

**ASSESSING THE POTENTIAL FOR
FRESHWATER AQUACULTURE
DEVELOPMENT IN TIMOR-LESTE USING
GIS MODELING**

TEOH SHWU JIAU

UNIVERSITI SAINS MALAYSIA

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GIS MODELING**

by

TEOH SHWU JIAU

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
ALGIS	Agriculture and Land Geographic Information System Timor-Leste
FAO	Food and Agriculture Organization of the United Nations
GIFT	Genetically Improved Farmed Tilapia
GIS	Geographic Information Systems
MAF	Ministry of Agriculture and Fisheries Timor-Leste
MCE	Multi-Criteria Evaluation
NDFA	National Directorate of Fisheries and Aquaculture Timor-Leste
SOFIA	State of World Fisheries and Aquaculture
WLC	Weighted Linear Combination

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PENILAIAN POTENSI PEMBANGUNAN AKUAKULTUR AIR TAWAR DI TIMOR-LESTE MENGGUNAKAN PEMODELAN GIS

ABSTRAK

Timor-Leste telah menggunakan Strategi Pembangunan Akuakultur Nasional (2012–2030) untuk meningkatkan kadar keterjaminan makanan dan kehidupan luar bandar dengan mempromosikan akuakultur air tawar di kawasan-kawasan yang mempunyai sumber yang mencukupi serta keadaan sosioekonomi yang menggalakkan. GIS telah digunakan secara meluas dalam penyelidikan akuakultur, namun aplikasi GIS dalam penyelidikan akuakultur kolam air tawar di Timor-Leste masih kurang dimanfaatkan. Kajian ini dilaksanakan untuk menangani jurang tersebut melalui pembangunan model yang bersesuaian berasaskan GIS disamping dapat diadaptasi dengan keunikan biofizikal dan sosioekonomi di Timor-Leste. Kepelbagaian faktor biofizikal dan sosioekonomi telah dikenal pasti melalui kajian literatur, diperhalusi dengan rundingan bersama pihak berkepentingan serta menggunakan kaedah penglibatan dalam GIS untuk mencapai konteks yang berkaitan. *Analytical Hierarchy Process* (AHP) digunakan untuk menilai kriteria secara sistematik dan *Multi-Criteria Evaluation with Weighted Linear Combination* (MCE-WLC) mengintegrasikan semua kriteria untuk menilai kesesuaian. Transformasi logik kabur (*fuzzy*) digunakan untuk menangani ketidakpastian dan mewakili kesesuaian peralihan secara berterusan. Model GIS yang menggunakan data lokasi kolam sebenar menunjukkan ketepatan sebanyak 84% dan mengenal pasti kawasan yang bersesuaian seluas 1,312 km² di tiga wilayah: Bobonaro (588.1 km²), Viqueque (373.2 km²), dan Lautem (350.6 km²). Kawasan penumpuan yang paling sesuai berbanding jumlah

kawasan wilayah adalah paling banyak tertumpu di Ermera (43.1%), Bobonaro (42.7%), dan Aileu (39.6%). Data produktiviti yang telah diintegrasikan dianggarkan pada 4.3 ± 1.5 t/ha/kitaran, menunjukkan pelaksanaan akuakultur sebanyak 1% dalam kawasan yang paling bersesuaian dalam setiap wilayah berpotensi mencapai sasaran penghasilan akuakultur nasional sebanyak 12,000 tan menjelang tahun 2030. Kawasan dengan kesesuaian rendah pula menawarkan peluang untuk mencapai sasaran intervensi bagi meningkatkan potensi akuakultur. Pembangunan perisian berasaskan Excel yang khusus diintegrasikan dengan API IDRISI memudahkan automasi model, mengemas kini, menggabungkan data baharu, dan melaraskan pemberat (weight) serta permulaan yang sesuai untuk perancangan yang dinamik. Kajian ini menangani jurang yang kritikal dalam model kesesuaian akuakultur berasaskan GIS dengan kaedah holistik yang mengintegrasikan faktor biofizikal dan sosioekonomi, memperincikan kriteria berdasarkan input dari pihak yang berkepentingan, menggunakan AHP dan logik kabur, serta mengesahkan output daripada data lokasi kolam yang sebenar. Hasil kajian ini sejajar dengan strategi nasional dan menawarkan pandangan praktikal untuk pihak berkepentingan, termasuk agensi kerajaan, NGO, sektor swasta, dan penderma, bagi menyokong pengembangan akuakultur. Penyelidikan ini juga telah merapatkan jurang antara pemodelan teori dan aplikasi praktikal, menyediakan rangka kerja holistik untuk pembangunan akuakultur yang mampan di Timor-Leste serta metodologi yang boleh direplikasi untuk perancangan akuakultur di negara tropika lain.

ASSESSING THE POTENTIAL FOR FRESHWATER AQUACULTURE DEVELOPMENT IN TIMOR-LESTE USING GIS MODELING

ABSTRACT

Timor-Leste adopted the National Aquaculture Development Strategy (2012–2030) to enhance food security and rural livelihoods by promoting freshwater aquaculture in areas with adequate resources and favourable socioeconomic conditions. Despite the widespread use of GIS in aquaculture research, its application to freshwater pond aquaculture in Timor-Leste remains underutilized. This study addresses this gap by developing a GIS-based suitability model tailored to Timor-Leste's unique biophysical and socioeconomic conditions. Biophysical and socioeconomic factors were identified through a literature review and refined via stakeholder consultations and participatory GIS methods to ensure contextual relevance. The Analytical Hierarchy Process (AHP) was used to weight criteria systematically and Multi-Criteria Evaluation with Weighted Linear Combination (MCE-WLC) integrated these factors to assess suitability. Fuzzy logic transformations accommodated uncertainties and represented continuous suitability transitions. The GIS model, validated using actual pond location data with 84% accuracy, identified 1,312 km² of highly suitable areas across three municipalities: Bobonaro (588.1 km²), Viqueque (373.2 km²), and Lautem (350.6 km²). High-suitability areas relative to total municipality areas were most concentrated in Ermera (43.1%), Bobonaro (42.7%), and Aileu (39.6%). By integrating productivity data, estimated at 4.3 ± 1.5 t/ha/cycle, implementing aquaculture in 1% of the most suitable areas in each municipality could achieve the national aquaculture production target of 12,000 tons by 2030. Low-suitability areas provide opportunities for targeted interventions to enhance

aquaculture potential. A custom-built Excel-based tool integrated with the IDRISI API facilitated model automation, allowing updates, incorporation of new data, and adjustments to weights and thresholds for dynamic planning needs. This study addresses critical gaps in GIS-based aquaculture suitability models by adopting a holistic approach that integrates biophysical and socioeconomic factors, incorporates stakeholder-driven criteria refinement, applies AHP and fuzzy logic, and validates outputs with actual pond location data. The findings align with national strategies and offer actionable insights for stakeholders, including government agencies, NGOs, private sectors, and donors, to support aquaculture expansion. This research bridges the gap between theoretical modeling and practical application, providing a holistic framework for sustainable aquaculture development in Timor-Leste and a replicable methodology for aquaculture planning in other tropical countries.

CHAPTER 1

INTRODUCTION

1.1 Background

Timor-Leste (officially the Democratic Republic of Timor-Leste), also known as East Timor, is situated on the eastern half of the Lesser Sunda islands and northwest of Australia. It is a small country with a land size of 14,919 km² and much of the area is mountainous (United Nations, 2019). Timor-Leste is one of the world's newest nations, achieve official independence from Indonesia on 20 May 2002, but it faces significant post-conflict challenges. The country has Human Development Index (HDI) value of 0.606 for 2019, positioning it in the medium human development category at 141st out of 189 countries and territories (Conceição, 2020). The 2014-15 Timor-Leste Survey of Living Standards (TLSLS-3) found that the poverty rate declined from 50.4% in 2007 to 41.8% in 2014 based on the national poverty line (World Bank, 2016). Despite the progress in poverty reduction, malnutrition remains a national concern. The nation ranks “serious” hunger levels at 108th out of the 116 countries (ordered from lowest to highest hunger levels) in the 2021 Global Hunger Index (GHI) and has the second-highest prevalence of child stunting in the world, with levels 52.2% (von Grebmer et al., 2021).

In order to address the challenges of poverty and malnutrition, Timor-Leste's Strategic Development Plan (SDP) 2011-2030, which is in line with the United Nations Millennium Development Goals, acknowledges the importance of agricultural development and the potential of the fisheries and aquaculture sectors to diversify livelihoods and increase food and nutrition security (López-Angarita et al., 2019). Fish is a valuable food for improving nutrition and health. Fish contains high concentrations

of bioavailable minerals and vitamins, essential fatty acids and animal protein (Thilsted et al., 2016; Bogard et al., 2015; Wheal et al., 2016), which are all essential in every stage of life, especially in the first 1000 days (Byrd et al., 2022; Andersen et al., 2013).

Despite Timor-Leste being surrounded by the sea, the fisheries and aquaculture sectors are underdeveloped. The annual per capita fish consumption in Timor-Leste is particularly low, with an estimated average of 6.1 kg per capita compared to the global average of 20.5 kg per capita in 2019 (López-Angarita et al., 2019) or the lower-middle-income nation's average 15.2 kg per capita (FAO, 2022). The Timor-Leste National Aquaculture Development Strategy (NADS) 2012-2030, which was endorsed by Ministry of Agriculture and Fisheries (MAF) in 2013, aims to increase aquaculture production up to 12,000 tonnes per year by 2030, contributing 40% of the domestic fish supply, with the remainder coming from capture fisheries. This aquaculture development's target can be met through freshwater, brackish water and marine culture activities. Freshwater aquaculture has been identified as a major activity for improving food and nutrition security in inland communities, whereas brackish water and marine culture provides small scale of business and income-generating opportunities.

Aquaculture is a relatively new sector in Timor-Leste. Almost all of the fish hatcheries established in the early 1980s collapsed during the conflict following Indonesia's withdrawal in 1999. From the findings of the background study during the development of the NADS in 2012, the area used for freshwater aquaculture is estimated approximately 41 ha, with production is expected around 46 tonnes. To date, the government still not consolidated accurate aquaculture statistics at the national level (López-Angarita et al., 2019; NDFA/MAF, 2012b). Therefore, it is challenging

to obtain an overview of the distribution of aquaculture ponds and calculate the total area of ponds across the country. However, to reach the NADS's aquaculture supply target of 12,000 tonnes of fish annually by 2030, current aquaculture production needs to be increased.

To implement the NADS and expand the aquaculture area, one of the actions is to identify suitable areas with favourable environmental, social, and economic contexts for aquaculture development. Selection the right sites is one of the most important factors in determining the feasibility of successful aquaculture and ensure its sustainability. This involves the identification of areas that are environmentally, socially, economically, and have potential to commercially viable (Garlock et al., 2024; Asmah, 2008; McLeod et al., 2002). Site selection generally based on the species to be cultured and the culture system to be adopted or technology to be employed (Stelzenmüller et al., 2017; Kutty, 1987; Pillay & Kutty, 2005). There are factors such as agro-ecological conditions, access to inputs, access to markets and road network accessibility. Some of these factors are map able. Geographic Information Systems (GIS) can be employed to address spatial issues in the planning, development, and management of aquaculture (Falconer et al., 2019; Aguilar-Manjarrez et al., 2017).

GIS combines computer hardware, software, data, and personnel to collect, store, manipulate, analyse, and display geospatially referenced information (Burrough, 1998; Rahel, 2004; Kennedy, 2013; Longley et al., 2015). The Canadian government developed the first GIS application in the 1960s to map land resources (Meaden, 2009; Ross et al., 2013). Since the 1980s, the Food and Agriculture Organization of the United Nations (FAO) has recognized that GIS could be an important tool for aquaculture and fisheries (Caddy and Garcia, 1986) and has produced a series of FAO technical papers related to marine or aquatic resource mapping (Butler et al., 1987;

Meaden and Chi, 1996; Jenness et al., 2007a & 2007b), using GIS to identify potential aquaculture sites (Kapetsky, 1994 and a reassessment by Aguilar-Manjarrez & Nath for Africa, 1998; Kapetsky and Nath, 1997 for Latin America; Kapetsky et al., 1991 for Ghana), and a first technical report in introducing GIS and remote sensing for inland fisheries and aquaculture (Meaden and Kapetsky, 1991).

The purpose of this research is to develop a robust GIS-based model for assessing the potential for promoting freshwater pond aquaculture in Timor-Leste, a key focus of the NADS's sectoral development plan. The model based on a holistic approach by integrating diverse bio-physical and socio-economic factors using multi-criteria evaluation (MCE) to identify favourable areas for freshwater aquaculture development. While primarily focusing on tilapia, the study also considers carp and prawns, which share similar culture requirements and are identified as key target species in the NADS. By comprehensively analysing critical determinants, developing a national-level GIS model, and assessing freshwater fish production potential using the GIS-model's results, the study aims to provide evidence-based insights and decision support for strategic freshwater aquaculture development in Timor-Leste.

1.2 Problem Statement

The application of GIS for aquaculture site selection has been extensively documented across various scales and environments (Ross et al., 2009; Ross et al., 2013). These studies span global (Handisyde, 2015), continental or regional (Aguilar-Manjarrez & Nath, 1998; Kapetsky and Chakalall, 1998), national (Berg et al., 2021; Ssegane et al., 2012), subnational (Bandira et al., 2021; Abdullah et al., 2021; Calle

Yunis et al., 2020) and small-area or water body assessments (Asmah et al., 2021; Mulanda Aura et al., 2021; Tarunamulia et al., 2019). They also address diverse environments, including brackish water (e.g. Jayanthi, 2022; Tarunamulia et al., 2019), freshwater (e.g. Berg et al., 2021; Mustafa et al., 2021) and marine (e.g. Aghmashhadi et al., 2022; Haghshenas et al., 2021). Despite these studies highlight the versatility of GIS in assessing aquaculture suitability at various scales and environments, a significant gap remains in the effectiveness of such models, particularly within the specific context of concerning freshwater pond aquaculture development in Timor-Leste.

The first freshwater aquaculture suitability assessment in Timor-Leste, conducted in 2012 by WorldFish, aimed to support the development of the National Aquaculture Development Strategy (NADS). This study assessed the potential of municipalities (formerly districts) to implement subsistence freshwater aquaculture, primarily targeting domestic consumption with surplus production sold to local consumers to improve local food security (NDFA/MAF, 2012b). However, this early study faced several limitations. It relied on coarse-scale data, lacked precision for informed decision-making, and excluded key determinants such as soil properties, livestock waste as organic fertilizer, fish-inclusive meal programs, and the use of improved aquaculture strains such as Genetically improved farmed tilapia (GIFT). These factors significantly influence site suitability but were not considered in the earlier study.

To address these limitations, this study provides a refined and comprehensive evaluation of aquaculture potential, focusing on small-scale freshwater pond aquaculture development tailored to Timor-Leste's unique context. This study develops a GIS-based model that is aligned with the specific needs and anticipated

growth of the country's aquaculture sector by incorporating additional key determinants, as well as more recent and higher resolution data. The study focuses on tilapia as the primary species of interest, given its suitability for low-input systems and similar culture requirements with other species such as carp and prawns.

This study adopts a holistic approach to bridge theoretical and practical gaps in aquaculture site selection. It integrates biophysical and socio-economic factors within a multi-criteria evaluation (MCE) framework, engaging stakeholders to refine criteria, applying the Analytic Hierarchy Process (AHP) for systematic weighting, and using fuzzy logic transformations to address uncertainties. Validation with actual pond location data ensures reliability and contextual relevance. The national-level assessment identifies municipalities with high aquaculture potential, enabling effective planning and investment in areas with favourable resource bases and socio-economic conditions.

This study not only contributes to the theoretical understanding of aquaculture site selection but also offers practical applications for Timor-Leste's aquaculture development. The GIS modeling results was used to assess the freshwater fish production potential, providing evidence-based recommendations and actionable insights to guide government entities, potential donors, non-governmental organizations, and private sector actors in identifying suitable areas for aquaculture development. Ultimately, the study supports Timor-Leste's national goal of increasing aquaculture production to 12,000 tonnes annually by 2030, fostering food security, livelihood diversification, and sustainable economic growth.

1.3 Research Questions

Aligned with the background of the study and problem statement, this study was carried out to address the following research questions:

- 1) **What are the key biophysical and socio-economic factors** that influence the feasibility of freshwater aquaculture development in Timor-Leste?
- 2) **How can a GIS-based model be developed** to identify municipalities with high potential for freshwater aquaculture at the national level?
- 3) **How can GIS model results be utilized to assess freshwater fish production potential** and support evidence-based decision-making for freshwater aquaculture development in Timor-Leste?

1.4 Research Objectives

This study aims to achieve the following research objectives:

- 1) **To identify key determinants** of critical bio-physical and socio-economic factors (criteria) that influence the feasibility of freshwater aquaculture development in Timor-Leste.
- 2) **To develop a comprehensive GIS-based model** at the national level to identify municipalities with high potential for promoting freshwater aquaculture in Timor-Leste.
- 3) **To assess the potential for freshwater fish production** by utilizing GIS model results to provide strategic guidance, evidence-based recommendations,

and decision support for evaluating freshwater aquaculture development potential in Timor-Leste.

1.5 Research Scopes and Limitation

The GIS modelling area at national-level covered all municipalities in Timor-Leste, excluding the Oecusse Special Administrative Region (SAR), islands of Atauro and Jaco. Oecusse SAR is situated in part of the province of Nusa Tenggara Timur, Indonesia, and separated from the rest of Timor-Leste municipalities. Travel from Timor-Leste to Oecusse SAR needs to go through Indonesian checkpoint across the border crossings into Indonesia. Considering the GIS model included accessibility indicators, it was difficult to quantify since it involved international checkpoint and Indonesia data. Atauro Island, situated 25 km north of Dili, is allocated solely for seaweed cultivation. Meanwhile, Jaco Island is an unpopulated island situated in the easternmost part of Lautem municipality.

The GIS models developed in this study are generally applicable to freshwater aquaculture, however Nile Tilapia (*Oreochromis niloticus*) is the main species targeted, considering that the government and public-private partnership (PPP) hatcheries in the country are producing Genetically Improved Farmed Tilapia (GIFT) fingerlings for farmers to culture (i.e. the improved tilapia strain introduced by WorldFish Malaysia) at this stage. There are no fingerlings for other species in Timor-Leste (López-Angarita et al., 2019). Collecting fingerlings from wild stocks is unsustainable.

Timor-Leste's Ministry of Agriculture and Fisheries (MAF) developed the National Aquaculture Development Strategy (NADS) 2012-2030 with WorldFish's technical support in 2012. Since the aquaculture sector is relatively new and continues to develop, the government has not collected data from different projects to provide aquaculture statistics at the national scale, so exact numbers of households engaged in aquaculture, areas under production, and yield are unavailable. Particularly, there are no accurate GPS locations represented for active aquaculture ponds throughout the country (López-Angarita et al., 2019). Data used for this study model validation is mainly collected from the WorldFish's Partnership for Aquaculture Development in Timor-Leste (PADTL) project implemented between 2014 and 2019 in three municipalities (Baucau, Bobonaro and Ermera). Hence, limited sites data could be collected and used to verify the model's results.

1.6 Research Significance

This study significantly contributes to advancing both the theoretical and practical dimensions of aquaculture development, particularly in data-scarce environments like Timor-Leste:

- 1) **Holistic methodological framework:** The study adopts a holistic approach to developing a robust GIS-based model that integrates multi-criteria evaluation (MCE) with Weighted Linear Combination (WLC) to assess aquaculture suitability. By incorporating the Analytic Hierarchy Process (AHP) for systematic weighting of criteria, fuzzy logic for managing uncertainties, and stakeholder engagement to ensure contextual relevance, the methodology

enhances inclusivity and precision. Validation using actual pond location data further reinforces the reliability of the model, representing a methodological advancement in aquaculture site selection and strategic planning.

- 2) **Innovative, reproducible and adaptive planning tools:** A key contribution of the study is the development of a custom-built Excel-based tool integrated with the IDRISI API, enabling model automation. This tool supports the incorporation of new data and allows adjustments to weights and thresholds, ensuring adaptability to evolving planning needs. Its replicable design makes it highly suitable for application in other tropical regions, offering a valuable resource for aquaculture development in similar contexts.
- 3) **Applicability in data-scarce environments:** The methodology leverages freely accessible national and global datasets, making it practical for resource-constrained environments. By addressing the challenge of data scarcity, the study provides a framework that can be effectively implemented in developing countries under similar pressures to expand aquaculture sustainably. This highlights the importance of using open data to overcome common barriers in aquaculture planning and management.
- 4) **Strategic support for national goals:** The study highlights the potential of GIS modeling to support Timor-Leste's National Aquaculture Development Strategy (2012–2030) by identifying high-potential areas for freshwater aquaculture and estimating production potential. The GIS-generated suitability maps offer a detailed spatial overview to aid zoning, investment prioritization, and strategy development at both national and municipal levels. These findings contribute to diversifying livelihoods, enhancing fish consumption and

nutrition, stimulating economic growth, and attracting external investments, aligning with broader developmental objectives.

- 5) **Informed intervention and constraint mitigation:** Beyond identifying suitable areas, the study emphasizes the importance of addressing constraints in low-potential areas, such as water resource limitations or poor market access. This understanding enables the design of targeted interventions to enhance viability. By integrating aquaculture into community livelihood support programs, the study fosters equitable development and promotes sustainable growth.

1.7 Operational Definition of Key terms

Following are definitions of the key terms that have been used throughout this thesis.

GIS (Geographic Information System) model: A GIS model is a representation of real-world geographical processes, phenomena, or systems within a GIS. It involves the use of spatial data, such as maps and satellite imagery, to create simulations, analyses, and predictions of various geographic phenomena. GIS models help in understanding and visualizing how different factors interact within a geographical context (Goodchild, 2003).

MCE (Multi-Criteria Evaluation): Multi-Criteria Evaluation is a decision-making technique used in spatial analysis and GIS. It involves evaluating and comparing multiple criteria or factors to make informed decisions. MCE helps assign

weights to different criteria, considering their relative importance, and combines them to produce an integrated result. This technique is often used in suitability assessments and spatial planning (Eastman, 2016).

MCE-WLC (Multi-Criteria Evaluation with Weighted Linear Combination): MCE-WLC is a specific approach within multi-criteria evaluation. It involves assigning weights to various criteria based on their importance and combining them using a weighted linear combination method. This technique allows for the integration of multiple factors or indicators into a single suitability map, providing a comprehensive view of the suitability of different areas for a specific purpose (Eastman, 2016).

Factor or Criteria: In the context of GIS modeling and decision-making, a factor or criteria is a specific characteristic or parameter used to evaluate the suitability of a location for a particular activity or purpose. Factors can be physical, environmental, economic, or social in nature and contribute to the overall decision-making process (Eastman, 2016).

Indicator: An indicator is a measurable variable or parameter that provides information about a specific aspect or condition. In GIS modeling, indicators are often used to quantify different factors or criteria that influence decision-making. They help in assessing the suitability or potential of different locations for specific activities or purposes (Eastman, 2016).

Constraint: A constraint refers to a limitation or condition that restricts the suitability of certain areas for a particular activity. In GIS modeling, constraints are factors that determine where an activity can or cannot take place. They help refine the

analysis by excluding areas that do not meet specific requirements or conditions (Eastman, 2016).

AHP (Analytical Hierarchy Process): AHP is a structured technique for analyzing complex decisions by decomposing them into a hierarchy of criteria, sub-criteria, and alternatives. AHP, developed by Saaty (1977), facilitates the systematic quantifying evaluation of multiple criteria and their relative importance in decision-making. It involves comparing two criteria against each other using a scale. AHP then computes relative weights for criteria and alternatives, which are then used to select the best option based on a thorough evaluation of the decision factors. AHP is commonly used in various fields, including business, engineering, urban planning, and environmental management, to make informed and rational decisions when multiple factors are involved (Eastman, 2016).

Aquaculture: Aquaculture refers to the practice of controlled cultivation or farming of aquatic organisms. This encompasses various activities, including breeding, rearing, and harvesting of these aquatic organisms in environments characterized by freshwater, marine, or brackish water conditions. Aquatic organisms, such as fish, shellfish, and aquatic plants, are used for commercial, recreational, or conservation purposes. Aquaculture plays a crucial role in providing food, income, and employment opportunities, as well as contributing to biodiversity conservation and resource management (FAO, 1988; Troell et al., 2013).

Aquatic food: Aquatic food refers to any form of edible organisms harvested from aquatic environments such as oceans, seas, lakes, rivers, and aquaculture systems. This includes a wide range of organisms such as fish, shellfish, crustaceans, and aquatic plants that are consumed for their nutritional value. FAO has adopted the term

“aquatic food” instead of “fish consumption” in its recent The State of World Fisheries and Aquaculture (SOFIA) 2022 report. Aquatic food is an important source of protein and nutrients for many people around the world and plays a significant role in global food security (FAO, 2022).

GIFT (Genetically Improved Farmed Tilapia): GIFT is a strain of Nile tilapia (*Oreochromis niloticus*), a commonly farmed freshwater fish species. GIFT tilapia is known for its rapid growth, high reproductive capacity, and adaptability to various environmental conditions. It has been genetically selected for improved traits related to growth rate, disease resistance, and overall productivity (Pant et al., 2019). GIFT tilapia is widely used in aquaculture to enhance fish farming efficiency and increase production. In this study, GIFT tilapia is referred to as a WorldFish-developed GIFT strain.

1.8 Organization of the Thesis

This thesis is structured into the **five chapters** described below.

Chapter 1 describes the research background, including the problem statement, the aims and objectives of this research, the scope of this research, and the significance of this research.

Chapter 2 provides a comprehensive literature review to align with the 3 key objectives of this study. It focuses on several key aspects, including gaining an understanding of the study area, the various aquaculture systems, the current status and trend of aquaculture, the criteria that influence the selection of freshwater aquaculture

sites, and previous GIS studies or applications in assessing aquaculture suitability sites. The review includes the level (scale) of analysis, the targeted cultured system and species, and the methods. The synthesis of these findings helps to identify gaps and provides insights for the development of the methodology for this study.

Chapter 3 describes the comprehensive methodology developed to assess the potential for freshwater aquaculture development in Timor-Leste. This methodology is carefully designed to achieve research objectives, including the identification of key determinants that influence the feasibility and suitability of freshwater aquaculture development and the integration of bio-physical and socio-economic determinants through GIS modelling. It also outlines the methods for assessing the freshwater fish production potential using GIS model results to offer actionable insights for informed decision making.

Chapter 4 presents the results and discussions obtained from this study.

Finally, **Chapter 5** concludes with a summary of findings, limitations of the results and research recommendations for the future.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Aquaculture plays a crucial role in addressing food security, enhancing livelihoods, and fostering economic growth in many countries, including Timor-Leste. As the demand for fish protein continues to rise, the sustainable development of aquaculture holds significant promise. To harness this potential effectively, a comprehensive understanding of the factors that influence aquaculture suitability is required. This chapter of the literature review will explore the existing body of knowledge that aligns with the 3 key objectives of this study, with a focus on how these objectives contribute to understand the complexities of aquaculture development, particularly freshwater aquaculture.

The **first objective** is to identify the key factors that influence the feasibility of freshwater aquaculture development. In this regard, the literature review focuses on the study area (**Section 2.2**), an overview and characterizations of aquaculture systems (**Section 2.3**), the current status and trend (**Section 2.4**), and the biophysical and socioeconomic factors that influence the freshwater aquaculture potential (**Section 2.5**).

The **second objective** is the development of a comprehensive GIS model to identify high-potential areas for promoting freshwater aquaculture. Previous studies have been examined in the context of the various applications of GIS in aquaculture site selection at different levels of analysis, including global, national, sub-national, and small-area, farming environment, species, and methods used in aquaculture suitability analysis (**Section 2.6**).

The **third objective** highlights the pivotal role of utilizing the GIS model results to assess freshwater fish production potential and generate evidence-based recommendations and strategic guidance for aquaculture development. Drawing from the literature, suitability maps are highlighted as dynamic tools that support land use planning and policies, as well as enhanced decision support for sustainable growth in the aquaculture sector (**Section 2.7**).

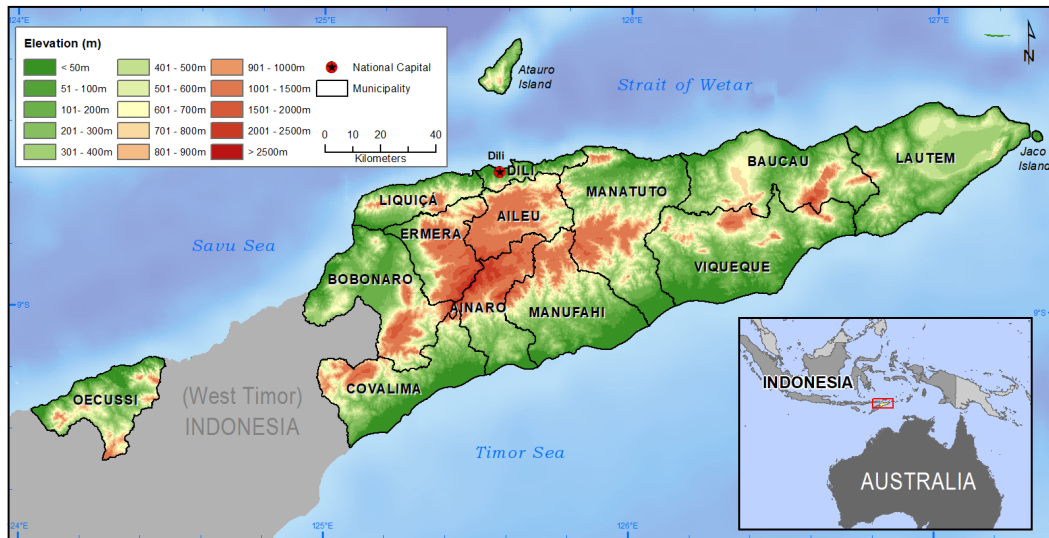
2.2 Study Area

2.2.1 Geographical location and landscape

Timor-Leste (also referred to as East Timor), officially the Democratic Republic of Timor-Leste, occupies the easternmost portion of Timor Island within the Indonesian archipelago. Located between latitudes 8.1°S and 9.5°S and longitudes 124°E and 127.3°E. It encompasses the eastern portion of the Lesser Sunda Islands and is bordered to the south by the Savu Sea and to the north by the Timor Sea. Timor-Leste's strategic location places it within the Coral Triangle, a globally significant marine region renowned for its exceptional marine biodiversity. The country's coral reefs and blue waters contribute to its importance as a marine biodiversity hotspot.

Timor-Leste's landscape, which encompasses approximately 15,000km² is dominated by mountainous terrains (see Figure 2.1), with slopes exceeding 40% spanning 44% of its total land area (Barnett et al., 2007). Due to the dominance of steep slopes, only about 7.5% of Timor-Leste's total land is arable despite its relatively small land area (World Bank, 2020). As illustrated in Figure 2.2, the land cover map produced by the Copernicus Global Land Service reveals that the forest covers an area

of 9250 km², accounting for approximately 61% of the overall land area in Timor-Leste. However, it experiences a yearly reduction of 0.15% (FAO, 2020).



Data source: CGIAR-CSI SRTM v4.1 (2008)

Figure 2.1 The topography of Timor-Leste (Source: Created by author, 2011)

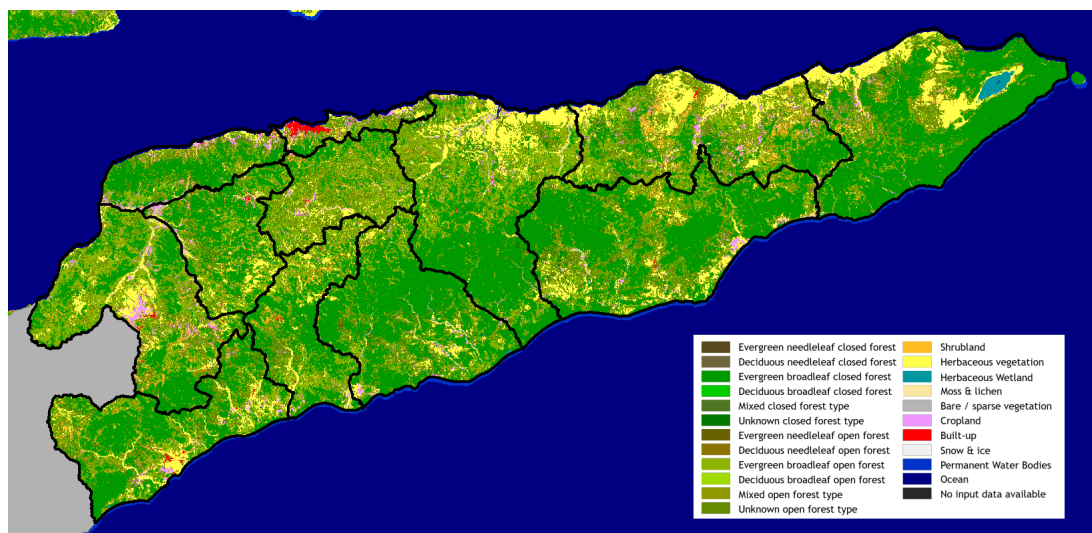
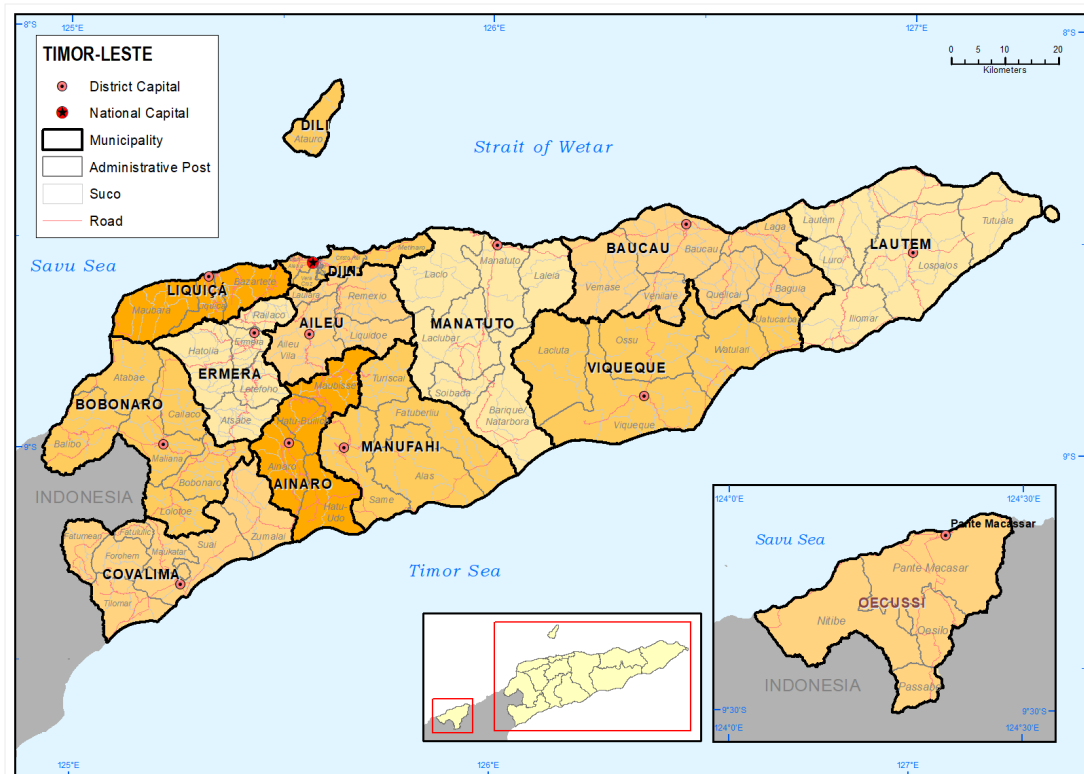


Figure 2.2 The Copernicus Global Land Service (CGLS) Land Cover Map V3.0 at 100 m resolution for year 2015 with 23 discrete classes

2.2.2 Administrative divisions and population

Timor-Leste, a relatively young nation, gained its independence from the Indonesian government on 20 May 2002. As shown in Figure 2.3, the country is organized into 13 municipalities (formerly districts), which are then divided into 65 administrative posts (formerly subdistricts), and further segmented into 442 sucos (villages). Dili serves as the capital city of Timor-Leste. The municipalities include Aileu, Ainaro, Baucau, Bobonaro, Cova Lima, Dili, Ermera, Lautém, Liquiçá, Manatuto, Manufahi, Oecusse, and Viqueque (NDS, 2010).



Data source: ALGIS 2010

Figure 2.3 The administrative divisions of Timor-Leste (Source: Created by author, 2011)

According to the 2010 Census, Timor-Leste had a population of over 1,066 million, with a population density about 71.3 persons per km². The urban population

accounts for 29.6% of the overall population, with the majority being concentrated in the capital city of Dili, which constitutes 60.9% of the urban population. A significant proportion, specifically 70.4% of the population, continues to reside in rural areas (NDS, 2010).

2.2.3 Economy and Food Security

Oil and gas resources constitute significant revenue sources for Timor-Leste's economy. However, price fluctuations in oil during 2014-16 raised concerns regarding long-term sustainability. Around 80% of households engage in crop cultivation, primarily maize, legumes, and tubers. Additionally, 86% are involved in livestock rearing, focusing on chickens, pigs, cattle, and goats (Ferreira, 2016). Agricultural practices, predominantly traditional and subsistence-based, encounter various challenges like variable rainfall, inadequate irrigation facilities, droughts, poor soil fertility, and a lack of organic fertilizers and agricultural inputs (da Cruz, 2016). The growth of commercial farming is hampered by limited farm size and undeveloped marketing infrastructure (Paudel, 2022).

Although 80% of the population relies on agriculture for a living (GDS, 2020), approximately 75% of the population in this nation suffers from varying degrees of food insecurity (MAF, 2019). The country's Human Development Index (HDI) for 2019 is 0.606, ranking 141st out of 189 countries and territories in the medium human development category (Conceição, 2020). According to the 2014-15 Timor-Leste Living Standards Survey (TLSLS-3), which is based on the national poverty line, the poverty rate in Timor-Leste declined from 50.4% in 2007 to 41.8% in 2014 (World Bank, 2016). Despite the decline in poverty, malnutrition continues to be a national

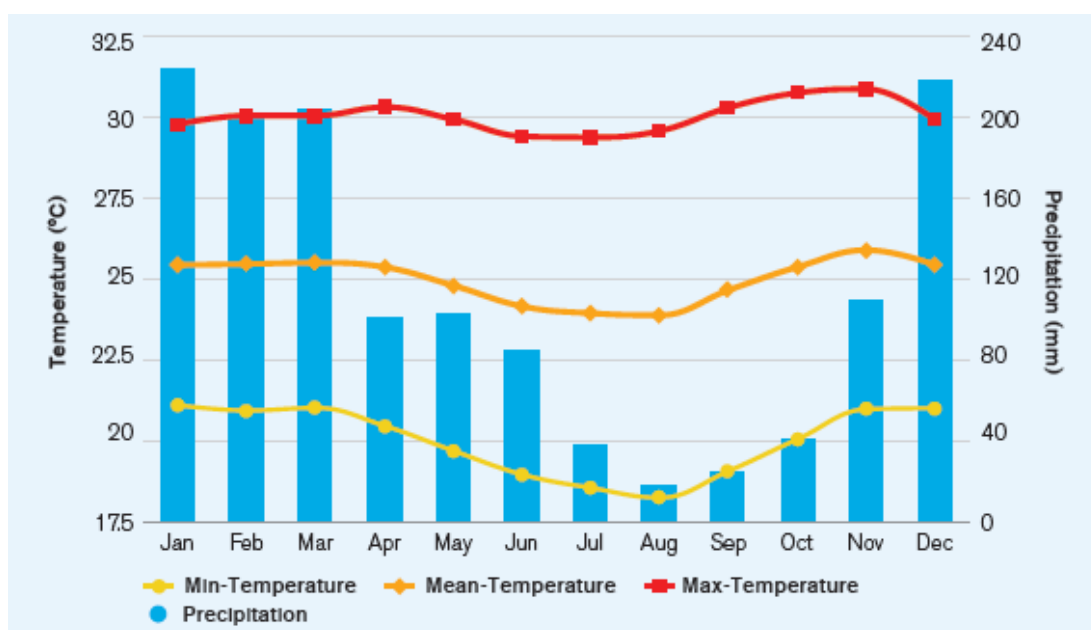
concern. On the 2021 Global Hunger Index (GHI), Timor-Leste ranks 108th out of 116 countries (from lowest to highest hunger levels) for "serious" hunger levels and has the second highest prevalence of child stunting, at 52.2% (von Grebmer et al., 2021).

The primary factors identified as contributing to food insecurity are low agricultural productivity, the adoption of low-value livelihood strategies, and a heavy reliance on a single livelihood strategy (MAF, 2019). The Strategic Development Plan of Timor-Leste 201-2030 outlines the objective of enhancing agrobiodiversity by prioritizing the cultivation of nutritious and high-yielding crops, including coffee, coconut, and other potentially profitable crops such as cocoa, cashews, hazelnuts, and spices (GoTL, 2011). The Ministry of Agriculture and Fisheries Strategic Plan outlines the country's agricultural objectives: (i) increase rural incomes and reduce poverty; (ii) improve crop varieties, forestry, livestock species, and fisheries, (iv) conserve, manage, and utilize natural resources (MAF, 2012).

2.2.4 Climate

Timor-Leste has a tropical climate that is hot and humid, with a wet season from December to May and a dry season from June to November. The climate of the country is heavily influenced by the West Pacific Monsoon and its mountainous terrain. As shown in Figure 2.4, the average temperature in mountainous regions ranges from 24°Celsius to 26°Celsius and becomes cooler as altitude increases. The average monthly temperature varies by only 1.3°C throughout the year, from a minimum of 24.1°C in July to a maximum of 25.4°C in November. October to April are the warmest months of the year, while June, July, and August are the coldest. The average monthly precipitation varies throughout the year, ranging from 12 to 18

millimeters (mm) during the driest months of August and September to 222 to 252 mm during the wettest months of December to March. The country is vulnerable to climatic challenges such as high risk of cyclones, tsunami, flash floods, drought, and landslides, highlighting the importance of resilience-building measures (World Bank & ADB, 2021).



Source: World Bank & ADB (2021)

Figure 2.4 Average Monthly Mean, Minimum, and Maximum Temperatures and Rainfall in Timor-Leste (1991–2020)

2.2.5 Aquaculture ponds

The distribution of aquaculture ponds in Timor-Leste is widespread, with concentrations in municipalities where government or I/NGO initiatives have promoted aquaculture development. These ponds are mostly small-scale household ponds that are often earthen (see Plate 2.1) due to cost considerations, with only a few that are cemented. They play a vital role in providing households with both nutrition

and additional income. These ponds generally range in size from 200 to 1000 m², which is typical for Timor-Leste's conditions (Pant et al., 2019).

Mapping these ponds using remote sensing techniques poses significant challenges, primarily due to their small size and dispersed distribution. This situation complicates the government's monitoring efforts and data collection, which tend to lack proper documentation and organization by municipal MAF officers. Figure 2.5 showcases the presence of ponds in a Google Earth image. These ponds are frequently mixed with paddy fields, hide under trees, and are difficult to differentiate from ponds used solely for water storage. Hence, the application of remote sensing and image classification becomes challenging in Timor-Leste context.

Although advanced remote sensing algorithms have been developed to map aquaculture ponds by enhancing their differentiation from other water bodies, these methods face limitations. They require extensive sample data across multiple categories (e.g., aquaculture water bodies, non-aquaculture water bodies, and non-water bodies) to train and validate machine learning models effectively. Moreover, such approaches have primarily been applied to smaller, well-defined study areas, which may not be directly applicable to Timor-Leste's context (Diniz et al., 2021; Hu et al., 2024).

To address these challenges, this study used a more direct and ground-based approach, collecting GPS data in collaboration with local aquaculture officers from the Department of Fisheries. These officers possess extensive local knowledge regarding the locations, sizes, and types of aquaculture ponds in their area. Their insights can help guide the GPS data collection process, ensuring that all relevant ponds are

correctly identified and mapped for the focal area of interest, as well as providing a practical solution to the limitations of remote sensing in Timor-Leste's unique context.



Plate 2.1 Earthen ponds in Timor-Leste