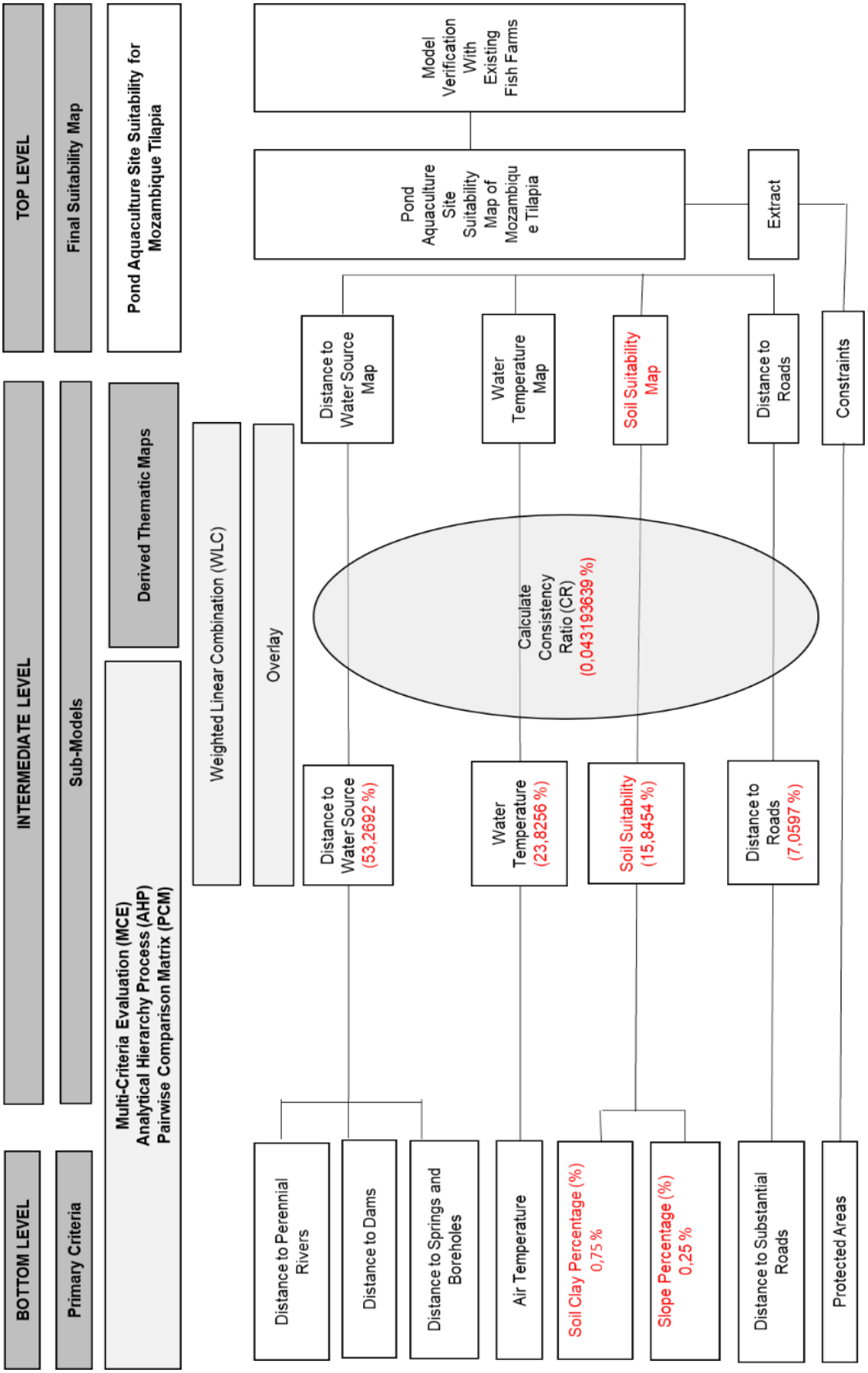


Figure 3.36 Flow chart of the geospatial modelling process.

3.3.2.3.4 Model transfer to the GIS

The flow chart in Figure 3.36 was transferred to the spatial environment by creating the elements in Esri ArcMap 10 Model Builder (Esri, 2018) as displayed in Figure 3.37.

In Figure 3.37 a schematic flow diagram of the model can be seen as it appears in the original ArcMap 10 Model Builder (Esri, 2018) interphase. After much thought, trial, error and consultation with the Esri software vendors (De Munnik, R., 2024: Personal communication), it was decided that the toolbox that contains the entire model, should house the model in ten individual steps rather than one step (process).

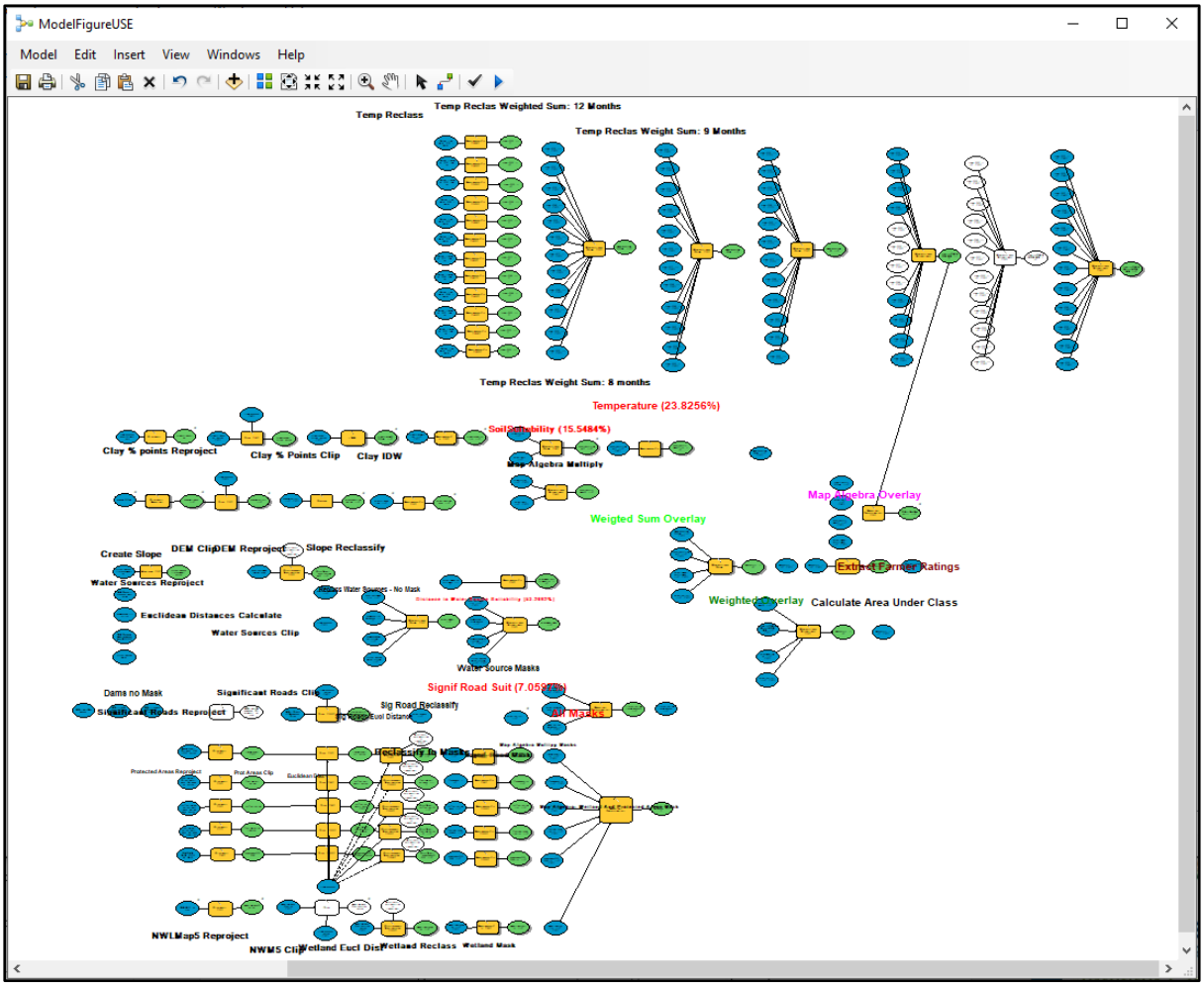


Figure 3.37 Schematic diagram of the original Suitability Model in ArcMap Model Builder.

In the flow chart in Figure 3.37, the elements and processes flow from left to right. The blue ellipses represent the input variables and the yellow boxes the spatial commands that lead to the outcomes (green ellipses).

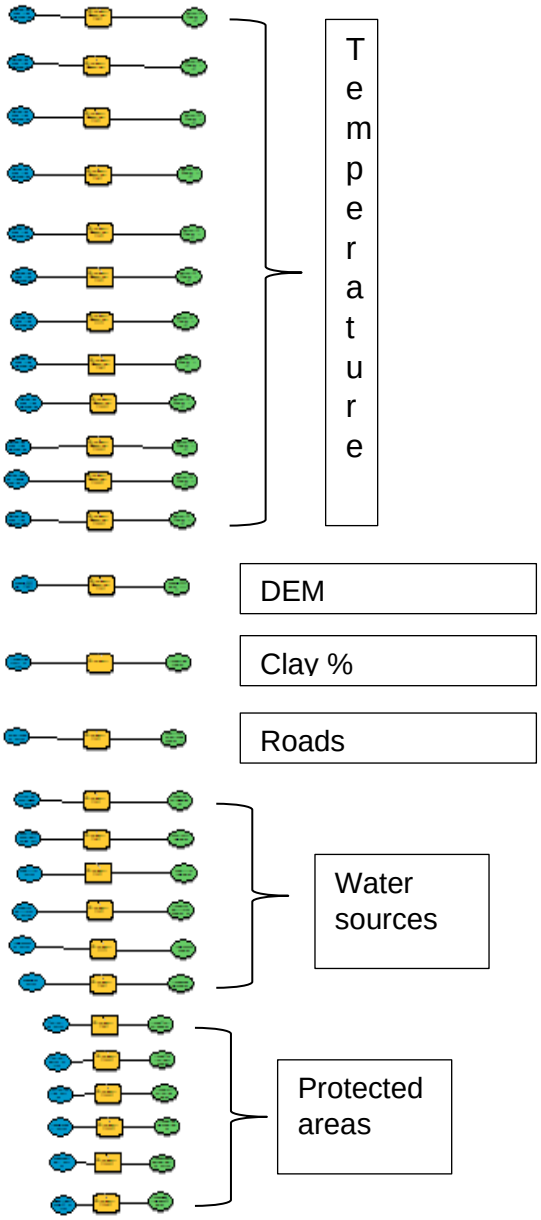


Figure 3.38 Model Step 1: Reproject to Albers.

In Figure 3.38 the first step in the modelling process in the Model Builder environment, is displayed. All the input layers that are not in the desired Albers projection, are reprojected to Albers Equal Area suitable for the whole of South Africa. This projection uses a Central Meridian of 24 and a Standard Parallel (SP) one of -18 and a SP two of -32. From Step one through to Step 8, every model step can be exported as a Python script for programmers who prefer it to the Model Builder interphase. All Steps can be imported into the Esri ArcGIS Pro (Esri, 2023c) software.

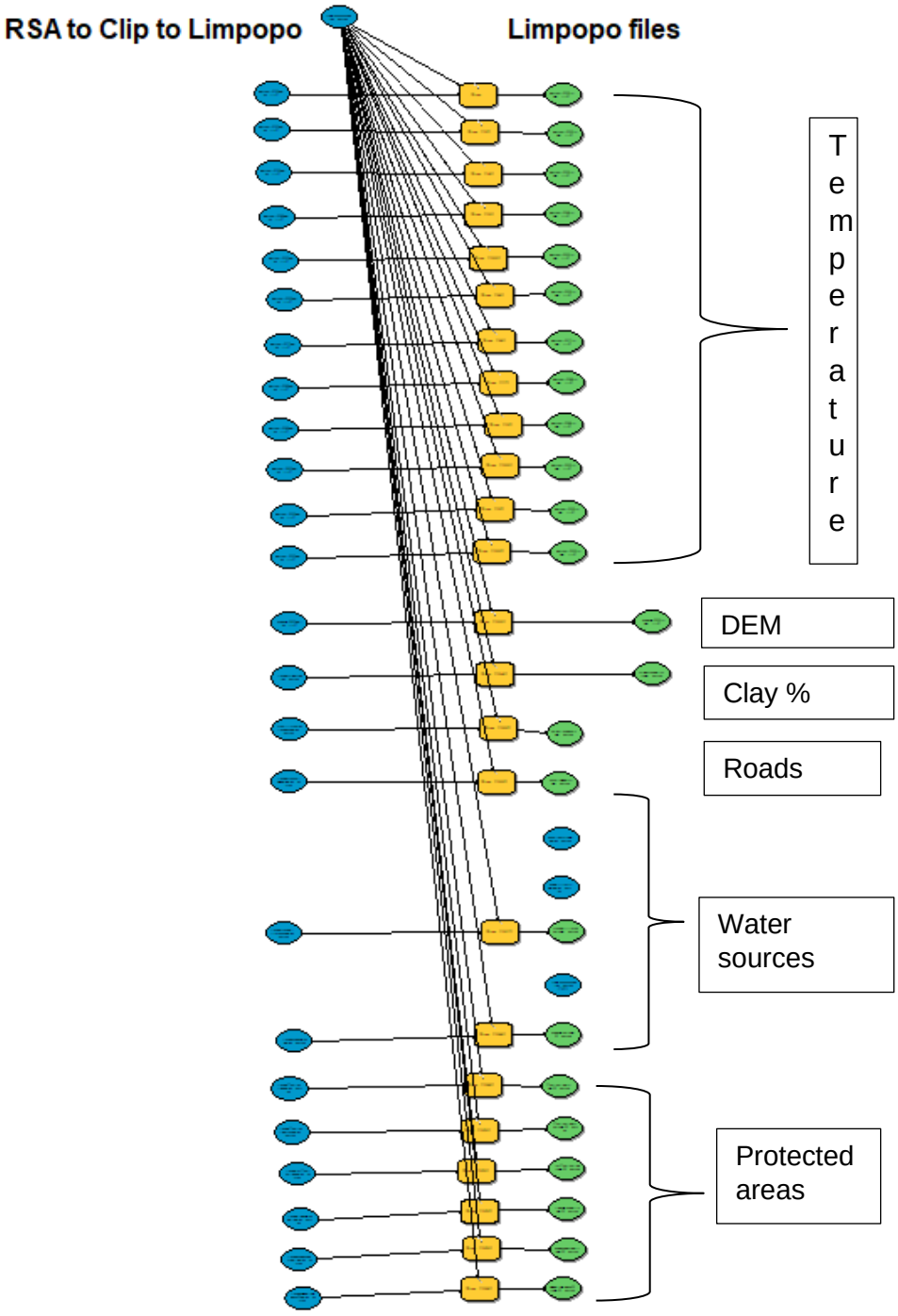


Figure 3.39 Model Step 2: Clip.

The reprojected layers from Step one, were clipped as depicted in Step two (Figure 3.39). The Clip tool was used to clip all the unclipped input layers to the boundaries of the reprojected Limpopo province shapefile.

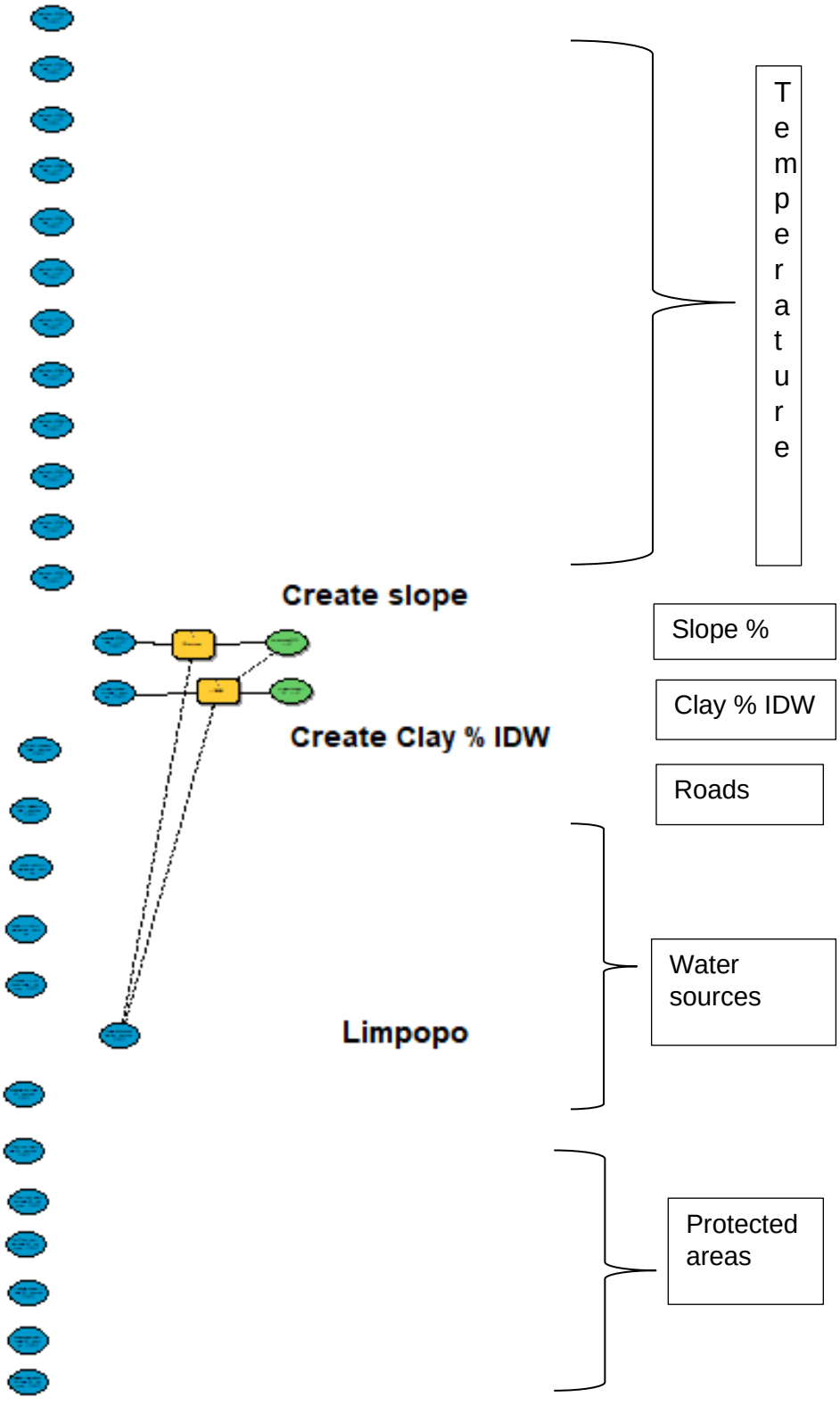


Figure 3.40 Model Step 3: Create soil clay percentage raster and slope percentage rise raster.

During Model Step three, the SRTM DEM was converted to the slope percentage rise Tiff, using the Create slope Tool (from DEM raster, which is a Tiff image) to a Slope Tiff image. The clay percentage shapefile was converted to the clay percentage raster

Tiff image, with cell sizes of 30.77 meters, as it was resampled in the tool by snapping it to the Slope percentage raster.

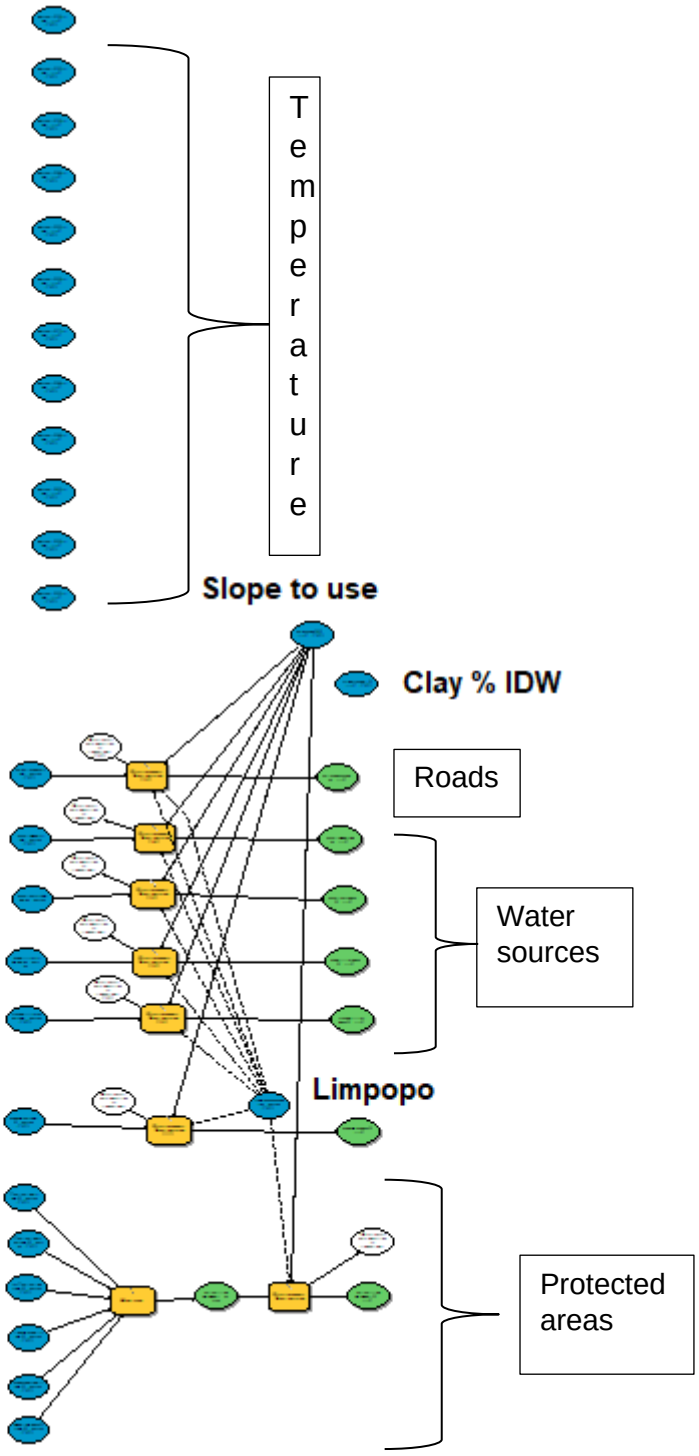


Figure 3.41 Model Step 4: Merge masks and Calculate Euclidean distances for masks shapefile, all water sources, and substantial roads.

During Model Step 4, all the restricted area variables are merged with the Merge Tool after which the Euclidean Distance Tool was used to create the distances in meter from all restricted areas raster. All the distance to water source input variables named in Chapter 3, Section 3.4.2.1.1, as well as the substantial roads shapefile, are used to create the Euclidean distances rasters (Tiff images). All Tiff images are resampled to the Slope Percentage Tiff image and were clipped according to the Limpopo provincial boundaries in the model.

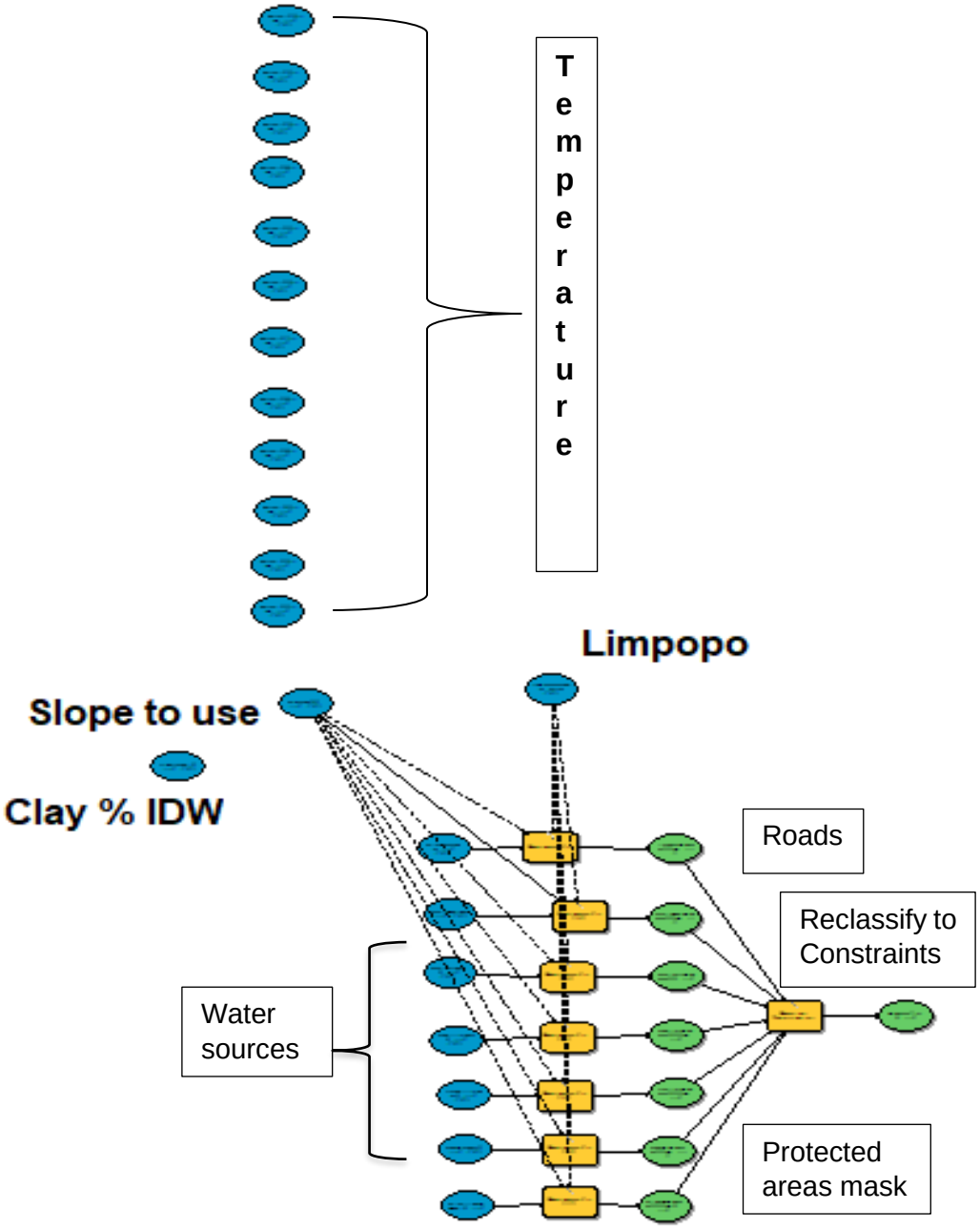


Figure 3.42 Model Step 5: Roads, and all water sources combined and reclassified as 0 or 1 to create the Restricted area mask via the Reclassification Tool.

During Model Step 5, the substantial roads Euclidian Distance Tiff image, the combined Euclidian distance water source variables, and the combined mask Euclidian Distance Tiff image were reclassified as 0 (restricted) or 1 (Available for analyses) to create the Restricted Areas mask via the Reclassification Tool. This mask was used with the final suitability maps and imagery to discern the areas that were restricted (in grey) in the maps in Section 4.4.

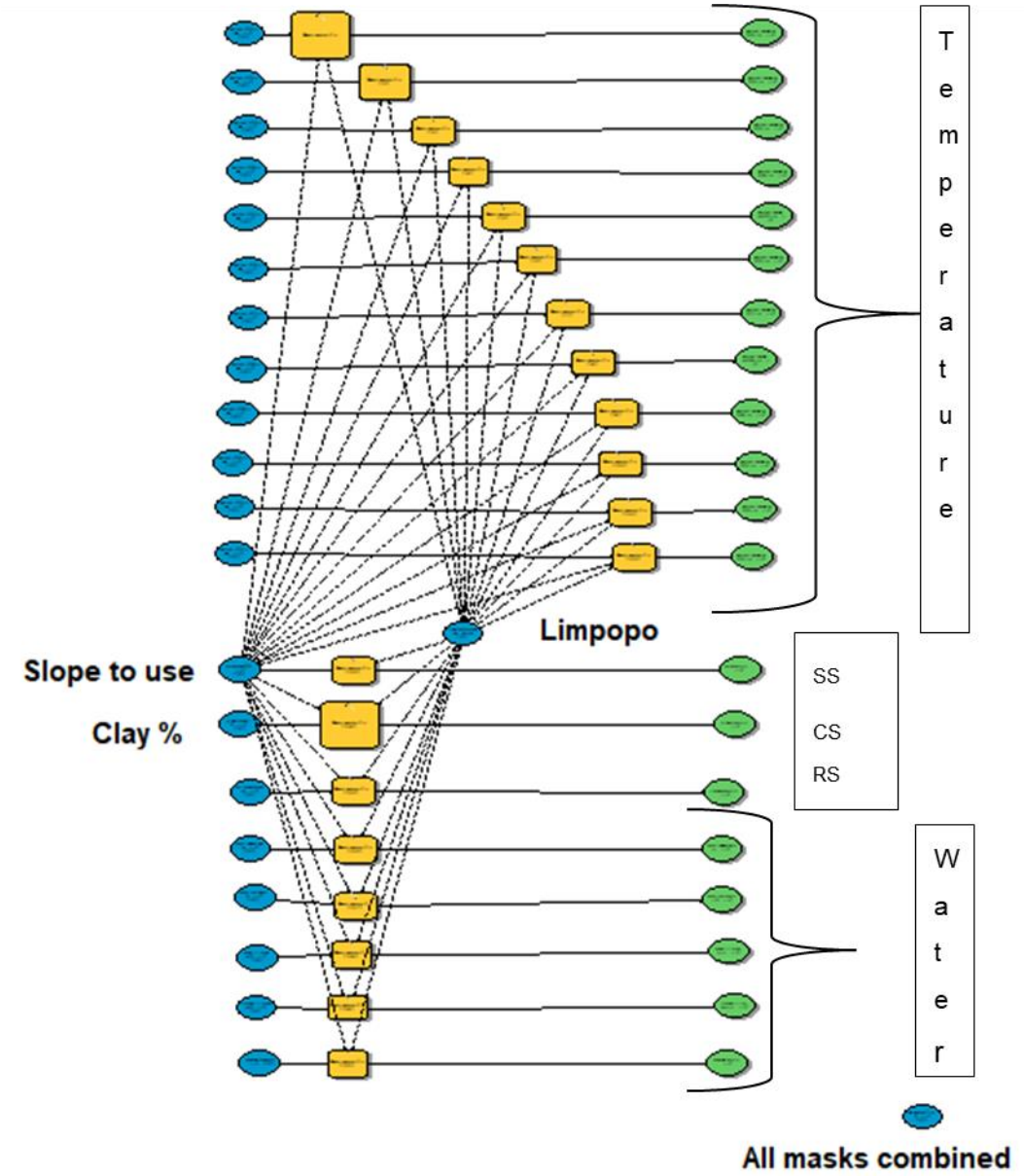


Figure 3.43 Model Step 6: Reclassify Tool for producing suitability outputs.

With the mask (or Restricted areas Tiff Image) created in Model Step 5, the rest of the input variables were inserted and reclassified according to each variable's thresholds in Model Step 6 (Figure 3.43). This was done using the Reclassify Tool for reclassification of all the rasters produced (blue ellipses) from the earlier steps of the input variables, to produce the suitability classified Tiff images (green ellipses). In Step 6, the temperature suitability Tiffs, clay percentage-, slope percentage- and road suitability Tiffs, (SS, CS, RS) were produced. Below them in Figure 3.43 all the Distance to water Euclidian Distance input rasters were reclassified according to their thresholds in Table 3.8 in Section 3.4.2.2.

In Model Step 7a (Figure 3.44), the sub-model outputs from Step 6, were combined making use of the Weighted Overlay (WO) and Weighted Sum Overlay (WSO) methods. In Model Step 6 as well as Model Step 7a, dams were included as a source of water.

However, after careful consideration of the different authors' opinions about inclusion of dams as a source of water for ponds (Table 3.7 and Table 3.8 in Chapter 3, section 3.4.2.2), it was decided by the researcher that the dams spatial layer should be excluded as in Model Step 7b, (Figure 3.45, bottom left blue ellipse).

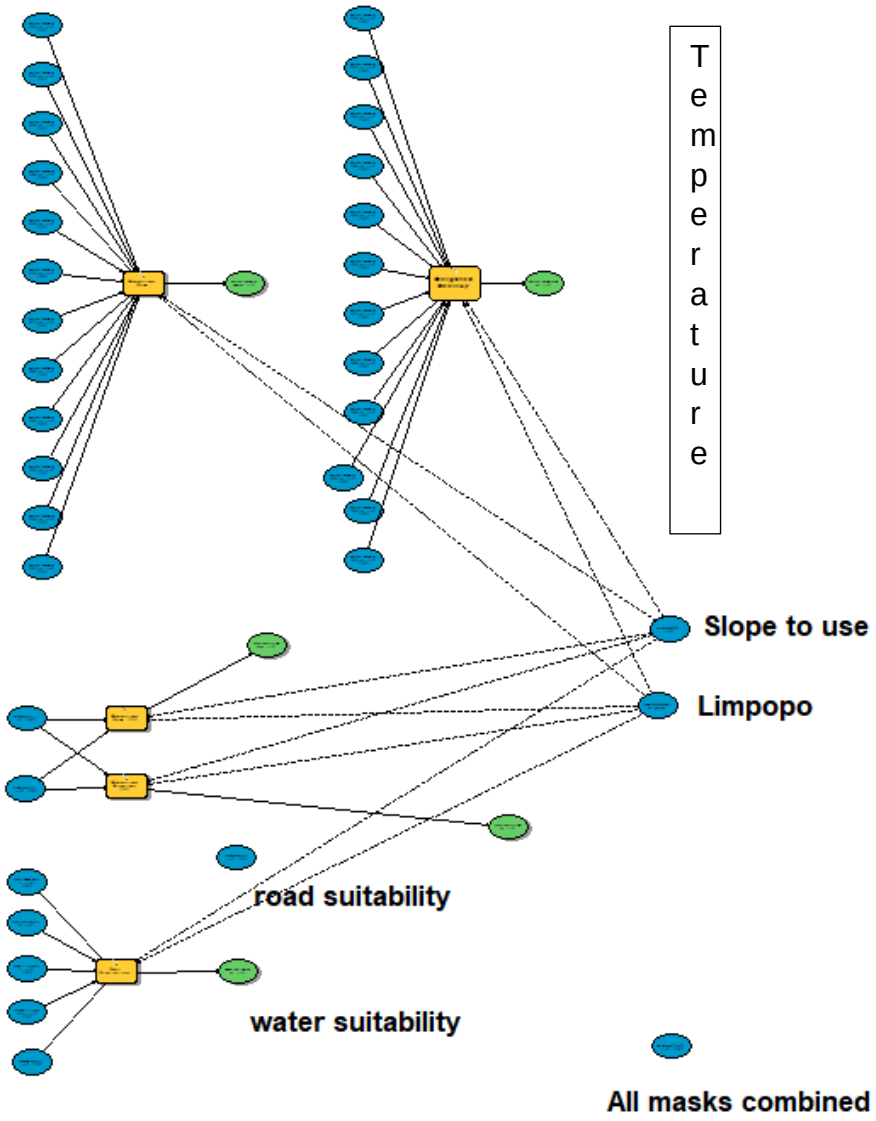


Figure 3.44 Model Step 7a: Combine inputs to Sub-Model output rasters via WO and WSO Tools to create suitability layers (Dams included as a source of water).

In Model Step 7a and Model Step 7b, the water suitability Tiff image rasters were created using the Cell Statistics Tool in Model Builder, first including dams, and then excluding dams as a water source. This iteration modification in the model, also shows the ease with which variables in a sub-model can be added or removed from the model as the user sees fit. The Cell Statistics Tool was opened to display the use of the "maximum statistic" choice in the interphase (Figure 3.46).

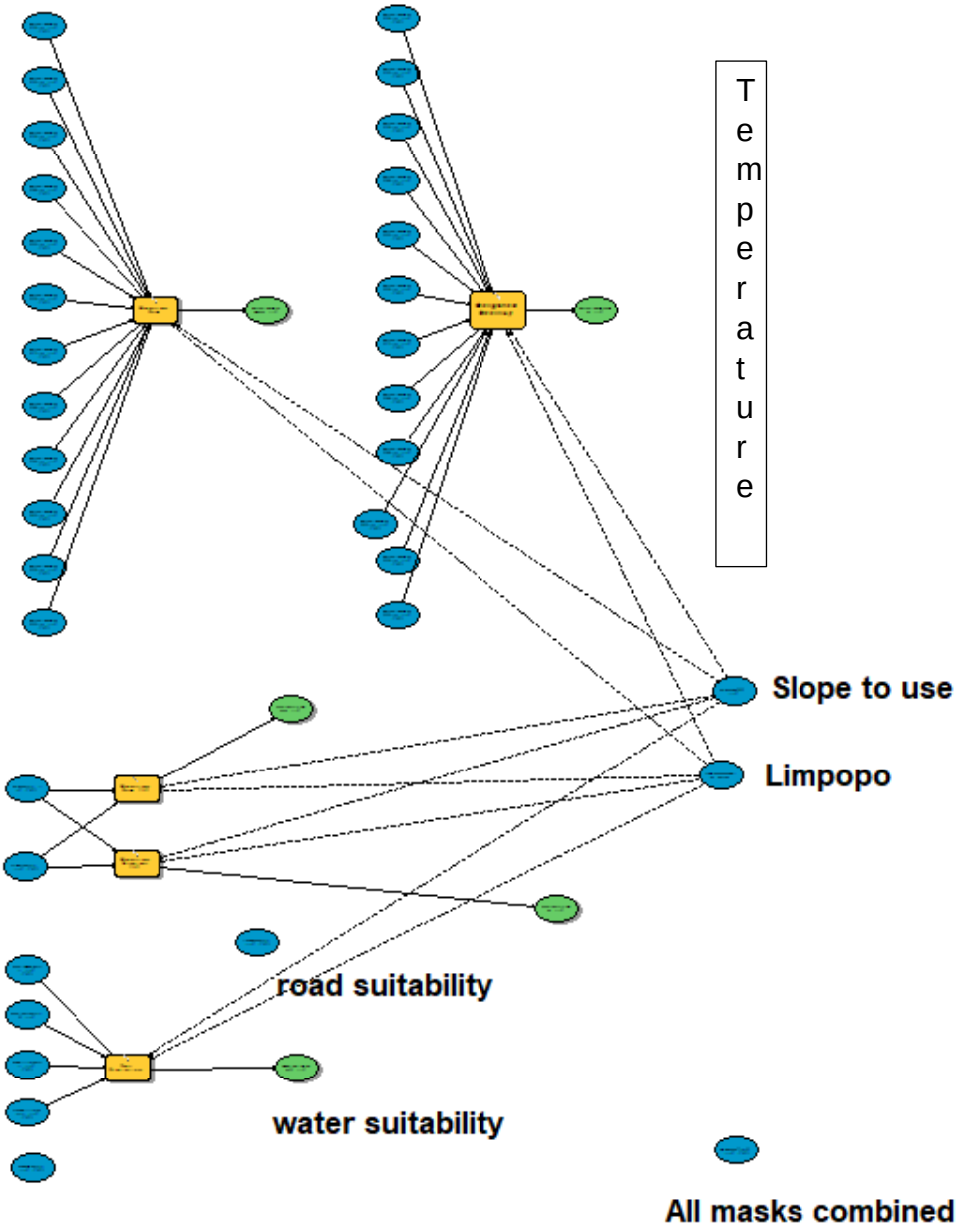


Figure 3.45 Model Step 7b: Combine inputs to Sub-Model output rasters via overlay Tools to create suitability layers (Dams excluded as a source of water).

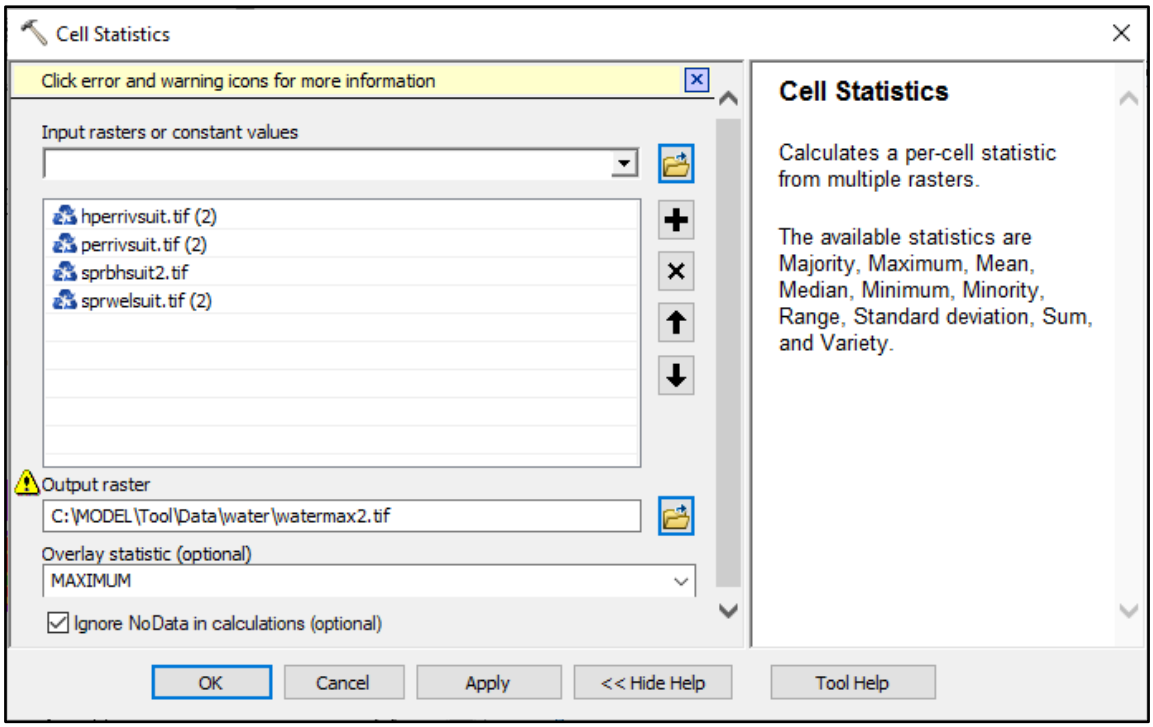


Figure 3.46 Calculating the maximum statistic of water sources from Step 7b.

From Model Steps 7a and 7b, the slope suitability and clay suitability Tiffs were created by the WO and WSO processes. Several parts of Model Step 7 can be isolated to change the thresholds of one or more inputs or outputs. Examples of these modifications and close-ups of the different steps from Step 7a and 7b, are displayed in Figure 3.47 and Figure 3.48. Model Step 7c and Step 7d display the creation of the Soil Suitability sub-model's output Tiff image.

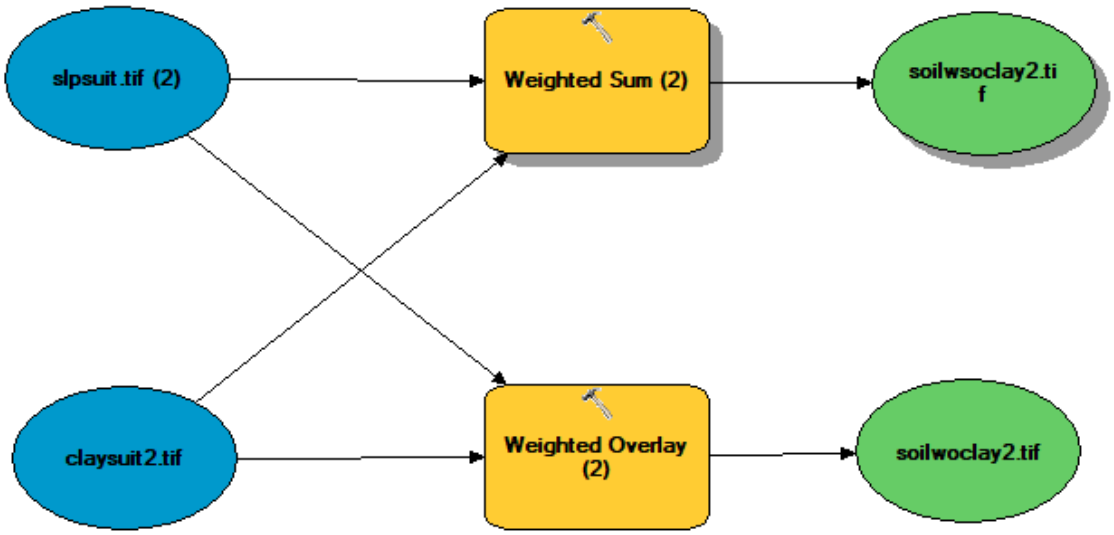


Figure 3.47 Model Step 7c: Close-up of calculating soil WO and Soil WSO suitability separately if required.

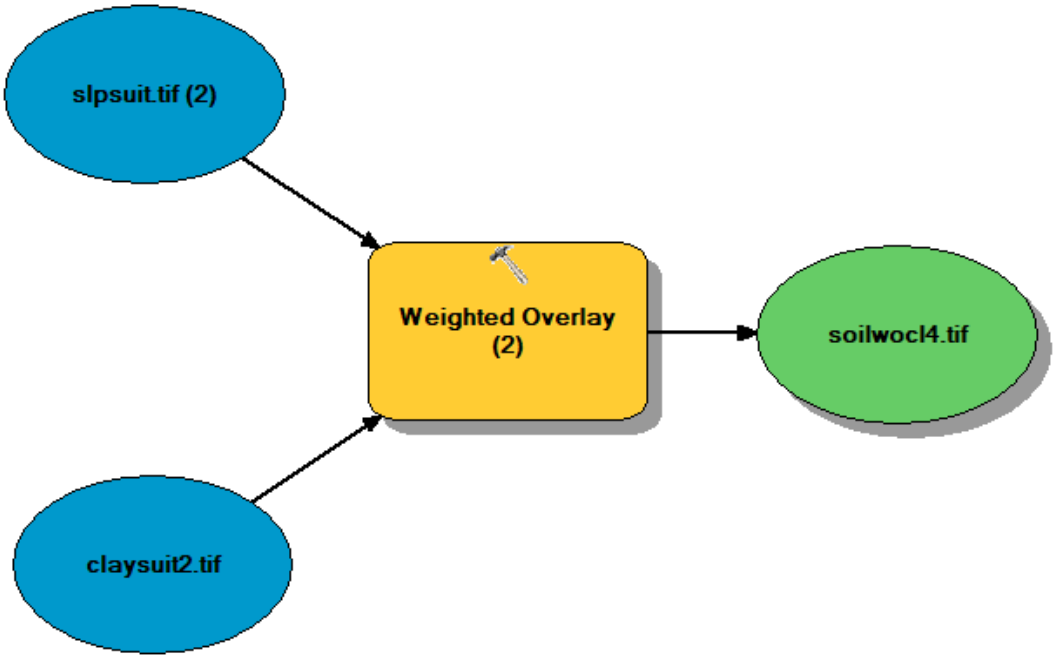


Figure 3.48 Model Step 7d: Close-up of isolating and calculating soil WO suitability separately if required.

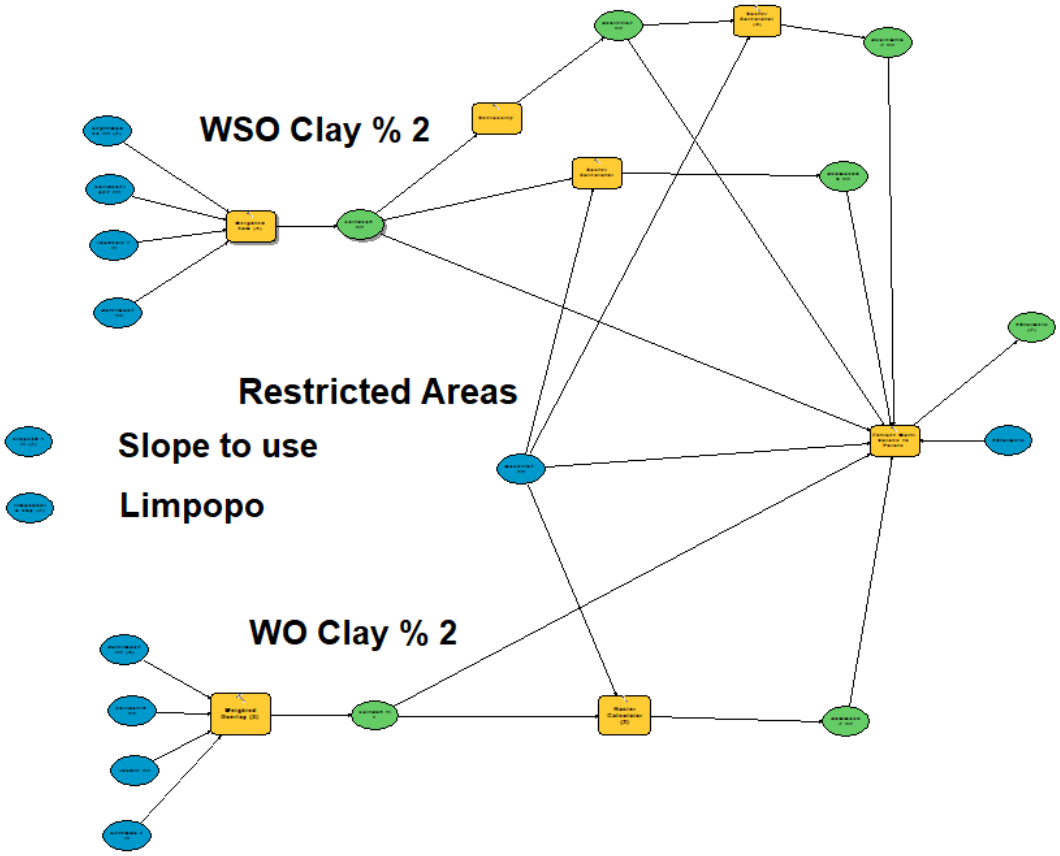


Figure 3.49 Model Step 8a: WO and WSO Tools to create final WO and WSO pond aquaculture suitability raster images. “Extract Multi Values to Points” Tool to extract output layers to farms (Dams excluded as a water source).

After Model Step 7, which contains the suitability calculations for the different sub-models’ outputs, Model Step 8a (Figure 3.49) displays the WO- and WSO Tools to create the final WO and WSO pond aquaculture site suitability Tiffs, from which the final suitability maps were produced. As with Model Step 7, the different tools and processes in Model Step 8 can be isolated or copied and used separately for making changes to thresholds (as depicted in Figure 3.49, Figure 3.50 and Figure 3.51).

The final process in Model Step 8, is the extraction of the final suitability products to the Farmer’s GPS points (Far right) using the “Extract Multi Values to Points” Tool to extract the suitability values to the farms (excluding dams as a water source) in Step 8a).

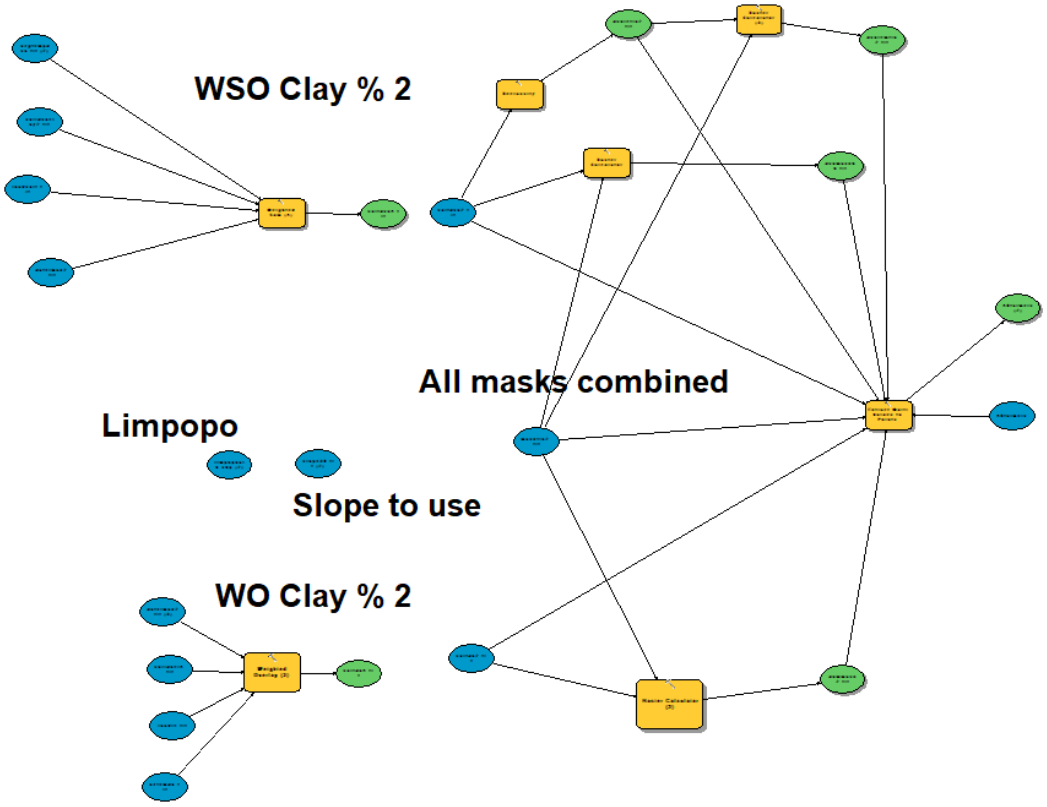


Figure 3.50 Step 8b: WO and WSO Tools isolated or separated from the extraction to points process.

In Model Step 8b, Figure 3.50, the same procedures that were described in Model Step 8a, were followed. The ability to change thresholds in the model is highlighted. This scenario would also be useful in the case where the amount of RAM required to execute a certain step in the modelling process, is not sufficient to run the entire Model Step 8a in one step.

The WO and WSO pond aquaculture suitability raster images extracted in Step 8b, can thus be separated from the right side of the Model Step 8a process, as in Model Step 8c (Figure 3.51). Model Step 8c depicts the isolated right-hand side of the Model Step 8a and Step 8b. Model Step 8c still makes use of the “Extract Multiple Values to Points” Tool to extract the output layers I.E>, the restricted Areas (or Mask), the WO and WSO to the farms. The dams were still excluded as a source of water in the second iteration from Model Steps 7 and 8.

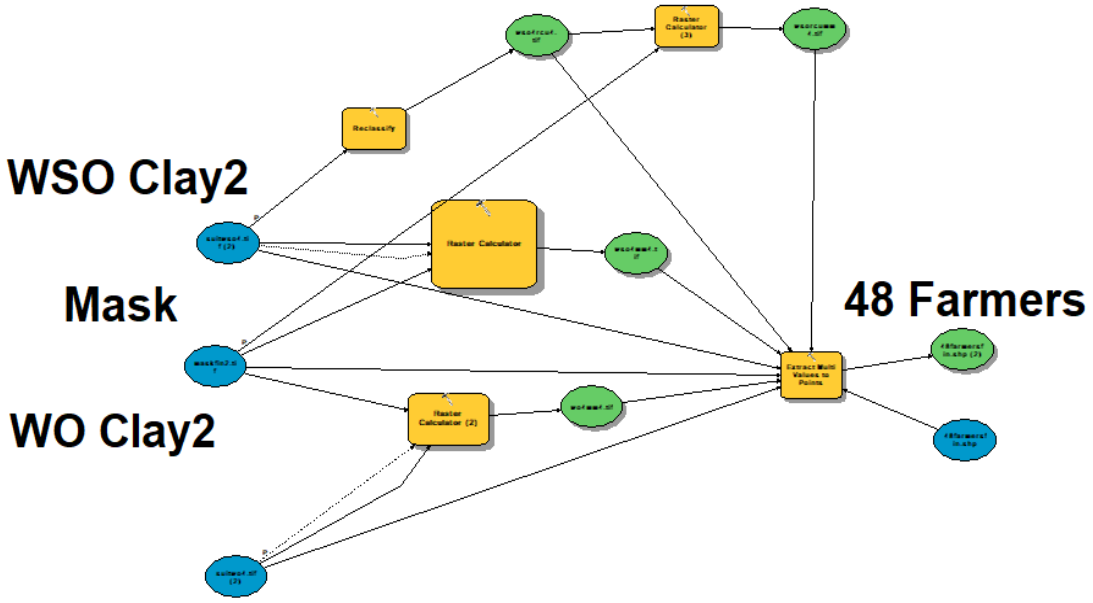


Figure 3.51 Model Step 8c: Isolation of the “Extract Multi Values to Points” Tool to extract Masked areas, WO and WSO output layers to farms (Dams excluded as a source of water).

The isolation of the “Extract Multiple Values to Points” Tool to extract Masked areas, WO and WSO output layers to farms (Dams excluded as a source of water), was done so that the farmer points could be changed or a different set of GPS values in the form of a shapefile. It should be kept in mind that every time a new WO or WSO suitability input is added or changed, the extraction to the GPS point shape file takes place and will create the new results in the Attribute Table of the farmers shape file or the GPS point shape file, every time the model is executed.

In ArcGIS Model Builder all models can be exported as Model Tools, images (pictures) and Python scripts for sharing to other users. After being exported from the ArcGIS10.4.6 Model Builder environment, it can be shared with others via email or directly copied. This is what the GIS programmer will use if he/she prefers to work in Python instead of the Model builder environment. The same goes for the Model’s Steps 1 to 8 in that they can be saved and emailed or shared digitally to other GIS users, who can populate them with the current data or with their own area’s spatial input data.

3.3.2.3.5 Model sharing

The GIS specialist could use the final suitability raster produced and extract suitability from this product to areas or points of interest. This information could guide the process of selecting the more suitable areas for fund allocation for new developments or the support of currently existing aquaculture enterprises. Querying could be done in three environments due to the development of the AQUASUIT App. Firstly in the ArcGIS or ArcGIS Pro environments. Secondly via the AQUASUIT App on a desktop or laptop and thirdly on a smart device like a tablet or cell phone. The App can be shared via a link to any of the above devices. Sharing of the link first takes place from within the Arc Enterprise platform. Any user with access to the Internet can use this link to open the App platform to do suitability querying. The App makes it possible for site suitability queries by GIS specialists to extension workers in the field or indoors.

The model can be shared in the Esri ArcMap Toolbox (Esri, 2018) format. The Toolbox can be emailed to another ArcMap user. During the time of this research, ArcMap10 users were encouraged to migrate to the ArcGIS Pro (Esri, 2023c) software by March 2024. Being aware of this transition, the researcher ascertained and confirmed that the Toolbox was transferable to ArcGIS Pro from the ArcMap 10 version. The GIS user can thus import the ArcMap Toolbox into ArcGIS Pro. ArcMap was still supported but not offered for sale after March 2024 by Esri.

The model was built and executed in the Model Builder interphase of the Esri ArcMap 10 (Esri, 2018) software. Many users were using the ArcMap 10 version of Esri's GIS software during the time of this research. Esri ArcMap will be supported but sales were discontinued after 31 March 2024 (De Munnik, R., 2024: Personal communication).

The model is transferable to the Esri ArcGIS Pro software Model Builder environment. The model can be received, duplicated, and used to produce site suitability maps. The site suitability model was thus developed in a stable GIS environment with ongoing software support by the software vendor. The model can be shared from its developmental stages such as the MCE flow diagram, MS Excell or the automated python scripts. The Python scripts can be exported from the Model Builder Tool and imported by some open-source GIS software like QGIS. The model can be received, duplicated, and used to produce site suitability maps and score GPS points in ArcGIS Pro as it was in ArcMap.

The model development in Microsoft Excel and the flow diagram were documented in Chapter 3, as documenting is one good way of communicating the methods and results to secondary users. The documentation of the flow diagram explains the purpose, inputs, outputs, parameters, and the assumptions made during this research's analysis. Instructions, examples, and screenshots were provided in Chapter 3. The developmental stages of the model were documented from the design stage to the Toolbox steps. This documentation process enhances the credibility and the sharing of the GIS Toolbox, the design and execution of the model. The model's credibility facilitates user collaboration and the learning experience of secondary users (Esri, 2025a).

It is good practice to disseminate models and scripts to collaborate with others. There are different ways to share GIS scripts and models, depending on the audience, purpose, and format of the analysis. For example, the Python scripts generated in Model Builder in this research can be shared with other GIS users. One way is to make use of ArcGIS Online or ArcGIS Enterprise to publish them as geoprocessing services or web tools. (Esri 2025b).

To share Model-Builder models with other ArcGIS Pro users, one can use packages or toolboxes to export and import them. Online platforms can also be utilised to host, version, and distribute code (Esri, 2025c).

Importing and using the model and toolbox is important in the model sharing process. The objective was to use meaningful names and labelling as well as a clear structure to describe each step's functionality. The using of relative pathways ensures that the variables' data can be read from different workspaces on different users' workstations and laptops (Esri, 2025c).

The importance of reproducibility, which is the ability to obtain the same results from using the same data sets and model steps but from a different work-location or for a different spatial-location is crucial for validating, verifying, and replicating the GIS model analysis. To make the GIS scripts and models reproducible, the data and code were made accessible, reliable, and compatible by using these stable and secure data sources and data formats for the analysis and distribution (Esri, 2025c).

Model sharing may also encompass the migration of the model from ArcMap to ArcGIS Pro. Model Builder in ArcGIS Pro is fundamentally like Model Builder in ArcMap. The

model diagram appearance is similar, and the user builds models by adding data and geoprocessing tools and connecting them to form processes. In ArcGIS Pro, one can view, edit, and run models built in previous versions of ArcMap (Esri, 2023). The model builder toolbox can be shared via email to another ArcMap user and the Python scripts are automatically generated and included.

Esri ArcMap Model builder runs on Python scripting in the background. ArcGIS Pro can import the Toolbox developed in earlier versions of ArcMap software. Open-source software, like QGIS, which uses C++ and Python languages, can import the Python scripts.

There is also the possibility of incorporating the toolbox function and the suitability datasets into the ArcGIS Online Application. With the Application builder in ArcGIS Online (Esri, 2023), the suitability outputs can be added to the app using the Suitability Model widget (Esri ArcGIS Webb App builder, 2023.) The AQUASUIT app and the uploaded data are then to do suitability queries. The following browsers support the use of the App: (Esri, 2023):

- Google Chrome version 111 and later.
- Microsoft Edge version 111 and later.
- Mozilla Firefox version 113 and later.
- Mozilla Firefox version 102 (ESR)
- Safari version 15 and later. (Esri, 2023).

When the user decides to migrate to ArcGIS Pro from ArcMap, a few cautions are covered in the bullet points below to assist with smooth transformation and sharing to users of ArcGIS Pro. The transfer (or import) of the ArcMap Model Builder Toolboxes and Models into the ArcGIS Pro environment:

- Some tools are not supported in ArcGIS Pro, so if a model uses one of these tools, the user will need to fix the model or find an alternative in Pro. However, no Tools that are unavailable in ArcGIS Pro, are currently used in the model built in this research.

- Some data types, namely personal geodatabases (PDBs), are not supported in ArcGIS Pro, so if a model uses these data types, the model will have to be updated. However, the model produced in this research does not make use of PDBs, but utilises shapefiles and Tiffs.

- One of the most common tools, Calculate Field, no longer supports Visual Basic calculations, so one will need to update your model to use Python or Arcade

expressions instead. The suitability model built in this research, however, does not make use of “calculate field” functions.

One will need to make a backup of the toolbox that contains the models before using them in ArcGIS Pro. This is due to the fact that if you make changes and save the models, they will no longer be able to be used in ArcMap. (Zemo, J., 2024: Personal communication).

3.3.2.3.6 Site Suitability App (AQUASUIT)

The AQUASUIT App was built in ArcGIS Enterprise, using data uploaded to ArcGIS Online software. The AQUASUIT App was completed in September 2024. App modification can take place in the ArcGIS Enterprise platform. The AQUASUIT App was designed to be a tool which anyone with the link can open and use to do site suitability queries. Site suitability queries can be done for points and areas (polygons) in the App. It was envisioned that the App would assist all stakeholders and funders to do suitability queries, no GIS experience required.

An example of the use of the App is that the user clicks on a point or selects an area on the map on their smart device, and the suitability and floating-point value x 1000 appears. The App user draws a polygon or clicks on a GPS location anywhere on the suitability map, and the outcome will be a table with the statistics of the area in square kilometres as well as the percentage belonging to each suitability class or, for a point, just the suitability value. Both results can be exported to a .csv table format to their phone or tablet. The App was designed containing the suitability layers for the Limpopo province pilot study area in vector format. The App was populated with the WO integer as well as the floating point WSO, which were both converted to polygons first before they were incorporated into the App. The WSO polygon required more RAM and disk space due to its large size. Therefore, the WSO raster was multiplied by 1000 to convert the values to no decimal points, thus four integer numbers, then converted to a shapefile, appropriate for querying GPS points of farmers. The App was appropriately named “AQUASUIT”.

Populating the AQUASUIT App with the WSO shapefile, required a large amount of storage space as well due to the conversion of the floating-point WSO suitability raster to a polygon. It also consumed a lot of credits in the ArcGIS Online system. The converted WO suitability polygon shapefile required less space and credits due to the

integer nature of the WO Tiff that was converted to a polygon. The AQUASUIT App can be used for site suitability queries of points and polygons, or GPS WSO x 1000 values, for scoring and ranking points.

3.3.3 Data collection

There were two types of data collection: namely, the sourcing of spatial data from different providers as well as fieldwork and telephonic interviews to collect GPS locations of the existing known aquaculture farms at the time (2019). The list of farmers was obtained from the then Limpopo Department of Agriculture (LDA, 2019).

3.3.3.1 Input data sourcing

Every variable present in Table 3.7 has data associated with it. Each sub-model containing certain variables was populated with sourced data either in a Geodatabase or other GIS or spatial format or in the form of an excel spreadsheet that could be converted to a shapefile or Tagged Image File Format (GEOTIFF), which is georeferenced raster imagery (Ritter and Ruth, 1997). Data collection was done by contacting the relevant institutions, custodians and experts (within and outside of the ARC).

3.3.3.2 Collecting location data

A second set of data was collected separately by means of an in-field situational analysis in the Limpopo province by visiting 48 current tilapia farmers from 2019 to 2021. A production related questionnaire was presented to the farmers verbally and captured by the field staff. Photos and GPS points of each farm entrance and each of its ponds were collected. Water quality readings were captured from the existing ponds and their water sources.

From this situational analysis, the GPS points captured were transferred into ArcMap 10.6.3 and used to map the locations of 48 current fish farmers. These GPS locations were used in conjunction with the final site suitability product to score and rank the farmers. The questionnaire (Refer Appendix A) data were not used for this research, but it could be supplemental in the subsequent phases of the overhead project, where the ranking can be supplemented with the production data to assist with optimizing the

allocation of funds to support enterprises with more suitable circumstances than others. (Refer ethical clearance certificates and communication: Appendix B, C and D).



Figure 3.52 Field team at a pond in the Limpopo province.

3.4 Data analysis

The data analyses process in this research involved three steps, namely: loading of the processed data into the model, model execution in ArcMap 10.6.3 and data visualization after every step of the suitability process. Extraction of the suitability values to the existing farmers was done in the final step in the model in the suitability toolbox.

3.4.1 Suitability model execution

From the literature review, only the most crucial variables were selected and included in the five sub-models. The outputs from the sub-models were created using their respective thresholds in the suitability model in the GIS environment. The suitability results were presented in the form of maps from the Tiff outputs.

Some of the authors in Table 3.7 (Hadipour, Vafaie and Hadipour, 2015. Nayak, et al, 2014) suggest the inclusion of dams, lakes, and perennial pans as water sources to pond aquaculture enterprises. Other authors (Assefa and Abebe, 2018; Ssegane et, al, 2012), however, (Table 3.8), suggest the exclusion of dams, lakes, and pans in pond aquaculture as water sources.

The dams or water bodies dataset used in this research, do in some cases distinguish between dams and lakes and pans, but the size, quality of the water and the perennial attribute of the water body is not always known or indicated. Therefore, it was decided to remove the “dams” as a source of water, created in step 6 of the model, in step 7 in the model. The dams Euclidean distance layer was only used as part of the masked or restricted areas image. Thus, the suitability maps were all created excluding dams as a source of water for pond aquaculture, except for Figure 4.1 and Figure 4.2, which include dams as a source of water and made use of the first clay percentage iteration using the thresholds displayed in the various tables discussed.

3.4.2 Scoring and ranking of farmers

During a field-work exercise that took place in 2018, described in Dekker, et.al., (2019), the Limpopo Department of Agriculture presented the ARC field work team with a list of existing tilapia aquaculture pond farmers situated in the Limpopo Province. These farmers were contacted telephonically, and it was established that 19 farms contained ponds with water, with or without fish, which was a prerequisite to receiving a situational analysis visit. Later, eight Limpopo farmers were added to the list, bringing the total to twenty-seven farmers. In 2022, more farmers were added from different field visits or telephonic communication. At the time of this research analysis, there were 48 farmers that had GPS coordinates associated with their farms and ponds, and they were thus included in the scoring and ranking process of this research. Only their GPS points were used in this thesis, their identities as well as the situational analyses questionnaires were not used for the purposes of this research. However, in later research, it may come in handy to further refine the suitability scores and ranks allocated to each individual farmer.

The WO and WSO suitability maps (Figure 4.3, Figure 4.4, Figure 4.7, Figure 4.8 and Figure 4.9) were used to score and rank the farmers according to the GPS locations

of their farms collected from the situational analysis. The reason for using the WO and WSO suitability maps, is that the scoring and ranking that is most applicable to the farmers are the final WSO map (excluding dams and using the second clay iteration including or excluding the restricted areas). This is because of the floating-point nature of the WSO output. Using the WO product, many of the 48 farmers scored the same integer suitability class number, e.g. 1, 2, 3 or 4. This makes it difficult to prioritise which farmers to support if there are all have the same integer score. This makes it difficult to rank the 13 farmers which each scored a suitability value of 4, effectively. The WSO suitability product, however, allowed floating point scores with decimal values to be assigned to each farmer, making ranking them according to their scores, more defendable and precise. By extracting the underlying WSO suitability value to the GPS point in ArcMap, each farmer was assigned their respective suitability score in Table 4.6.

Firstly, the scoring was done without the inclusion of the restricted areas and secondly, the restricted areas (or masked out areas), were included to indicate which farms were perhaps assigned a suitability value, but in fact were situated in an unsuitable or restricted area, like for instance a wetland. Therefore a “distance from wetland” value was included in the tabulated results (Table 4.6), which contains the farm number (linked in a separate data base to the farm name, for the sake of protecting the farmer’s identities, the score, the ranking, the distance to the nearest wetland as well as a suitability colour code for easier assessment.

Results of the scoring and ranking of current aquaculture farmers are available in Table 4.6 and summed in Table 4.7. Making use of WO suitability map’s scores, the 48 existing farmers’ GPS locations were used to extract the underlying suitability value.

The Weighted Sum Overlay results in Table 4.6 were rounded by the researcher, by perceiving that as seen in column 6 in Table 4.6. This meant that if a farmer has received a score of for example 3.5, it was regarded as a 4, a value of 2.5 would be rounded to a 3 and while rounding down farmers will result in a score of 3.5 rounded off to a value of 3. In this research any value above value 3.5, was rounded up while any value below 3.4 was rounded down using 3 decimals. The WSO values were thus rounded as perceived by the researcher and not, rounded-up, rounded down, using

integer function nor truncated (Table 4.6). It was not calculated but assigned subjectively (not objectively as per formulas mentioned further to the right columns of the table).

3.5 Limitations

In Table 4.3, the calculations of the Weighted Overlay (WO) Suitability cell count, area calculated per suitability class and the percentage of the Limpopo province belonging to each were considered. This can be compared with the results in Table 4.4, which shows a table of the calculations of the Weighted Overlay (WO) Suitability cell count, area, and percentage of the Limpopo province for each suitability class, including the restricted areas.

Some of the limitations in the design of the models are to be kept in mind. Although the model can be adjusted, integrating new variable types, such as proximity to farm inputs, would require redesigning the MCE and AHP elements from the start to ensure unbiased results and adjustments of all variable's relative importance. The same applies to variables that could be added for commercial aquaculture suitability, like market size, farm gate sales, and distance to markets. The accuracy of the model was not assessed through a ground-truthing (in-field evaluation) exercise. It is essential to recognise that this model is a representation of reality, not reality itself. Models aim to approximate actual conditions as closely as possible, but each type has its own strengths and limitations. This research found that this model is well-suited to the specific needs of government at this time, effectively addressing a niche requirement.

Another limitation of this model is that no appropriate flood-zone data were available. This important restriction layer was thus omitted from the model. Especially with climate change future suitability scenarios, ponds should not be located in 100-year flood zones. Flood-zone data from SANSA was available in terms of meters, but flood zone data for 20-, 50-- and 100 years is required on provincial scale. It might however be available from the local authorities.

Model transferability maintains flexibility for government use, allowing for quick adjustments to suit different fish species, countries, or new data, like water temperature, as it becomes available. However, a crucial factor is ensuring that each

province’s GIS division has access to the necessary datasets. Provincial DFFE departments have Esri licences and can obtain these datasets, which supports the model's transferability.

Both in the WSO and WO products, there were very few unsuitable sites, only some restricted areas. The overlaying process of weighted variables renders areas marginally suitable when they contain some higher suitable areas and some unsuitable areas. The model can be revised by replacing the unsuitable score of one during overlay, with a zero. This will depend on the user. If the user would like to eliminate unsuitable areas, it can be done in this manner. It is however advised that the sub-model suitability products be consulted for the reasons behind a suitability classification, as they contain grey areas of unsuitability before they were overlayed with each other. While the model provides a powerful tool for site suitability analysis, it is important to remember that it is only a representation, not reality itself. The model has not yet been tested for transferability to open-source GIS software. If new suitability variables—such as distance to markets, pollution sources, or farmgate sales (e.g., population density), are needed, the model will require redesigning from the MCE, AHP, and PCM stages. This adaptation would require expert GIS designers to incorporate and optimise the new variables in an enhanced version of the model.

The 1km spatial resolution of the temperature input rasters, overlap at the Southern borders of the Limpopo province. The temperature input rasters do not reach the Limpopo provincial boundaries completely at the Northern borders. This is before being incorporated into the suitability model calculations. This remains even after being resampled to the 30-meter SRTM. The SRTM Tiff cells follow the Limpopo provincial boundary much closer due to its 30.77 m spatial resolution, as displayed in (Figure 3.53).

The 1 km by 1km surface-air temperature Tiff images overlap the Limpopo province border in the South. In the North of the Limpopo province however, these Tiffs do not cover the entire province area at some locations along the border. The air temperature Tiffs were resampled to the Slope Tiff, which was created from the DEM. The total surface area of the Limpopo Province calculated from the 30-year long-term air temperature data is thus slightly less than that of the other input data sets. The total

surface area of the Limpopo province and the differences can be viewed in detail in (Table 4.5).

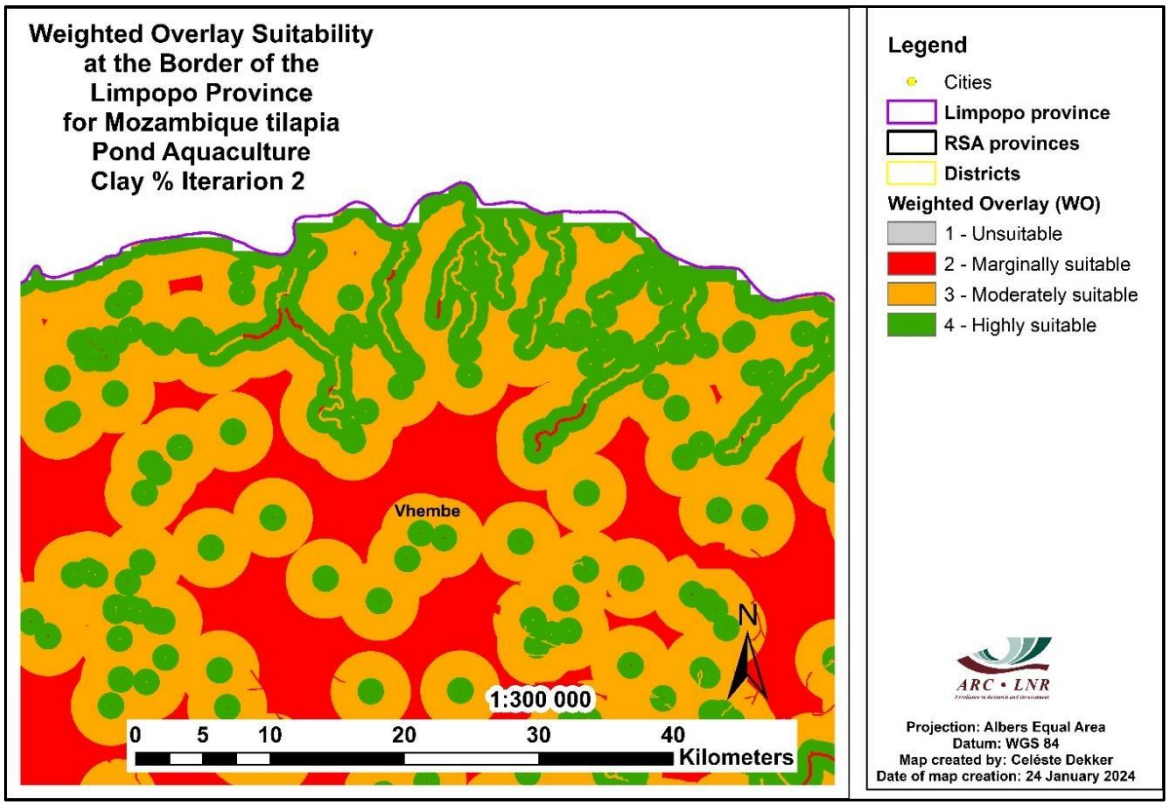


Figure 3.53 The 1: 300 000 scale map of the northern border of the Limpopo province depicting the gaps in the pond aquaculture site suitability raster due to differences in the temperature input rasters and the SRTM DEM cell sizes.

When one is zoomed-in closer to the Limpopo border, at a scale of 1: 300 000, Figure 3.53, this phenomenon depicts the discrepancy. The difference due to the 1 km temperature cells can be corrected. First the interpolated temperature surfaces must be received in a size that overlaps the Limpopo provincial borders on all sides. Then the temperature Tiffs should be resampled to the DEM.

During the research the then existing, known farmers were scored and ranked according to the WO suitability map, for comparison purposes to the WSO product. However, it was decided not to round-up or round-down the WSO resultant suitability raster (Tiff). By rounding-up to the nearest highest integer class value or by rounding-down to the nearest lower integer class value, using reclassification, the resultant classified rasters would introduce bias into the data. The colours used for suitability

class colour assignment for the classified farmers, were: Green for the farms situated in highly suitable areas, orange for the farms situated in the moderately suitable areas and red for the farms situated in the marginally suitable areas. The grey colour was assigned to the farms in restricted and unsuitable areas.

At first the original model was a single process in the Model Builder Tool. It was later split into 10 Model Builder steps in the Toolbox, each executable separately in the tool.

The MCE, AHP and PCM approach has limitations. The same is true for the WLC method of overlay (Malczewski, 2000). The aim of this research was not to provide an absolute model or finitely correct solution to the question of the suitability of the Limpopo province for Mozambique tilapia pond aquaculture site suitability. The model and this research could provide insights into the problem statement and its possible solutions. The question of which specific WLC technique and the best practice approaches to follow in every step of the WLC process, to solve this question of site suitability in a GIS, will always be open to improvement (Malczewski, 2000).

The percentage of farmers in every suitability class was calculated in Table 4.7. However, these percentages cannot be interpreted as being representative of the current state of all the pond aquaculture farmers in Limpopo. The reason being that these GPS positions were not randomly chosen. The list received from the then LDA (2018) did not contain all the current existing Limpopo pond-aquaculture farms. Table 4.7. is thus representative of the areas where the then known farmers were farming.

3.6 Conclusions

In this chapter, the ontological and epistemological standpoints of this research regarding GIS research philosophy were described. The methods of data collection and data analysis techniques were also explained. The methodology chapter forms the backbone of this research (Hofstee, 2006). By using the MCE method and PCM in the AHP, it was strived to minimise the possibility that the weights of the chosen suitability variables were assigned subjectively.

The maps produced by the classification of the intermediate suitability outputs, produced in each sub-model, can provide insight into the possible reasons for the final suitability classification of an area. The reason behind the specific scores assigned to

existing farmers could also be explained by referring to the maps produced in the sub-models.

The final step in the modelling process, was the extraction of the created suitability products to the existing farmers' location points. Adding a new shapefile containing different GPS points, is possible. Changes can be made to the thresholds and constraints in the model, which will alter the end products as well as the values extracted to every GPS point. The following chapter, Chapter 4, describes the results from the processes and outputs produced in Chapter 3.

Chapter 4

Results

4.1 Introduction

This chapter discusses the findings deducted from this research. The findings in this chapter are tied to the themes that were conjectured from the main research questions depicted in Chapter 1, Section 1.3. The main themes around which this chapter unfolds, are:

i. The design of the site suitability model in a Geographic Information System (GIS) environment, using Multi Criteria Evaluation (MCE). The selection of only the most crucial variables and their thresholds required to build and populate this simple, yet robust Mozambique tilapia *(Oreochromis mossambicus)* pond aquaculture site suitability model and applying these chosen variables and their thresholds in this model. This venture includes identifying and collecting the spatial data tied to each variable in the designed suitability model. The next step is the execution of every step in the model pertaining to the variables to produce suitability outputs per sub-model that each serves as inputs into the final suitability products.

ii. The execution or running of the site suitability model was done to produce two Mozambique tilapia pond aquaculture site suitability output rasters (Tiff images) classified to produce two maps. Each of the two maps have a specific use. The first suitability map produced by Weighted Overlay (WO) and the second suitability map is produced by Weighted Sum Overlay (WSO). Both maps are for the entire surface area of the Limpopo Province.

iii. The application and interpretation of the final created suitability map products. The WO suitability map was used for site suitability classification and the scoring and rating of the 48 known existing farmers for comparison with the second suitability map's scoring and ranking of them. The WSO product was used to score and rank the 48 existing known tilapia farmers' suitability according to their current GPS locations on the suitability map.

The research themes above were extrapolated from the three main research questions, by unpacking each research question into three achievable research

objectives. According to the three main research themes depicted above, this chapter starts off with the findings of the model. The most crucial variables and their thresholds required for determining the site suitability of specifically the Mozambique tilapia *(Oreochromis mossambicus)* for pond aquaculture was used. The chapter then discusses the findings of searching for a site suitability model that can be executed in a GIS environment and selecting the GIS model and the methodology of choosing and designing the GIS model in the MCE environment. Furthermore, this chapter goes on to showcase how the variables and their thresholds were utilized in the design of the suitability model in the GIS environment.

This discussion then leads to the final suitability products that were produced. Maps were created from these raster outputs, for each variable that was inserted during the modelling process of the two final suitability maps created from each of the final suitability output GIS rasters (Tiff images). The results from these two final site suitability maps for the entire surface area of the Limpopo province were then tabulated, discussed, and interpreted. The tables were created from extracting the suitability in square meters and square kilometres and calculating the percentages of the Limpopo province's area pertaining to every suitability class.

Finally, one of the applications of the use of the Weighted Sum Overlay (WSO) produced site suitability raster output (Tiff image), is considered. This site suitability raster produced floating point suitability numerical values for every (approximately) 30 meters by 30 meters raster cell. The suitability scoring of each of the existing 48 tilapia aquaculture farmers known at the time, was executed by using their GPS locations to extract their underlying suitability on this WSO suitability raster. The chapter then goes on to explain how this scoring was used to rank the farmers. To conclude, the ranking results were tabulated, percentages calculated, and the final results were analysed to explain how higher-ranking farmers should be identified for selection to focus fiscal and other means of support on.

4.2 Model results

The process of choosing the correct model and the specifications to which this model had to comply was described in Chapter 3. The results from the design and execution of the Multi-Criteria Evaluation (MCE) -based model (Eastman et al., 1993) in the Esri

ArcMap 10 Model Builder (Esri, 2018) Geographic Information System (GIS) environment were produced. The execution process is described in modelling steps from one to eight. During these steps, the products for the five (5) sub-models were created and the final two suitability maps were the result. These suitability maps were created using the Weighted Overlay (WO) and the Weighted Sum Overlay (WSO) techniques. The extraction from the results of these two overlay processes, to the 48 farmers, took place in the final step, Model Step eight (8).

4.3 Suitability sub-model outputs

This section describes the findings from the results of the chosen main variables that determined the suitability of the pond aquaculture outputs from the site suitability model described in Chapter 3. It depicts the findings from the maps produced in the sub-models that flowed from executing the model. These results all pertain specifically to the needs of the Mozambique tilapia *(Oreochromis Mossambicus).*

4.3.1 Distance to water source

As described in Chapter 3, the choice of the variables that made-up the distance to water source sub-model, produced the resultant map in Figure 3.7. The map depicts the suitability of the Limpopo province for pond aquaculture in terms of access to water as sources for their ponds. The input variables and their thresholds were described in chapter 3.

From the Weighted Overlay of the distance to water source's input variables and their respective thresholds (Figure 3.36), the results indicate that much of the province displays highly suitable areas. Some unsuitable areas are visible due to being too far from the required water source.

4.3.2 Temperature suitability

The following findings from the 12 temperature suitability maps are described in this section. The January temperature site suitability for Mozambique tilapia of the Limpopo Province is depicted in Figure 3.8. It is encouraging to note that a large part of the Limpopo province is highly suitable to pond aquaculture of the Mozambique

tilapia, in terms of its January temperature thresholds. The inland and southern parts of Limpopo are moderately suitable.

In Figure 3.9, February's outlook is much the same as January's temperature suitability. A large part of the northern Limpopo province is highly suitable to pond aquaculture of the Mozambique tilapia, in terms of its temperature variable thresholds. Mostly the same central inland and southern parts of Limpopo are moderately suitable, as is the case with January's map.

In Figure 3.10 one can start to notice, that as winter approaches, lower temperatures start to influence the March temperature suitability map so that in the southern regions, the highly suitable areas have been replaced with moderate suitability.

The depiction of the April temperature suitability map in Figure 3.11, starts to show a moderate suitability for pond aquaculture according to the Mozambique tilapia's temperature ranges throughout most of the Limpopo province, Three areas in the east still are highly suitable temperature-wise.

On the May temperature suitability map in Figure 3.12, areas of marginal suitability start to appear in the southern regions of the province. June is a winter month in Limpopo and the June map (Figure 3.13) displays moderately suitable areas in the northern half of Limpopo and marginally suitable areas in the southern half of the province. This seems to indicate that the northern areas in Limpopo are more suitable temperature-wise.

The July temperature suitability map (Figure 3.14) displays much the same pattern as that of June, but with the marginally suitable areas proceeding further to the North of the Province. By August, (Figure 3.15) temperatures start to increase. Most of Limpopo is then moderately suitable again with patches of marginally suitable areas scattered in the southern parts of Limpopo.

The September temperature site suitability map in Figure 3.16 displays mostly the same scenario as April, with most of Limpopo moderately suitable with a small area of high suitability in the north-east. The October temperature suitability map (Figure 3.17) looks much the same as that of the month of March (Figure 3.10). The north-eastern highly suitable areas are clearly visible, however, in October, the areas in rest of the province are moderately suitable.

The temperature suitability maps for November (Figure 3.18) and December (Figure 3.19) seem similar to those of the January (Figure 3.8) and February (Figure 3.9) maps. The highly suitable areas along the Eastern, Northern and Western border areas in the November map, are similar to that of the December map. The moderately suitable areas that are mainly in the southern parts in both maps, increased in size in the December map.

From visual inspection of the twelve temperature suitability maps (Figure 3.8 to Figure 3.19) the finding is that there are no areas in the Limpopo province that are unsuitable for pond aquaculture of the Mozambique tilapia. It was found that the northern parts of the province show more favourable temperature suitability conditions than the areas in the south.

The results from the final 12-month temperature suitability output indicates that the Limpopo province displays mostly highly suitable areas along the Northern parts and moderately suitable areas in the interior and towards the South. Despite the winter months, no areas were found unsuitable to pond aquaculture for Mozambique tilapia in the Limpopo Province.

The pond aquaculture site suitability model was designed so that Climate Change Models' air temperature data or water temperature data could be incorporated into for instance the Temperature sub-model stage. Data from Global Circulation Models (GCMs) can be imported into the model to delineate future site suitability for pond aquaculture. This could also be useful for the selection of fish sanctuaries for the preservation of the Mozambique tilapia for future generations. The temperature thresholds can be adjusted in the model to calculate suitability for any other fish species' water temperature suitability ranges.

4.3.3 Soil Suitability

On first visual inspection, the two soil suitability maps above seem quite different, in that the first soil suitability map contains more marginally suitable and unsuitable areas than the second, created from iteration two of the soil clay reclassification process. This illustrates the influence that changing a variable's thresholds can have on a final suitability product and thus also will have on the final outcome of the pond aquaculture site suitability map.

From the two described iteration processes, the two resultant soil suitability maps (Figure 3.27 and Figure 3.28) were created from the two slightly different sets of thresholds (Table 3.5 and Table 3.6). In the map resulting from the first set of thresholds, in Table 3.5, slight visual differences between the two maps are clearly indicated in the areas of marginal suitability in red and the unsuitable areas in grey. The first map (Figure 3.27) has more marginally suitable- and unsuitable areas than the soil clay suitability map produced by the second iteration (Figure 3.28).

4.3.4 Distance to substantial roads

By visual inspection alone, most of the Limpopo province seems to be highly suitable in terms of distance to a substantial road. Tiny pockets op moderately-, marginally and unsuitable areas are present throughout the province.

It was found that the distance to a substantial road for the aquaculture farmer to transport fish, fingerlings, feed or to facilitate farm gate sales in the area was crucial. The thresholds for the four different suitability classes were depicted in Table 3.7 and Table 3.8. However, it is difficult to judge the percentage of the Limpopo province that is within the different suitability classes. Without a spatial component, tabulation iof these results will not be of use. The use of the maps is in extracting suitability for specific areas and points of interest.

4.3.5 Restricted areas for pond aquaculture

Thus, make mention of the restricted areas map findings in the text and describe my findings in Chapter 4, my findings plus why in Chapter 5 and my conclusions about my findings in Chapter 6.

As explained in Chapter three, Section 3.4.2.1.5, there are certain areas that should be avoided or are restricted by law for pond aquaculture (Aquaculture Innovations, 2010; Aguilar-Manjarrez and Nath, 1998; Francisco, et al., 2019).

Thirty-nine percent (39%) of the total area of the Limpopo province is restricted. Either by law (e.g., wetlands and protected areas) or cannot be utilised due to physical or economic considerations or elements present in the environment (as discussed in Chapter 3). Sixty-one percent (61%) of the Limpopo Province’s surface area is

available for the suitability evaluation. This 61% represents 76 650 km^2 of the 125 754 km^2 (Table 4.1).

Table 4.1 Calculation results of the areas and percentages of restricted and available land for pond aquaculture in Limpopo.

Mask	Cell count	Cell size (m²)	Area (m²)	Area (km²)	% of total area
Restricted	51879660	947	49104149087	49104	39
Allowed	80982235	947	76649764875	76650	61
Total	132861895	125753913962	125753913962	125754	100

This illustrates how including or excluding certain variables in different steps, could influence the final suitability results.

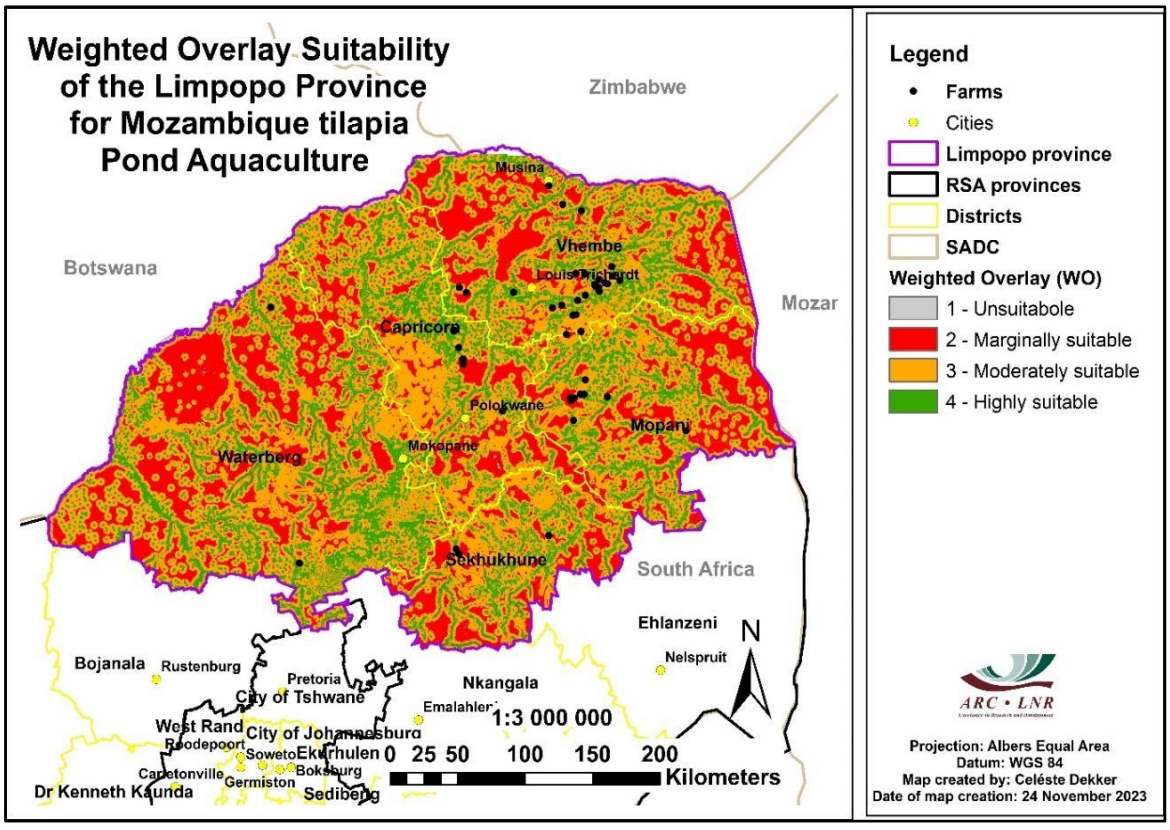


Figure 4.1 Weighted Overlay (WO) Suitability with first clay percentage iteration for the Limpopo province, including dams as a source of water.

By visual comparison alone, at a glance, one can witness some differences between the final suitability product which included dams as a source of water and using the first clay iteration (Figure 4.1). By comparing Figure 4.1 and Figure 4.2 to Figure 4.3

and Figure 4.4, which excluded dams as a source of water and made use of the second clay suitability iteration, Figure 4.1 compared to Figure 4.3 seem to look much the same. These figures are displayed without restricted areas and then with restricted areas, to give the user an idea of where the different suitability classes reside spatially and where pond aquaculture is restricted.

The maps in Figure 4.1 to Figure 4.4 were created from the Weighted Overlay (WO) suitability Tool in the different steps in the model to produce maps that depict Integer values that were classified in the mapping phase depicting the different suitability classes and in the legends of all the WO suitability maps in this section of the research. The chosen suitability variables were classified into four classes: Highly Suitable (4), Moderately Suitable (3), Marginally suitable (2) and Unsuitable or Restricted/ Constraints (1) adapted from the methodology used by Assefa and Abebe, (2018).

Visual inspection on this fine scale of the entire Limpopo Province can be difficult to draw conclusions from, even when the maps containing the restricted areas are visually inspected. What can be seen is that most currently available farmers are situated in a cluster in the Vhembe district along the more suitable (green) areas.

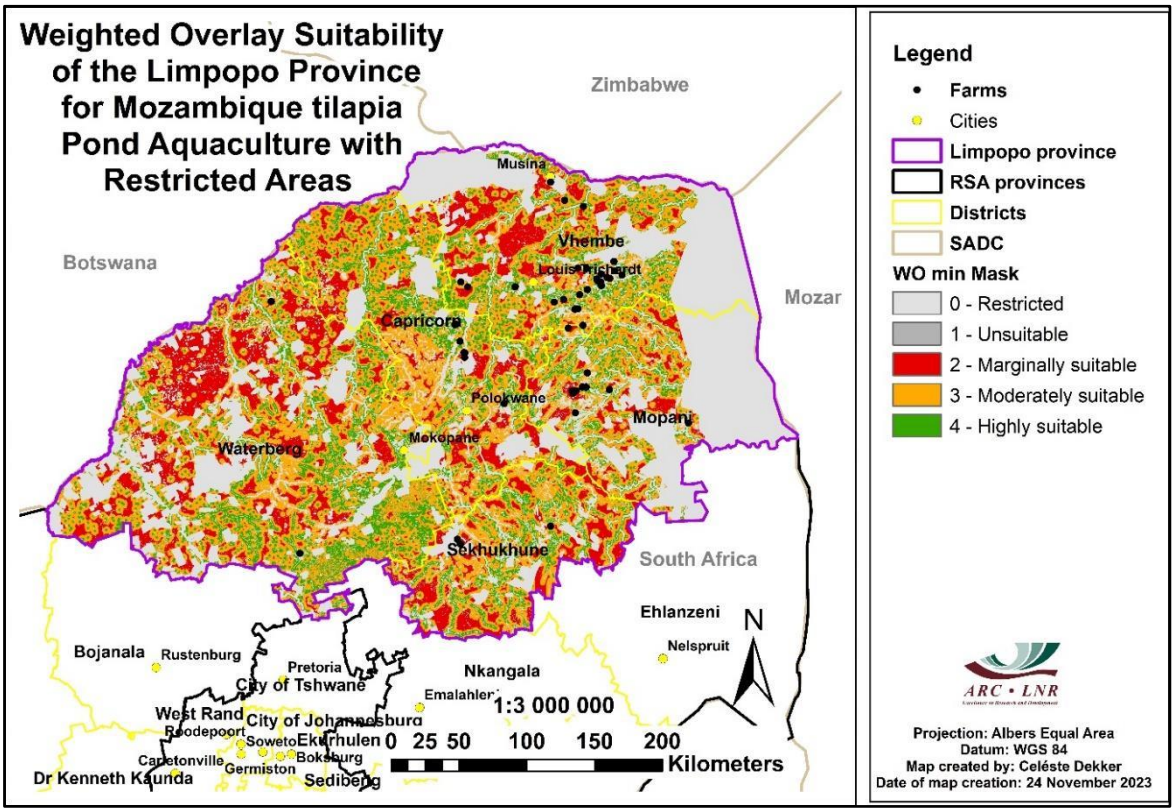


Figure 4.2 Weighted Overlay (WO) Suitability making use of the first clay iteration showing restricted areas for the Limpopo province.

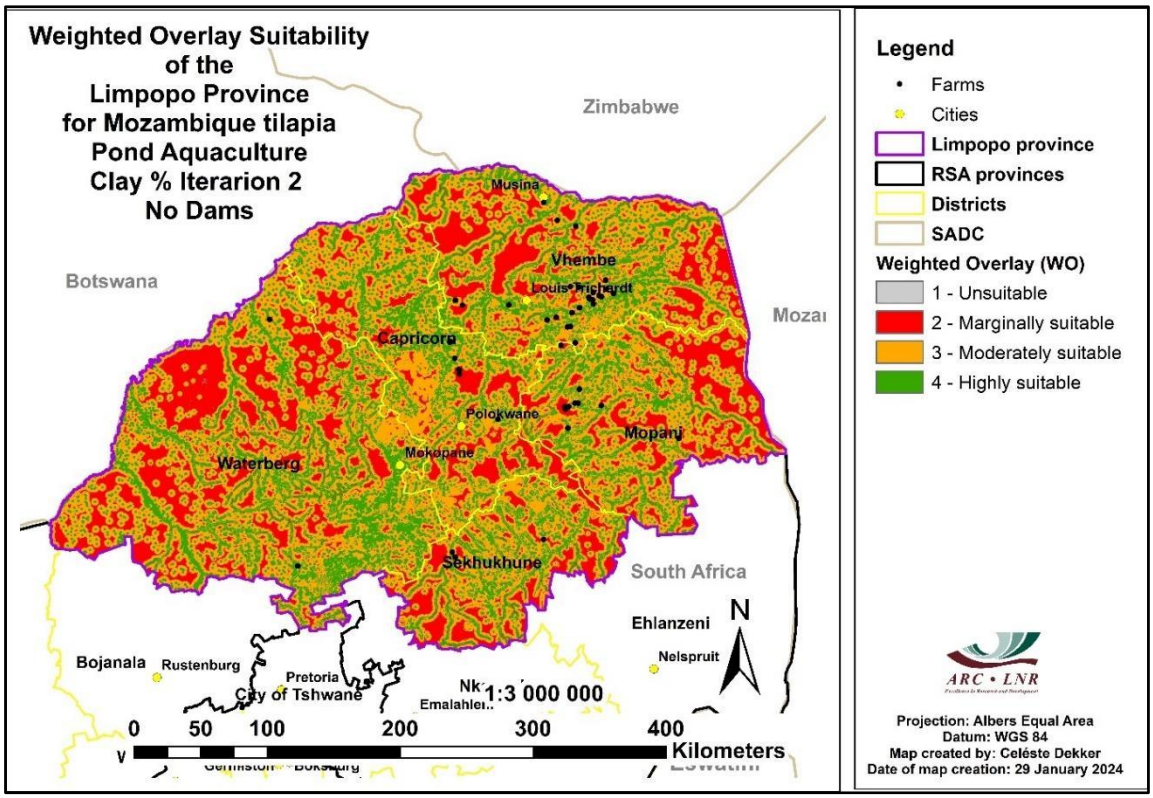


Figure 4.3 Weighted Overlay (WO) Suitability making use of the second clay percentage iteration for the Limpopo province, excluding dams as a source of water.

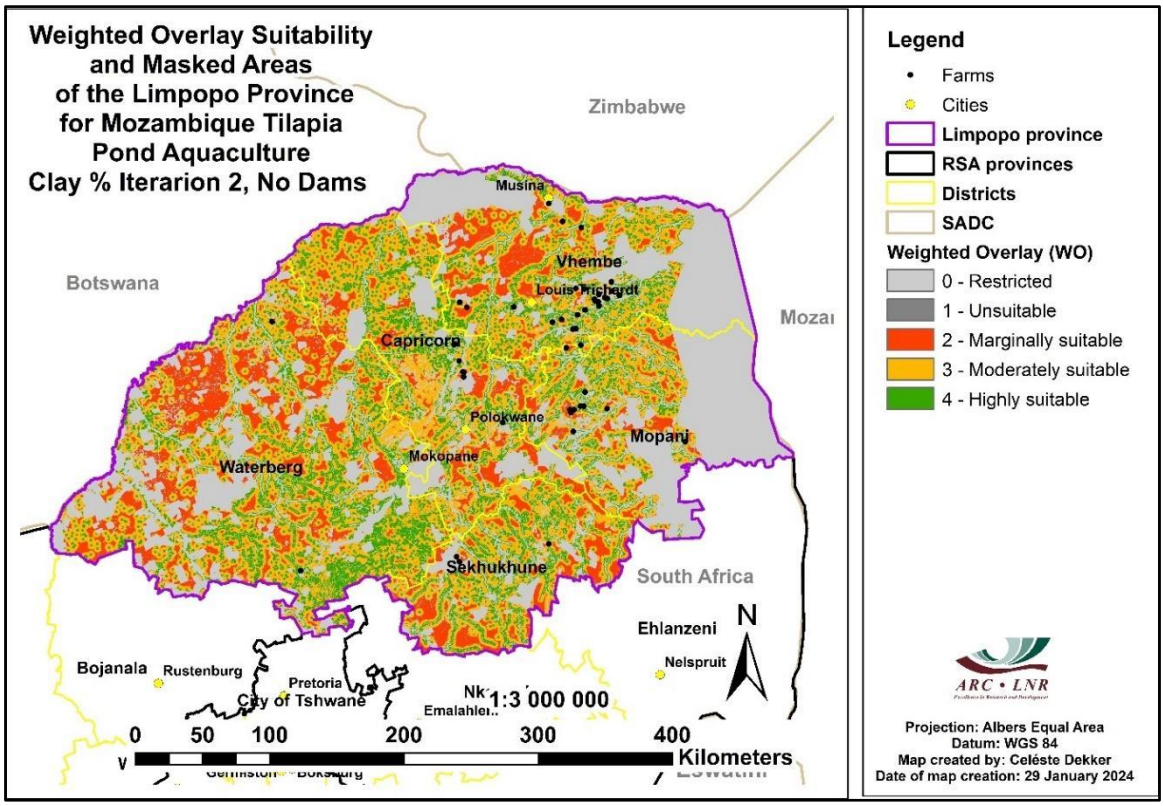


Figure 4.4 Weighted Overlay (WO) Suitability (2nd clay percentage iteration, excluding dams as a source of water, showing restricted areas for the Limpopo province.

As explained in Section 4.3, the Weighted Sum Overlay (WSO) process, produced floating point images, from which the maps in Figure 4.5, Figure 4.6, Figure 4.7, Figure 4.8 and Figure 4.9 were classified to visually try and depict the different suitability values across the Limpopo province. The purpose of the floating-point Tiff images created, was to be able to plot GPS points and the currently available farmers' positions on these images so that their exact suitability can be extracted up to 6 decimal places. This lends itself to precise scoring and subsequent ranking to produce the results in Section 4.5.

As visually depicting floating point images poses a unique challenge to the GIS professional to map the WSO results in such a way that visual inspection and comparison could be made easier for the end-user, Figure 4.5 to Figure 4.8, were classified utilising a unique colour scheme. This colour scheme was chosen by the researcher and assigned to different sections of the entire suitability spectrum between the values of 4 and 1. These arbitrary classes could have been chosen differently, i.e. by rounding up, rounding down, allowing Excel to round each floating-point value off or by Truncating. But the researcher decided how to round off the value class boundaries, the same as in Figure 4.9, where these chosen boundaries are depicted in the same colours as the integer maps.

By visual inspection of Figure 4.5 to Figure 4.8, there seems to be slight differences in the end-resultant WSO maps, by including and excluding dams as a source of water and making use of the second clay iteration thresholds instead of the first one.

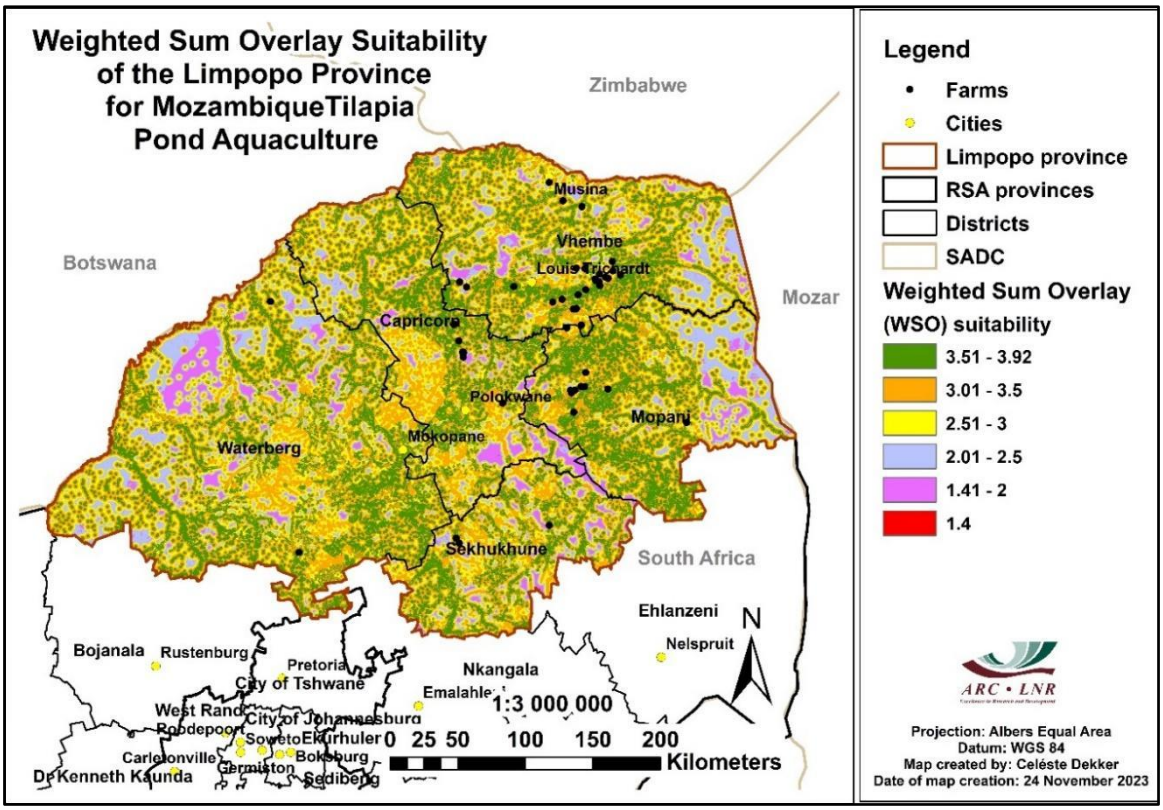


Figure 4.5 Weighted Sum Overlay (WSO) Suitability created using dams as a source of water for pond aquaculture for the Limpopo province and the first clay iteration thresholds.

By visually comparing Figure 4.5 and Figure 4.7, there seem to be no values visible below 1.4 (in red) in any of them. The lilac-coloured class (between 1.4 and 2.0) is more prevalent in Figure 4.7 in the southern and central parts of Limpopo then the higher suitability in the same areas in the interior of Figure 4.5.

Another noticeable difference is that there are more light blue areas (floating point values between 2.01 and 2.5) in the northern parts of Limpopo in Figure 4.7 than in the northern parts in Figure 4.5. The areas between 2.51 and 3, in yellow however are more prevalent all over the first map. The values in the orange in green classes, are also more prevalent in the first WSO map than the second. The same comparison was made for Figure 4.6 and Figure 4.8, which contain the restricted areas.

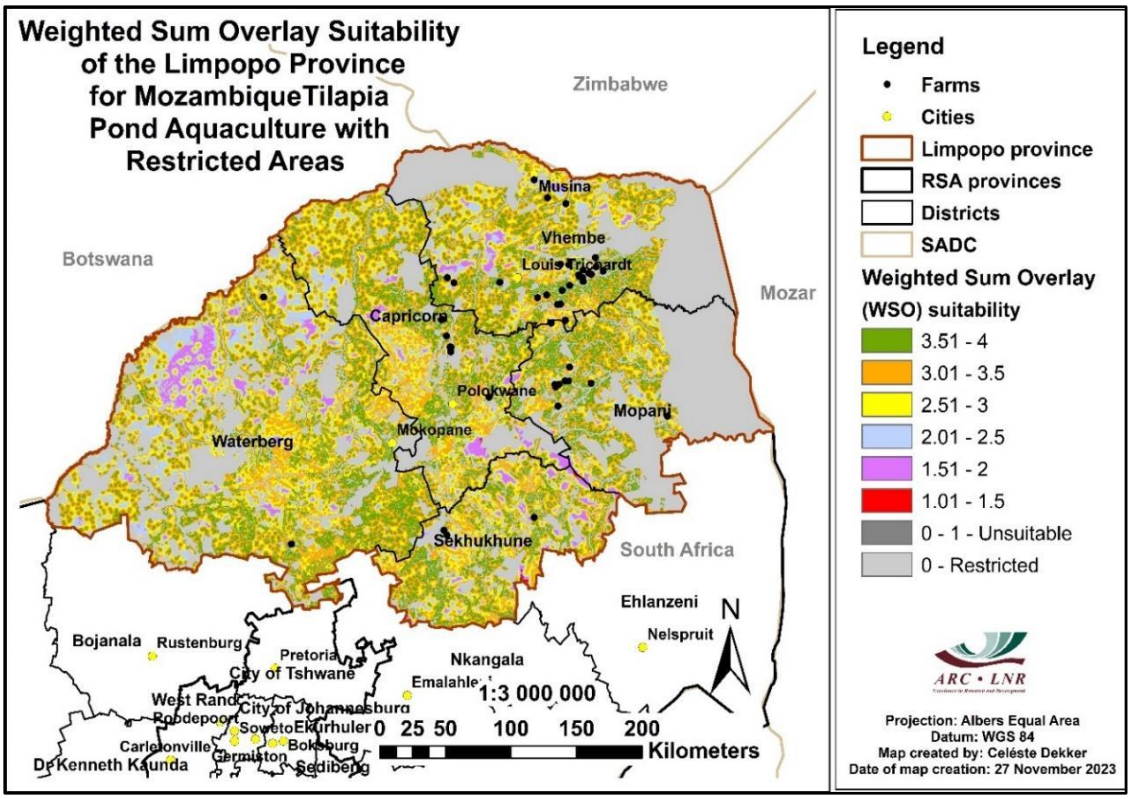


Figure 4.6 Weighted Sum Overlay (WSO) Suitability created using dams as a source of water for pond aquaculture and depicting restricted areas for the Limpopo province.

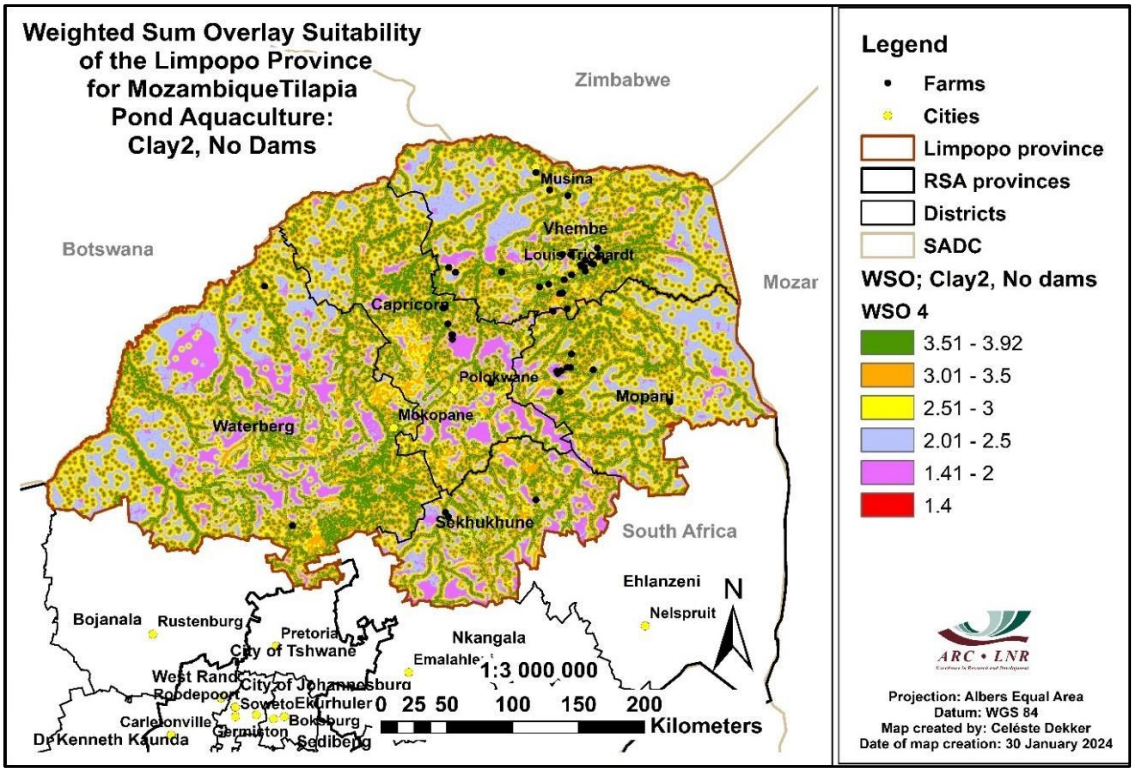


Figure 4.7 Weighted Sum Overlay (WSO) Suitability map resulting from excluding dams as a source of water for pond aquaculture, using the second soil clay percentage iteration for the Limpopo province.

The restricted areas leave only certain parts of the province available to pond aquaculture for analysis. For instance, in Figure 4.6 the same phenomena and differences are visible as the differences between the unrestricted WSO resultant maps. It is very difficult to quantify visually how each output map is performing by an overall eye-scan of the different WSO maps. It is recommended that comparisons be done for smaller areas at a time and again by tabulation of the area(s) in square kilometre and percentage of the area belonging to every class.

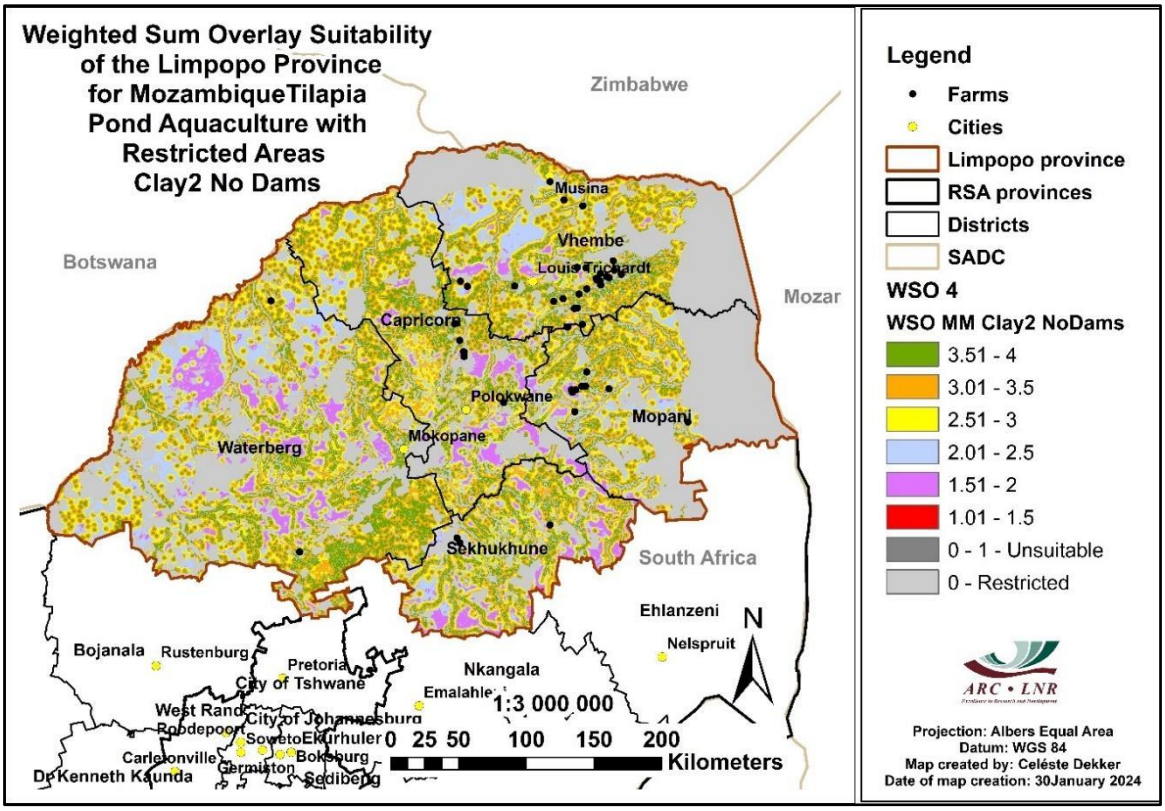


Figure 4.8 Weighted Sum Overlay (WSO) Suitability created excluding dams as a source of water for pond aquaculture and using the second clay percentage iteration and depicting restricted areas.

It is to be kept in mind that the reason for creation of the WSO maps were for GPS and area point extraction and interpretation for scoring and ranking. Therefore, Figure 4.9 was created to help with the interpretation of the suitability classes in the same colours as the integer WO produced maps.

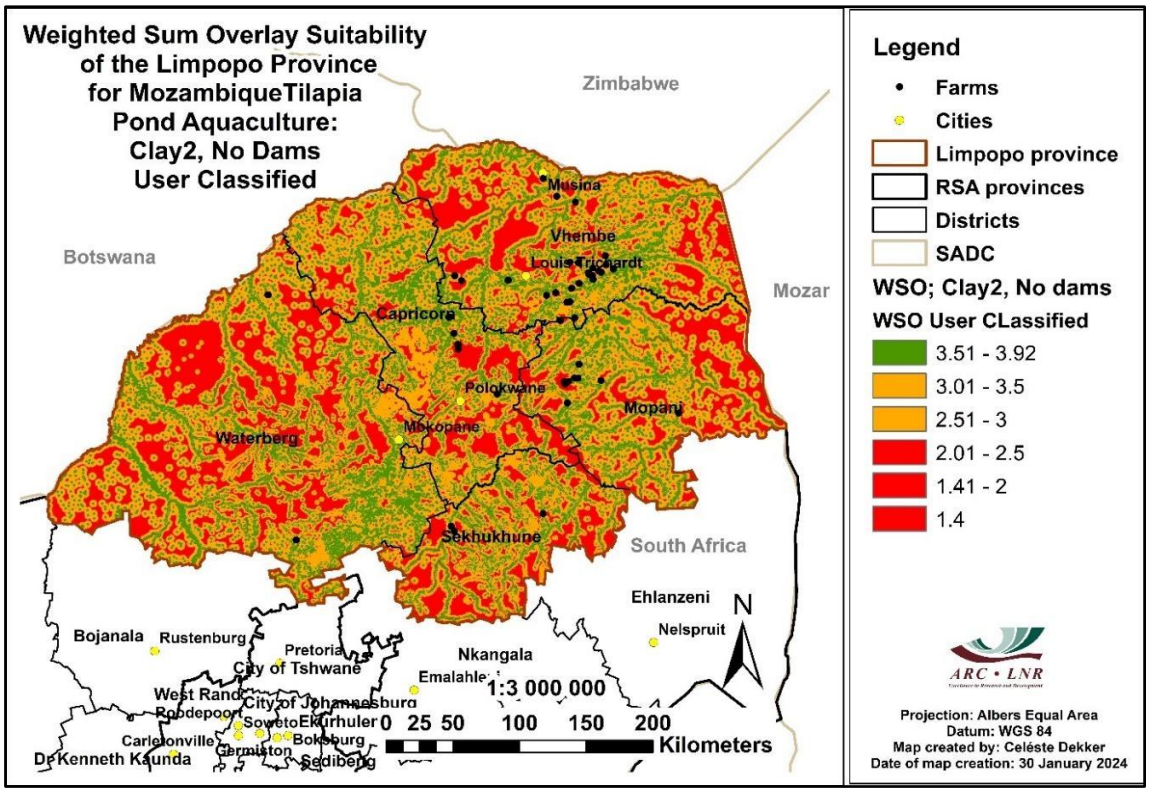


Figure 4.9 Weighted Sum Overlay (WSO) Suitability using the researcher's classification, excluding dams as a source of water, and using the second clay iteration for the Limpopo province.

The researcher classified the Weighted Sum Overlay floating-point raster as in Figure 4.9 on the basis that if a value is closer to a 4 than a 3.4 it will be displayed and classified as a 4: Highly suitable. If the value is closer to a 3.4 and 3.0 the value will be classified as a 3: Moderately suitable. A value between 1.5 and a 2, was be classified a 2: Marginally suitable., By visually inspecting Figure 4.9 vs Figure 4.3, detecting differences on a provincial scale is difficult, as the maps seem very much the same. As the values are not integer, the user-defined classification was applied to the values to display the different classes to which the values in Figure 4.9 belong. As described earlier in this section, the user decided to which class each value should belong. For a better illustration of this, the values assigned to each of the 48 farmers in Table 4.6, illustrate the different ways of rounding off the WSO suitability values.

4.4 Suitability modelling in the other eight provinces

The importance of this research lies in that the suitability outputs should be useful in guiding government where to invest their funds. The suggestion is to focus funding on the higher suitability areas, zones, and farms. This is because by investing only in the high suitability areas, the chosen aquaculture enterprises should produce more fish more efficiently than farmers in lower suitability areas. Investing in higher suitability areas could accelerate the growth rate of aquaculture in the Limpopo province, but also for any of the other eight provinces of South Africa via the model roll-out process (Meaden and Kapetsky, 1991; Chentouf, 2023). This could lead to improved food security in South Africa via the increased protein production of Mozambique tilapia, which could generate an increase in employment and lead to more sustainable livelihoods (Shava and Gunhidzirai, 2017; Wambua, 2018; Njagi and Huka, 2013). The wastage of resources on less suitable, for instance marginally- or unsuitable areas, can be prevented by not investing in these areas. Farms / farmers in marginally suitable areas for pond aquaculture production, have a high likelihood of being less efficiently producers and less productive than ventures in highly suitable areas. This is due to the less suitable economic and -environmental factors associated with the location of farmers in less suitable areas (Aguilar-Manjarrez and Nath, 1998; Bosma and Verdegem, 2011; Fynn, 2014: Steer, 2006; Handisyde, 2015; Stander, 2023; Urban-Econ, 2018).

4.4.1 Model modification

Due to the nature of the roll-out process, three types of users of the results, created from the model, i.e. the WO and WSO suitability raster outputs and the suitability maps subsequently created by classifying them, will emerge. The goal of these users of the model and maps is to do queries for government as to where to focus their funding. The first level of user will be a person or persons with GIS skills to receive and run the model with the respective province's own data sets and to do suitability queries on the output. This user can be found within a GIS software-enabled environment. The GIS user will be able to receive, import, populate and run the model, create suitability maps, interpret the results themselves, and convey the recommendations of where to invest to the stakeholders. The second level user could be a funder or government official querying suitability on their desktops, tablets or smartphones, as the maps are

publishable. They might have some level of GIS skills. Due to the “AQUASUIT” App that was built from the outputs from this research, there will be a third-level user, with no GIS skills required, who will simply draw areas or pinpoint GPS locations on their smart handheld devises (phones or tablets) to query the underlying suitability for decision making purpose in the App. The App is shared via a link and any user that receives the link, having a computer, tablet or smart phone, will be able to access the App and do queries on their devices. The App was designed for use on all of these devices.

4.4.2 Model sharing

The pond aquaculture site suitability model was developed in Esri ArcMap Model Builder (Esri, 2018). To make the model available to other users for roll-out to other provinces in South Africa, it can be shared between GIS users. The receiver of the model can change the thresholds of variables to account for other fish species, economic- or environmental conditions. The model can also be changed for larger-, commercial-scale pond aquaculture suitability. The suitability outputs and maps can also be shared. The sharing of the model and suitability maps to a specific end-user depends on the role of the end-user in the site suitability querying process. Decision making might range from high-level government officials, funders and providers of aid.

Although the model was developed for the Limpopo province pilot study area, it was designed for adoption by the other 8 provinces of South Africa. Thus, the model was designed to be accessible and transferable. The GIS user can use the model to create suitability surfaces, generate maps and do suitability queries. The outputs from this research were designed to assist in informing all aquaculture stakeholders of the suitability of a site.

4.4.3 Site Suitability App (AQUASUIT)

The outputs from this research were designed with the possibility in mind of helping government to know where to focus their funding. The Mozambique tilapia pond aquaculture site suitability outputs (i.e. the rasters (Tiffs) from which the maps were generated via classification), were created to empower the South African government. They could provide information about where the most suitable sites are, so that

funders can focus their funding initiatives on those, without wasting expenditure on unsuitable sites. By interpretation and application of the suitability outputs produced from the model in this research, the empowerment of aquaculture farmers and the improvement in food security of especially small-scale, female-headed rural households was envisioned. Therefore, the model was designed to be sharable and duplicable for effective application in the other eight provinces of South Africa as well through the national roll-out of this initiative by the South African government.

The AQUASUIT App was designed to facilitate the empowerment of all stakeholders in the development of aquaculture in South Africa. There are three levels of App users. All three types of users can query suitability information about a specific location point or an area (polygon) in the AQUASUIT App.

The App was designed to make the site suitability analysis end products easily available for spatial suitability querying. The different users, who have different functions, can access the different forms of the model, in different ways. However, the App can be used by all three levels of users needing to have suitability information at their fingertips. These include the users with GIS skills (level 1), extension officers (in field use), the farmer and all stakeholders, funders and government officials (level 3).

The App is downloadable via a link that was created and is sent via Arc Enterprise. Any user that has received the link can open the App on their device. The prototype AQUASUIT App was hosted using the creator's institute licence for the testing phase. After this phase, Esri will host and modify the App, adding additional suitability layers as they are created from the model in this research. Existing sub-model suitability layers as well as new suitability outputs emanating from model can be inserted in the App at any time. It is envisioned that later the App could be hosted by a governmental institution. ArcGIS Enterprise can be used to create and update the desktop version of the App with any layers from the roll-out process to the other eight provinces. It is possible that in future the App could be developed to be downloadable from the Apple App Store or Play Store and used in IOS or Android (De Munnik, R., 2023: Personal communication).

4.5 Suitability map results

By mere visual inspection of Figure 4.1 to Figure 4.4, there seems to be less marginally suitable areas in the central parts of Limpopo using the second clay iteration and excluding dams as a source of water. Another observation is that it seems that some of the marginal areas have now been replaced by moderately -and highly suitable aeras throughout the province. An addition to visual inspection, is tabulating the suitability classes as areas in square kilometres and the percentage of the Limpopo province occupied by of each suitability class.

However, these tables will not indicate where in Limpopo the different suitability hot-spots or clusters of similar areas reside. For such results, interpretation by way of querying points and polygons or areas is required in GIS or the AQUASUIT App.

The final WO results produced by the five sub-models were mapped at a provincial scale of 1:3 000 000. The second clay iteration's thresholds and the exclusion of dams as a source of water for pond aquaculture, were considered the final results and were tabulated.

The final suitability map (Figure 3.56) contains the four suitability classes as well as the restricted areas. Including the restricted areas in the final area calculations is required for correct interpretation of the suitability results. Table 4.2 displays that 61 percent of the Limpopo province's area is available for pond aquaculture site suitability analysis. The rest of Limpopo (39 percent), Table 4.2, is restricted to pond aquaculture activity. Protected areas and wetlands are vulnerable and were included in the restricted areas sub-model. However, during the fieldwork completed for this research, it was observed that some of the existing farmers (at that time) have already established their aquaculture practices is existing wetlands.

Table 4.2 Areas restricted to pond aquaculture and available areas.

Mask	Cell count	Cell size (m^2)	Area (m^2)	Area (km^2)	% of total area
Restricted	51879660	947	49104149087	49104	39
Allowed	80982235	947	76649764875	76650	61
Total	132861895	125753913962	125753913962	125754	100

The restricted areas mask is required to put the suitability map results in perspective. If the entire surface area of the Limpopo province were available for pond aquaculture suitability evaluation, the results would be as displayed in Table 4.3 below. These results were calculated from Figure 4.4, which is the Weighted Overlay (WO) suitability analysis without taking restricted areas into account.

Table 4.3 Weighted Overlay (WO) suitability calculations of the entire Limpopo province area, without restrictions.

WO Class - no dams	Cell count	Cell size (m^2)	Area (m^2)	Area (km^2)	% of total area
1 - Unsuitable	12756	947	12073567	12	0
2 - Marginally suitable	30966497	947	29309819790	29310	23
3 - Moderately suitable	66082200	947	62546867130	62547	50
4 - Highly suitable	35355585	947	33464095888	33464	27
Total	132417038	125332856375	125332856375	125333	100

The area calculations of each suitability class calculated in Table 4.3 differ from the results in Table 4.4 due to the fact that Table 4.4 has taken the restricted areas into account. Of the 61 percent of available area, 16 percent was classified as highly suitable, 31 percent was found to be moderately suitable. It was calculated that 13 percent of the Limpopo province area available for evaluation, belonged to the marginally suitable category.

Table 4.4 Area calculations of the Weighted Overlay (WO) Suitability of the Limpopo province, including the restricted areas.

WO no dams min Mask	Cell count	Cell size (m^2)	Area (m^2)	Area (km^2)	% of total area
Restricted	51544981	947	48787375085	48787	39
1 - Unsuitable	245	947	231893	0	0
2 - Marginally suitable	17709054	947	16761636985	16762	13
3 - Moderately suitable	41665470	947	39436408231	39436	31
4 - Highly suitable	21497288	947	20347204182	20347	16
Total	132417038	125332856375	125332856375	125333	100

Findings from the limitations in Section 3.5 are displayed in Table 4.5 below. These calculations reveal the differences in area between the final suitability product and the SRTM DEM input. The SRTM DEM was used to resample all the inputs to a 30 m by 30 m Tiff following the shape of the Limpopo province border. There is a pixel size difference between the 1km by 1 km grid cells of the temperature input raster image data and the 30.77 m by 30.77 m grid cells of the Limpopo SRTM DEM raster.

This resultant difference can be observed in the calculated area of the Limpopo province between the final suitability map, containing the restricted areas, and the restricted areas Tiff. This is due to the 1 km by 1 km temperature input Tiffs before being resampled. The difference is an area of 421 square kilometres (Table 4.5). The cell sizes of all the resampled input Tiffs are 30.77 meters by 30.77 meters (946.501 square meters (m^2)) or 947 km^2. Multiplied by the number of cells, the total area of the Limpopo province must be the same as that of for instance the restrictions layer (Table 4.1), I.E.: 125 754 km^2 (Table 4.5).

Table 4.5 Differences in area and spatial resolution of the temperature input raster and the SRTM DEM raster.

Total Area (m2) Limpopo province	Total Area (km2) Limpopo province	Cell size X*Y	Cell Size X	Cell Size Y
125754000000000	125 754	946.501	30.77	30.77
Total Area Mask (m2)	Total Area Mask (km2)	Cell size X*Y	Cell Size X	Cell Size Y
125753913962	125754	946.501	30.77	30.77
Total Area WO min Mask (M2)	Total Area WO min Mask (km2)	Cell size X*Y	Cell Size X	Cell Size Y
125332856375	125333	946.501	30.77	30.77
Difference in cell count	Difference in cell count	Cell size X*Y	Cell Size X	Cell Size Y
444857	444857	946.501	30.77	30.77
Difference (m2)	Difference (km2)	Cell size X*Y	Cell Size X	Cell Size Y
421057587	421	946.501	30.77	30.77

4.6 Scoring and ranking of farmers

The third objective of this research was to score and rank 48 existing Limpopo aquaculture farmers, known at that time, from the list provided by the (then) Limpopo Department of Agriculture (LDA, 2019). This was to illustrate how the WSO suitability product could be utilised. This product was developed to assist stakeholders like government and other funders to select farmers that are situated in higher scoring and -ranking positions than others. Now it is possible to focus aid on the selected, rather than lower scoring and lower ranking farmers. The scoring, ranking and rounding of floating point WSO values per farmer are found in Table 4.6.

Table 4.6 Scoring and ranking results of the 48 existing farmers.

Farm Number	Farm name (*Linked to Farm Number)	Distance to Wetland (meters)	In masked area: Yes = 0 No = 1	WSO - No dams	WSO - User Rounded: No dams	WO - No dams	WSO Rounded Down (RD)	WSO Rounded Up (RU)	Truncated (TRUNC)
36	*	2932	0	3.710410	4	4	3.000	4.000	4
7	*	280	0	3.690630	4	4	3.000	4.000	4
40	*	3093	1	3.690630	4	4	3.000	4.000	4
11	*	2530	1	3.670860	4	4	3.000	4.000	4
8	*	9440	1	3.631980	4	4	3.000	4.000	4
15	*	4735	1	3.631980	4	4	3.000	4.000	4
24	*	3892	1	3.573330	4	4	3.000	4.000	4
14	*	1659	0	3.556580	4	4	3.000	4.000	4
22	*	5534	0	3.556580	4	4	3.000	4.000	4
23	*	5009	1	3.552180	4	4	3.000	4.000	4
25	*	1262	0	3.552180	4	4	3.000	4.000	4
29	*	0	0	3.552180	4	4	3.000	4.000	4
30	*	3405	0	3.516340	4	4	3.000	4.000	4
9	*	2125	0	3.478830	4	3	3.000	4.000	3
39	*	728	0	3.478830	4	3	3.000	4.000	3
31	*	166	0	3.478150	4	3	3.000	4.000	3
3	*	1677	1	3.457380	4	3	3.000	4.000	3
5	*	232	0	3.439960	3	3	3.000	4.000	3
28	*	448	0	3.439960	3	3	3.000	4.000	3
18	*	1187	1	3.437610	3	3	3.000	4.000	3
20	*	1100	0	3.379940	3	3	3.000	4.000	3
27	*	404	0	3.341750	3	3	3.000	4.000	3
19	*	1085	0	3.341070	3	3	3.000	4.000	3
12	*	2929	0	3.245580	3	3	3.000	4.000	3
34	*	1790	1	3.177710	3	3	3.000	4.000	3
41	*	1297	1	3.177710	3	3	3.000	4.000	3
33	*	6205	1	3.176350	3	3	3.000	4.000	3
16	*	4544	1	3.138160	3	3	3.000	4.000	3
10	*	1592	0	3.119060	3	3	3.000	4.000	3
21	*	427	0	3.097920	3	3	3.000	4.000	3
37	*	595	1	3.078140	3	3	3.000	4.000	3
38	*	407	0	3.039260	3	3	3.000	4.000	3
42	*	4839	1	2.981290	3	3	2.000	3.000	3
32	*	600	1	2.962880	3	3	2.000	3.000	3
45	*	2515	0	2.946140	3	3	2.000	3.000	3
46	*	2944	0	2.946140	3	3	2.000	3.000	3
17	*	3579	0	2.926360	3	3	2.000	3.000	3
35	*	4168	1	2.924690	3	3	2.000	3.000	3
13	*	891	1	2.885810	3	3	2.000	3.000	3
26	*	2108	1	2.625230	3	3	2.000	3.000	3
4	*	4187	0	2.491180	3	2	2.000	3.000	2
6	*	2565	0	2.431170	2	2	2.000	3.000	2
1	*	954	1	2.033880	2	2	2.000	3.000	2
2	*	2430	0	1.956130	2	2	1.000	2.000	2
43	*	445	0	1.954080	2	2	1.000	2.000	2
47	*	1148	1	1.954080	2	2	1.000	2.000	2
48	*	1861	0	1.954080	2	2	1.000	2.000	2
44	*	5771	0	1.859590	2	2	1.000	2.000	2

To summarize Table 4.6, the resultant number of current farmers in each suitability class as well as the percentages of farmers situated in each suitability class, is depicted in Table 4.7. According to the user-rounded values of the Weighted Sum Overlay (WSO) results in Table 4.7, 35 percent of the existing farmers were in highly suitable areas. Of the 48 existing farmers, 50 percent were in moderately suitable areas, while 15 percent of them were located in marginally suitable areas (Table 4.7).

According to the WO, in Table 4.7, 27 percent of the evaluated farmers were in highly suitable areas. More than half (56 percent) of the current 48 farmers were in moderately suitable areas. The smallest number of farmers (8) were in marginally suitable areas, namely 17 percent.

Deducted from Table 4.7 most of the farmers, 85 percent (WSO) and 83 percent from the WO, were established in highly suitable and moderately suitable areas. This might indicate that the suitability products created from the model might well be useful in farmer selection.

The shapefile's attribute table was transferred to MS Excell, where the 48 farmers were scored and ranked according to the above extracted vales. Comparison using colour coding of the suitability classes allows for comparison with the integer values of the WO suitability. The scores and ranking compared relatively well with each other.

One of the outcomes of the scoring and ranking exercise of the current farmers, was that it indicated that most of the then known current farmers (2018) were situated in the higher suitability areas. Of the 48 farmers, the results show that 85% of the farmers are situated in highly suitable (35%) and moderately suitable (50%) areas respectively.

Table 4.7 The number and percentages of the 48 farmers classified into each WO and WSO suitability class.

Suitability class	Number of farmers per WSO suitability class	Percentage of farmers per WSO suitability class	Number of farmers per WO suitability class	Percentage of farmers per WO suitability class
Highly suitable	**17**	**35**	**13**	**27**
Moderately suitable	**24**	**50**	**27**	**56**
Marginally suitable	**7**	**15**	**8**	**17**
Restricted	**N/A**	**N/A**	**N/A**	**N/A**
Total:	**48**	**100**	**48**	**100**

4.7 Conclusion

This chapter described the results from the findings of the three objectives. The GIS site suitability model was developed to create suitability maps from. These maps were used to evaluate the suitability of the entire surface area of the Limpopo province of South Africa for specifically the Mozambique tilapia *(Oreochromis mossambicus)* pond aquaculture using only the most crucial environmental and economic factors. This model can be modified for use in the other eight provinces of South Africa. Using these suitability outputs, existing tilapia farmers were scored and ranked.

The suitability results of this research could assist funders, decision makers, farmers, and extension workers to make more informed decisions about the locations of where to invest their limited resources.

The following chapter (Chapter 5) will discuss and interpret the results from Chapter 4.

Chapter 5

Discussion

5.1 Introduction

The aim of this research was to create a Mozambique tilapia pond aquaculture site suitability model which could be implemented to create suitability maps for all nine provinces of South Africa. However, the model and the suitability outputs and maps were created for the Limpopo province pilot study area. These suitability outputs and maps were used to score and rank 48 existing aquaculture farmers in the Limpopo province. The reason for the creation of this model and its outputs, was that it should be used as a tool for the acceleration of aquaculture in South Africa.

The literature underscores the need for precise site selection before investing in aquaculture (Steer, 2006; Meaden and Kapetsky, 1991; Handisyde, 2015). Site selection is the first critical step in implementing good management practices in aquaculture (FAO/Worl Bank, 2015).

In this study the effectiveness of a GIS-based model over traditional methods was described to determine its value for government-led aquaculture initiatives and policies in South Africa. These governmental aquaculture development programs, legislation and policies are aimed at the development of aquaculture in South Africa (FAO/World Bank, 2015). The desired effect of the use of the model and suitability products by government is the acceleration of aquaculture in South Africa.

The feasibility of expanding this model to other provinces is discussed. With its academically and scientifically sound foundation, this model could enable government to prioritise efficient producers in each province, thereby directing funding towards enterprises with the highest potential. This selective approach could foster growth in the aquaculture sector, driving productivity and accelerating national aquaculture development (FAO/World Bank, 2015).

5.2 Design of the GIS site suitability model

The first of the three objectives to achieve the aim of this research was to create a site suitability model for Mozambique tilapia *(Oreochromis mossambicu*s) pond aquaculture. Aquaculture in South Africa is still in an infant state (Adeleke et al., 2021).

The feasibility of using this general model to create suitability products for the other nine provinces is discussed.

This section's purpose could be summed up as examining why the government should use this GIS site suitability model, methodology, and outputs rather than alternative site selection techniques for Mozambique tilapia pond aquaculture to inform them where to geographically concentrate their limited resources Using GIS-based MCE for site selection enhances resource allocation and sustainability in aquaculture, benefiting both new sites and existing farmers (Chentouf et.al, 2023). This methodology has been widely used to ensure sustainable resource allocation and assistance to the development of new inland aquaculture sites and existing fish farmers (Ssegane et al, 2012).

Using a GIS-based site suitability approach before investing in pond aquaculture could be more economical and effective than traditional site selection methods. Numerous studies support the cost-effectiveness of GIS in site selection compared to methods like trial and error, word of mouth, or proceeding without prior site selection (Urban-Econ, 2018; Fynn, 2014; Falconer et.al, 2020; Steer, 2006; Handisyde, 2015; Chentouf et al, 2023; Aguilar-Manjarrez and Nath, 1998; Meaden and Kapetsky, 1991; Ssegane, 2012). GIS-based models are especially effective for determining spatial suitability, with traditional approaches being costlier and more time-intensive (Aguilar-Manjarres and Nath, 1998).

Although GIS models are only representations of reality (Falconer et al., 2018; Falconer et al., 2020; Ross, 2020), they provide a practical framework for site selection, with models such as the Multi-Criteria Evaluation (MCE) and more complex crisp and fuzzy models proving particularly valuable (Ross, 2020; Aguilar-Manjarrez & Nath, 1998; Ssegane et al., 2012).

The Mozambique tilapia pond aquaculture suitability model was created within a Multi-Criteria Evaluation (MCE) framework in GIS. The Multi-Criteria Evaluation (MCE)

approach (Eastman et al., 1993) utilised together with the the Pairwise Comparison Matrix (PCM) (Saaty, 1977) and the Analytical Hierarchy Process (AHP) minimized researcher bias in ranking the relative importance of the input variables. The MCE approach, widely used in GIS, was effective for combining multiple layers and variables that impact site suitability in aquaculture (Aguilar-Manjarrez and Nath, 1998; Assefa and Abebe, 2018; Ssegane, et. al, 2012; Hosain, et. al, 2017).

The GIS model in this research employed WSO and WO overlay techniques, utilising an Analytical Hierarchy Process (AHP) and Pairwise Comparison Matrix (PCM) to minimise user bias (Saaty, 1977; Francisco et al., 2019; Salam et al., 2003; Ssegane et al., 2012). This MCE method effectively combines multiple economic and environmental layers, with each layer weighted according to its impact on pond aquaculture suitability (Ross, 2020).

The GIS model used in this research focuses specifically on the Mozambique tilapia, distinguishing it from other models. It identifies the suitability of an Area of Interest (AOI) for this species, both presently and it is possible to delineate future suitability, based on environmental and economic criteria essential for sustainable aquaculture. These suitability maps provide specific investment locations for Mozambique tilapia aquaculture, proving to be a more reliable guide than speculation or traditional site selection (Steer, 2006). The Aquaculture Development Zones (ADZs) initiative seeks to identify and develop specific areas for aquaculture development, could make use of this model, to promote investment and creating an enabling environment for aquaculture projects (Operation Phakisa, 2021)

The selection of only the most crucial variables for the suitability model, was to keep the model simple and easy to use. Additional suitability variables that could be added to the suitability model were discussed in Chapter 2. The five sub-models contain a minimum number of input variables to keep the data requirements for model execution low and simple. Only the few most crucial variables that determine pond aquaculture site suitability were used to produce the suitability outputs. These variables were chosen and applied to produce the five sub-models. These five sub-models were developed from variables that are vital to the sustainability and success of a pond aquaculture enterprise (Aguilar-Manjarrez and Nath, 1998; Assefa and Abebe, 2018; Ssegane, et. al, 2012; Hosain, et. al, 2017). Only a few selected suitability variables

and thresholds specific to Mozambique tilapia pond aquaculture were used to ensure model robustness. The sub-models which are crucial for environmental and economic viability were identified as the distance to water source, temperature, soil suitability and distance to substantial roads (Aguilar-Manjarrez and Nath, 1998; Verster, 2017).

The model is particularly suitable for small-scale aquaculture but can also guide larger commercial operations. Small-scale farmers can become more than self-sufficient. The model can cater for this transition to commercial farming by modifications to variables in the design phase. Commercial scale suitability variables like distance to markets, distance to fish processors, distance to feed producers and market size (market availability) could be added (Aguilar-Manjarrez and Nath, 1998, Assefa and Abebe, 2018). Adding a variable like the distance to large commercial markets would enhance the model's applicability to commercial aquaculture site selection. As an economic factor, this could be incorporated into the model, with proper research on thresholds and relative weight adjustments for optimal suitability analysis.

Ssegane et al, (2012) included a “Farm Inputs” sub-model that accounted for the distance to feedlots and poultry availability. While these enhancements add value, they significantly increase the complexity of the model calculations, time, data and GIS skill requirements. The model’s practical application could be hindered in the absence of any such data or skills. Thus, simplicity and accessibility remained priorities, especially to meet the urgent needs of government stakeholders. Data on distance to chicken- and cattle manure are not always readily available.

Ssegane et al., (2012) included a water availability sub-model or a water requirement sub-model to their suitability model. The inclusion of such variables could either supplement the distance-to-water-source sub-model or be added as a separate sub-model. This sub-model involved a net water balance calculation based on seepage rate, precipitation, pond size, and potential evapotranspiration (PET). Ssegane et al., (2012) also accounted for variability in pond sizes and seepage rates, unlike Aguilar-Manjarrez and Nath (1998), who used standardized seepage rate values.

There are many other additional suitability variables that could be added to a suitability model that might assist in determining the economic and geographic suitability of a site for pond aquaculture (Dapieve et al., 2023).

- The addition of a comprehensive Water availability sub-model: Comprising of potential evapotranspiration (PET_0), seepage rate, pond size and -depth, size of the catchment area and precipitation (Ssegane, et.al, 2012).
- The addition of three variables for a simpler Water availability sub-model could be: Precipitation (mm) minus (PET_0) minus the standard seepage rate (as used by Aguilar-Manjarrez and Nath, (1998).
- Adding pond dimensions: Pond size (average pond sizes and pond depth for the area, applicable to Southern African countries), to account for each pond's seepage rate, size and depth that differ between ponds (Ssegane et al, 2012).
- Incorporating catchment area size required to account for the ponds' water availability needs to keep the ponds full (Ssegane, et al, 2012).
- Include runoff data in the water availability model.
- Using the average preferred smaller farm-gate sales tilapia market size (of 150 to 400 grams), thus 2 crops produced per year.
- Linking production size (in grams) with suitability classes would allow for tailored site recommendations based on anticipated yield as done by Aguilar-Manjarrez and Nath (1998).
- Flood zone restrictions: Aquaculture ponds should ideally not be in flood zones (Aguilar-Manjarrez and Nath, 1998). 10-, 15-, 20-, 50-- and 100-year flood zone data are required for the restrictions sub-model. This data was however not available.
- Add potential farm gate sale data. This is calculated from population density statistics data (Ssegane et al, 2012).
- Addition of water-temperature. Water temperature can be calculated from air-temperature. Use water temperature data in the model instead of surface air temperature. Although the two are very closely related, at a certain point in the higher and lower temperature ranges, the water temperature curve does not follow that of the air temperatures. It is an S-curve. However, a simple and robust way of determining water temperature, is to use Equation 5.1, in Ssegane et al, (2012), as also used by Kapetsky, (1994).

Equation 5.1: Water temperature from air temperature

$T_{water} = 1.3\ T_{air} - 6.35$

While GIS tools are powerful for generating suitability outputs (Falconer et al., 2018; Falconer et al., 2020), further economic feasibility studies are advisable to evaluate potential aquaculture sites for their viability before development (Falconer et al., 2018; Wambua, 2018). Over-reliance on subjective assessments or inadequate spatial data can lead to costly, unscientific site selections (Aguilar-Manjarrez and Nath, 1998; Chentouf, 2023; Falconer et al, 2018; Falconer et al, 2020; Steer, 2006). However, GIS site suitability assessment could significantly reduce the need for costly field evaluations of potentially unsuitable sites (Steer, 2006; Fancisco, et. al, 2019; Meaden and Kapetsky, 1991).

A GIS-based model for identifying optimal sites for aquaculture funding can significantly enhance government investment outcomes. By focusing resources on high-suitability locations, returns on investment improve, and sector growth is promoted, resulting in increased fish production and strengthened food security in South Africa (Shava & Gunhidzirai, 2017; Wambua, 2015; Njagi and Huka, 2013).

The Mozambique tilapia pond aquaculture suitability model was created within a Multi-Criteria Evaluation (MCE) framework in GIS. The Multi-Criteria Evaluation (MCE) approach (Eastman et al., 1993) utilised together with the Pairwise Comparison Matrix (PCM) (Saaty, 1977) and the Analytical Hierarchy Process (AHP) minimized researcher bias in ranking the relative importance of the input variables. The MCE approach, widely used in GIS, was effective for combining multiple layers and variables that impact site suitability in aquaculture (Aguilar-Manjarrez and Nath, 1998; Assefa and Abebe, 2018; Ssegane, et. al, 2012; Hosain, et. al, 2017).

In developing the pond's distance-to-water-source sub-model, multiple chosen variables were combined. The distance to a water source is widely regarded as a key factor in assessing spatial suitability for aquaculture (Aguilar-Manjarrez and Nath, 1998; Verster, 2017). However, incorporating additional variables—such as for a "Water Availability" sub-model—could require pre-calculated importance ratings and weights, both for individual variables and for their relative importance within the overall model. This weighting might best be handled during the statistical design phase using the MCE and AHP statistical design phase. If a new sub-model can be integrated into an existing one, adjustments to variable thresholds and weighting can be made directly within the ArcGIS environment. The results of the distance-to-water-source sub-model

generated suitability maps for the Limpopo province, illustrating each pixel’s proximity to water sources. This underscores GIS's capability to integrate diverse datasets for simultaneous evaluation of multiple factors.

The model's design allows for temperature suitability analysis across any of the 12 months, enabling assessments for year-round or seasonal suitability. The suitability of an area for producing tilapia crops all year round or just for the eight warmest months, for instance, can be determined. A GIS-literate user can adjust these settings without modifying the model structure. GIS users can customise the number of months that they would like to analyse for temperature suitability. Using a period of for instance only the eight or nine warmest months is thus possible. Using any number of months in the temperature sub-model is possible. These outputs could enable farmers interested in shorter grow-out periods of 4 to 6 months, to assess the site suitability based on selected months, by a GIS user. According to Stander, (2023), the ideal market size is 350 to 400g (8 to 10 months old) for whole fish. This is the farm-gate size for tilapia that small scale farmers sell. Thus, in the eight warmest months, small-scale production of subsistence farmers in rural areas without much market access other than farm gate sales, would be sufficient. The lower temperatures of June and July would then not affect these small-scale farmers in Limpopo.

The model was designed to be transferable and duplicable via sharing in both Esri ArcMap and Esri ArcGIS Pro software, allowing it to produce site suitability maps for other provinces in South Africa. The model supports national or regional data inputs and can be adapted by modifying variable thresholds to accommodate other fish species’ requirements, such as temperature tolerances.

By adjusting the model's variable threshold ranges and incorporating climate change temperature data, future suitability maps can also be developed for other fish species. Climate change adaptability was tested by incorporating General Circulation Models (GCMs) such as the Co-Ordinated Regional Downscaling EXperiment)-CORE (COmmon Regional Experiment (CORDEX) temperature data (Teichmann et al., 2020) into the model. The inclusion of this data indicated the potential for generating future suitability maps at both farm and regional (provincial and national) scale.

The integration of climate change data from General Circulation Models (GCMs) to produce future suitability maps is possible. This can be achieved by substituting the

current 30-year historical data with 30-year projections from CORDEX or CMIP6 datasets (Gebrechorkos et al., 2023) without modifying the model itself.

The model's adaptability allows for it to be utilised during rolled out to other eight provinces. The original model designer or other GIS users can populate the model with data pertaining to any of the other eight provinces. The adaptability of the model makes the model a valuable tool in aquaculture research. No other GIS-based, shareable Mozambique tilapia pond aquaculture model for the Limpopo province producing outputs at a detailed 30 x 30-metre scale, was found in literature.

5.3 Production of the site suitability maps

The second objective of this research was to use the model to create site suitability outputs which could be classified into site suitability maps.

The importance of the model's suitability outputs lies therein that the outputs could assist the South African governments' aquaculture initiatives like Operation Phakisa by providing information regarding the site suitability, to guide resource allocation to the most suitable areas.

Funding and support should target existing or potential Mozambique tilapia aquaculture farmers, farms, enterprises, or planned ventures within these highly suitable areas. Aquaculture initiatives in such areas are not only economically viable but also more likely to thrive long-term due to their alignment with the optimal environmental and economic conditions.

Limpopo was an appropriate pilot study area choice. This was due to the availability of GPS data on existing tilapia farms from the Limpopo Department of Agriculture, which enabled fieldwork. The province also produced 37% of South Africa's tilapia output (Urban-Econ, 2018) and is home to the endemic Mozambique tilapia (IUCN, 2021; Urban-Econ, 2018).

Only 61 percent of the total area of the Limpopo province was found unrestricted and available to be analysed for pond suitability. Of the available area, 16 percent was classified as highly suitable, 31 percent was found to be moderately suitable, 13 percent was marginally suitable. Farms in high-suitability areas may yield higher returns and income. Supporting sustainable livelihoods for rural households, often led

by women. Increased protein availability and job creation could reduce poverty and grow aquaculture into a key contributor to national food security, resilience, and economic stability, supporting South Africa's growing population.

Focussing funding on highly suitable sites rather than less suitable ones can improve viability and sustainability and returns on investment of enterprises. This could yield better production, protein supply, improved rural incomes, sustainable livelihoods, job creation, and food security, especially for small-scale, often female-headed households. This in return could advance aquaculture from its infancy to a robust industry (Shava and Gunhidzirai, 2017), and as was the case in Kenye (Wambua, (2018).

However, high suitability areas do not translate automatically to successful farmers. Shava and Gunhidzirai, (2017) highlighted that many Southern African countries could be expected to be highly suitable for aquaculture, but it does not translate to the same number of successful fish farms. Optimal GIS selection of sites and fish farmers, require that government provide essential infrastructure, training, access to markets and access to fingerlings and fish feed (Shava and Gunhidzirai, 2017, Wambua, 2018). Lack of funding often contribute to enterprises being unsuccessful even though they are spatially well situated (Moyo and Rapatsa, 2021, Wambua, 2018). Addressing these needs post-site selection is crucial to improve outcomes for fish farmers situated in highly suitable areas (Shava and Gunhidzirai, 2017). Successful funding of aquaculture enterprises could be improved with increased use of geostatistical analyses and GISs before establishing aquaculture enterprises (Fynn, 2015).

Aquaculture is said to cause an increase in protein production and the creation of employment (Ssegane et al, 2012; Shava and Gunhidzirai, 2017). Concentrating investment on efficient areas, such as those identified in Limpopo, could streamline production, thereby accelerating growth in aquaculture and enhancing food security for South Africa's growing population. The suitability maps generated in this research could guide government investment, targeting optimal areas for Mozambique tilapia pond aquaculture, and creating sanctuaries for this endemic species.

Government funding remains crucial for expanding both new and existing aquaculture ventures. Wambua (2018) emphasises that funding models must be carefully structured to align costs, expected benefits, and support mechanisms. He also

advocates for the formation of farmer clusters, which group farmers by locality, as a means to strengthen networks and build capacity. By forming clusters of 15 to 100 farmers, production, procurement, marketing, and value addition can be streamlined across the value chain, enhancing collaborative activities such as sharing equipment, producing on-farm fish feeds, and marketing harvests (Wambua, 2018).

Strategic partnerships between the government and private entities are also essential for driving sector growth. These collaborations can bolster all aspects of aquaculture, from producing high-quality fingerlings and feed manufacturing to processing and marketing (Wambua, 2018). Such partnerships enable the aquaculture sector to grow at an accelerated pace by integrating resources and expertise from both sectors. (Wambua, 2018).

In summary, using GIS suitability maps together with other tools can help make investment more successful. Different interventions in farming techniques and training by government is recommended. These strategies, alongside diligent farm management practices, are recommended to optimise productivity across highly suitable areas and help farms reach their full potential on a national scale.

Using the GIS model and suitability maps to help investors prioritise funding could strengthen aquaculture across South Africa. Farms in high-suitability areas may yield higher returns and income, supporting sustainable livelihoods for rural households, often led by women. Increased protein availability and job creation could reduce poverty and grow aquaculture into a key contributor to national food security, resilience, and economic stability, supporting South Africa’s growing population.

Different interventions in farming techniques and training by government is recommended. These strategies, alongside diligent farm management practices, are recommended to optimise productivity across highly suitable areas and help farms reach their full potential on a national scale.

GIS enables the integration of key environmental and economic variables—such as soil clay content, temperature, slope, proximity to water sources, and road access. These variables are vital for site the suitability and sustainability of aquaculture operations. Funding should be channelled at the more sustainable enterprises (Wambua, 2018). Sites identified as highly suitable support more efficient production than marginal or unsuitable sites (Njagi and Huka, 2013; Meaden and Kapetsky, 1991;

Chentouf, 2023). Each variable selected in this study's model significantly impacts aquaculture efficiency (Aguilar-Manjarrez and Nath, 1998, Moyo and Rapatsa, 2021; Bosma and Verdegem, 2011; Njagi and Huka, 2013).

The outputs presented here highlights sites with greater investment potential. Highly suitable sites comply with essential requirements, promoting operational sustainability and economic viability (Fynn, 2015). Fynn's (2015) research on "pond aquaculture spatial distribution, production and productivity determinants in Ghana" emphasises that site selection critically affects an enterprise's economic success, influencing initial capital, production costs, yield, and market access (Fynn, 2015; Chentouf, et, al, 2023).

Empirical evidence supports that efficient sites located in more suitable areas produce more fish per unit of investment, increasing profitability and contributing to food security (Aguilar-Manjarrez and Nath, 1998; Bosma and Verdegem, 2011; Fynn, 2014: Steer, 2006; Handisyde, 2015; Stander, 2023; Urban-Econ, 2018; Wambua, 2018).

Investing in more viable and sustainable enterprises could yield higher returns on investment than funding less suitable sites. This approach could lead to enhanced protein production, improved rural incomes, sustainable livelihoods, job creation, and food security, especially for small-scale, often female-headed households (Wambua, 2018; Shava and Gunhidzirai, 2017).

The model generated site suitability outputs and maps that could help government and stakeholders allocate resources efficiently to optimal areas, zones, or GPS points. Thus zoning, hot-spots and clusters of highly suitable areas could be identified from the final site suitability outputs, which are valuable outputs to government (FAO/World Bank, 2015).

With the identification of highly suitable areas for pond aquaculture, the government can focus funding on sites that are more efficient producers. This strategy could potentially increase fish production, providing a valuable protein source to support food security. Moreover, if suitability information generated by this model is applied across all nine provinces, it could accelerate aquaculture growth throughout South Africa.

Some limitations of the outputs and maps from the model are that other factors such the farmer's management capabilities, institutional support, the scale of production,

and the risks of crop failure (due to diseases, water quality problems and theft) also contribute to a farmer's efficiency (Bosma and Verdegem, 2011).

Suitability maps clearly delineate suitability levels (highly, moderately, or marginally suitable) down to a 30x30 metre scale, guiding investment decisions spatially. Sub-model suitability maps for individual variables, such as distance to water sources, soil suitability, road proximity, and temperature, add further value. These TIFFs and maps, provide insights on the final suitability results of an area or point. suitability at various scales, from provincial to GPS locations. For instance, a site might be marginally suitable due to its distance from a water source, even if other factors, such as soil or road access, rate as moderately or highly suitable.

The development of the site suitability AQUASUIT App, forms part of the model roll out to other provinces. The App is easily accessible via a link. The App could facilitate the process of making suitability end products more easily available for spatial suitability querying. The App could make site suitability information more accessible to all levels of users and decision makers such as individual prospective pond aquaculture farmers not part of a project but in their own capacity. With the implementation of the model during national roll out, the App could be used by government to know where to focus their funding. Generally, Apps contribute to making information, such as information contained in maps, more readily available (Harder, C., 2015).

The percentages and areas (in km^2) provided in Table 4.4, pertaining to each suitability class, could be helpful to select zones of highest suitability. The Aquaculture Development Zones (ADZs) of Operation Phakisa could find these calculations useful to designate hot spots, zones or clusters of existing farmers for funding (Operation Phakisa,2021).

In some cases, areas deemed unsuitable or restricted for aquaculture may still offer viable options, though choosing less suitable sites can lead to increased operational costs (Ssegane et al., 2012). An example of such a scenario is where there is abundant water supply, but the soil is too sandy for instance, or the slopes are too steep, a remedy could be using smaller ponds or tanks.

5.4 Scoring and ranking the farmers

The third objective was to use the WSO suitability product to score and rank farmers. Wambua (2018) states that those with responsibility for spending public money need to know that they are choosing the best option (FAO, 1986) in Wambua, 2018). Scoring and ranking GPS locations for suitability is thus a required activity for funders to know which farms to prioritise in the support efforts. The results of the scoring and ranking of farmers, could guide funders to concentrate their funding on higher ranking farms. The WSO's floating-point values, allows precise ranking of the scores. Selecting the appropriate farmers to support can also assist funders in their zoning efforts, choosing farmers in appropriate positions for inclusion in zoning, which could be beneficial to certain clusters of farmers (FAO/World Bank, 2015.)

Scoring farmer GPS points using the WSO could assist in ensuring that funding is directed toward enterprises with the highest potential greater production. Farmer success can be increased by focussing on changing and improving management strategies to address the physical issues that reduce suitability (Ssegane et al., 2012).

Farmers within restricted areas can still be evaluated. The final output table from the modelling process, Table 4.6, has a column that indicates the distance to the nearest wetland from every farmer. Another column indicates whether a farmer is located in a restricted area.

With its academically and scientifically sound foundation, this model could enable government to prioritise efficient producers in each province, thereby directing funding towards enterprises with the highest potential. This selective approach could foster growth in the aquaculture sector, driving productivity and accelerating national aquaculture development. The FAO's Aquaculture for Local Community Development (ALCOM) programme has tried to identify the criteria for supporting target groups of aquaculture farmers, but the criteria are diverse as is the relevance of different approaches to particular contexts (ALCOM, 1994).

Government support in infrastructure, training, and resource allocation is critical to maintaining efficiency in aquaculture operations (Fynn, 2015). Farmers' management skills and knowledge of fish farming significantly affect efficiency, even in optimally suitable areas (Wambua, 2018; Shava and Gunhidzirai, 2017; Fynn, 2015; Bosma,

and Verdegem, 2011, Njagi and Huka, 2013). Thus, ongoing training is essential to maximise farm performance post-investment (Wambua, 2018; Shava and Gunhidzirai, 2017; Njagi and Huka, 2013, Bosma and Verdegem, 2011).

According to Ssegane et al., (2012), any area that is unsuitable can be overcome to a certain extent by management practices. Unsuitable areas could be used for aquaculture. Even tanks can be implemented in unsuitable areas. (Ssegane, et al., 2012).

A farm or area earmarked for pond aquaculture could be evaluated pixel-by-pixel. Every pond could also be digitized in Google Earth, and the WO and WSO results per existing ponds be evaluated.

During the collection of GPS points on the 48 visited farms, the centre point between all the ponds was used to extract the GPS suitability value. If the ponds were widely spread out, using the centre point might not sufficiently be representative of the ponds' overall suitability. Using the location of only one of the ponds, could also not be an accurate representation of the ponds or farm's suitability for pond aquaculture. When rating a farmer using a GPS point, caution and a site evaluation is advised to assess the size and layout of the ponds and farm.

5.5 Conclusion

The aim of this research was accomplished by achieving the three research objectives. In the final chapter, Chapter 6, the synthesises of this research, conclusion and recommendations are made regarding the outputs and further research. The desired outcome of this research was that it would be used as a tool to assist government in the acceleration of aquaculture in South Africa.

Chapter 6

Conclusions and Recommendations

6.1 Introduction

This chapter summarises the main findings and outcomes of this research, focusing on the themes that arose from the aim and three objectives. The chapter concludes with recommendations for applying the GIS model to map Mozambique tilapia pond aquaculture site suitability nationwide. Key challenges and limitations encountered during the research are highlighted, along with possible model improvements. The chapter concludes by recommending further research opportunities which could be explored.

6.2 Summary of the research findings

6.2.1 GIS Model

The model was designed to support low start-up and -maintenance cost, sustainable aquaculture systems aimed at rural, small-scale, often female-headed households. The model was designed to combine only the most crucial variables relevant to Mozambique tilapia pond aquaculture, with a specific focus on small-scale, rural aquaculture farmers. The model can accommodate modification of variables and thresholds to make it applicable to more commercial enterprises or for other fish species suitability.

GIS offers a cost-effective alternative to trial and error, reducing the risk of misplaced investments. A stable GIS environment, provided by Esri, was chosen to support model users during roll-out and offer reliable user support. Although open-source software was considered, Esri's environment was preferred for its support services.

Literature research confirmed Multi-Criteria Evaluation (MCE) as a highly reliable and widely used approach to integrate multiple suitability variables, minimising user bias through the Analytical Hierarchy Process (AHP) and the Pairwise Comparison Matrix

(PCM). These methods allowed for the inclusion of relative importance and threshold weights directly in the GIS model interface.

The Mozambique tilapia pond aquaculture site suitability model produced valuable findings through the design and application of suitability maps using two overlay methods: Weighted Overlay (WO) and Weighted Sum Overlay (WSO). Both methods offered essential outputs that address site suitability in the querying process.

The model was also designed for transferability, allowing government agencies to use and adapt it in other South African provinces. Its simple, robust structure makes it relatively easy to share, duplicate, and modify for other fish species or for incorporating additional economic or environmental layers into sub-models. The model can be transferred across platforms, from MCE design to Model Builder in ArcMap, or to ArcGIS Pro and potentially open-source alternatives like QGIS.

To ensure the suitability results are accessible and user-friendly, different formats were created for three primary user levels. The querying of the suitability outputs from the model, can be done by three levels of users. Using the suitability outputs requires different approaches for each of the three user levels. Decision-makers and stakeholders with GIS skills or GIS skilled employees, such as government or organisational representatives, can have access to the suitability outputs in a GIS. For GIS professionals, suitability area and point queries can be conducted to provide stakeholders with precise suitability values from the WSO and WO products. GIS-skilled decision makers can perform desktop suitability value queries on the Tiff outputs to explore specific locations. These are level 1 users. Both the Department of Agriculture and the Department of Environment (DFFE and DALRRD, are Esri clients, equipped with GIS Enterprise licenses and trained personnel.

Level 2 users include GIS-skilled users as well as stakeholders that can query the maps created from the suitability Tiffs that were converted to polygons in the ArcMap software. These maps contain the WO and WSO polygons that can be queried using the link of the App to open the maps in on their computer or other smart devices. However, the GIS skilled user can also do these map queries in ArcMap or in the App interphase.

In the AQUASUIT App users can be anyone, from funders, farmers, extension officers and the public. Using the App interface, users can query the suitability of specific locations (points or polygons) directly in the App. This can be done in-field or in the office, or from anywhere, as long as the user has the link to the App. These are level 3 users. Point and area queries yield outputs detailing the area in square kilometres, the number of cells, and the percentage of each suitability class for the selected regions.

6.2.2 Site suitability maps

The model produced two types of suitability outputs through two overlay processes: the WO and WSO processes. The WO process generated TIFF images for each sub-model, along with a final suitability TIFF raster for Limpopo province. This raster formed the basis for the suitability map, where integer values were used to classify each suitability variable into four distinct classes, each with a specific colour code: Highly Suitable (4, green), Moderately Suitable (3, yellow/mustard), Marginally Suitable (2, red), and Unsuitable (1) or Restricted (0, grey). Calculations of each suitability class's area, expressed in square kilometres and as percentages of Limpopo's total area, were performed using the WO suitability output.

The suitability outputs of the model were Tiff images that were created during the sub-model execution as well as during the final suitability product generation. These outputs were all classified to produce suitability maps. The suitability maps, created from the WSO and WO Tiffs, are valuable tools for government and policymakers aiming to strategically support new and existing pond aquaculture ventures. These maps could be a starting point for identifying "hot spots" or zones of high suitability, indicating areas where investment and development efforts are most likely to succeed.

Both the Mozambique tilapia site suitability maps created from the model in this research, proved to be very useful in indicating exactly where the highest suitability areas were. Using a GIS, the exact suitability of GPS points and areas (zones) is thus possible, and the maps also indicate where zones of farmer clusters or connected areas of higher suitability or hot spots are situated for government to invest in for current or planned pond aquaculture ventures.

Thes TIFF images and maps are easily shareable in formats such as Tiff or JPG and can also be exported in various file types. Investors can assign a GIS technician to conduct technical queries on the suitability maps. These maps serve as practical tools for funders by clearly indicating high, moderate, marginal, and restricted areas, helping them make well-informed decisions on where to direct investments and avoid unsuitable areas, thus ensuring efficient use of resources.

6.2.3 Scoring and ranking farmers

The research involved scoring and ranking 48 existing pond aquaculture farmers in Limpopo based on their GPS positions relative to the WSO raster and suitability map. The WSO process produced suitability outputs in TIFF format, allowing for a user-classified suitability map from the floating-point image. The result was that the farmers were scored and ranked according to their floating-point suitability values, which makes it easier to prioritise the most suitable farmers for limited funding. By scoring and ranking farmers, funding based on their higher suitability, can be focussed to invest in high-potential farms only.

6.2.4 Site suitability App (AQUASUIT)

The suitability end products were made readily available for spatial suitability querying via the AQUASUIT App. For all three levels of users, such as for instance farmers, the AQUASUIT App could provide simplified access to suitability querying. Using the app on a computer, laptop, tablet and smart phone, end-users can assess specific site suitability information by selecting points or area locations. These queries can be done while they are in-field or in-office. The suitability outputs from the model are thus made accessible to users without specialised GIS knowledge, and without being in the field.

The querying of existing pond aquaculture farmers can be done in the App, by clicking on the GPS point. The AQUASUIT App was developed to handle queries on any computer, laptop, or smart device. The AQUASUIT App is downloadable via a link to any computer or smart device. All three levels of suitability information users can use the App to do suitability queries, as anyone with the link can access the App. This information could facilitate the empowerment of all stakeholders in the development of aquaculture in South Africa. This suitability information could indicate to government

where to focus their funding efforts. By focussing funding only on the highly suitable areas and farmers, this could empower government to grow aquaculture in South Africa as the App can be populated with suitability information input from data of any of the nine provinces in South Africa by the App developer.

6.3 Recommendations

6.3.1 Suitability model recommendations

Using GIS for site suitability is only a tool. To keep the model simple and robust, only the most critical variables were included to populate the five suitability sub-models for the final outputs. However, additional variables could be added to create a more complex model. These could include distance to hatcheries, distance to points of pollution. Such a variable could be part of the restrictions sub-model (as a zero value). Manure proximity could be included. The proximity to farm inputs related to chicken and cattle manure for pond bottom fertilisation could indicate the availability of different fish feed inputs. The distance to fish feed suppliers could also be included in the model.

The GIS model can accommodate new data, making it feasible for other provinces to adopt the model. However, it may be required that the original model developer assist in expanding it nationally, as all required datasets are available, but some skills transfer might be needed. This would ensure consistency and maximise the model's efficiency of use for use in rollout for the rest of South Africa.

Any additional variables must have clearly defined thresholds based on expert input and a thorough literature review. Furthermore, relevant datasets must be spatially available or adaptable, such as population density statistics or climate data. The model, the input variables and the thresholds should be kept uniform for all nine provinces when executed for national during roll-out.

To query and compare areas using the average suitability of each site is not advisable. Rather select and export the AOI attribute table to MS Excell. This table will contain the suitability class, area in square kilometres, percentage of cells belonging to every suitability class and the cell count. These detailed tables can be compared for

assessing each area's suitability composition and inform more accurate funding and development decisions.

It is recommended to consulting one sub-model output at a time to understand the reason behind a final suitability outcome. The weight of every one of the sub-model outputs also need to be considered. Every suitability sub-model has a different relative weight, assigned to it via the MCE process. For instance, temperature is only one of the suitability variables, and although each of the months in the temperature sub-model carry the same relative weight, the overall temperature suitability output has a relative weight of 28.8256 % assigned during the Multi Criteria Evaluation (MCE) modelling process.

In the future, climate change data could be incorporated to forecast suitable areas for future aquaculture, assess current farms, or identify areas for fish sanctuaries. The CORDEX model's temperature data, at a 22 km spatial resolution, was prepared for inclusion at the time of this research and may serve users like DALRRD, DFFE, extension workers, and farmers needing such forecasts. Additionally, replacing near-surface air temperature data with water temperature data could yield even more accurate results, though suitable-scale water temperature data for Limpopo is currently unavailable but could potentially be calculated.

Utilising the suitability outputs from the model, such as the maps, which can be exported as picture formats or polygons from the classified WSO and WO Tiff images, in the GIS, has limitations due to the model that does not contain all the suitability variables found in literature. Variables that were not included in the model, such as pollution risks, can be added as sources of pollution.

Environmental impact assessments and feasibility studies are recommended for every area or farm before proceeding with funding or development.

The limitation caused by the initial temperature inputs, is the discrepancy in the total area calculations of the final suitability outputs and the other input data sets. This cell size difference can be corrected. This can be done by clipping the original temperature input rasters to an area which overlaps all the Limpopo borders. The original temperature Tiffs, overlap the Limpopo province's borders in the south, but does not completely reach the borders in the north. Then the clipped input rasters should be resampled to the slope Tiff, as was created from the DEM Tiff image. This should be

done by starting from Model Step 1 in the modelling process and running the process again through all the steps, up to the last step eight.

The model outputs could be supplemented by the situational analyses' information. An example of insights gained from the situational analyses of 48 existing farmers' completed questionnaires could provide a practical understanding of potential problems some farmers experienced. For example, one of the highest-ranked farmers encountered a significant operational delay due to prolonged conflicts among its owners, highlighting the importance of situational considerations beyond technical suitability.

A formal ground-truthing exercise is recommended. Field verification, or ground truthing, is essential in validating the model's predictions. By evaluating added existing farms in Limpopo, the accuracy of the model's predictions can be confirmed, further validating its practical applications. There is much potential for further model development, such as conducting workshops with diverse stakeholders to identify additional variables and requirements from these users after the model and it's suitability outputs were made available.

6.3.2 Site suitability map recommendations

When using the maps for indicating suitability through visual inspection, the scale of the map must be kept in mind. The maps are a starting point for identifying areas of suitability. These suitability maps visually display the four suitability classes on a scale ranging from national or provincial overviews to high-resolution 30x30-metre farm and pond pixels. How maps are utilised is highly dependent on the user's requirements.

Large, interconnected green zones (highly suitable areas) may indicate favourable areas for potential investment. However, government bodies like DFFE and GDARD, are equipped with Esri licences and GIS-trained personnel. These GIS users are required to assist in querying the underlying suitability Tiffs that these maps were created from. It is more advisable to start the suitability decision process with an area in mind than to visually inspect a map on the national scale to try and find suitable areas for investment.

Suitability maps are tools for the visualisation of the site suitability of areas or points. The actual querying process should be done in the GIS or the AQUASUIT App interphases, starting off with specific areas in mind that one wants to inspect.

6.3.3 Recommendations regarding the scoring and ranking of farmers

It is suggested that scoring and ranking farmers or their farms according to the WO and WSO using only a GPS point, should be done using caution. Discernment should be used in choosing the position of the GPS point. One can use more than one point per farm and place them over the ponds respectively. For this research, many GPS points were collected during the situational analysis fieldwork. Exactly which point to use to draw a suitability conclusion about an entire farm (or farmer) will depend on many factors. In this research a GPS point was collected at every pond's edge, at the farmhouse, the farm entrance gate and other features like the water source and manure sources. The number of ponds, pond size and the 30x30 m pixel size of the suitability map all may influence the outcome. A GPS point closest to the centre of the ponds on the farm should be selected in Google Earth. This point should be used as the point to include in the shapefile containing the 48 farmers.

In evaluating GPS-based point suitability scores, it is generally advisable to avoid aggregating the 30x30 metre raster cells to form an average suitability score for an entire farm, as this may obscure important local variations. Scoring could be done per pond using the WSO Tiffs and maps to query cells in and around the ponds.

When assessing a farm or farmer for pond aquaculture suitability in a GIS or the App, the attribute table is populated with the WSO scores of the chosen area. The table can be exported to Excel, where the number of pixels belonging to every suitability class is listed. The area in square kilometres and percentage of each suitability class can be calculated using the pixel size. The choice of method of scoring farms or farmers should align with the specific suitability information required by the user.

The information from the situational analysis questionnaire (Appendix A), completed for each farm, was not used in this research. Only the GPS location and a numeric identifier was used. The situational information could later be utilised and integrated into the decision-making process in later phases of the project by the stakeholders involved. Consulting these responses for additional insights and conducting an

economic feasibility study for the higher-ranking farmers can strengthen the final decisions on which farms to support. This approach may also identify farmers who would need fewer additional capital inputs to achieve success.

It is advised that for the chosen farmers, not only their scores but also their complete situational analyses, which contains valuable information gathered during the fieldwork excise, should be considered to assess their overall suitability and viability. This information could be incorporated with an environmental assessment and economic feasibility study. This could strengthen the reliability of investment decisions. Some farmers in highly suitable areas reported issues such as theft, predatory animals, or unresolved co-owner conflicts in their situational analysis. Such issues could require additional resources to mitigate or even disqualify them from aid, even if they are situated in highly suitable areas.

6.2.5 Site suitability App (AQUASUIT) recommendations

It could be an advantage if the App were developed to be downloadable from the Play Store for Android and Apple App Store for IOS users. In this way, the App could permanently be on user devices and accessed directly instead of via the link.

6.4 Recommendations for further research

- GIS model development: Develop a GIS method using fuzzy membership functions derived from crisp criterion limits, following an extensive literature review to refine this approach for aquaculture site suitability.
- Accuracy assessments and ground truthing: Future studies should incorporate accuracy assessments through ground truthing. This would involve gathering GPS data for existing farm sites and conducting field visits to validate model predictions.
- Multi-Criteria Evaluation (MCE) Modelling: Construct a model using Analytic Hierarchy Process (AHP) and Pairwise Comparison Matrix (PCM) with additional sub-models for water availability. Factors such as evapotranspiration, standard seepage rates (e.g., 8.0 cm per day), and historical annual precipitation data over 30 years should be included to enhance accuracy while maintaining model simplicity.
- Commercial scale Integration: Incorporate “Distance to Major Markets” (e.g., fresh produce and large retail markets) into the model’s economic sub-model to support commercial-scale site suitability.

- Flood-zone data Inclusion: Integrate flood-zone data from local municipalities or private contractors into the restricted areas sub-model. A 100-year flood zone dataset could prevent modelled suitability for flood-prone areas.
- Climate Change projections: Use CORDEX and CMIP6 climate change data at 30-year intervals to create future suitability maps, extending the model's predictive capability to assess aquaculture viability until 2100.
- Inclusion of water temperature data: Improve the model suitability outputs by incorporating water temperature data using the formula: $T_{water} = 1.3T_{air} – 6.35$, to calculate water temperature from air temperature, as provided in Section 6.3.
- Develop custom water temperature equations: Use weather station data and Landsat 8 thermal bands to develop site-specific water temperature equations for near-surface temperature. Insert these water temperature data into the model instead of the 30-year long-term historic air temperature grids. Compare the suitability outputs.
- Model transferability to Open-Source platforms: Investigate the potential of how to practically transfer the model from ESRI Model Builder to an open-source package, such as QGIS, to improve accessibility and reduce dependency on proprietary software.
- Suitability map generation: Generate detailed maps from suitability outputs for each sub-model and final outputs (WO and WSO processes). Integrate these maps into the App for accessibility to both GIS users and non-GIS users for suitability analysis. These sub-product maps in the App could reveal the reason for the end products values.
- Continued testing of the App: Refine the App using Esri software like ArcGIS Online and Arc Enterprise. Esri provides continued support due to licencing. Iterative testing by users for modification suggestions and improvements to the App is suggested.
- GPS-Based farmer scoring: Develop sensitive scoring and ranking mechanisms based on farmer GPS points to avoid misclassification. GPS data should ideally be collected as close to ponds as possible, given that the WSO suitability output is based on a 30x30m grid.
- Aggregate cell analysis for pond suitability: Research the effectiveness of using aggregated cell values for each pond or the entire pond area to provide a comprehensive suitability assessment for individual farms.
- Functionality testing for App layering: Test the App's response time to point an area suitability layer queries. Test the layer visibility functionality when displaying multiple layers, such as suitability polygons, restricted areas, and other sub-model outputs.
- GIS as a site selection tool: While GIS remains central to site selection, future research should explore additional tools and statistical methods to complement GIS insights. The model should be designed to smoothly keep up with GIS software developments in Esri and other GIS open software, such as QGIS.

- Fieldwork and feasibility data integration: Add functionality within the App to incorporate data from fieldwork, situational analysis, and feasibility studies for potential sites to aid in investment decisions.
- A GIS research study is suggested for identifying suitable dams in South Africa for cage aquaculture. It should focus on specifically the Mozambique tilapia, as temperature thresholds for suitability for this indigenous species have extensively been researched in this thesis.

The above recommendations may serve as a starting point for further advancement in the use of GIS in aquaculture site suitability modelling.

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APPENDIX A

Field visit questionnaire for existing known aquaculture farmers

DATE:_____

POND NUMBER:_____

FARM NAME:_____

GPS POINT:_____

PROVINCE:_____

NEAREST TOWN:_____

Readings to take for EVERY Pond:

1.	Ph. meter	
2.	EC meter	
3.	Water Temperature meter	
4.	Water sample in a water bottle	
5.	Mark every sample bottle	
6.	Take perimeter of every pond with GPS	
7.	Ask farmer for depth of every pond	
8.	GPS Point of every pond	
9.	Photos of every Pond	

Questions to ask about EVERY Pond:

1.	What is the water source of every pond?	
2.	How far is the pond from the water source?	
3.	What do you use as pond fertiliser?	
4.	Nile or Mozambique tilapia or Hybrid in every pond?	
5.	Are the ponds lined?	

6.	From when to when do you stock the pond with fingerlings?	
7.	From when to when do you stock the pond for grow-out purposes?	
8.	How long do the tilapia take from stocking to fully grown/market ready/pond clearing?	
9.	Yield per pond? Kg/m^3 or kg/pond or fish per pond?	
10.	Crops per year per pond?	
11.	In which months can the tilapia survive in the ponds?	
12.	How far is the offset market/selling point from your farm?	
13.	How often have you experienced flooding of the ponds?	
14.	Water availability? Rain/supplementation?	
15.	Source of supplementation: Borehole /rain/ municipal water/ spring/ well/ river (channelled water)	
16.	Water temperature data?	

OTHER REMARKS:	
Theft	
Predation	
Distance to feed market	
Distance to processing market	

Other	

APPENDIX B

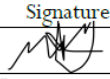
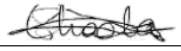
Wits Ethical Clearance Certificate: C Dekker

SIGNATURES (REQUIRED)

Declaration: We, the signatories, declare that all information on this form is correct and that we will strive to maintain the highest ethical standards in this research at all times, according to disciplinary and university expectations, recognising that ethical practice in research is always a continuing process.

I recognise that it is my responsibility to conduct my research in an ethical manner according to Guidelines of the University of the Witwatersrand, according to any laws and/or legal frameworks that may apply, and according to the norms and expectations of my discipline. In preparing this Application for Ethics Clearance form, I have consulted the ***Guidelines for Human Research Ethics Clearance Application / Non-Medical*** (available on this website https://www.wits.ac.za/research/researcher-support/research-ethics/ethics-committees/). In receiving ethics clearance, I agree to abide by the conditions of data collection as outlined in the *Guidelines* document.	[X] Yes	[ ] No

By signing this form, the researcher and supervisor of this project undertake to ensure that any amendments to this project that are required by the Human Research Ethics Committee (Non-Medical) and School Ethics Committees are made before the project commences.

	Date	Name	Signature*
Applicant	2023-01-03	Ms Celéste Dekker	
Supervisor	2023/01/03	M.S Thaela-Chimuka	

*electronic signatures are permitted but there are requirements governing this – please see *Guidelines* document.

APPENDIX C

Application: Fieldwork Aquaculture Farmers Visit

ARC • LNR
Excellence in Research and Development

Enquiries / Navrae:
Dr M-J Thaela-Chimuka
Ref / Verw:

ARC-ANIMAL PRODUCTION INSTITUTE
LNR-DIEREPRODUKSIE INSTITUUT

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Mr. T.S Ndove
The Chief Director
Limpopo Department of Agriculture and Rural Development
Directorate: Agriculture Advisory Services
67/69 Biccard Street
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0700, South Africa
Tel: +27 15294 3294
Mobile: +27 82882 6824

23 August, 2018

Dear Sir

RE: REQUEST TO DO A SITUATION ANALYSIS IN LIMPOPO PROVINCE MOZAMBIQUE TILAPIA FARMERS

The Department of Science and Technology (DST), with the Department of Agriculture, Forestry and Fisheries (DAFF) and the Agricultural Research Council (ARC) are jointly implementing a project entitled "The Limpopo fresh water aquaculture cluster". The project aims to increase tilapia production base; improve Mozambique tilapia farm viability for resource poor farmers; and improve aquaculture production skills of aquaculture scientists, technicians and farmers in South Africa.
In collaboration with the Limpopo Department of Agriculture and Rural Development officers, Forty two (42) farms with fish and water were identified to participate in the pilot study whereafter:

a. Six farmers will be supported via the breeding project to be innovative small-scale hatcheries; and

b. Twenty two farmers will be supported via the breeding project to be innovative grow-out farmers.

The plan is to conduct situation analysis in Vhembe district from next week which will be followed by fin clip sampling during the summer.

The ARC requests your support for this work programme. Our commitment is to communicate clearly in advance of visits, with someone you delegate. We shall communicate the purpose and timing (and methods and equipment) of each fieldwork visit to farmers in the province so that staff of the Province can keep track of the work of the ARC and provincial staff can opt to join the ARC fieldwork team, if their work programme and supervisors allow this.

N.B. Appendix of the purpose of the study and participating projects.

Kind Regards,

Dr M.S Thaela-Chimuka
Senior Researcher: Aquaculture Unit,
ARC-Animal Production Institute

Appendix

1. *PROJECT IMPLEMENTATION PLAN FOR THE LIMPOPO FRESH WATER AQUACULTURE CLUSTER*



The purpose of the study is to establish a Fish Value Chain

In South Africa, the Value Chain for freshwater fish is not clearly defined. Stakeholders especially freshwater fish farmers fail to get institutional support and this negatively affects profits and ultimately production.

This project seeks to establish a fish value chain platform to facilitate communication and trade within the industry. Different sectors involved include the following:

- Production
- Genetics
- Transport
- Policy
- Value adding/processing
- Market
- Consumers

The main objectives are as follows:

- Mapping of farms to form a cluster. This mapping will help to identify farmers that will participate on this model in Pilot phases 1 and roll out phase 2.
- Conduct a situation analysis of farms (current status) based on their potential to produce the Mozambique tilapia and farmers aquaculture skills and experience determining if training is required.

Selection Criteria

- To qualify as a beneficiary, selection criteria will be based on the following;
  - GIS site suitability identification for inland freshwater aquaculture(Geographical survey of location and boundaries of the water bodies, Water Quality Assessment, average depth /volume of each water body)
  - Business sustainability, Competence, entrepreneurship and potential to produce Mozambique Tilapia etc.,

Impact

- The anticipated impact of this study will be a well-established fish value chain, promoting the access of farmers to markets, input supply and processing plants. All this will done through Continuous Improvement and Innovation programme (CI&I)

Therefore, we request Limpopo Department of Agriculture and Rural Development to assist us in communicating with the extension officers in the districts and inform them about our proposed visits to the province so they can assist us in communicating with farmers and travel with us if possible to the farms.

- The first visit will be a situation analysis where, farmers will be taken through a questionnaire in order to score them.
- The second visit in summer (as you proposed) will be sampling, tissue sample collection (fin clip) conducted to assess the genetic status (to determine the availability of pure Mozambique tilapia and genetic diversity) of fish.

2. Proposed visiting plan to Mozambique tilapia farmers in Limpopo Province.

VHEMBE DISTRICT			
CENTRAL LOCATION: THOHOYANDOU			
1st cluster	2nd cluster	3rd cluster	4th cluster
• Dopeni • Shanzha • Mandala • Khalavha • phiphidi • Tshilapfene • Maranzhe	• Mutshenzheni • Mbahela • Tshifudi • Ha-lambami • Tshikonelo	• Tshitavha • Mianzwi • Matangari • Khubvi • Tshidzini	• Lwamondo • Mvelaphanda • Muledani • Tshilivho • Muraga • Makwarela

MOPANI DISTRICT	
CENTRAL LOCATION: TZANEEN	
• Baloon • Maseke	• Malungani • Sekhuting

SEKHUKHUNE DISTRICT
CENTRAL LOCATION: BURGERSFORT
• Phetwane • Tubatse

WATERBERG DISTRICT
CENTRAL LOCATION: THABAZIMBI
• Radium

APPENDIX D

Fieldwork Permission Aquaculture Project Communication

From: Mary Jane Chimuka
Sent: Friday, 24 August 2018 10:11
To: Mohamed Mohamed Ahmed <MohamedAhmedM@arc.agric.za>; Khaled AA. Abutaleb <AbutalebK@arc.agric.za>
Cc: Celeste Dekker <Celeste@arc.agric.za>; Thendo Tshilate <TshilateT@arc.agric.za>
Subject: FW: REQUEST TO DO A SITUATION ANALYSIS IN LIMPOPO PROVINCE MOZAMBIQUE TILAPIA FARMERS

FYI



From: T.S Ndove <ndovets@gmail.com>
Sent: Friday, 24 August 2018 09:48
To: Mary Jane Chimuka <ThaelaMJ@arc.agric.za>
Cc: Ndove Terri <ndovets@agric.limpopo.gov.za>; BelemaneS@daff.gov.za; Eric.Watkinson@dst.gov.za; ramaboeam@agri.limpopo.gov.za; Phosa Jacky <Phosamj@agric.limpopo.gov.za>; phosamj@gmail.com; rirhandzumkhari@gmail.com; Mkhari.RN@agric.limpopo.gov.za; Celeste Dekker <Celeste@arc.agric.za>; Mohamed Mohamed Ahmed <MohamedAhmedM@arc.agric.za>; Khaled AA. Abutaleb <AbutalebK@arc.agric.za>; Thendo Tshilate <TshilateT@arc.agric.za>; Maisela Ramatsimele <maiselarj@agric.limpopo.gov.za>
Subject: Re: REQUEST TO DO A SITUATION ANALYSIS IN LIMPOPO PROVINCE MOZAMBIQUE TILAPIA FARMERS

Dear Dr. Thaela-Chimuka

I am confirming the receipt of your email and its contents . Since you have been in contact with our officials on this matter and that you have also bounced this project

with HOD, and given that the assessment need to commence next week as per your plan, I therefore will accordingly request Mr. Ramaboea to let Mr. Phosa to coordinate this project. I have raised with you about the desire of the province to utilize water resources like Nandoni Dam for aquaculture purposes at a higher scale and sustainable level, this can turn Madzivhandila College into the aquaculture hub of the province and many communities and entrepreneurs can benefit from such an initiatives. I will be happy if you can visit the area and give us your opinion on this concept.

I hope the results of your assessment will be made available to the province, and that any plan that will emanate from this exercise, the province will be thoroughly engaged before finalized. I wish you the best.

Regards

Terri

On Thu, Aug 23, 2018 at 6:09 PM Mary Jane Chimuka <ThaelaMJ@arc.agric.za> wrote:

Dear Ntate Ndove

As per our conversation earlier this morning, find attached summary of the Department of Science and Technology (DST), Department of Agriculture, Forestry and Fisheries (DAFF) and the Agricultural Research Council (ARC) joined Limpopo fresh water aquaculture cluster project summary

Regards

Disclaimer: This email and any files transmitted with it are confidential and intended solely for the use of the individual or entity to whom they are addressed. If you have received this email in error please notify the sender immediately. Please note that any views or opinions presented in this email are solely those of the author and do not necessarily represent those of the ARC. A full copy of this disclaimer can be accessed on http://www.arc.agric.za/Pages/Terms-and-Conditions.aspx

Terri Ndove

Chief Director: Agric Advisory Services

Limpopo Department of Agric and Rural Dev.

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