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Assessment and Vulnerability Modeling of Vanuatu's Mangroves using GIS and Remote Sensing

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Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:
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Abstract: Mangrove loss has been reported globally at rapid rates and predicted to be high in the Pacific region due to the combined influence of anthropogenic pressures and climate change related pressures. In small island developing states like Vanuatu, mangroves play an important role in fisheries, alternative livelihoods, coastal protection and shoreline stabilization. Information on the present status of mangroves and spatio-temporal changes of mangrove cover are needed to develop any mangrove conservation program, coastal management and land use policies. For a country like Vanuatu which lacks robust current estimates of baseline mangrove cover, mangrove monitoring is a financially and logistically intensive process due to its multiple remote islands and lack of infrastructure. This study used remote sensing and geographic information science and a supervised maximum likelihood classification to provide a comprehensive mapping of mangrove forests in Vanuatu at a resolution of 30 m. The results revealed a current mangrove area of 1987.56 ha of mangroves nationally and a loss of mangroves since 2001. This study also identified vulnerable mangrove areas that should be of conservation importance by identifying change drivers and developing a vulnerability spatial model. The results based on the vulnerability model revealed that 39% of mangroves are highly vulnerable. The results from this study are archived online which can be useful for developing the land use plans, setting up mangrove conservation targets, fulfilling the targets of multiple visions and plans of Vanuatu by 2030 and providing a template for monitoring and assessments in Vanuatu.

Keywords: Remote sensing, GIS, mangrove monitoring, vulnerability modelling, Vanuatu, mangrove conservation

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Chapter 1: Introduction

1.1 Background

Coastal zones along with flood plains have been one of the most attractive areas for human settlements throughout history. Coasts are known to be rich in resources, have logistical access points for trade and transport and wide range of recreational activities between land and water. This has resulted in some of the world's mega cities being developed in these areas with more than 44% of the world's population living within 150 km from the coast (Cohen et al., 1997). However, these areas of high demand are also areas where highly biodiverse ecosystems of mangroves are found. Mangroves forests are one of the most productive forests and are situated in the interface between the sea and the land in tropical and sub-tropical regions of the world (M. Spalding, Kainuma, & Collins, 2010). This overlap of mangrove areas with areas of rapid human development has resulted in degradation and decline of these unique ecosystems globally, and consequently become areas most in need of conservation strategies (Giri et al., 2011). Mangroves play a critical role in small island developing countries as mangrove loss will not only reduce terrestrial and aquatic production but also impair the environmental and economic stability in these areas (Duke et al., 2007; Veitayaki, Waqalevu, Varea, & Rollings, 2017). The loss of mangroves will result in the loss of important ecosystem goods and services like protection as natural barriers, carbon sequestration and loss of biodiversity (D'Angelo & Wiedenmann, 2014; DeGroot, Stuip, Finlayson, & Davidson, 2006; Giri et al., 2011; Maxwell, 2015; Webber et al., 2016a).

Alarmingly 30% of the world's mangroves have been lost since 1980 to 2000 (Duke et al., 2007) compared to 0.8% of tropical forests (Valiela, Bowen, & York, 2001) and 19% of global coral reefs (Block, n.d.). The predicted rate of loss of mangrove have been at 1 to 2% per year which is greater or equal to in comparison to coral reefs and tropical rainforests (Duke et al., 2007; Giri et al., 2011). The threatened status of mangroves worldwide is of high concern especially in countries with developing economies and small island developing states (SIDS) (Daniel M. Alongi, 2007; Veitayaki et al., 2017). A study done by United Nations Environment Programme (UNEP) in the Pacific islands predicted that as per IPCC's upper projection of temperature around 13% of mangroves could disappear from the islands by the end of this century (Gilman, Lavieren, et al., 2006). The Pacific island mangroves are particularly susceptible to consequences of climate change(Bhattarai & Giri, 2011). As most Pacific islands have a tidal ranges of less than 1m, studies predict that mangrove ecosystems will be disrupted by a sea level rise of 0.3m and will advance landward with a sea-level rise of 1m (J. C. Ellison, 2000; Gilman, Ellison, Jungblut, Van Lavieren, et al., 2006).

Maxwell (2015) meta study shows that the landward migration of mangrove will eventually result in shoreline destabilization, exacerbating beach erosion. Loss of mangroves in these pacific island areas can also release large amounts of stored carbon which will further exacerbate global warming challenges (DeGroot et al., 2006). As a result, pacific island governments have prioritized the need for mangrove conservation efforts (SPREP 1999). For SIDS that have limited capacity to adapt to sea level due to their smaller land mass, high population density, poor infrastructure, limited funds and high susceptibility to recurring natural disasters (J. C. Ellison, 2000; Gilman, Lavieren, et al., 2006; Nurse et al., 2001; Veitayaki et al., 2017) having focussed mangrove conservation is vital for sustainable development and resilience to climate change. However, many of these countries can still not determine the factors which are influencing the sustainability of the mangroves (Veitayaki et al., 2017). As a result, some countries in the Pacific Island like Vanuatu still do not have focussed mangrove management plans.

Although the rate of mangrove loss in Vanuatu is presumed to be low, there is a possibility of increase in a rate of loss due to the developing economy and focus on tourism and urbanization in the country (Baereleo pers. comm). Barbier and Cox (2003) cross country analyses developed economic models that observed increasing losses of mangroves within countries with larger coastlines and developing economies which are also characteristics of Vanuatu. There are no specific estimates of the rate of loss of mangroves in Vanuatu. The remoteness of the island country and spread of mangrove areas over multiple islands has also made monitoring and assessing the mangrove ecosystem difficult.

1.2 Justification for study

Valiela et al. (2001) noted that very few studies reported multi-year mangrove data for countries. To examine linkages between human activities and losses of mangrove habitats long term changes of mangrove studies are needed. Information on mangrove changes is critical for the future land and marine spatial planning and mitigation of climate change impacts in Vanuatu. Recognizing prolific loss of mangroves areas can be used for future predictions of site specific vulnerabilities to land erosion and natural disaster. It will also help managers and conservations for targeted restoration projects as natural solutions to adapt to climate change. As mangroves are found along the coastal zone; assessing the status of mangroves nationally is valuable for the growing human settlements and socio-economic activities of the country within the framework of adaptive resilience to climate change

In a data deficient country with limited infrastructure and funds geospatial monitoring techniques provide the accessibility and convenience to recognize changes over time which can be used to plan the future of these vulnerable island nations. Satellite remote sensing has been used for the management of natural resources worldwide. The repeated coverage of an area by satellites, remote sensed imagery is a viable source of data gathering at local, regional and global scales (Srivastava et al., 2015). Remote sensing has made it possible to study changes in land cover, over a shorter time, lower cost and with good accuracy.

The study will use literature review, geospatial analyses and expert opinion to assess the status of mangroves in Vanuatu. This project will be the first to provide a baseline national level data on the rate of change of mangrove ecosystem in Vanuatu. So far, most of the published data on mangroves of Vanuatu yields very little data on mangrove change trends of Vanuatu. Furthermore, the main drivers of change will be identified using literature review and informal interviews with experts.

1.3 Research contribution

Nationally, the information generated by this thesis will address the data gaps identified by the only exhaustive project on mangroves done in Vanuatu (MESCAL), it will also provide baseline information that address the objectives of the Vanuatu National Environment Policy and Implementation Plan 2016-2030 and Vanuatu Climate Change and Disaster Risk Reduction Policy 2016-2030. Globally, this information will also feed into the mangrove data base that is being created from national to global scales (Giri, 2016).

1.4 Research Question and Objectives

This research aims to contribute to the natural resource management initiatives of Vanuatu by using satellite technology and geospatial tools to monitor and assess the mangrove forests nationally. It also aims to develop a repository of available GIS data and resources for future access and easy availability for the purposes of management. To achieve this goal, the following study is divided into the following research question. Each research question will be answered using the specific objectives.

The aforementioned research question (RQ) and its corresponding objectives (OB) are as follows:

- RQ1: How did the mangrove forest cover change in Vanuatu?
    a) Estimate the extent of mangrove area changes from 2001-2017.

b) Analyse the greenness change in mangrove cover from 2001-2017

- RQ2: What are the vulnerable mangrove forests in Vanuatu?

a) Review available literature and use expert opinion to identify drivers of change of mangrove forests

b) Using vulnerability modeling to model identified drivers of change, identify vulnerable mangrove areas in Vanuatu.

1.5 Organization of the study

This study is presented in six chapters. **Chapter 1** involves the background of the study, justification for the study and the research questions. **Chapter 2** of the study includes a literature review of relevant information and key concepts that sets the premise for the study. It provides a description on the study area and its mangroves, research done till date on mangrove monitoring in Vanuatu, and threats facing mangroves and the current conservation strategies in place for mangroves in Vanuatu and the vulnerability framework. **Chapter 3** of the study provides the theoretical framework for using remote sensing to study mangroves, an overview of the suitability of remote sensing and geospatial tools and algorithms used for mangrove research. **Chapter 4** provides the research design and methodology used to answer each research question. **Chapter 5** describes the analyses in detail along with the results of the mangrove delineation and change identification and results of vulnerability modeling for Vanuatu's mangroves. **Chapter 6** provides the limitation and identifies the future policies that are impacted by this research. **Chapter 7** concludes by summarizing the research findings and providing recommendations for further research.

Chapter 2: Literature Review: Mangroves and Vulnerability Framework

The first part of this chapter provides addresses the key concepts of this study. This chapter also describes the conceptual frameworks relevant for this study through lens of eco-geographical hierarchical theory, sustainable livelihood and disaster management framework. This chapter also involves a literature review of the studies up to date at Vanuatu and identifies the data gaps and limitations of the previous research.

2.1 Mangroves: Definition and Distribution

Even until recently scientists have not accepted a unanimous definition for mangroves (Maxwell, 2015) . However, for this research, mangroves will be defined according to (Duke & Schmitt, 2016) as

"a tree, shrub, palm or ground fern that is generally higher than one half-metre in height, and normally grows above mean sea level in the intertidal zone of marine coastal environments and estuarine margins".

This definition is also one of the most widely used definitions globally (FAO, 2007; Giri et al., 2011; Maxwell, 2015). Thus, the term mangroves have been used to define the trees living in the inter tidal zone along with the communities they form (Tomlinson, 1994). Thus, the term 'mangrove', 'mangrove forest', or *mangal* has been interchangeably used with the habitat. This study will focus on the 'mangrove forest' as an intertidal community of trees and plants that can be distinguished by remote sensing.

At a global scale, mangroves are distributed in the inter-tidal region between the sea and the land in the tropical and subtropical regions of the world largely between 30° N and 30° S latitude (Giri et al., 2011). These forests are known to be delimited by major ocean current and 20° C isotherm of seawater in winter and are typically distributed from mean sea level to highest spring tide (Alongi, 2009). Mangroves grow in extremely harsh environments like high salinity, high temperature, extreme tides, high sedimentation and anaerobic soils (Giri et al.,

2011) and fringe the transition zone between sea, land, estuaries, and reef environments. (Spalding et al., 2010)

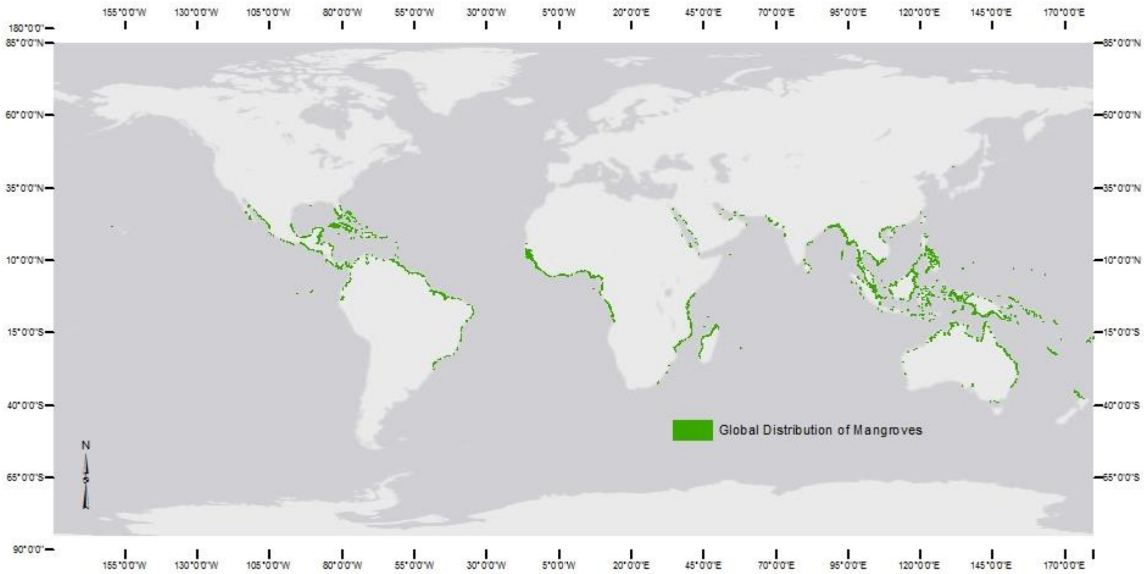


Figure 1 Global distribution of mangroves, mangroves shown in green. (Giri et al 2011; Data source: http://data.unep-wcmc.org/datasets/4).

Giri et al. (2011) is the first study to estimate the area of world mangroves from ~110,000 to 240,000 km^2 (Figure 1). At regional scale, mangroves are influenced by the landforms of coastal regions (Twilley, Rivera-Monroy, Chen, & Botero, 1998). The landforms have characteristic and complex interactions like rainfall, sea level, sediment dynamics and natural disasters which further influence mangroves (Alongi, 2002). At the local scales, mangroves can be said to be influence by the chemical and hydrological patterns of the soil (Twilley 1996). All these different factors together can be used to integrate environmental factors influencing community mangrove structures and spatial patterns of mangroves (Twilley et al., 1998).

2.2 Mangroves: An Undervalued Resource

Mangroves traditionally have been thought of as ‘swamps or wastelands’ with little value. This resulted in many mangroves worldwide being converted to agriculture, aquaculture, urban development, overharvesting for fuelwood and timber and other anthropogenic activities (M.

Spalding et al., 2010; Valiela et al., 2001). However, the last two decades have seen an increasing work on disseminating information on the important ecosystem good and services provided to humans by mangroves.

As per the (Millenium Ecosystem Assessment, 2005), mangroves provide many provisional, supporting, regulating and cultural services to human (Figure 2).

Provisioning Services Fisheries	Cultural Services	Regulating Services	Supporting Services
• Fisheries • Aquaculture • Construction material • Fuelwood • Tannins • Honey • Traditional medicine • Paper • Textiles	• Mangrove tourism • Educational • Recreation • Spiritual	• Nursery habitats • Sediment trap • Coastal protection • Shoreline stabilisation • Climate regulation • Bioremediation	• Carbon sequestration • Nutrient recycling • Biodiversity maintenance • Water filtration • Pollution regulation

Figure 2 Main ecosystem services provided by mangroves. Source: (Webber et al., 2016b)

This literature review will provide an overview of ecosystem services provided by mangrove forests and focus on specific ecosystems services which are relevant to this study. Webber et al. (2016) and Lavieren & Spalding (2012) provide a good review of ecosystems services provided by mangrove forests.

Mangroves are known to provide habitat for a wide variety of organisms and juvenile fish that play an important role in maintain coral reef ecosystems(Ellison & Fiu, 2010; Mumby et al., 2004; Nagelkerken et al., 2000). Although the exact functional linkages between mangroves and mangrove dependent in-shore fisheries and pelagic fisheries are known, mangroves are known to be nursing habitats for many commercial fisheries (Alongi, 2009). They are also known to provide other regulating services like water filtration (Alongi et al., 2003) and pollution regulation (Primavera, 2005; Walters et al., 2008). They also provide provisioning ecosystem services like aquaculture (Primavera, 2005), pharmaceutical production (Maxwell, 2015), timber and fuelwood (Walters et al., 2008) and cultural services like recreation and tourism (Brohman, 1996) and educational and cultural values (Webber et al., 2016a).

Mangroves also play a special protective role from natural disasters. Harada et al. (2002) was one of the earliest studies to establish the role of mangroves as an effective barrier against tsunamis. After the Asian Tsunami of 2004, Hurricane Katrina of 2005 and Typhoon Haiyan of 2013 many studies were focussed on the services mangroves provide like coastal protection through reduced flood risk, infrastructural damage and mortality with a general consensus on that the level of protection is dependent on multiple factors like the height of the wave, the area of the mangrove forest and the mangrove species (Alongi, 2007; Atkinson et al., 2016; Chatterjee, 2004; Chatterjee et al., 2008; Kongapai et al., 2015; Spalding et al., 2014). Although there are still debates about the effectiveness of mangroves as natural barriers, there is a consensus within the scientific community that mangroves do reduce the wave action (Giri, 2016; Maxwell, 2015). Recently in the World Risk Report 2017, Dr. Michael Beck, Lead Marine Scientist for The Nature Conservancy has said, *"Mangroves can reduce flood risks to people and property by 25% every year".*

Mangroves have also been known as land builders for some time now and there have been many global studies studying their sediment accretion and loss rates (Maxwell, 2015; Tran Thi et al., 2014)Taking into consideration the IPCC's predicted increase in global sea level rise from 0.15 m in 2000 to 1.0 in 2100, mangroves play an important role in coastal areas and SIDS as they are known to enhance sedimentation and assist in shoreline stabilization (Alongi, 2007; Gilman et al., 2006; Tran Thi et al., 2014). Souza Filho et al. (2006) showed that a mangrove shoreline is a good geoindicator of global coastal change. Mangroves are also helpful to detect short term changes of beach erosion and accretion, changes in sea level, waves and currents as they are found in tidal settings through remote sensed imagery easily showing accurate position.

As of April 2018, the global average atmospheric carbon dioxide (CO_2) rose to 409.46 part per million (ppm) (ESRL/NOAA 2018) In such times of increasing atmospheric carbon dioxide mangroves play an important role in carbon sequestration as they could sequester 22.8 million metric tonnes of carbon each year (Giri et al., 2011). Coastal ecosystems like mangroves, saltmarshes and sea grass are known to sequester carbon within their underlying sediments, within their living biomass (leaves, stems, branches and roots) and within non-living biomass like litter and dead wood (Chmura et al., 2003; Duarte et al., 2004; McLeod et al., 2011). Blue carbon is sequestered over a short term (decennial) within biomass and in long term (millennial) within sediment (Duarte et al., 2004). Although they occupy a much smaller area than terrestrial forests, mangroves' contribution to long term C sequestration is comparable to other ecosystems types (**Error! Reference source not found.**).

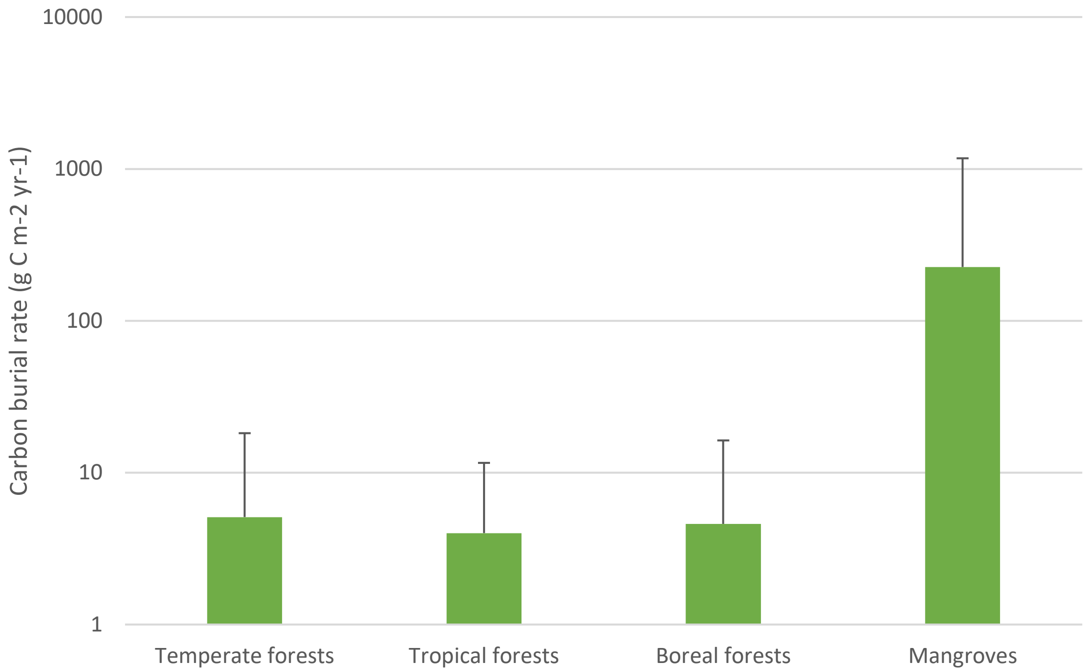


Figure 3 Mean long-term rates of carbon sequestration in soils in terrestrial forests and sediments in mangroves. Error bars indicate maximum rates of accumulation. The y axis is presented in the logarithmic scale. Data source: McLeod et al. (2011)

Studies have shown that loss of mangroves to anthropogenic activities not only results in the release of C as result of the removal of the forest but also more importantly the release of C in the sediments through oxidation (Sweetman et al. 2010; Donato et al. 2011).

Preliminary estimates state around 10% of global carbon emissions due to global deforestation are a resultant of mangrove loss despite accounting for just 0.7% of tropical forest area (Donato et al., 2011). Safeguarding mangroves can prove valuable even economically through carbon offsets for a developing country. Siikamäki et al. (2012) showed that majority of the potential global emissions can be avoided at a cost at roughly $4-$10 ton-1CO2 with the largest potential for the Asia Oceania region comprising two thirds of the global offset availability.

2.3 Drivers of mangrove change

The primary threat to mangroves worldwide are the conversion of mangrove habitat to and over exploitation of resources (Valiela et al., 2001). More than 52% of total mangrove loss by conversion of mangrove habitats has been attributed to be due to mariculture (38% shrimp culture and 14% other aquaculture, Valiela et al. 2001). Other pressures include to urban and agriculture expansion, industrial pollution (Polidoro et al., 2010), extraction of fuel wood, tourism and conversion to agriculture (Primavera, 2005; Spalding et al., 2010; Valiela et al., 2001; Webber et al., 2016a). Studies have also shown destruction of mangrove habitats due to interception of fresh water through changes in river basins and use of herbicides for 'mangrove control' (Valiela et al., 2001).

Another major threat to mangroves is climate change (Gilman, et al., 2006; Lavieren & Spalding, 2012; Webber et al., 2016a). The IPCC projects the global mean sea level increase of 0.09 to 0.88 m between 1990 and 2100 (IPCC, 2001). Mangrove areas most vulnerable to sea level rise are agreed to be low-relief carbonate islands, with a low rate of sediment supply as well as those in dry arid or sub humid regions (Webber et al., 2016a). Studies have shown that despite local and regional variance in mangrove response to sea level rise on average, mangrove will gradually move landward and the seaward margins die off if the pace of sea level rise allows it (Alongi, 2007). Along with sea level rise, the sediment budget available to mangroves to counteract the rising sea levels is an import factor that will affect mangroves. The sediment budget will further be influenced by land-use changes, dams, groundwater usage, petroleum and gas exploration which will affect the below sediment salinity levels and other geo chemical processes of the substrate available (Godoy & De Lacerda, 2015). Other climate change related changes like changes in air and sea temperature, stresses from storms variations in precipitation level can also adversely affect mangrove forests (Webber et al., 2016a).

2.4 Study Area: Vanuatu

2.4.1 Environment and development context

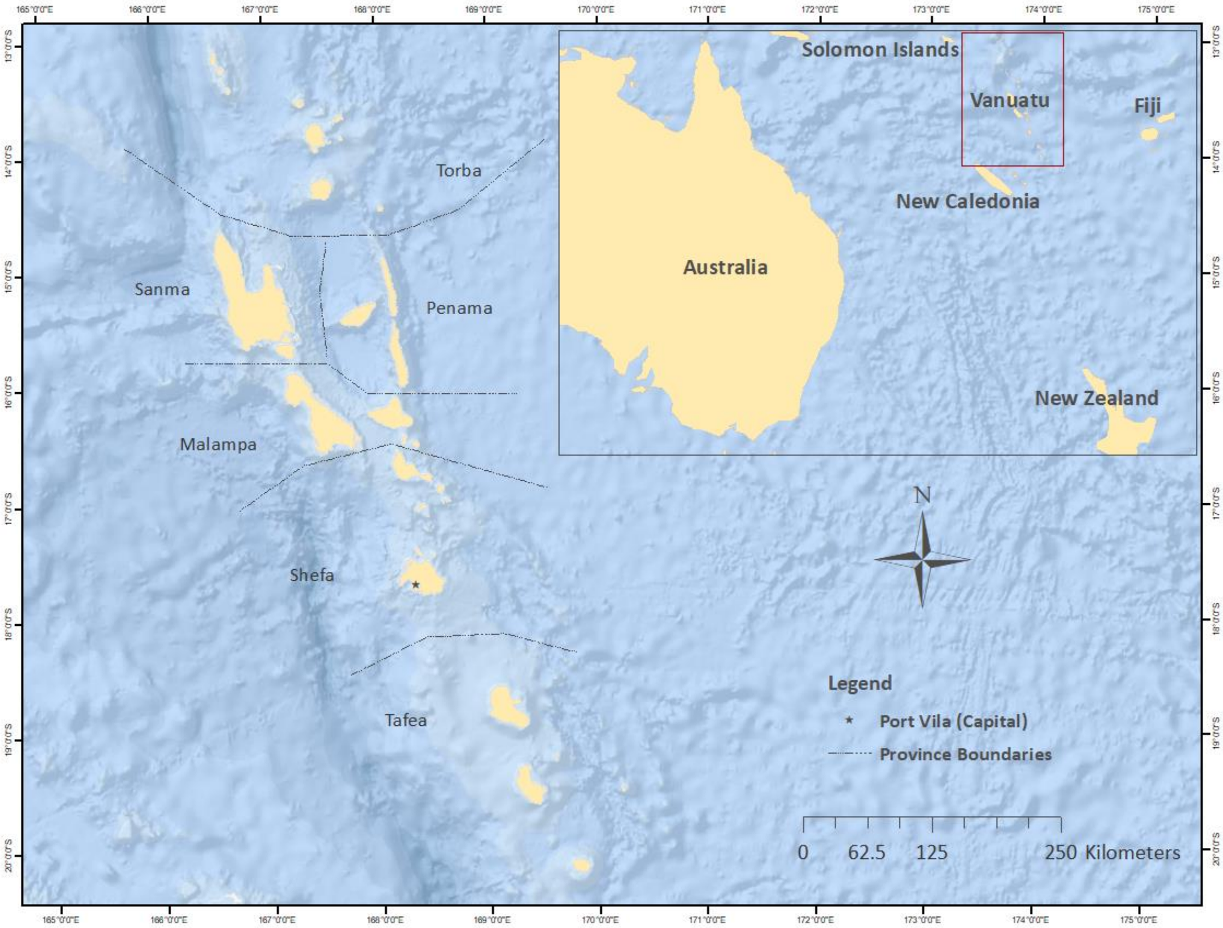


Figure 4 Location of Vanuatu

Vanuatu is an archipelagic nation located in the South Pacific Ocean and is located from 1,750 kilometers east of northern Australia, 500 kilometers northeast of New Caledonia, and south of the Solomon Islands, near New Guinea Figure 4. It is composed of 83 islands with a total land area of 12200 square km in a north south direction between the equator and the tropic of Capricorn (Republic of Vanuatu, 2017b) with a current population of 272,459 (Vanuatu National Statistic Office, 2017). 73% of these volcanic origin islands are forested and approximately 75.13 % of the population live in rural areas which are often on remote islands of the archipelago (Vanuatu National Statistic Office (VNSO), 2017).

Although small Vanuatu is highly culturally diverse with 108 living languages (Republic of Vanuatu, 2017b). Most ni-Vanuatu (i.e. indigenous Vanuatu people) communities are involved in subsistence farming and derive their income from copra agriculture, fishing, cattle rearing, logging and tourism. In the case of economy, the service sector is the dominant sector. The smaller industrial and agricultural sector have started a slower expansion. A large part of the agriculture is informal driven by the rural community (Republic of Vanuatu, 2017b).

Vanuatu has a high degree of biological diversity and endemism and is recognised as one of the biodiversity hotspots of the world (Critical Ecosystem Partnership Fund, 2012). The high reliance of the country on its natural resources for livelihood, along with increasing pressures of urbanization and population growth of 2.3% pa (Vanuatu National Statistic Office (VNSO), 2017) has resulted in threatening this biodiversity. One of the main problems facing Vanuatu is the depletion of its key species like mangroves, invasive species, unregulated land use change practices which affect the surround erosion and coral reefs, loss of biodiversity and climate change (Republic of Vanuatu, 2017b). Compared to surrounding pacific islands Vanuatu has not faced high deforestation due to its rugged topography. However, it faces risks form future timber logging, land clearing for agricultural areas and lowland islands.

The 2012 United Nations report ranked Vanuatu as the highest risk country in the world and is still considered the highest risk country (Beck et al., 2012; Kirch et al., 2017). Vanuatu is vulnerable to a range of natural disasters especially accelerated sea level rise, ocean acidification, extreme weather events, saltwater inundation and intrusion of coastal land and groundwater, reduced availability of fresh water etc (Secretariat of the Pacific Community, 2015). All these changes will have major influence on the mangrove forests of Vanuatu (Ellison, 2000; Secretariat of the Pacific Community, 2015).

2.4.2 Importance of Vanuatu's mangroves

Pascal and Bulu (2013) conducted an ecosystem evaluation of mangrove systems on two islands, Malekula and Eratap and calculated that the mangroves produced ecosystem services worth (US$4300 per year per hectare) in Crab Bay and US$8500 per year per hectare in Eratap in 2012. The study valued the services like carbon sequestrated, proteins from subsistence fishery, commercial fishery, recreational fishery, extraction of wood, coastal protection, avoided costs from coastal protection against flood, revenue from mangrove tourism Figure 5.

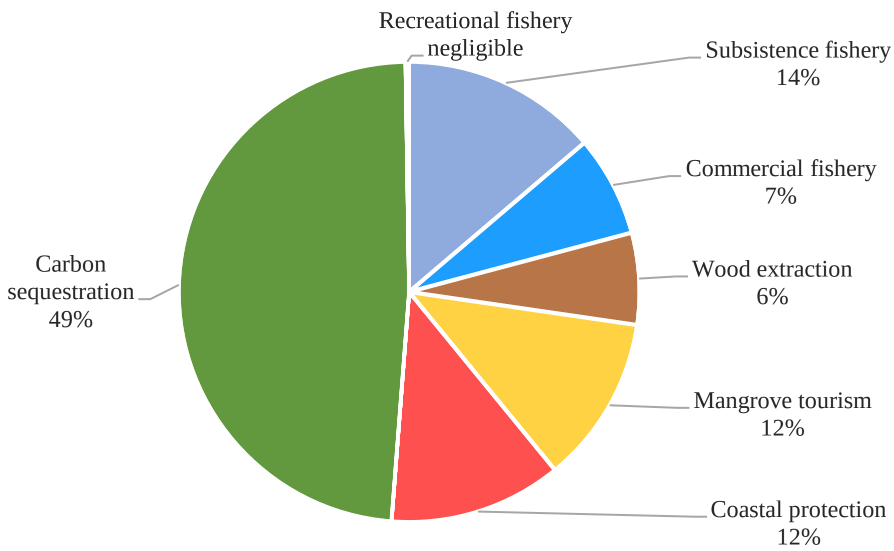


Figure 5 Distribution of estimated average value of services provided by mangroves on the two islands of Malekula and Eratap surveyed. This data is modified for representation. Source: Pascal and Bulu (2013)

Globally, Vanuatu's mangroves sequester approximately 17,000 tonnes of CO_2 per year worth approximately US$ 1.4 million per year (including seagrass) (Pascal et al., 2013). Locally, the importance of Vanuatu's mangroves to ni Vanuatu can be emphasized as 30% of the households rely on their coral reefs and mangroves for their daily protein intake (Pascal et al., 2013). Pascal and Bulu (2013) noted that mangroves contributed to 5-30% coastal protection in their study sites in Vanuatu based on variable of geomorphology and coastal exposure. Mangroves are also known to be used in traditional medicine and customary practices of the community like marriages etc. Researchers of the MESCAL project tried to record such uses but were met with secrecy from the community (MESCAL, 2013a).

2.4.3 Description of Vanuatu's mangroves

In Vanuatu, the latest estimate of mangrove cover nationally was done in the year 2000 amounting to around 1378.17 hectares using remote sensing (Bhattarai & Giri, 2011). A draft report by Gilman, et al. (2006) based on an interview with a forestry officer reported the total area of mangroves on the islands as 2430 hectares Table 1. However, the methodology of this data collection is not reported. Another estimate of national mangrove area reported in Vanuatu is 2051 hectares (M. Spalding et al., 2010)**.** However, the methodology and year of the data analysed was not reported. As you can see, there is no current reliable estimate of the country's mangrove resource. Different studies based on differing data sources and methods have provided values that range from 1300 hectares to 25000 hectares. Most of these studies were also conducted at a regional scale or a global scale and not specific to Vanuatu. As a result, these results reported could be at a coarse scale.

Table 1 Estimates of mangrove area in Vanuatu

Study	**Reported National Mangrove Area (ha)**	**Year of data analysed**
David 1985	2460	1985
(FAO, 2007)	2519	1993
(Gilman, Van Lavieren, et al., 2006)	2750	2006
(Gilman, Ellison, Jungblut, Lavieren, et al., 2006)	2430	2006
(M. Spalding et al., 2010)	2051	1993-2004
(Bhattarai & Giri, 2011)	1378.17	2000

There is consensus that the largest area is found on the island of Malekula distributed primarily between two areas Crab Bay/Port Stanley in eastern Malekula and the Port Sandwich/ Maskelynes Archipelago area in the southeast (Veitayaki et al., 2017). Although only 1% of the area of Malekula is covered by mangroves, it is known to represent approximately 80-90% of the mangroves found (Gilman, Ellison, Jungblut, Lavieren, et al., 2006; MESCAL, 2013a). The remaining islands that are known to have mangroves are shown in Table 2. However, it must be noted that these values do not correspond to the latest estimate and are the best available estimates of the possible distribution of mangroves.

Table 2 Spatial extent of mangroves on islands of Vanuatu as reported by Gilman et al 2006.

Island	**Area of mangrove (ha)**	**Area of island (ha)**	**% total mangrove area on island**
Malekula	1,975	205,300	81.3
Hui	210	5,280	8.6
Efate	10	92,300	0.4
Emae	70	3,280	2.9
Epi	60	44,500	2.5
Vanualava	35	33,100	1.4
Ureparapara	30	3,900	1.2
Motalava	25	3,100	1.0
Aniwa	15	800	0.6
Total	2,430	391,560	

Mangroves are primarily observed in the northers islands of Vanuatu and are found around the river mouths, inlets and lagoons (Veitayaki et al., 2017). Vanuatu is an island of volcanic origin which restricts its mangroves due to steep sloped and restricted tidal flats (Veitayaki et al., 2017). Vanuatu is known to have 23 mangrove species which account for 32% of the globally known species (Baereleo et al., 2013). The most common species of mangroves. The dominant mangrove assemblages seen in the south islands of Vanuatu are *Bruguiera gymnorhiza*, *Rhizophora* species, *Ceriops tagal*, *Xylocarpus granatum* and *Avicennia marina* (Baereleo et al., 2013).

2.4.4 Review of mangrove studies done in Vanuatu

The available data for mangroves in primarily Pacific region specific and not on a national scale. The majority of studies conducted on mangroves studied the distribution of mangroves in the Pacific (Bhattarai & Giri, 2011; Gilman, Lavieren, et al., 2006; Veitayaki et al., 2017). There are also ecosystem valuation studies conducted at Pacific islands scale (Atkinson et al., 2016). The UNEP commissioned study noted that of all the Pacific Islands Vanuatu faired comparatively poorly in baseline information on its mangroves. Vanuatu does not have a mangrove monitoring programme, there has not been site specific vulnerability assessments conducted (Gilman et al., 2006).

The main mangrove conservation work done in Vanuatu is through the Pacific Mangrove Initiative which aims at promoting sound management activities and capacity building. The initiative is a collaboration between IUCN, Secretariat of the Pacific Regional Environment Programme (SPREP), the UNDP and the six Pacific SIDS of Papua New Guinea, Solomon Islands, Vanuatu, Fiji, Tonga and Samoa. The initiative is delivered through two main projects in Vanuatu- the Mangrove Ecosystem for Sustainable Climate Change Adaptation and Livelihoods (MESCAL) project implemented in Fiji, Samoa, Solomon Islands, Tonga and Vanuatu and the Mangrove Rehabilitation for Sustainably Managed Forest (MARSH) (Veitayaki et al., 2017). The objective of the MESCAL project it to collect baseline information on mangroves. Another project with a focus on mangrove in Vanuatu is the Marine and Coastal Biodiversity Management in Pacific Island Countries (MACBIO) commissioned by German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) to Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) as part of International Climate Initiative, jointly implemented by SPREP, IUCN and GIZ from 2013 to 2018.

The available information on mangroves of Vanuatu are severely limited to the MESCAL project assessments on the islands of Efate and Malekula which included floristic and faunal surveys, shoreline assessments, fisheries surveys, socioeconomic surveys, traditional knowledge documentation and mangrove mapping on the two islands (Baereleo et al., 2013);

ecosystem valuation studies through the MACBIO project (Pascal & Bulu, 2013; Pascal et al., 2013), preliminary mangrove ecosystem health monitoring on Tanna island through visual surveys (Martin & Conolly, 2017); preliminary assessment of biomass and carbon content in mangrove (Norman Duke, Mackenzie, & Wood, 2013). This dearth in information on Vanuatu's mangroves are resultant of its many small islands that are spread across vast areas of ocean and their remoteness and limited infrastructure. There are two other studies that were done in relation to mangrove that the author is aware of – one that used GIS to digitize mangroves through Lidar imagery in 2012 and the other topic is unknown (Baereleo pers. comm). Despite repeated efforts to get in touch with the researcher of the first study, the author was not successful in accessing the research.

2.4.5 Change drivers

Indiscriminate harvesting of mangroves in rural areas for wood is one of the most common problems of Vanuatu. An ecosystem evaluation study of mangroves in Vanuatu reported the use of mangroves for firewood extraction in rural areas (Pascal & Bulu, 2013). Mangroves have also been lost on the island of Malekula to a logging project (MESCAL, 2013b). Development of tourism in Vanuatu is another major threat affecting mangroves. On Efate and adjacent islands, mangroves have been reclaimed for the development of tourism (MESCAL, 2013b). Mackenzie, Duke, and Wood (2013) note areas of mangrove degradation in Eratap Bay and Amal Crab Bay that looked like cutting of trees for timber. Expert opinion also highlighted the use of mangrove for fuelwood in Vanuatu.

However, there is still a data deficiency on the accurate extant of mangroves and the drivers of changes at Vanuatu. It is imperative for countries to have access and availability to timely and accurate database of mangrove changes, needed for resources planning, management, and reporting to international treaty and conventions (Giri, 2016).

2.4.6 Vanuatu's conservation strategies for mangroves

2.4.6.1 Institutional context

As the ecological boundaries of mangrove ecosystems do not necessarily remain within political and administrative boundaries or even strictly fall within sectors like fisheries or land use, the management of mangroves in Vanuatu is spread across a number of administrative levels with multiple policies being effective. There is no systematic governance of mangroves and the government relies on existing traditional mechanisms to address the mangrove management issues (MESCAL, 2013b). The Department of Environmental Protection and Conservation (DEPC) oversees all environment issues and the management of natural resources in Vanuatu. The Forestry Department is responsible for the mangrove trees as part of the coastal forests under the Forestry Act 26 of 2001.The mangrove land is regulated by the Ministry of Internal affairs (MESCAL, 2013b). The traditional form of management is still practised in Vanuatu in some provinces. According to these practices, the traditional village structure is headed by a leader 'chief' and the other supporters of the *nakamal* or the village court that oversees the management of marine resources. The government recognised the importance and value in safeguarding these practices and developed the Cooperative Management of Marine Resources Program in the 1990s (MESCAL, 2013b). Some of the most noted ones are the Uri, Narong, Wiawi, and Ringi Te Suh marine reserves on Malekula established in 1991 (Department of Environment and Conservation, Vanuatu). The successful management of the Amal-Krab Bay on Malekula is due to a committee set up to conserve marine resources in this *tabu* area involving the local community leaders. The *tabu* area was initially set up to protect the Amal bay crabs but also involved a ban in harvesting any resources within the mangroves (United Nations Development Programme, 2012). This includes any extraction of live or dead mangroves from the *tabu* area which are subject to fines of approximately USD 53(United Nations Development Programme, 2012). Similar management was attempted at other villages in Eratap but have failed mainly because villagers did not respect the rules (Pascal & Bulu, 2013). Pascal and Bulu (2013) hypothesize that the erosion of customary governance in these sites is a result of the village's proximity to Port Vila and the settlement of people from outside the community. Thus, the management of mangroves in Vanuatu does not have specific structural organisation and is in the hands of multiple agencies.

2.4.6.2 Policy Context

Currently at a national level, there are no policies that address mangroves specifically in Vanuatu. The forestry policy addresses the use and protection of mangroves as a part of the wetland (MESCAL, 2013b). However, there is a plan for the Integrated Coastal Zone Management Adaptation Plans (ICZMA Plans) to enhance resilience of coastal ecosystems to climate change which is expected to also develop mangrove management plans as one of its deliverables (MESCAL, 2013b). At a regional level, Vanuatu is a signatory of the Pacific Mangroves Charter to commit to the conservation of mangroves forests which is the first regional agreement to collaborate in the conservation of this resource (Seale, 2014). The Ramsar Convention on Wetlands is one of the most important and international convention dedicated to preserving mangroves and other wetlands. This is an intergovernmental treaty, which provides the framework for national action and international cooperation for the wise use of wetlands and their resources. Vanuatu has no current Ramsar designated wetlands. However, the accession was supposed to be completed by the second half of 2017 (Ramsar, 2017).

2.5 Vulnerability framework for mangroves

A meta study of 129 article on vulnerability studies of ecosystems has shown that vulnerability analysis of natural systems increases the efficiency of ecosystem assessment and management

(Weißhuhn, Müller, & Wiggering, 2018). The literature consensus is that vulnerability has 3 primary dimensions: 1) exposure -the probability of a hazard; 2) sensitivity – measure of susceptibility ; 3) adaptive capacity – ability to cope with hazard (Weißhuhn et al., 2018). Figure 6 these aspects can also be tied strongly to resilience. Vulnerability analysis for ecosystems has been described as method to understand the weakness of the system in relation to potential harm (Wisner et al., 2004) and is defined as a potential for loss (Adger, 2006). Conservation of ecosystems involve ecosystem management that aims to reduce the stressors to the system and keeps a desirable level of functioning. Vulnerability assessments of ecosystems need to be communicated to indicate vulnerable hotspots for conservation practitioners and policy makers (Weißhuhn et al., 2018). In this regard, using GIS tools to provide information spatial models of vulnerability are useful. (Ellison, 2015) exemplified how these three dimensions of vulnerability apply to mangroves and how vulnerability can be measured by looking at tidal range and relative sea-level trends relating to exposure; mangrove forest health and elevations within the mangroves relating to sensitivity and; mangrove protection status and local management capacity relating to adaptive capacity. Zulkifli et al. (2018) identified multiple criteria that are interdisciplinary by analysing response to social and ecological changes in the environment.

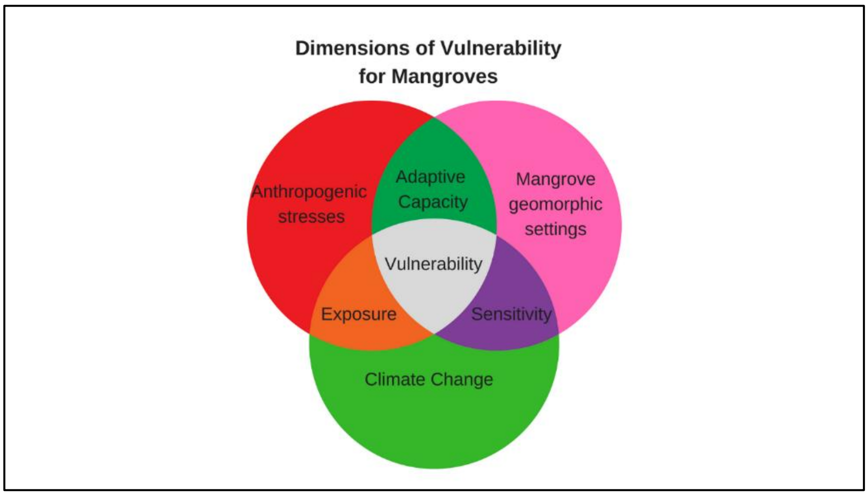


Figure 6 Vulnerability framework for mangroves developed for this study

Chapter 3: Overview of Remote Sensing and GIS application for mangrove assessment

3.1 Theoretical framework

Ecologists have studied mangrove ecosystems as having hierarchical organisations (Feller et al., 2010) based on the hierarchical theory (Twilley et al., 1998). This theory explains the relationship between ecological processes and their spatial and temporal patterns observed. This theory helps simplify the complex phenomena at a specific level of space and time to better understand the system. These eco-geomorphic hierarchical levels of mangrove ecosystems will be used as a guide while using remote sensing to study the mangrove ecosystem at various scales (Figure 7).

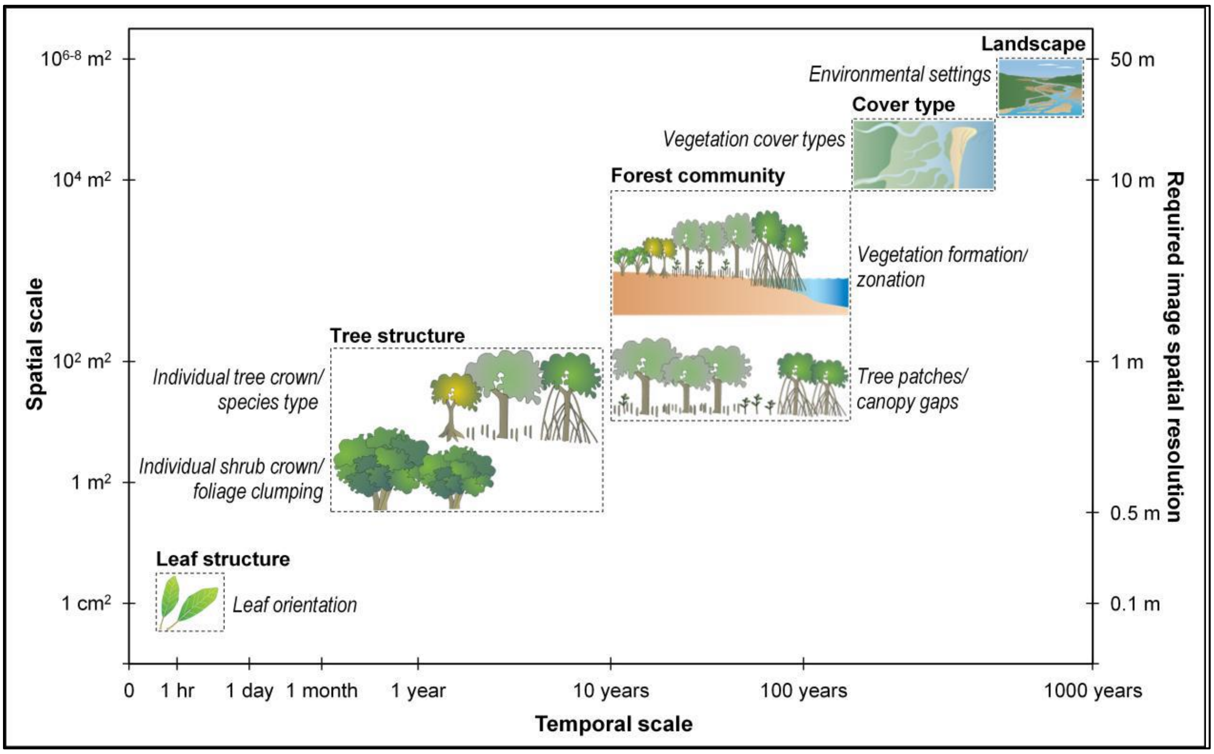


Figure 7 Conceptual temporal and spatial hierarchical organization of mangroves features identifiable from remotely-sensed images, and the required image pixel resolution for mapping the features. Source: Kamal (2015)

Mangrove areas are generally found in harsh environments with hard access which make ground surveying and field observations difficult, laborious and costly. Tidal changes in these areas make it even more cumbersome logistically for regular monitoring. Remotely sensed data are particularly considered advantageous as they provide spatial and temporal information which are easier to obtain. Thus remotely sensed data can be an appropriate tool for mangrove ecosystem studies which can reveal patterns of change that affect ecosystem dynamics (Kamal, 2015). Use of remote sensing has also been studied to be more cost effective in comparison to other methods for monitoring and management coastal wetlands with an accuracy of 70% (Mumby et al., 1999).

3.2 Remote sensing and GIS: Overview of technology

Remote Sensing is can be defined as "the acquisition of information about the state and condition of an object through sensors that are not in physical contact with it" (Chuvieco & Huete, 2010). The term was first utilized in the 1960s, to observe the Earth from a distance primarily using aerial photographs. However, the term has now expanded to the operation of different sensors and satellite systems, data acquisition and storage, data processing, analyses and interpretation of the results (Chuvieco & Huete, 2010). In brief, the technology is dependent on the sensors or satellites which detects the energy in the form of electromagnetic radiation that is reflected from the surface of the earth. In remote sensing, the earth's surface receives energy directly from the sun or from an external self-emitted sensor. The vegetation, soils, water, landforms and other man-made structures interact with this energy due to their physical and chemical composition and reflect a part of the energy, which is detected by the sensor. The sensor measures and records this energy in different bands which is transmitted back to receiving stations on the ground for data processing.

Remote sensing is integrated with geospatial technology like Geographic information system (GIS) and global positioning system (GPS). GIS provides tools to and a flexible environment for the processing and storing and displaying of the digital data from remote sensing. Many software has been created to help a user develop the GIS database and organise and analyse the imagery. Some of the software used in the study are ENVI®, Arc GIS®, Google Earth Pro® and Arc GIS Pro®.

ENVI Ver 5.4[1] (Environment for Visualizing Images) is a widely used commercial software application to process and analyse geospatial imagery by remote sensing specialists developed by Harris Geospatial Solutions. It was accessed through the University of Manchester student license. Arc GIS is another commercial software developed by Esri that is used for geospatial analyses and map developments.

3.3 Review of studies using remote sensing for mangrove research

Remote sensing has been widely accepted and considered to be a tool to monitor an map mangrove ecosystems in the last few decades (Kuenzer, Bluemel, Gebhardt, Quoc, & Dech, 2011). In mangrove studies, remote sensing has been used to study habitat inventories, change detection, ecosystem evaluation, productivity assessments, rehabilitation and restoration, water quality assessments, disaster managements, ecological functioning and dynamics and understanding historical extent with traditional ecological knowledge (Brown, Pearce, Leon, Sidle, & Wilson, 2018; Chatterjee et al., 2008; Kamal, Phinn, & Johansen, 2015; Kuenzer et al., 2011; P J Mumby et al., 1999; Onwuteaka, Uwagbae, & Okeke, 2016; Pascal & Bulu, 2013). These mentioned studies are not an exhaustive list and are only representative of all the ways remote sensing is used for mangrove research. Kuenzer et al. (2011) provides an exhaustive review of the methods and techniques used in remote sensing for mangrove research.

Table 3 provides a synopsis of the data and methods used to map mangrove extent, distribution and cover change which is the focus of this research.

[1] ENVI Ver 5.4. Issued 2010. Harris Geospatial Solutions, Boulder, Colorado.

Table 3 Overview of data and methods used to map selected mangrove studies*

Year	Author(s)	Image	Method	Biophysical properties
2017	(Abd-El Monsef, Hassan, & Shata, 2017)	Rapideye	Pixel based (veg indices)	Canopy cover, mangrove suitability area
2016	(Onwuteaka et al., 2016)	Landsat Pleides	Hybrid object based (CART based classification, veg indices)	Mangrove extent and mangrove conservation suitability area
2016	(Pasha, Reddy, Jha, Rao, & Dadhwal, 2016)	Landsat MSS Landsat TM Landsat ETM IRS P6 LISS III	Pixel based (visual changes)	Change detection
2016	(Dan, Chen, Chiang, & Ogawa, 2016)	Landsat TM Landsat ETM+	Pixel based (veg indices, support vector mechanism)	Change detection
2015	(Kanniah et al., 2015)	Landsat TM Landsat ETM+ Landsat 8	Pixel based (MLC and SVM)	Mangrove extent
2015	(Kamal et al., 2015)	Landsat TM ALOS AVNIR 2 Worldview 2 LiDAR Aerial Photographs	Object based (rule sets and NN classifiers)	Species composition
2015	(Kongapai et al., 2015)	IKONOS THEOS	Pixel based (supervised maximum likelihood classification)	Disaster caused changes
2015	(Srivastava et al., 2015)	IRS LISS II IRS LISS III	Pixel based (hybrid classification)	Climate change impact
2014	(Long, Napton, Giri, & Graesser, 2014)	Landsat	Pixel based (Decision tree classification)	Change detection
2014	(Tran Thi et al., 2014)	Landsat SPOT Aerial Photographs	Pixel based (veg indices)	Shoreline changes
2014	(Pagkalinawan, 2014)	Landsat 8	Pixel-based (ISODATA clustering with iterative labelling)	Mangrove extent
2013	(Kirui et al., 2013)	Landsat TM Aerial photographs	Pixel based (unsupervised classification)	Land cover change

2008	(Conchedda, Durieux, & Mayaux, 2008)	SPOT XS	Object based (rule sets and NN classifiers)	Change detection
2008	(Chatterjee et al., 2008)	IRS-LISS IV	Pixel based (supervised maximum likelihood classification)	Disaster caused changes

* this table is not a comprehensive list of literature on mangrove mapping using remote sensing datasets.

3.4 Characteristics for identifying mangroves using RS data

One of the key abilities to use remote sensed data effectively is to be able to recognize the features of the data used for further analyses. These features can be recognized based on spatial, spectral and temporal resolution. Mangroves have several characteristics which can be used to successfully interpret the data. A few of these characteristics involve zonation patterns, location, canopy textural properties and the specific reflectance characteristics of the canopy.

3.4.1 Zonation

Mangroves are known to exhibit zonation patterns based on spatial variation of dominating species (Duke & Schmitt, 2016; Spalding et al., 2010). Many of these communities also are known to exhibit succession of forests with time (Alongi, 2009). Some of the most widely reported patterns of zonation follow elevation patterns (Spalding et al., 2010). Besides elevation the nature and extent of these zones are also influenced by physio chemical properties like salinity, topography, tidal regime, sediment properties, water content, nutritional concentration. The zonation patterns are thus helpful descriptors but cannot be extrapolated to local specific areas as they vary dependent on the response (Spalding et al., 2010; Webber et al., 2016a). Classification is generally more successful too when the zone is dominated by a single species. Some studies have identified very detailed zonation patterns (Schaeffer-Novelli, Cintrón-Molero et al., 1990) whereas some have reported an absence of zonation pattern due to the biology of the system(Ellison et al., 2000). However, in this study the widely accepted zonation patterns of elevation will be used to study the extent of mangroves.

3.4.2 Texture

Canopy of mangroves are known to be more homogenous and smoother compared to other tropical forests. Thus, texture can also be used to identify mangroves. Texture is defined as *"the spatial heterogeneity of a given cover , that is the spatial contrast between the elements of which it is made"* (Chuvieco & Huete 2010 pp142). It provides us information about the tones of the image. A greater variation of reflectance will correspond to a rougher texture(Chuvieco & Huete, 2010).

3.4.3 Spectral signature

Mangrove forests are known to have a distinct spectral reflectance signature particularly corresponding to visible red, near infrared and mid infrared that is obvious through optical sensors (Giri, 2016; Spalding et al., 2010). Spectral reflectance signatures can be defined as "*the reflectance behaviour of an object over various wavelengths of the electromagnetic spectrum*" (Chuvieco & Huete 2010, pp33). Each object on the surface of earth has a distinct spectral signature as result of its physical and chemical properties. The value of spectral response of mangroves in mid-infrared is lower compared to other vegetation (Figure 8) (Pagkalinawan, 2014).

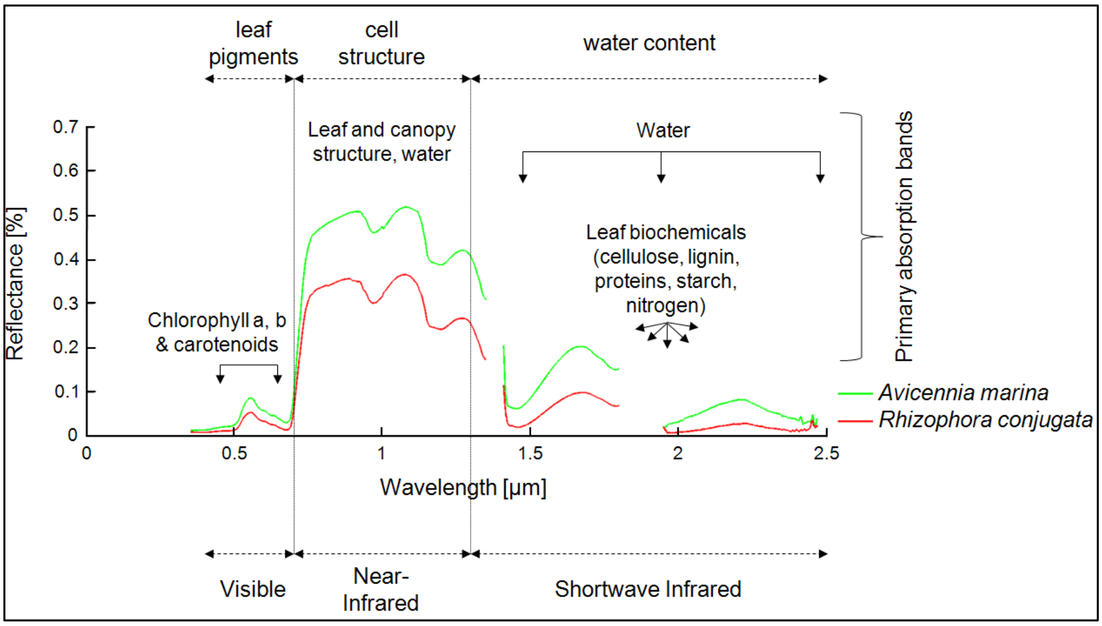


Figure 8 Spectral characteristics and their influencing parameters in mangrove species *Avicennia marina* and Rhizophora conjugate as measured with a field spectrometer in Ca Mau Province, Vietnam, January 2010 as observed by Jones et al. 2004.

There have been many studies that have utilised the mangrove's spectral reflectance to map mangrove ecosystems (Canto, 2011; Giri et al., 2011; Kamal et al., 2015; Kongapai et al., 2015; Sirikulchayanon et al., 2008). However, it has also been observed that the spectral reflectance of mangroves is also influenced by tidal effects on soils, distance of measurement, type of leaf structure resulting in mixed pixels (Díaz & Blackburn, 2003; Kamal, 2015). Díaz and Blackburn (2003) showed spectral variation in canopy properties are dependent on several factors like leaf area index, background inclination and leaf reflectance Figure 8. However, these spectral variations are only slightly different between species. Thus, it makes it difficult to identify between species without other identification techniques. However, as this study does not aim to classify mangroves at a species level, the spectral signature of mangroves can be effectively used.

3.5 Review of classification algorithms used for mangrove studies

Several studies have been carried out to identify the most suitable classification algorithms for mangrove mapping (Kuenzer et al., 2011). Classification is simply defined as the assignment of a given pixel or raw data to the appropriate class or category on a thematic map (Lillesand, Kiefer, & Chipman, 2004). Classification methods can be divided into parametric and non-parametric, pixel based or object-oriented, contextual or non-contextual (Lu & Weng, 2007). Lu & Weng (2007) have provided an exhaustive review of available classification algorithms and techniques for remote sensing data. For this study, only the most commonly observed classification algorithms for mangrove mapping will be discussed.

The pixel-based methods are the commonly used methods and have been traditionally further categorised as unsupervised and supervised classification. The unsupervised method defines the spectral classes based on clusters with similar spectral characteristics. The most common clustering algorithms used are the k means and the Iterative Self-Organizing Data Analysis Technique (ISODATA) clustering algorithm. An unsupervised classification is generally undertaken when there is no previous knowledge of study area (Chuvieco & Huete, 2010). However, a limitation of the unsupervised classification is that the spectral similarity may not necessarily identify the same cover as open/closed water and water logged urban area. Unsupervised classification may also produce more number of classes than expected with no meaningful differences.

The supervised classification is advantageous as the distinct categories and spectral signature of the categories are known prior to processing. However, this requires the analyst to have some prior knowledge of the geography of the area. The classification is done by creating a 'training field' on the computer which the computer then uses to categorize other pixels. The supervised classification is done using various algorithms like maximum likelihood, minimum distance, artificial neural network, decision tree classifier. The application of the supervised Maximum Likelihood Classifier (MLC) is considered one of the most widely used and robust methods of classification for mangrove mapping (Gao, 1998; Green et al., 1998; Kuenzer et al., 2011; Rasolofoharinoro et al., 1998; Tong et al., 2004). The MLC is a parametric method that assumes that statistics in each class is normally distributed and calculates the specific pixel value based on posterior probabilities. The smooth canopy structure and their distinctive spectral signature makes mangrove easily identifiable when classified as mangrove, non-mangrove vegetation and other terrestrial areas using MLC. These classification results have been highly improved by incorporating other bands like vegetative indices (Brown et al., 2018; Vaiphasa, Ongsomwang, Vaiphasa, & Skidmore, 2005), brightness index (Rasolofoharinoro et al., 1998), Support vector mechanism (SVM) has been proved to be popular for hyperspectral data. It is a non-parametric classifier and does not assume to model the distribution of the data. SVM separates the data into discrete predefined number of classes in a manner consistent with the training data (Mountrakis, Im, & Ogole, 2011)/ It divides the data by searching for the best margin known as the hyperplane between them through machine learning iterations. SVM is known to be promising even with a smaller training sample (Mantero, Moser, & Serpico, 2005). However, Kanniah et al. (2015) showed that MLC provided significantly higher user, producer and overall accuracy and lesser 'salt pepper effects' compared to SVM techniques.

A limitation of the pixel based methods is its inability to statistically represent a concept of an object or patch as a discrete spatial pattern (Blaschke & Strobl, 2001). Object-based classification or geographic object-based image analysis (GEOBIA) is another recently developed classifier algorithm (Burnett & Blaschke, 2003). This algorithm groups pixels that are similar to one another based on measures of spectral properties, size, shape and texture based on neighbouring pixels. The advantage of GEOBIA is that it can incorporate neighbourhood properties and counteract sensor limitations (Burnett & Blaschke, 2003). Conchedda et al. (2008) used GEOPBIA to map fragmented mangrove cover and change with high accuracy. Wang et al. (2004) used the GEOBIA approach to differentiate mangrove species using high resolution imagery. One of the limitation of using the GEOBIA method is the need for high resolution imagery which are generally not available freely.

Chapter 4: Methodology

This chapter explains how the research was carried out in detail. The entire research can be divided into three parts based on data collection, pre-processing of the data and the final analyses of the data.

4.1 Research design

The flow of the research is guided by the following research design **Error! Reference source not found.**. The research first identifies areas of mangroves and then develops a spatial multicriteria map to predict vulnerable mangroves.

Table 4 Research Design

Research Question	**Objectives**	**Steps**
RQ1: How did the mangrove forest cover in Vanuatu?	Ob1: Estimate the extent of mangrove area changes from 2001-2017	Literature review of all mangrove mapping in Vanuatu Collect historical data Collect remotely sensed data Supervised classification (Figure 9) Thematic map creation
	Ob2: Estimate the density of mangrove change from 2001-2017	
	OB3: Create a database of mangrove area at province and council levels	
RQ2: What are the vulnerable mangrove forests in Vanuatu?	OB1: Identify major drivers of mangrove change in Vanuatu	Literature review Statistics collection Consultation with experts and creation of vulnerability criteria Vulnerability maps creation using vulnerability modeling
	OB2: Develop a vulnerability model to identify vulnerable mangrove areas	

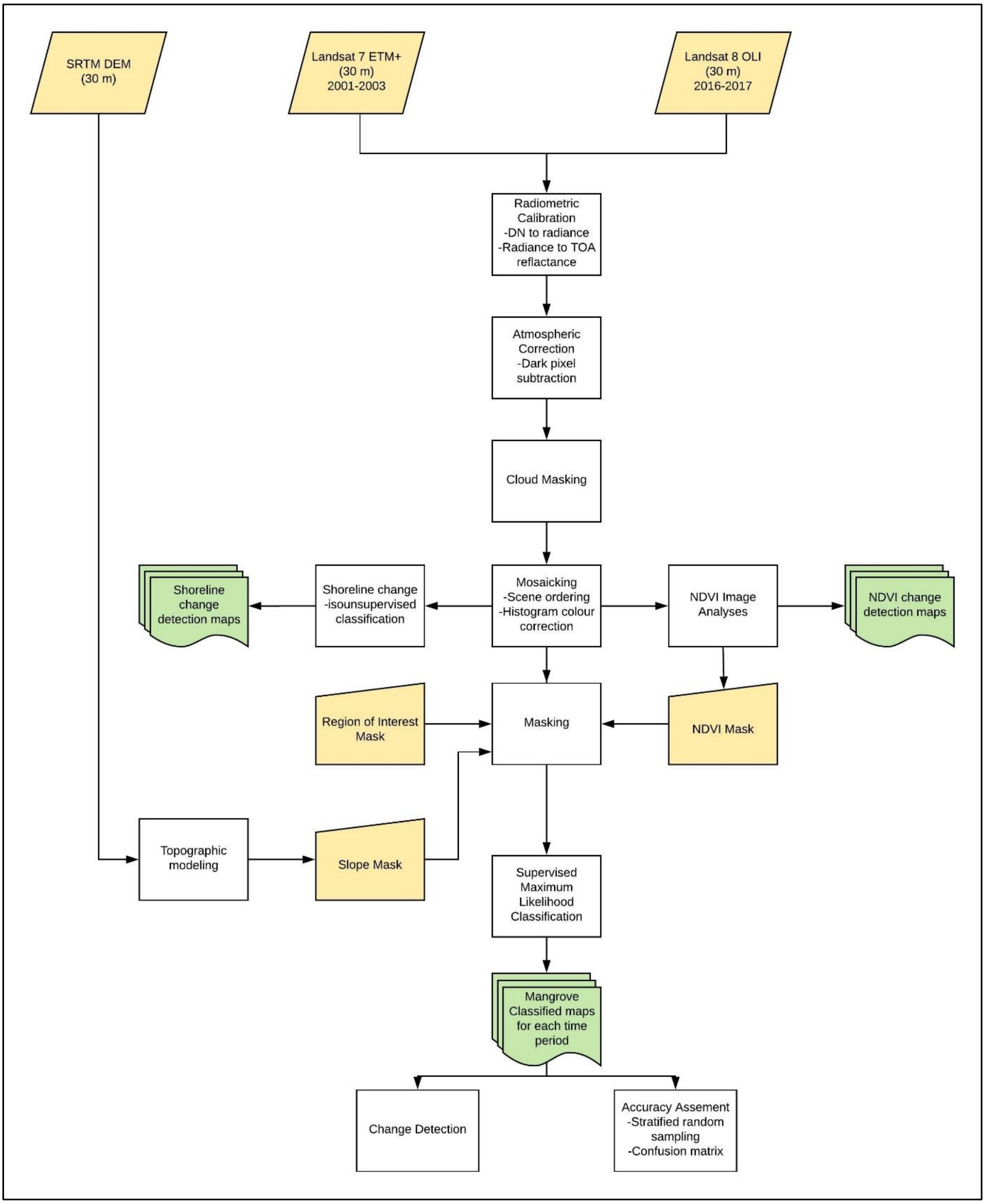


Figure 9 Remote sensing analyses methodological flowchart of RQ1

4.2 Data collection

The data collection step considered two main factors while conducting research- data that was freely available and data that was under usable spatial resolution of medium resolution.

Appendix A is a repository of data researched that is potentially accessible and can be used for future research processes.

4.2.1 Existing mangrove data

The present mangrove data was obtained by through literature review and talking with experts in the field. The current extent of mangroves in Vanuatu was found through the global mangrove database on Oceandata viewer.

4.2.2 Remotely sensed data for RQ1 and RQ2

As the study aims to accurately map current mangrove range in the country remotely sensed data was collected from U.S. Geological Survey Earth Explore online search. The imagery was collected for two periods: 2001-2003 and 2016-2017. Images for 2001-2003 were collected from Landsat 7 ETM+ and 2016-2017 from Landsat 8 OLI. The Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global data by National Aeronautics and Space Administration and the National Geospatial-Intelligence Agency provides worldwide coverage of void filled data at a resolution of 30 meters. Digital elevation model (DEM) data created by SRTM for the areas was downloaded from the USGS Earth Explorer website.

4.2.3 Vulnerability criteria data for RQ2

2016 census data (Ref) for RQ2 was collected from the Vanuatu National Statistics Office data repository. Data for the road layers was downloaded from OCHA website. The shoreline data was produced from the downloaded Landsat data in Arc GIS Pro which will be discussed in the following section.

4.3 Image pre-processing

The pre-processing of Landsat imagery was done using ENVI 5.4 radiometric and cloud corrections tools. The data was then mosaiced in ENVI using the seamless mosaic tool. As the mosaiced imagery was very large in size (22 GB), the data was reduced by using masks of elevation and removal of ocean pixel values to exclude areas not of interest using the extract by mask tool in Arc GIS Ver 10.2. The composite band tool was used to create multiple band raster dataset that are displayed as red green blue (RBG) composite to identify mangroves using various band combinations. Based on literature review and exploration of band combinations, a band combination of 4-5-6 for Landsat 7 and 5-6-7 for Landsat 8 was used.

4.4 Supervised Classification

All spatial data were projected to the Universal Transverse Mercator (UTM) WGS_1984 UTM ZONE_58S before analyses using Arc GIS. The cell size used for all analyses is 30 meters. Image classification toolbar from the spatial analyst extension in Arc GIS was used to created training polygons and signature file for supervised classification. The signature file was evaluated using statistics and scatterplots within the tool to be confident of spectral separability. The unsupervised isoclassification for shore line delineation was done in Arc GIS Pro using the classification wizard workflow tool. Classified imagery was further cleaned using majority filter in Arc GIS. Statistics of the classified mangroves was extracted using the summary statistics tool in Arc GIS.

4.5 Accuracy assessment

A stratified random sampling method for accuracy assessment was chosen and the results were analysed using a confusion matrix which provided the overall accuracy, user’s and producer’s accuracy and Kappa coefficient. The user’s accuracy can be defined as the probability that a point randomly chosen on the map will have the same landcover as in reality and producer’s accuracy is the probability with which a randomly selected point on the ground is correctly mapped. The Kappa coefficient ranges from 0-1 and takes into consideration if the results produced are significantly better than random chance where 1 accounts for perfect agreement and 0 for no agreement. The following equation is used to calculate Kappa coefficient (Congalton, 1991)

$$\widehat{K} = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i}^{r}(x_{i+} * x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} * x_{+i})} \quad (2)$$

Where $\widehat{K}$ is the KHAT statistic (an estimate of Kappa), r is the number of rows in the matrix, x_{ii} is the number of observations in row i and column i, x_{i+} and x_{+i} are the marginal totals of row i and column i, respectively, and N is the total number of observations.

4.6 Assessment of mangrove changes

The results of the classification were transformed into thematic mangrove maps to explore changes in mangrove forests. Change in the areas of mangroves was conducted by subtracting the classified image of the later time period from the classified image of the initial time period. It is one of the most common methods of change detection and has been used widely post classification methods (Chuvieco & Huete, 2010). Rate of change was calculated using the following equation

$$rate\ of\ change\ (R) = \left(\frac{1}{T_2 - T_1}\right) \ln\left(\frac{A_{i2}}{A_{i1}}\right) \quad (3)$$

Where R = rate of loss (ha/year); T1 is the initial time, T2 is the later time and Ai1 is area at initial time t1 and Ai2 are at later time t2.

The mangrove density change was analysed using the image analysis toolbar in ArcGIS to detect NDVI changes using threshold values. Maps were produced to showcase change in vegetation density from 2000 to2018.

4.7 Identifying vulnerable mangrove areas

The thematic map of mangroves created through supervised classification was then analysed using a combination of geospatial data layers and statistics to identify vulnerable mangrove areas. The parameters used for analyses which represented drivers of changes in these mangroves was based on literature review and expert opinion. The parameters used were distance from roads, elevation, number of households using firewood as a primary choice of cooking fuel and distance from shoreline. These parameters were spatially modelled after being given separate weights of importance and then calculated using the following algorithm that summed all the weighted parameters

$$CVI = \sum (X_i * N_i) \quad (4)$$

Where X is the individual parameter and N is the assigned weight. The spatial modeling was done in Arc GIS using the Spatial Analyst toolbox, Data management toolbox and Conversion Toolbox.

Chapter 5: Mangrove Assessment and Vulnerability modeling

This chapter describes the analyses and results for RQ1 which aims at delineating and understanding the changes in mangrove forests in Vanuatu. This chapter also describes the vulnerability modeling performed and the results.

The resolution of the data needed for remote sensing study is dependent on the purpose of the research. For this study, the satellite imagery used is the medium resolution imagery (MRSI) as it is ideal for mapping mangroves at a regional scale and has data spread over longer temporal extent. It also included several multispectral bands and near infrared and thermal and mid infrared bands which are highly used for mangrove classification. MRSI has also been widely used for change detection and assessment of damages and production of mangrove status maps (Kuenzer et al., 2011). As a result, there is a large database of studies that are foundational and have tried and tested methods. As this study did not intend to study mangrove at species level, the resolution of MRSI was sufficient. MRSI also provided frequent imagery within a season to be able to select best images which are cloud free. However, the frequency may not be sufficient to record some extreme impacts like tsunamis (Kuenzer et al., 2011). Image acquisition date is important for satellite imagery analyses as vegetation and crops are generally known to reflect differently in different seasons due to their phenological and temperature differences. Figure 10 provides the average climate differences seen in Vanuatu. Chuvieco and Huete (2010) suggest following the phenology calendar of vegetation to select optima times for discrimination. The study area's dominant mangroves are evergreen (Baereleo et al., 2013) and hence was assumed there are no leaf fall effects during the time series analysis.

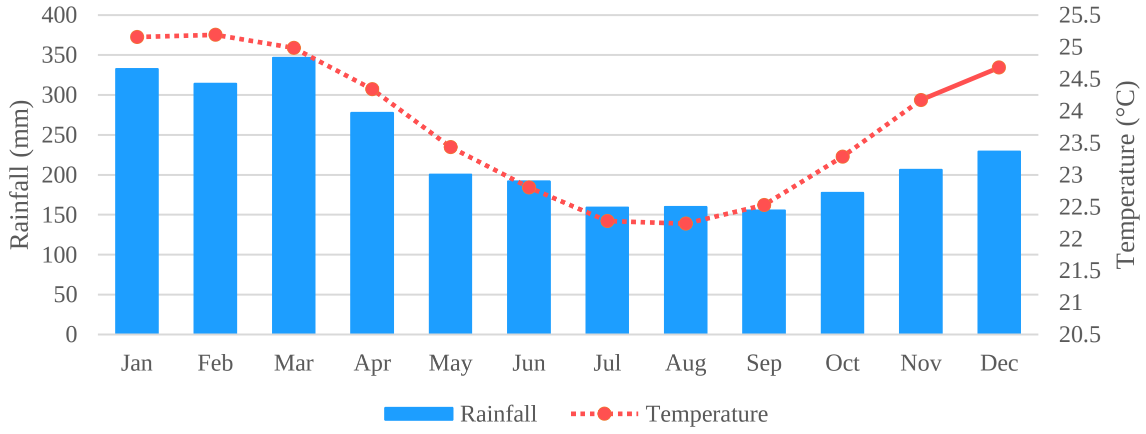


Figure 10 Average monthly temperature and rainfall for Vanuatu from 1901-2015. Data source: World Bank Data Portal (http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisCCode=VUT).

Most of the data collected is within the drier seasons to avoid cloud cover after the rains. Most other mangrove studies have also used the colder drier seasons to conduct analyses (Bhattarai & Giri, 2011; Giri et al., 2011). The positioning of the country in the Pacific and its climatic conditions made it necessary for the data to be acquired from other months in the year to avoid cloud covered data for analyses. Cloud free images were not available for the entire study area and only images with a cloud cover of less than 20% was used. As evergreen mangroves are not known to be highly different in their phenology during different times of the year (Sritharan persn comm), data from other times in the year was also considered for analyses. In all, 20 tiles were downloaded from the USGS earth explorer for analyses. Table 2 in the appendix provides detail characteristics of the Landsat imagery analysed. Each epoch from 2000-2003 and 2016-2018 consists of 10 Landsat scenes. Care was taken to review literature and use data from periods that did not have major storms or cyclones or major changes to group data into two epochs (Baelereo persn comm). Many mangrove studies have used datasets from multiple years to account for a single time period (Bhattarai & Giri, 2011; Giri et al., 2011; Kongapai et al., 2015).

5.1 Mangrove Delineation and Assessment

5.1.1 Corrections

Before analyses, it was necessary to pre-process the downloaded imagery to account for sensor, solar and atmospheric effects for time series analyses involving Landsat images that overlap large spatial and temporal scales (Figure 11). It was necessary to determine the right level of pre-processing for ecological analyses to ascertain that no further error was introduced into the data. Young et al. (2017) review of pre-processing Landsat imagery was used as a guide for the level of pre-processing needed in this study (Figure 12).

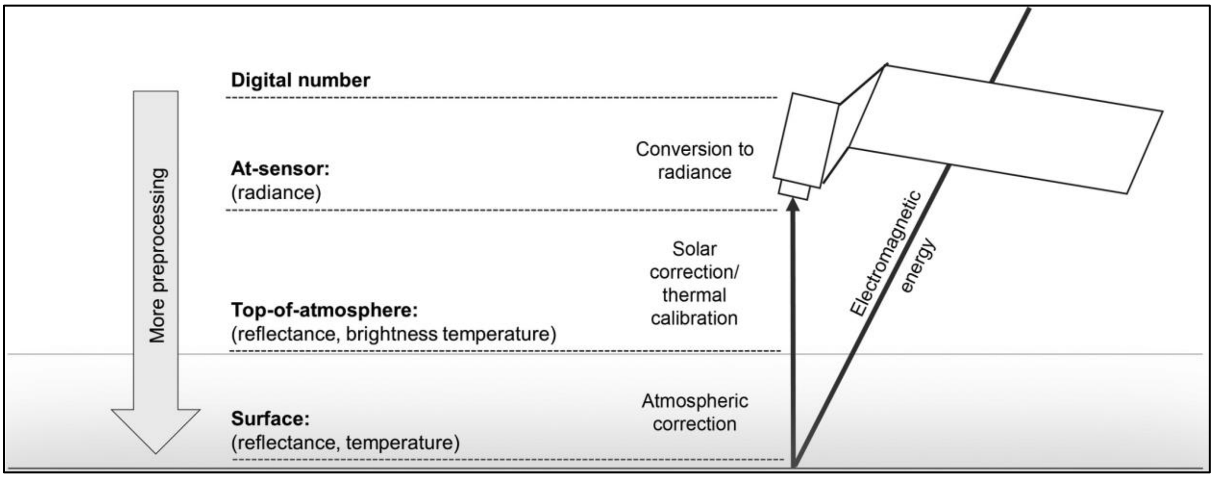


Figure 11 Common units of Landsat correction for ecological studies. Source: (Young et al. 2017)

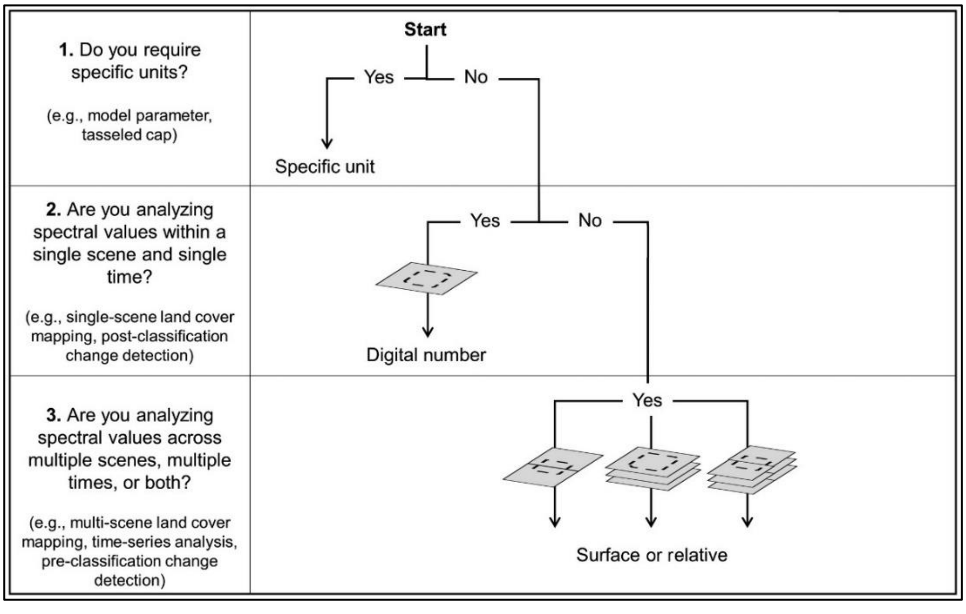


Figure 12 Decision tree used for determining the level of pre-processing for this study. Source: Young et al (2017)

Orthorectification was not conducted as all the data used for 2018 was in the L1TP format which is the most systematically terrain corrected processing. Even within the same Landsat scene, the earth-sun distance, and solar elevation angle vary with time, date and latitude. As a result, radiometric correction is needed to account for these discrepancies in pixel values. Radiometric corrections were conducted on ENVI 5.4 to standardize for light in the different satellite images times. Radiometric correction is done in two steps where digital numbers are corrected to radiance and then to the top of atmosphere reflectance (

Figure 11).

Landsat sensor's energy capture is also dependent on the Earth atmosphere and the effects it causes like scattering of light due to the presence of particles like dust, water vapour, gases and aerosols. To account for these effects during analyses atmospheric corrections are needed. However, accurate atmospheric corrections need measurements done during the satellite capture time. Thus, the simplest form of atmospheric correction was conducted in this study that does not need in situ measurements. The dark pixel subtraction is a method of atmospheric correction which assumes that some pixels in the image have zero reflectance like shadow, deep clear water and record the signal from those features is due to atmospheric scattering (Chuvieco & Huete, 2010). These dark pixel values are subtracted from all other pixel values as an assumption of atmospheric scattering effects. The dark object subtraction method was done using Envi 5.4 software to convert at satellite reflectance to on surface reflectance.

5.1.2 Mosaicking

Mosaicking was performed in ENVI using the seamless mosaic tool. To obtain optimal results the Landsat images were first ordered to avoid areas with cloud, and then histogram colour matched to a reference image to obtain similar values throughout the mosaic. The region of interest was then masked out for further analyses in Arc GIS Ver 10.2. Cloud masking was performed before mosaicking on individual Landsat tiles and will be explained further in the masking sections

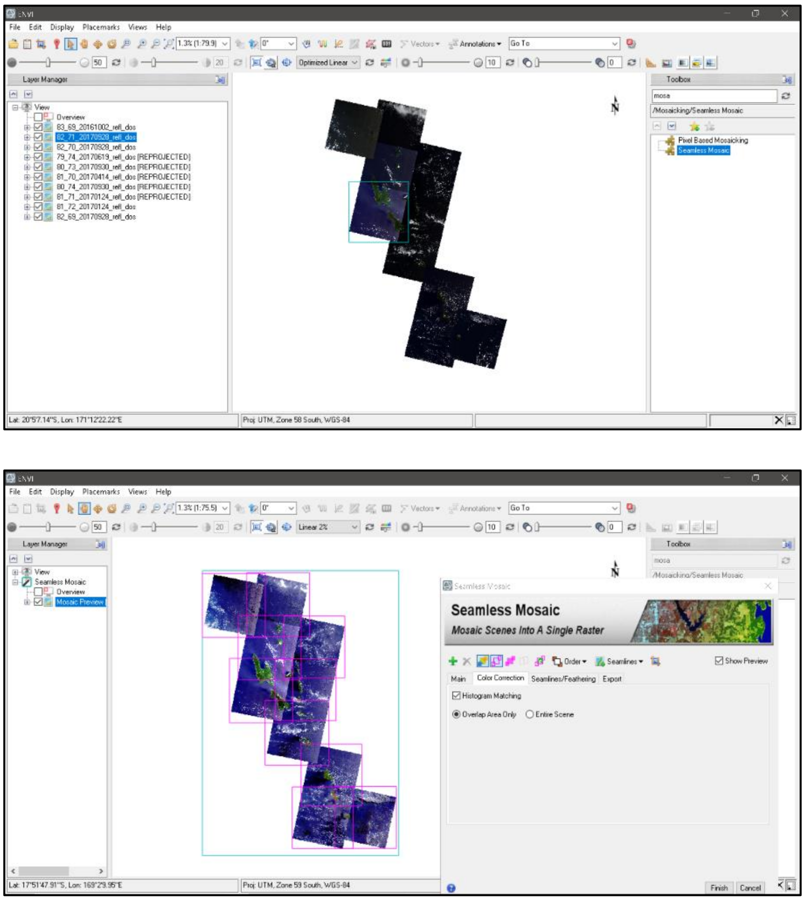


Figure 13 Layer ordering and colour correction while using the seamless mosaic tool in ENVI.

5.1.3 Masking

As the analyses is attempted at a national scale over a land area of 12,930 square km (Vanuatu National Statistic Office (VNSO), 2002) it was necessary to reduce the size of the corrected Landsat imagery to run accurate and relatively less time-consuming processing. As a result, masking was used to reduce the size of the analysed data (Figure 15). Mask is a raster file of having values of 0 and 1 that can be used to exclude pixels not needed for analyses. Masking is a pixel by pixel calculation and hence needs to be resampled to have same pixel size. All resampling was done to a cell size of 30m. One of the major problems of analysing time series data is the presence of clouds in the imagery during anniversary dates. The topography, geological position and tropical climate with a long rainy season made it difficult to find

Landsat imagery with minimal clouds in them. Cloud masking for the images was done using the cloud mask plugin in ENVI 5.4 (Figure 14). The cloud shadow mask was not performed as visual analysis of the Landsat imagery showed that mangroves were present in areas outside cloud shadow.

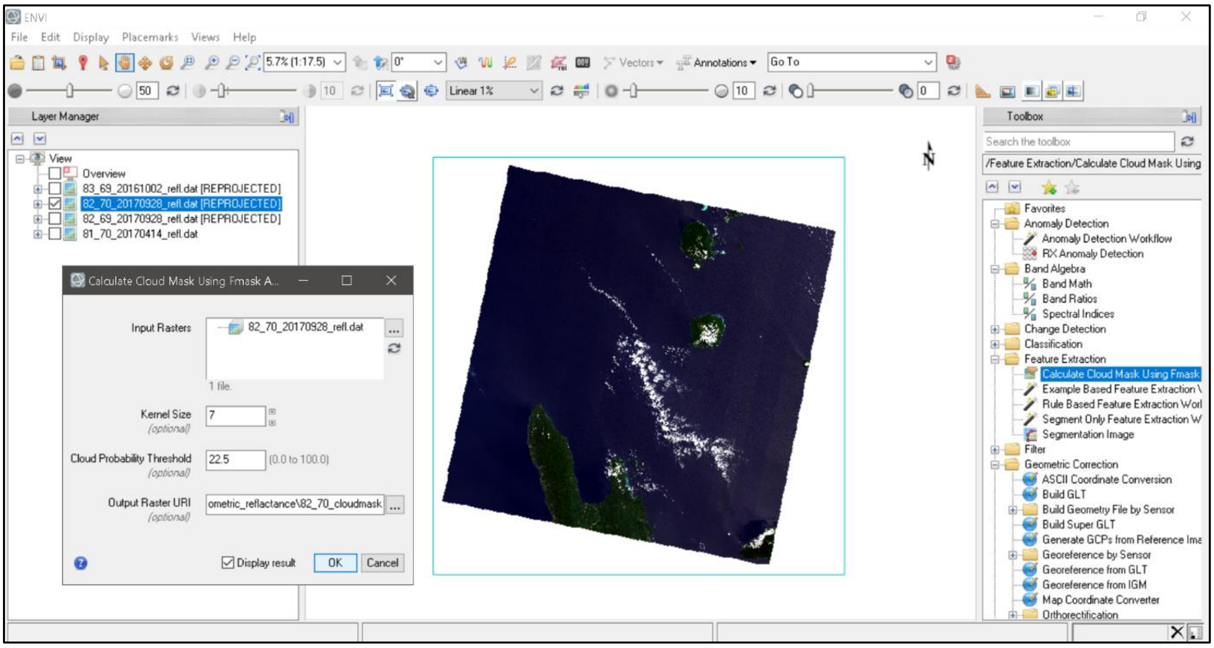
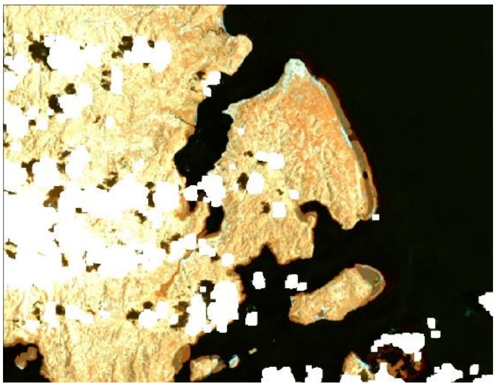
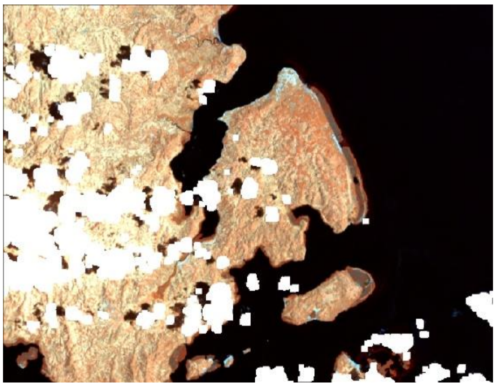


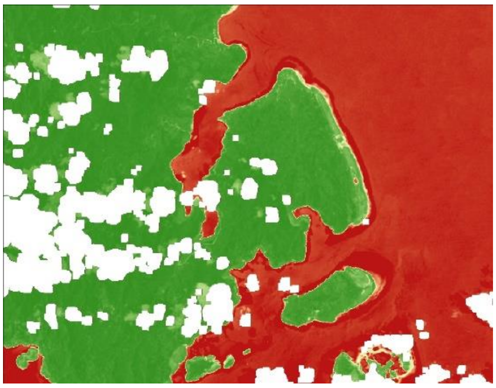
Figure 14 Fmask plugin used to create cloud mask in ENVI

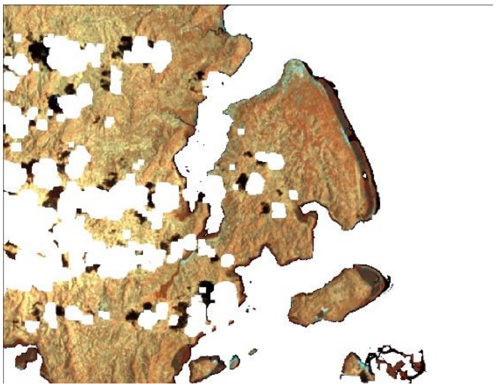
Before any other analyses was done the dataset was further reduced by creating a polygon shape file in Arc GIS around the land areas of Vanuatu. This polygon shape file was then used in the extract by mask tool in Arc GIS to define the region of interest. As mangroves are generally found in elevation zones below 30 meters (M. Spalding et al., 2010), DEM was used to exclude higher elevation areas using raster calculator in Arc GIS. All data >30m was not included in the study (Figure 15). NDVI has been used for mangrove identification (Abd-El Monsef et al., 2017; Brown et al., 2018; Conchedda et al., 2008). The NDVI is used to assess the chlorophyll content of plants. Greater the photosynthetic activity means greater a value which equates to a brighter pixel. NDVI values range from -1.0 to +1.0. NDVI was used to exclude ocean areas by selecting for NDVI higher than 0.2 using raster calculator (Figure 15). This threshold was decided after exploration of the area and literature review (Dan et al., 2016). NDVI was calculated from the Near Infrared (NIR) and Red bands using the equation (1) using the image analysis toolbar in ArcGIS.

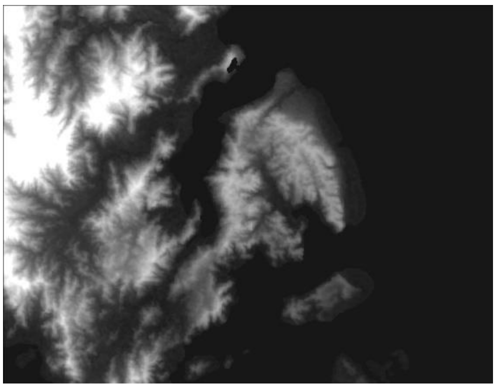
$$\text{NDVI} = \frac{\text{NIR Band} - \text{Red Band}}{(\text{NIR Band} + \text{Red Band})} \qquad (1)$$


1. Landsat image with no corrections


2. Landsat image with corrections and cloud mask


3. NDVI image analyses (Red areas are areas of lower NDVI like water)


4. NDVI mask applied to exclude water


5. Digital elevation modeling of SRTM data

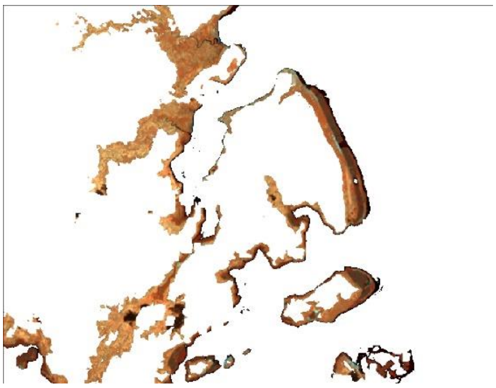

6. Elevation mask used to exclude areas of high elevation

Figure 15 Examples of Landsat image masking process to exclude data of no interest

5.1.4 Supervised Classification

Once the dataset was reduced to manageable levels, the mangroves areas were visually identified using historing mangrove regions and Landsat band combination. The characteristics of mangroves as discussed in chapter 3 was used to identify mangroves along with specific band combinations in landsat imagery (Figure 16).

Figure 16 Identification of mangrove forests from different band combinations of Landsat 8 using band combinations.

Based on the literature review conducted, supervised maximum likelihood classification was performed on both epochs of landsat imagery using Arc GIS Spatial Management tools. Training samples for the classification were created by careful investigation of pixels of the Landsat imagery to produce four land use land cover classes (LULC). These classes are as follows Table 5.

Table 5 Classification definitions

Landcover type	**Classification definition**
Mangrove	Mangrove forest ecosystem
Non-mangrove vegetation	Tropical rain forest, mixed forest lands, dense plantations
Used areas	Areas used for residential and commercial purposes, roads, agricultural areas. This class also includes scrubland and open barren land for ease of classification
Water	Rivers, permanent open water bodies, lakes, ponds, reservoirs, sea

As it was not possible to visit the study area for this study, the training samples were generated manually by using high resolution imagery from google earth pro, previously mapped area of mangroves in Vanuatu by UNEP and mangrove station coordinates from the IUCN Oceania MACBIO project. To be certain of the LULC type of the pixel being chosen, historical google earth imagery was also used to note if there are major changes. The training polygons were evaluated using scatter plots in ArcGIS to validate for spectral separability. After validation the training samples were used as signature files for classification. In total, 173 training polygons for 2017-2018 data and 261 training polygons for 2001-2003 data. The mangrove area results from the classified data was then extracted at provincial and area council levels. The raster mangrove values were extracted used the tabulate area tool in the spatial analyst tools. Once the table was created the data was joined to the boundary layer using object id.

5.1.5 Accuracy Assessment

Accuracy assessment is a crucial step of classification of Landsat data to evaluate the classification and validate it. The number of reference points chosen was based on the thumb rule of ten times the number of reference points for each class as the number of classes. Care was also taken to not pick reference points based on the training polygons to maintain integrity in validation. A minimum of 40 reference points for each class was selected to perform the accuracy assessment. To perform accuracy assessment, reference points were created in a new shape layer which was then categorised to different landcovers by editing the attribute table. The shape file was then converted to raster using Data Management tools in Arc GIS. This raster image was combined with the classified raster image using the tool 'combine' and then exported into Microsoft Excel using the 'Pivot Table' tool to calculate accuracy using the confusion matrix. Table 6 and Table 7 provide results of validity and accuracy of the classification. Mangroves produced high accuracy of 91.30% producer's accuracy and 97.67% user's accuracy for the most current data of 2016-2017 and 100% and 95.12% producer's accuracy and user's accuracy respectively for the 2001-2003 epoch. The lower accuracy in the used/bare land classification for both the epoch is explained as it includes a wide variety LULC types that range from urban developed areas to agricultural land, open shrub lands, sandy and barren area as non-mangrove areas which were because these areas behave spectrally similarly. The overall accuracy of 2016-2017 epoch and 2001-2003 epoch classified images were found to be 91% and 88% respectively. The kappa coefficient of these images was 0.88 and 0.84 respectively.

Table 6 Confusion matrix of 2016-2017 epoch representing classification accuracy of supervised classification. The columns represent actual values and the rows represents classified values. The shaded cells represent correctly classified pixels

2017							
Overall Accuracy - 91%				Overall Kappa - 0.88			
Classes	Mangrove	Non-mangrove vegetation	Used/ Bare land	Water	Ground truth total	Producer's Accuracy (%)	User's Accuracy (%)
Mangrove	42	0	0	1	43	91.30	97.67
Non- mangrove vegetation	1	39	0	1	41	92.86	95.12
Used/ Bare land	3	2	33	0	38	82.50	86.84
Water	0	1	7	43	51	95.56	84.31
Total	46	42	40	45	173		

Table 7 Confusion matrix of 2001-2003 epoch representing classification accuracy of supervised classification. The columns represent actual values and the rows represents classified values. The shaded cells represent correctly classified pixels

2001							
Overall Accuracy - 88%				Overall Kappa - 0.84			
Classes	Mangrove	Non-mangrove vegetation	Used/ Bare land	Water	Ground truth total	Producer's Accuracy (%)	User's Accuracy (%)
Mangrove	78	0	0	4	82	100.00	95.12
Non-mangrove vegetation	0	51	5	5	61	100.00	83.61
Used/Bare land	0	0	51	4	55	73.91	92.73
Water	0	0	13	50	63	100.00	79.37
Total	78	51	69	63	261		

As this research was interested in the delineation of mangroves, the results provided are focussed on the mangrove class. Figure 17 and Figure 18 provide the supervised classified results for 2016-2017 and 2001-2003 epoch. The IUCN Oceanian GPS points for current mangrove stations were available for only the island of Efate an Aniwa and these areas have been correctly identified as mangroves in the classified LULC map. The classification results for Vanuatu are provided at a provincial level Table 8 and area council level Figure 19. The detailed areal extent of mangroves for 2001 at a council level is provided in the appendix.

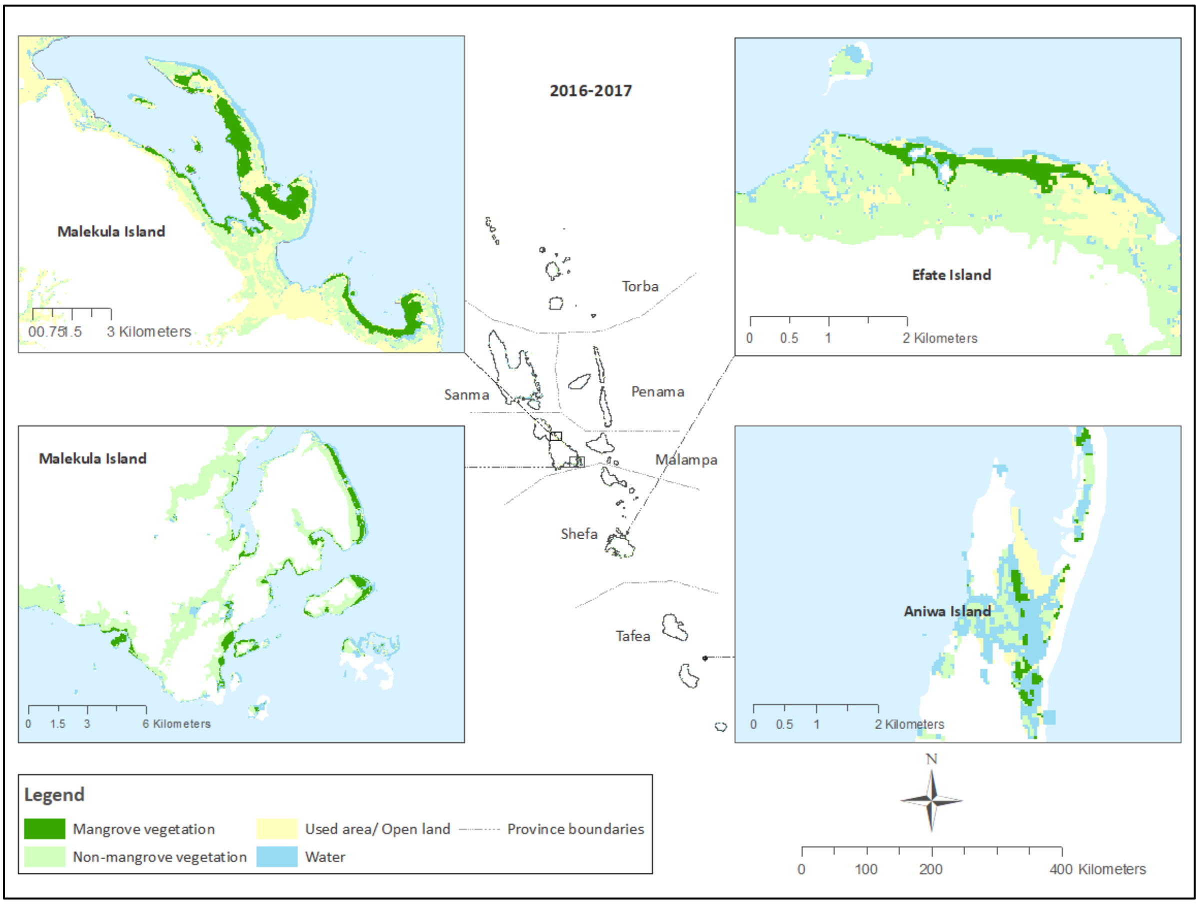


Figure 17 Land use / Landcover Classification map of 2016-2017 epoch showing mangrove areas on different islands.

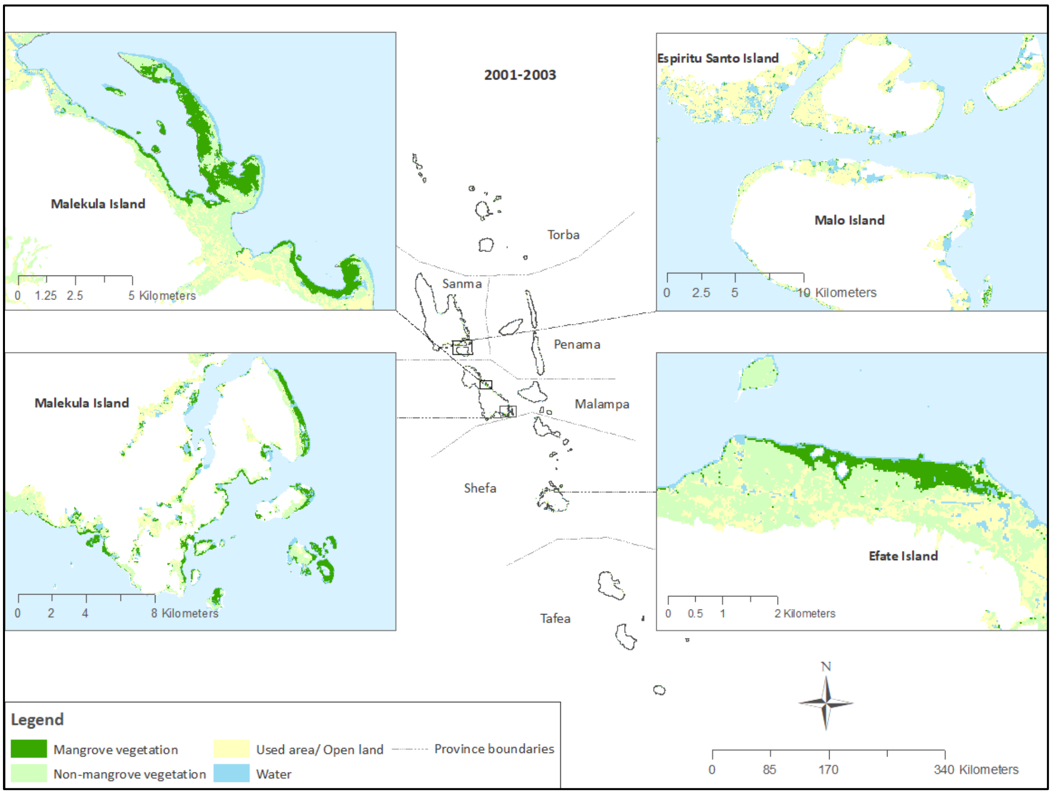


Figure 18 Land use / Landcover classification map of 2001-2003 epoch showing mangrove areas on different islands

It can be observed that the highest concentration of 62% of the total national mangrove area is in the Malampa province. This result corroborates with the literature review in chapter 2. These results also provide information of the presence and area extent of mangrove in other provinces on islands which can be used for mangrove conservation. This can be noted in Table 8 and Figure 19.

Table 8 Provincial level delineation of mangrove area in Vanuatu

Provinces	2017 Area in ha	% of national total of mangroves in 2017	2003 Area in ha	% of national total of mangroves in 2003	Rate of loss of mangroves ha/year
Malampa	1208.43	62	2520.81	39	0.04
Penama	109.35	6	431.73	7	0.08
Tafea	59.22	3	953.01	15	0.16
Shefa	280.89	14	1437.75	22	0.10
Sanma	196.83	10	444.51	7	0.05
Torba	106.02	5	759.33	12	0.12

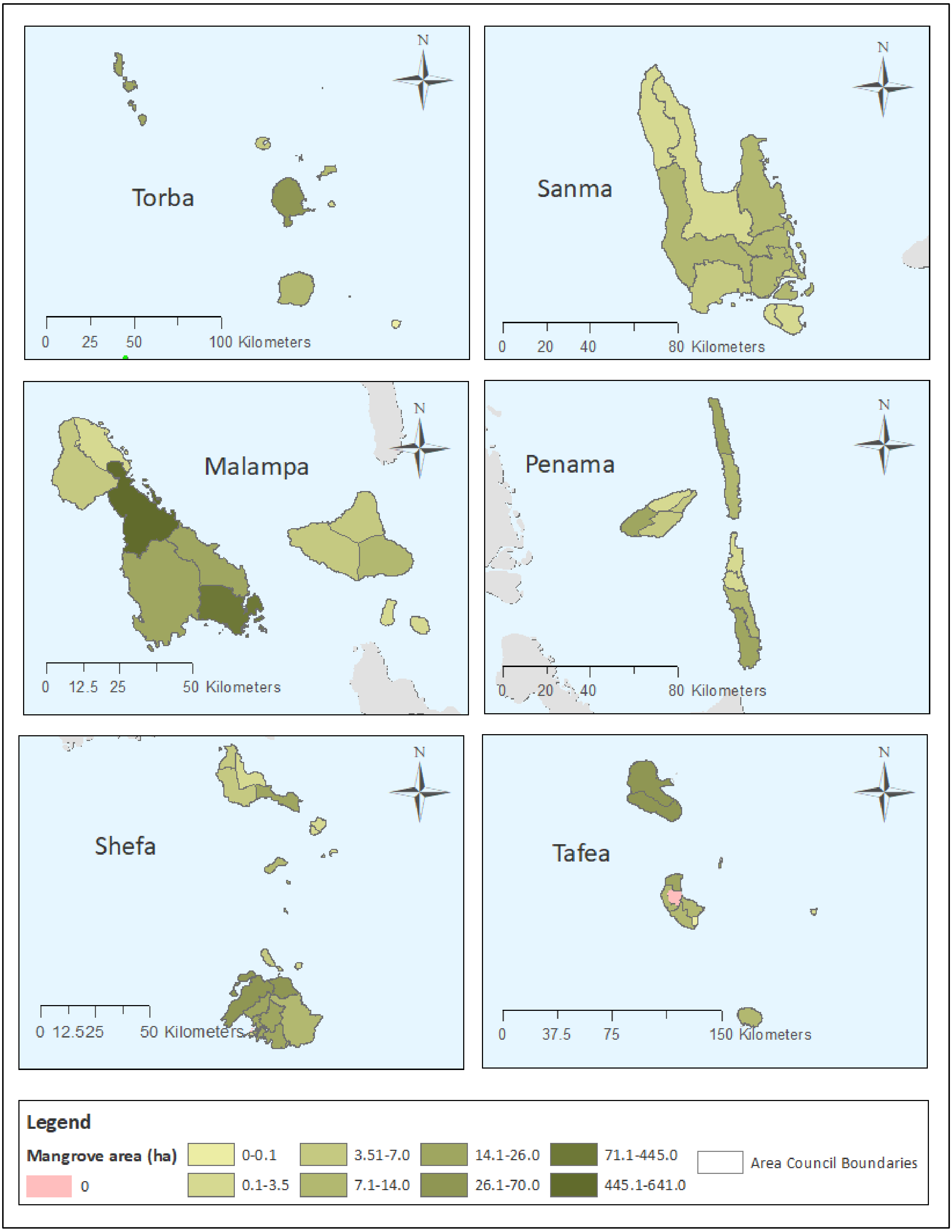


Figure 19 Map of area extent of mangroves at an area council level

5.1.6 Change in extent of the mangroves

After the Landsat images were classified for both epoch, post classification change detection was conducted to analyse the change. Both the classified raster files were reclassified to choose for only mangrove class using the reclassify tool. The reclassified raster was then analysed for change using the raster calculator tool by subtracting the raster for 2017 from the initial classified raster of 2001. This helped understand areas of mangrove loss and mangrove gain since 2001. Figure 20 shows the change in mangrove cover since 2001 on chosen areas of interest.

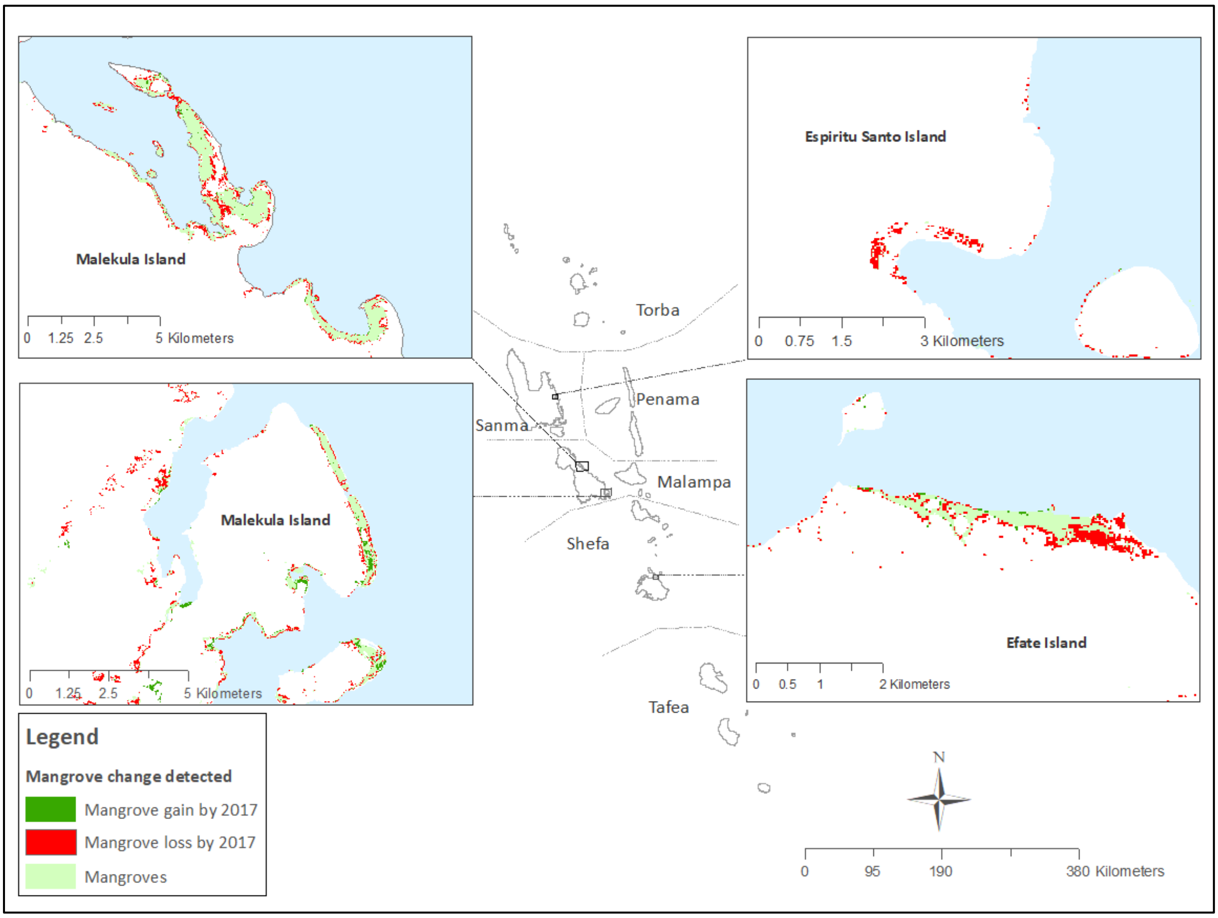


Figure 20 Map showing areas of mangrove cover change from 2001 to 2017

In the last 16 years, mangrove area in Vanuatu has decreased from 4782 ha to 1988 ha. This loss in mangrove cover accounts for a 58.43% decrease since 2000. The classified 2001-2003 results show a decrease in mangrove area from 2000 with a high overall accuracy of 88%. The annual rate of change of mangrove cover was accounted to be 0.05 ha/year nationally. The rate of change of mangroves was also calculated at a province level Table 8. Most of the mangrove cover was concentrated in the Malampa province in both the epochs. Tafea province and Shefa province have both seen a high mangrove loss of 15% and 12% respectively. These are also the only two provinces with area councils with no mangroves found after mapping. The highest mangrove area was found in the Central Malekula and South Malekula councils of Malekula island Figure 19.

5.1.7 NDVI change in mangroves

After calculating the areal change of mangroves, the density change of mangroves was calculated. Understanding the density changes is important as it highlights the gaps seen within mangrove areas from anthropogenic pressures and is an indicator of the health of the mangrove forests (Chellamani, Prakash Singh, & Panigrahy, 2014; Díaz & Blackburn, 2003; Giri, 2016; Wang et al., 2004). NDVI was calculated for mosaic of each epoch using the image analysis toolbar in Arc GIS. The red and infrared bands for Landsat ETM+ and Landsat 8 are 3,4 and 4,5 respectively. The difference tool in image analysis was used to detect the basic change in the two datasets. Within the layer properties, the remap arithmetic function was used to highlight the change. Highest density of mangroves was seen in the 2000-2003 epoch based on the NDVI results. Density of mangroves has seen a remarkable decrease in Malekula island. These indicate that not only mangrove areas have reduced since 2000 but have also had a change in their vegetation. Figure 21shows a clear change in NDVI values for the region from 2001-2003 to 2016-2017. The remapped change detection map increased levels of change in the areas that got urbanized. Within the mangrove areas the remapped change detection map shows lower levels of NDVI for 2016-2017 data as compared to 2001-2003. The mangrove loss areas in Figure 21 also coincide with areas of low NDVI values.

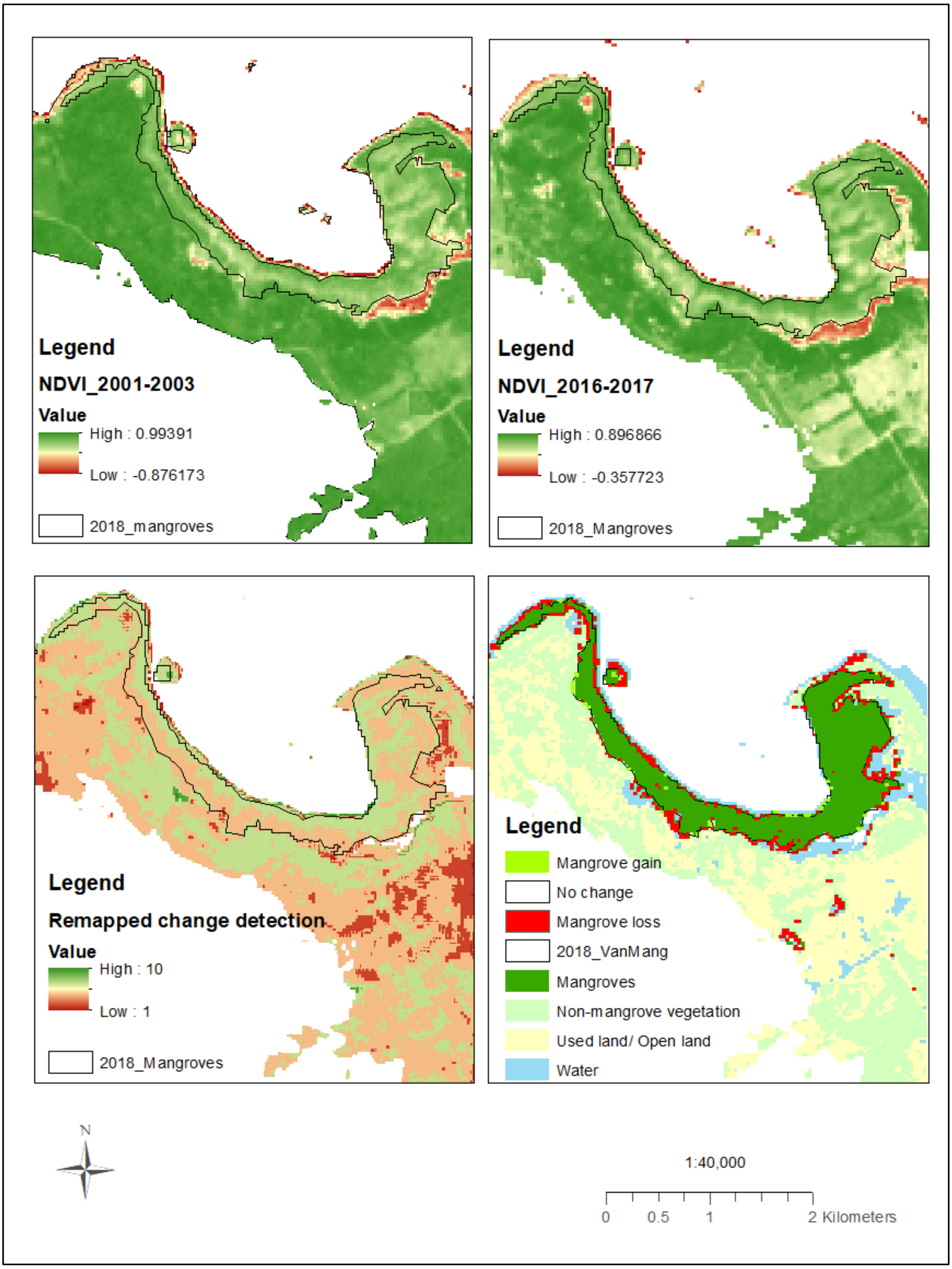


Figure 21 Map showing the change in NDVI values for Crab Bay in Malekula island

5.2 Mangrove Vulnerability Modeling

5.2.1 Evaluation and ranking of vulnerability parameters

Vulnerability modeling was conducted to identify the mangrove areas that are vulnerable and should be conservation priority. Vulnerability models are developed using spatial data, including socio-economic data by modeling them with mathematical relationships to understand the relationships between these factors. Several authors have used different parameters to study vulnerability of mangroves (Al-Nasrawi, Jones, & Hamylton, 2016; J. C. Ellison & Fiu, 2010; Omo-Irabor et al., 2011; Zulkifli et al., 2018). The main drivers of change for mangroves in Vanuatu have been listed as increased felling and cutting of mangroves for timber and coastal development, clear cutting for tourism like resort development, use of firewood and loss of beaches due to shoreline erosion from climate change and increasing sea levels (Baereleo et al., 2013; Gilman, Ellison, Jungblat, et al., 2006; Gilman, Lavieren, et al., 2006). Mangrove vulnerability mapping would ideally be done over local and small temporal scales and include parameters like geology, geomorphology, landcover, wave height, tidal range, frequency of storms, wind strength and phenological characteristics of the mangrove. However, the scope and extent of this study does not allow for such a detailed vulnerability assessment. As a result, the following criteria were chosen as a guide to map vulnerable mangroves.

Table 9 Vulnerability parameters chosen and their influence on mangrove forests in Vanuatu

Vulnerability Parameter	**Justification**
Number of households with firewood as first choice in 2016	Literature review and expert opinion provided information that mangroves are highly used for firewood extraction which can become a problem with increasing populations in the absence of alternatives for firewood (Baereleo et al., 2013; Pascal & Bulu, 2013)
Distance of mangroves from roads (m)	Presence of roads is being considered as a proxy for effect of human disturbance due to increased access to mangroves. Presence of roads for access is also being used as a proxy for increasing development and potential

	increase for tourism in these areas (Baereleo et al., 2013; Pascal & Bulu, 2013)
Distance of mangroves from shoreline (m)	Literature review and expert opinion emphasised effect of tropical cyclones and storms as another driving force for mangrove changes. Mangroves that are known to be closer to shorelines are known to be more vulnerable to effects of storms/cyclones (Adams, Stanford, Wiewel, & Rodda, 2011; Gornitz, 1991; Vieira, Salgueiro, Soares, Azeiteiro, & Morgado, 2018; Zulkifli et al., 2018)
Elevation (m)	Elevation reflects the susceptibility to flooding. The greater the elevation the greater the evidence of erosion (Vieira et al., 2018) which will be exacerbated along with increased sea levels . (Gilman, Lavieren, et al., 2006)

5.2.2 Vulnerability criterion and weighting

Once the parameters were chosen a vulnerability criterion Table 10 was created, all the criteria needed to be given weights Table 11 based on their influence on affecting change to mangroves in Vanuatu. This weighting was decided by literature review (Al-Nasrawi et al., 2016; Baereleo et al., 2013; Long et al., 2014; Vieira et al., 2018; Zulkifli et al., 2018) and expert opinion (Baereleo Persn comm)

Table 10 Vulnerability criteria for each parameter

Vulnerability Parameter	**1-Very Low**	**2-Low**	**3-Medium**	**4-High**	**5-Very High**
Firewood choice (No. of households)	0-350	351-700	701-1050	1051-1400	1401-1750
Distance from road (m)	>1000	500-1000	100-500	50-100	<50
Distance to shoreline (m)	>1000	200-1000	50-200	20-50	<20
Elevation (m)	>30	20-30	10-20	5-10	<5

Table 11 Parameters and weights by order of importance

Vulnerability Parameter	**Weight**
Distance from road (m)	0.325
Distance to shoreline (m)	0.325
Firewood choice	0.25
Elevation	0.1

5.2.3 Spatial vulnerability modeling

All the spatial data was converted to the same coordinate system of WGS UTM 58S when imported into Arc GIS. All analyses were performed at the cell size of 30m. It is also important to note that the processing extent and raster analysis in the geoprocessing environments be set correctly for all the following analyses in Arc GIS. 2016 census data for RQ2 was collected from the Vanuatu National Statistics Office data repository.

Figure 22 Map of number of household using firewood as their first choice of fuel at the area council level based on 2016 census data

The data for number of households that use firewood as an energy source was extracted from the dataset in Microsoft Excel. This data was available at an area council level and joined to the available vector layer with the council boundaries using joins and relates in Arc GIS.
Current roads layer data was downloaded from Open street map website. Multiple buffer rings were created around the roads of 50m ,100m ,500m ,1000m, 1500m using the multiple ring buffer from the Analysis toolbox in Arc GIS. A column was added to this shape file using the add field in the attribute table. The column was of the short integer format to add the ranks. These buffer rings were then convert to raster with a cell size of 30m and the mangrove mask was used on the raster to extract the areas of interest. The vulnerability modeling needed accurate shorelines to map distance from the shoreline to mangroves. However, all the available boundary datasets proved incorrect on analyses Figure 23. Thus, current shorelines were created using an iso cluster unsupervised classification with only two classes (water and land) in Arc GIS Pro. This classification was relatively easy due to the Arc GIS Pro's classification wizard flow tool. As the developed raster had pixel values in floating point it was necessary to convert it into integer format to create polygons. This was done by using the int tool in spatial analysis toolbox. The raster in integer format was then converted to polygon using the raster to polygon conversion tool and was cleaned further for analyses by editing extra vertices created. Distance from this shoreline was created using multiple buffer rings of -20m, -50m, -200m, -1000m and -1500m to draw buffers only inside the polygon. Like the road layer, the shoreline polygon layer was modified, and a rank field was added to the attribute table as a column. This polygon layer was then converted to raster using the rank field as value. The mangrove mask was then used to extract areas of interest from this raster layer.

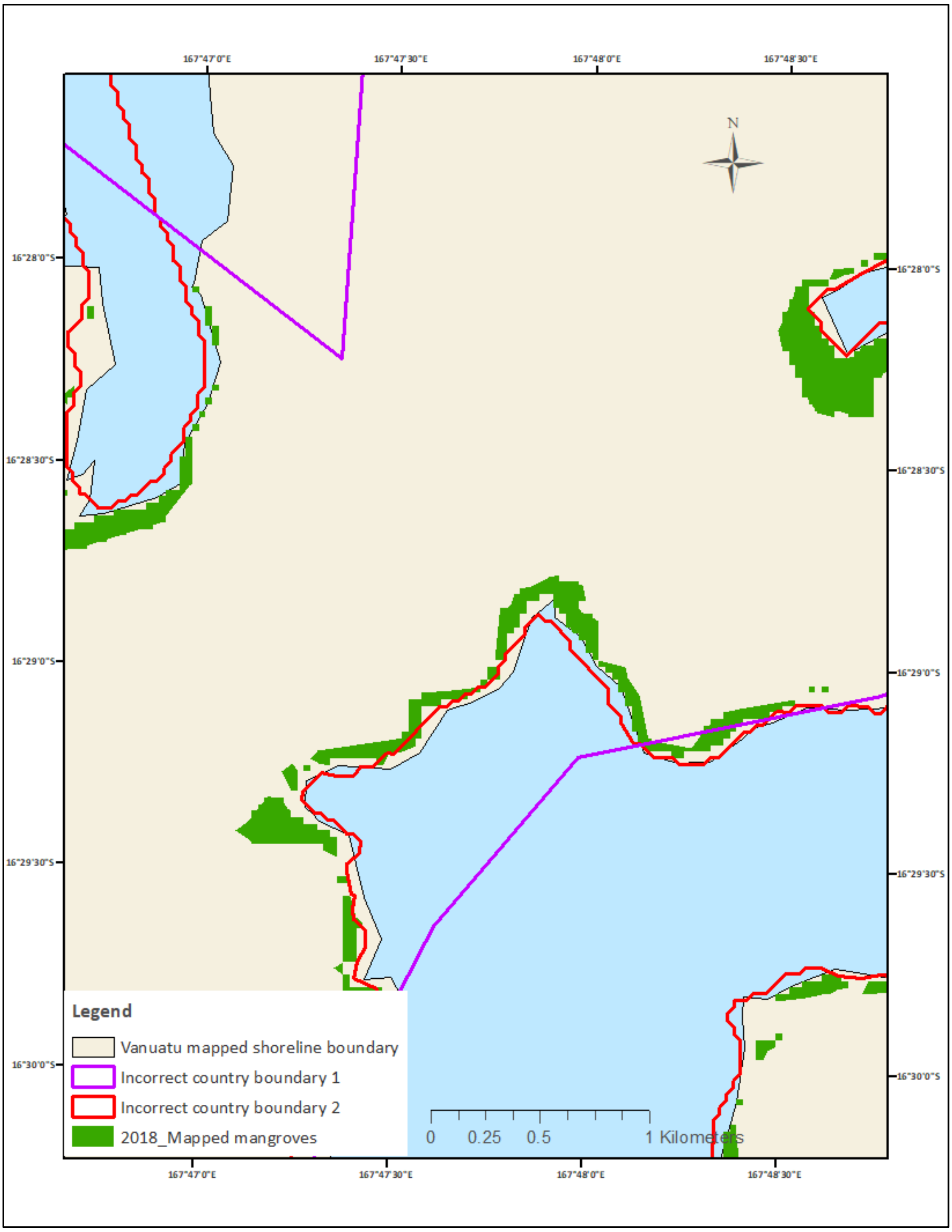


Figure 23 Map showing shoreline boundaries developed in this study as compared to available incorrect boundary data.

The elevation data is the same as the DEM data used for RQ1. The DEM data was reclassified using the reclassify tool in the Spatial Analyst toolbox using the developed vulnerability criteria and given the same ranks from 1-5. The mangrove area polygon was then used to extract the areas of interest by extract by mask. Once all the vulnerability parameters were created for the areas of interest, vulnerability was calculated using the weighted sum tool in the spatial analyst tool box to create a raster with highest value for vulnerable areas and lowest for least vulnerable mangrove areas. The created raster file lacked an attribute table. To build the attribute table, the raster was converted using the int tool to convert the floating-point pixel to integer. Once the int raster was created, the raster was reclassified using the reclassify tool to create the vulnerability ranks with a cell size of 30m. The statistics from this reclassified raster was used for further analyses in Microsoft Excel. The final overall vulnerability maps were created using the council level boundary shape file to understand the proportion of vulnerable mangrove areas in each council by using zonal statistics by table and then joining it to the vector layer. The results of the vulnerability mapping are shown in Figure 24. Based on Vulnerability modeling, 39% of mangroves of Vanuatu are highly vulnerable. This corresponds to an area of 497.1 ha. Only 17% (low and very low) of mangroves in Vanuatu are of lower conservation priority based on the index used. However, this conservation priority is considered at a national scale.

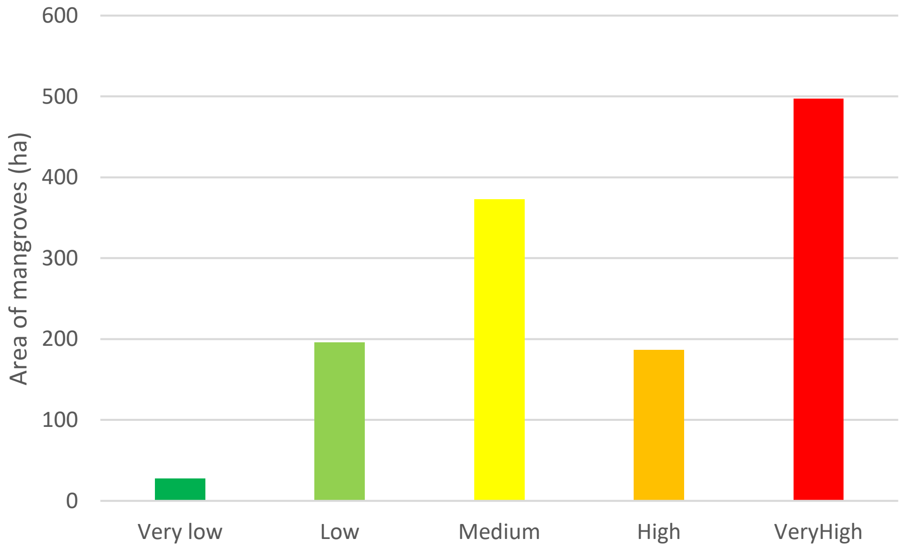


Figure 24 Vulnerable mangrove areas on a national scale based on vulnerability modeling.

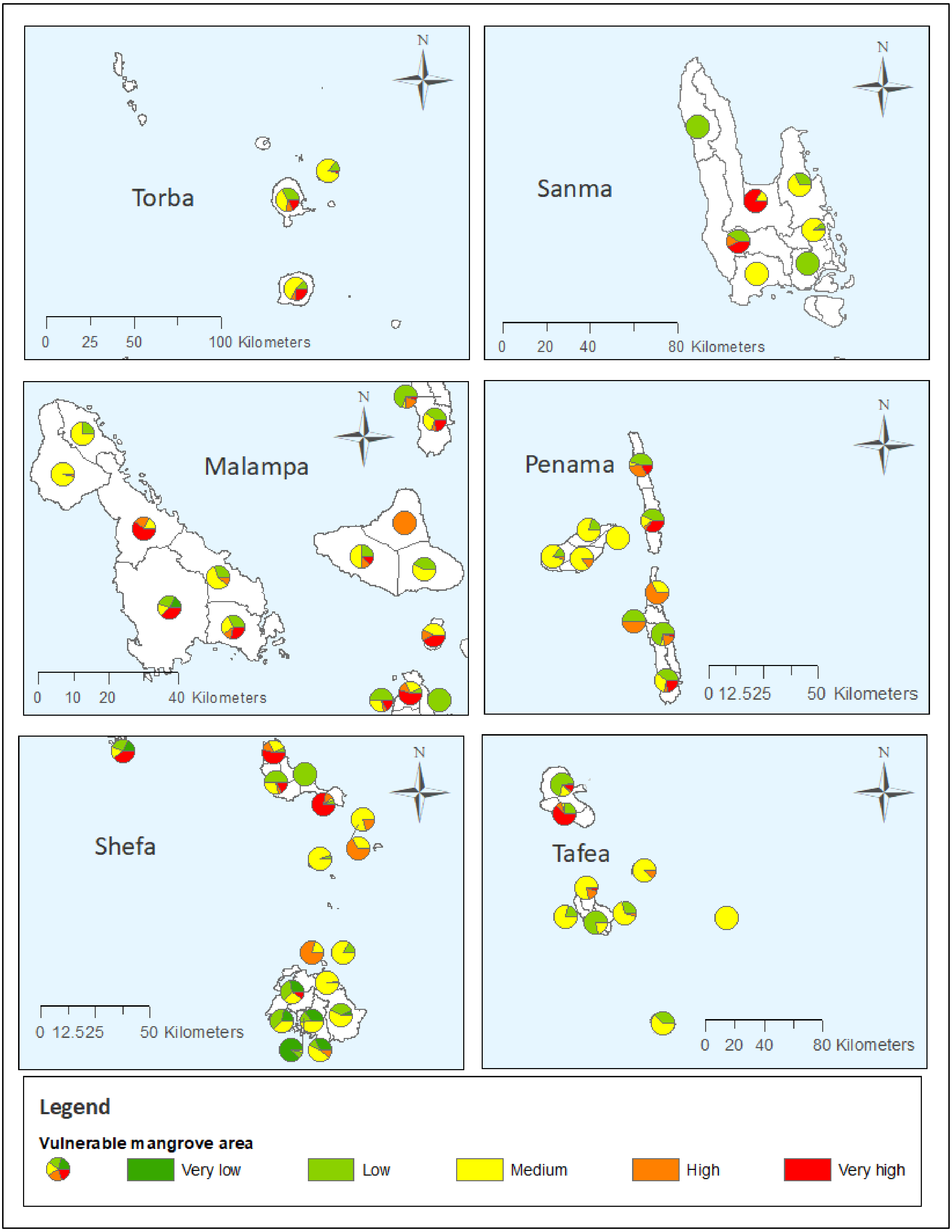


Figure 25 Map showing proportions of vulnerable mangroves within area councils of Vanuatu

The vulnerability model provided results of proportion of mangrove areas in each council that are vulnerable. Thus, the conservation priority of mangroves would change dependent on scale used for management (Figure 25).

Chapter 6: Discussion

The aim of this research which was to assess the mangrove cover change and identify vulnerable mangroves for Vanuatu was successfully completed. This chapter discusses the results of the research conducted for each of the research questions.

6.1 Mangrove cover change

Mangrove areas was mapped and delineated for Vanuatu for the epoch of 2001-2003 and 2016-2017. This study is the most comprehensive mapping done for Vanuatu and provides the latest estimates of mangrove area in Vanuatu. Prior to this study, the data on mangrove estimates were based on outdated global mapping or regional scale mapping studies. The present study indicates a loss of mangrove area since 2001 by 58.43 % which is a matter of strong concern.

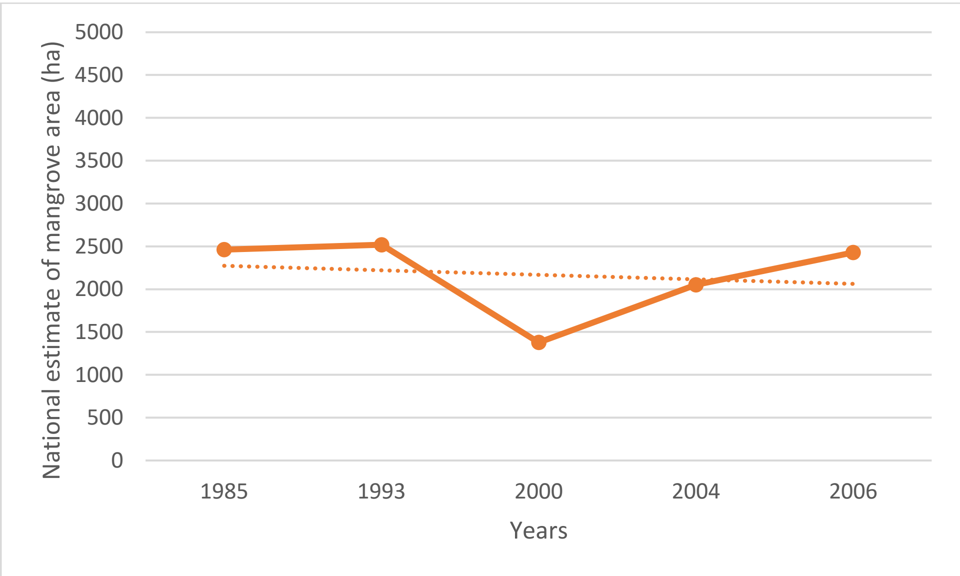


Figure 26 Trend in mangrove area change seen in Vanuatu. Estimates from other studies as reported in Chapter 2.

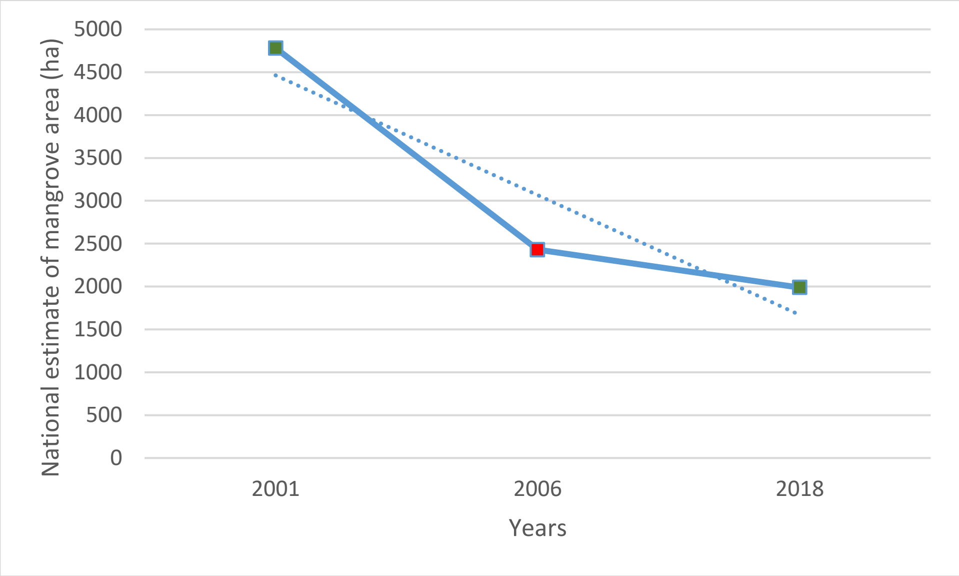


Figure 27 Trend in mangrove cover change as estimated in this study. The red square represents estimates from Gilman et al (2006).

Although this loss in mangrove area is very alarming, the high overall accuracy of 88%, a kappa coefficient of 0.84, producer's and user's accuracy of 100% and 95.12% for the classification of mangroves in the 2001-2003 dataset provides enough merit for this loss to be further investigated. It must further be noted that these estimates for mangrove areas Figure 26 except the 2000 estimate by (Bhattarai & Giri, 2011) could not be rechecked and analysed for methodology and use of datasets as they were not reported.

The 2017 result of 1987.56 ha from this study is closer to the latest estimate of 2430 (Gilman, Ellison, Jungblut, Van Lavieren, et al., 2006). Based on Gilman et al (2006) study it seems that mangrove areas were increasing in Vanuatu and with that in context a higher mangrove area result in this study that was found in 2001-2003 could be explained Figure 27. Spalding et al., (2010) estimate of 2051 ha of mangrove was estimated using Landsat data at a resolution of 30 m between 1994 and 2003. However, this estimate was reported with caveats for the level of accuracy. However, Bhattarai and Giri (2011) had reported a national mangrove area of 1378.17 based on data acquired between 1999 and 2004 which are confounding with this research results. To further understand the validity of this study's estimate, the accuracy of the estimate for Bhattarai and Giri (2011) mangrove area estimate for 2000 was reviewed. The methodology of study involved remote sensing and was done at a resolution of 30m and analyses using a hybrid supervised and unsupervised classification. However, it must be noted that the data was gathered over a large temporal span from 1999-2004. The overall accuracy of the study was reported at 92.5%, 0.9 kappa co-efficient. Although the estimates by Bhattarai and Giri (2011) seem correct, in the absence of Gilman, Ellison, Jungblut, Van Lavieren, et al. (2006) detailed methodology, the results of this study need to be considered due to it's high accuracy. However, the estimate reported in this study could have a source of error due to the presence of large cloud cover over the dataset and simpler atmospheric corrections used.

The high mangrove loss in Tafea and Shefa province can be attributed to the increase in development and urbanization around Port Vila, the capital of Vanuatu. The shoreline video assessment study of MESCAL also noted degraded fringing mangrove at Eratap on Efate island in Shefa province due to coastal development (Mackenzie et al., 2013).

Figure 20 shows areas that have had considerable mangrove forest loss since 2001. Certain areas like in Espiritu Santo Island which was reported to have mangrove areas by UNEP (2010) as seen in Figure 28 have seen a complete loss of mangroves now. The results of this study show that the current area reported by UNEP as mangrove areas in Vanuatu are overestimated and not accurate. This is also supported by independent ground surveys by the MESCAL project for two areas in Amal and Crab Bay mangroves (Baereleo et al., 2013).

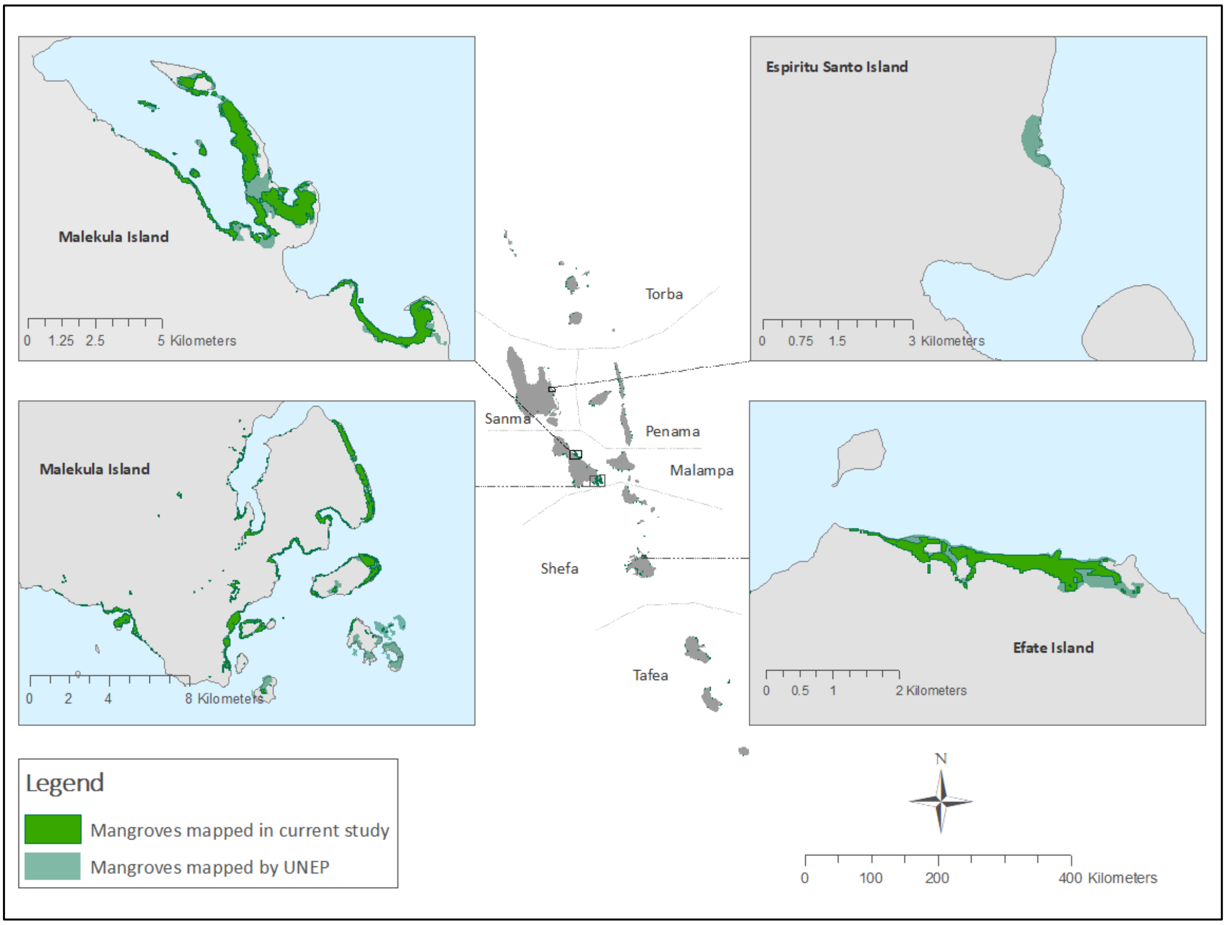


Figure 28 Change in mangrove area in Vanuatu as reported by UNEP compared to this study

6.2 Vulnerable mangrove areas

Vulnerability modeling was used as a tool to address the broader implication of social and economic development along with effects of climate change for the mangrove forests of Vanuatu. The loss in fringing mangroves in Vanuatu is attributed to increasing human pressures like felling for development and timber, and shoreline erosion (Baereleo et al., 2013).

The population growth rate of Vanuatu is 2.3% per annum (VNSO 2016). Vanuatu is also witnessing an increase in urbanization. This trend in increased urbanization and population growth will negatively affect mangroves. The analyses of 2016 census data for Vanuatu showed that firewood was used as primary source of fuel in Vanuatu by 90.5% of the households. However, mangrove is used as firewood mainly in the rural areas (Baereleo, R. Persn Comm). Baereleo et al. (2013) also noted increased cutting of mangroves stumps for the purposes of building posts and fences for houses. Thus, it was necessary to explore the placing of households and proximity to mangroves Figure 29 and include the number of households in a province using firewood as a vulnerability parameter. This parameter is also of relevance as Vanuatu is experiencing a period of population growth.

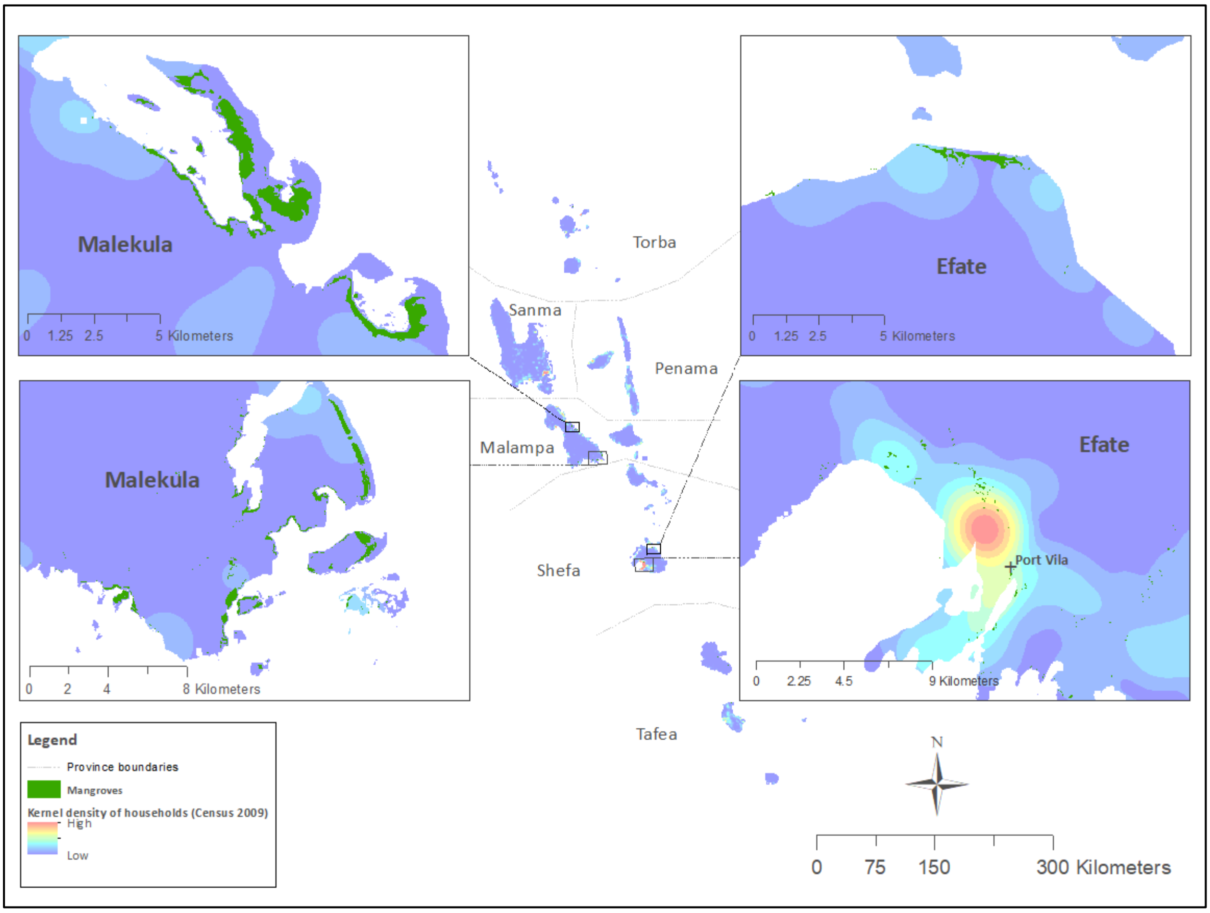


Figure 29 Kernel density of household in Vanuatu based on 2009 census

Another social aspect that was not considered in this work but has relevance to vulnerability of mangroves is the kind of land lease of mangrove cover. Vanuatu currently has around 11% of all leases assigned to commercial and tourism (Scott, Stefanova, Naupa, & Vurobaravu, 2012). An increase in land leases to tourism in the absence of mangrove management and regulated tourism will also adversely affect the mangroves. This vulnerability parameter was not included into the study due to unavailability of geocoded lease data. All the mangroves in Vanuatu are found in extremely flat areas Figure 30. The elevation of the mangroves in Vanuatu also play an important role soil erosion as steeper elevations are known to accelerate erosion (Sheik Mujabar & Chandrasekar, 2013; Vieira et al., 2018; Zulkifli et al., 2018). Steeper the elevation also halts the mangrove landward migration that mangroves undertake to escape beach erosion (Gilman, Lavieren, et al., 2006).

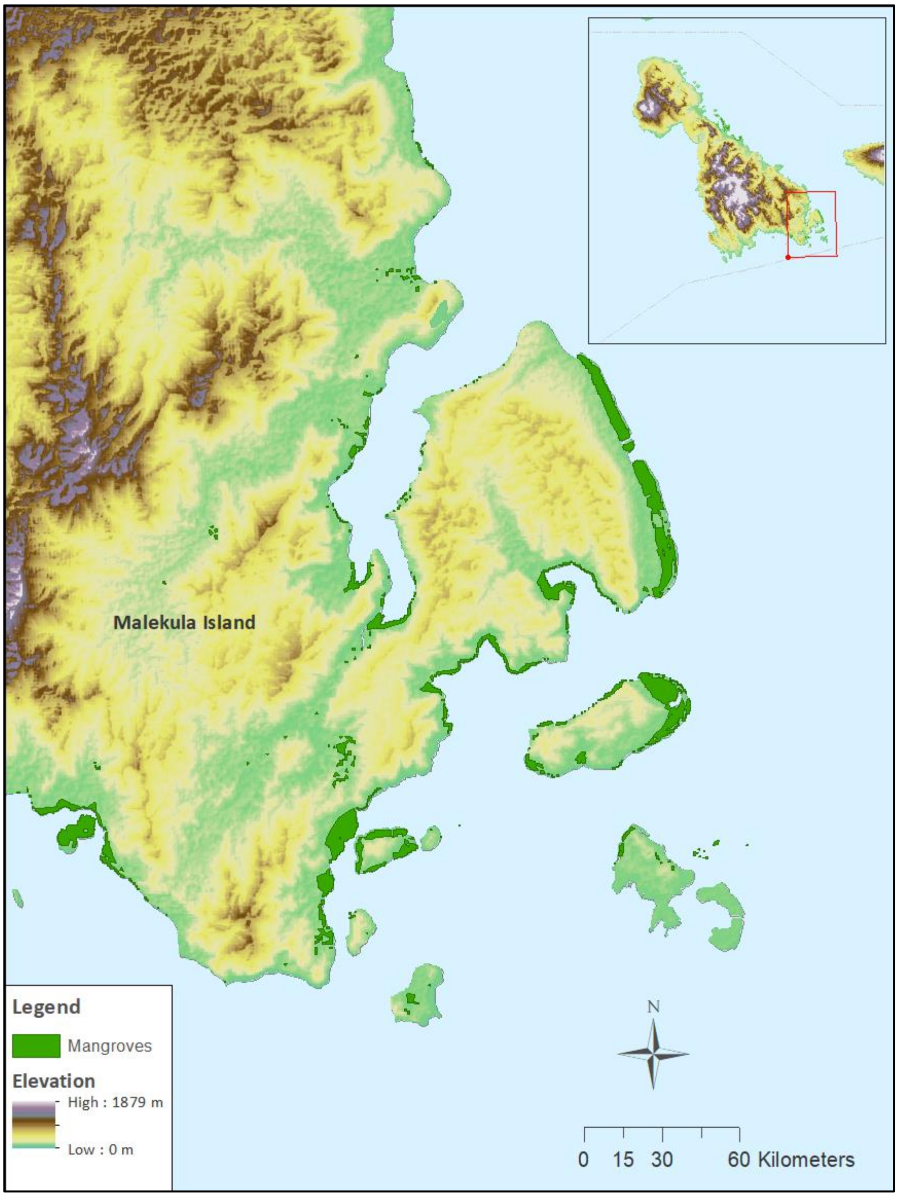


Figure 30 Map showing elevation range in Vanuatu and the presence of mangroves in low elevation areas

The urbanization trend due to rising GDP of Vanuatu is very high (Republic of Vanuatu, 2017a). As a result, increased conversion of mangroves for coastal development is expected currently. This trend which is visible globally will have a significant effect in Vanuatu in the absence of stringent mangrove conservation measures and land use planning. The result of growing coastal development has already been observed in Efate island with increased mangrove loss near Port Vila Figure 29. However, this area was not identified vulnerable area due to absence of huge mangrove areas already Figure 25. Vanuatu is already known to be affected by sea level rise. Mangroves near shorelines will be inundated by rising sea level and may be negatively impacted. Vanuatu is also a country that is known for its frequent cyclones and storms. The last cyclone Pam in 2015 destroyed Port Vila and displaced 3300 people (Secretariat of the Pacific Community, 2015).

The vulnerability areas identified are also dependent on the algorithm used. Vieira et al. (2018) study showed that based on different vulnerability indices used for modeling the results differed. As this vulnerability modeling was attempted to be basic with simpler parameters the results found were deemed acceptable for the national scale.

6.3 Limitations and sources of uncertainty

The advances in GIS and remote sensing have made it possible to understand our ecological systems in detail. However, the use of remote sensing data is not free from uncertainty in the absence of ground truth validation which is lacking in this study. Detailed ground truth validation throughout the country along with collection of biological parameters of the mangrove would have provided finer results. However, the spatial scale that was studied (approximately 12000 sq km), made it logistically and financially difficult to be carried out. Higher resolution images for large scale time series analyses data are generally preferable for such studies. However, it requires a larger time frame and expertise for analyses and. The high-resolution data are also not necessarily freely available data especially for historic imagery.

Some of the sources of uncertainty in the results are resultant of the level of pre-processing and absence of ground truth validation. For pre-processing complex atmospheric corrections were not done to this study which are generally performed in studies like this due to the unavailability of software licenses for students and the lack of expertise of the researcher. Atmosphere correction was also not possible on the historical data as the information needed for it was unavailable. No on ground data validation was possible for all islands due to the remote nature of the islands, time limitation, insufficient funding and limited capacity of this study. The available incorrect boundary files of the country could also be a source of the error. However, this error was avoided by creating boundary files for this study from the Landsat data. Although the researcher, produced shoreline boundaries from the Landsat images, the changing nature of the islands and presence of clouds on certain parts of the boundary needed the researcher to approximate the shoreline to best available political boundary shape file. Despite these limitations, mangrove classification provided higher accuracy than other types of classes and was well within the minimal needed accuracy for robust results.

The results of vulnerability modeling have been shown to be different based on the algorithm used and criteria used (Vieira et al., 2018). This study used a basic criterion for vulnerability modeling as a result some of the parameters could be over valuated. As mangroves are complex ecosystems situated in transition zones of land and water and influenced by anthropogenic pressures, they are influenced by multiple complex stressors that are interconnected. The parameters used in this study could be an oversimplification of the stressors and lacks some other important parameters like geomorphology, tidal range, erosion rate, anthropogenic activities etc. As all these values were also extracted using GIS, their strength lies in the accuracy of the GIS layers.

Policy relevance of the study

The underlying aim of this research was to create baseline information and template for mangrove monitoring in a country that is considered by UN as a high-risk country with developing technology and infrastructure. With this in regard, the following latest major policies have been reviewed to identify the relevance of the study and understand the direction of mangrove governance and management taken by the government. The results of this study will be valuable to answer the following policy objectives:

Vanuatu 2030 People's Plan

This is Vanuatu's National Sustainable Development Plan for the period 2016 to 2030 and serves as the Country's highest-level policy framework. Within this plan this study will have implications for the following objectives of the environment goals (Republic of Vanuatu, 2016b):

Identified Policy		Study Relevance
ENV2 Blue-Green Economic Growth	*ENV 2.1* ***Increase access to knowledge***, ***expertise and technology*** *to enact our blue-green growth strategies*	This research provides a template for use of remote sensing technology used in mangrove monitoring. It also provides an appendix of freely available remote sensing data for future use online at www.syslab.ceu.edu_MSc Thesis
	ENV 2.2 Ensure new infrastructure and development activities cause minimal disturbance to the natural land and marine environment	This research has indicated areas with maximum mangrove cover change and vulnerable areas (Figure 20, Figure 19, Figure 17)
ENV4 Natural Resource Management	*ENV 4.1* ***Strengthen local authorities and municipal planning authorities*** *to enact and enforce land use planning laws and regulations*	The study provides with spatial maps for better decision making. The results of this study will be shared with the Ministry of Environment Vanuatu and IUCN Oceania.
	ENV 4.2 ***Protect vulnerable forests***, *watersheds, catchments and freshwater resources, including community water sources*	The study has identified mangrove forests that have changed the most and may be vulnerable to further change (Figure 24 and appendix B)

Vanuatu National Environment Policy and Implementation Plan 2016-2030

The Vanuatu National Environment Policy and Implementation Plan 2016–2030 (NEPIP) is a framework that links existing environment related policies and develops a roadmap for the

DEPC and government to improve the governance and take long term environmental actions. It aims to address Vanuatu's commitments of Sustainable Development Agenda 2030 and the Sustainable Development Goals. This study will provide information for the following policy objectives (Republic of Vanuatu, 2017b):

Identified Policy		Study Relevance
PO (1) Conservation of biological, ecosystem, genetic, human and cultural diversity	*PO 1.1: Create and manage conservation and protected areas by* ***identifying proposed conservation areas****, effectively managed areas and special areas of interest for management that can be formalised as CCAs,* ***marine protected areas or marine reserves***	This research provides a template to create areas of interest for management and the vulnerability mapping results can be used with improvisation for identifying conservation areas
PO (2) Sustainable resource management PO 2.6: Reduce and prevent the degradation and erosion of foreshore and coastal areas by	*creating a* ***national forestry inventory of coastal areas*** *by 2025*	This research provides information for the most current (2017) mangrove forests areas at area council level
	collecting geological information from regional and international institutions and ***coastal morphology changes data****.*	The shoreline analyses and changes data from this study provides coastal morphology change information
PO (5) Environmental governance and capacity development	*PO 5.2: Build capacity and support local communities to manage natural resources by developing marine spatial maps*	The results of this study create foundational maps for future marine spatial maps at a national level and builds capacity by creating a template for monitoring and data repository

Vanuatu National Ocean Policy

The Vanuatu National Ocean Policy aims to develop resilience in its marine ecosystems and to sustainably use its ocean resources by integrating traditional marine resource management practices and knowledge with current management plans and policies (Republic of Vanuatu, 2016a). The following objectives of the policy have a link to this study:

Identified Policy	Study Relevance
PO (3.2.9.3) Protect naturally resistant or resilient areas including coral reefs that still have high coral cover and mangroves and coastal wetlands which can migrate inland	This research provides current mangrove maps for future conservation measures
PO (6.6.3.3) Expand Vanuatu's REDD+ and green carbon activities including for mangroves	REDD+ and carbon green activities needs baseline information about mangroves like area extent which is provided by this study

Vanuatu Forest Policy 2013-2023

The National Forest policy is a guide to manage the forest resources in an integrated and sustainable manner (Republic of Vanuatu, 2013). The forest policy objectives specifically propose actions for its wetland coastal and mangrove forests through PO (15). The other policies which have implications with the study are:

Identified Policy	Study Relevance
PO (5) Monitor and discourage change of forests to other land uses	This study provides information for mangrove forest change to other land uses since 2000
PO (13) Manage and protect areas vulnerable to erosion	The vulnerability maps produced by this study maps areas vulnerable to erosion due to mangrove loss
PO (15) Identifying and implementing management plans, conserving, protecting and sustainably managing mangrove forest ecosystems.	Results of this study can be used in the preparation of mangrove management plans

Climate Change and Disaster Risk Reduction Policy 2016-2030

This policy provides a framework through whish risks are identified, assessed, reduced and manged by taking a practical approach and considering Vanuatu's resources, exposure to risks and demographics. It aims to strengthen existing governance and traditional knowledge using natural solutions (Republic of Vanuatu, 2016c). The following policy objectives (PO) have direct implication to the study:

Identified Policy		Study Application
PO (7.3.2) Knowledge and information sharing	*By developing new materials that are relevant and compatible to the local context*	All the maps and results produced in this study are relevant to national level
PO (7.4.3) Ecosystem-based approaches	*Support ecosystem adaptation and risk reduction services by: prioritising "soft" ecosystem-based adaptation over "hard" engineered infrastructure for ecosystem function maintenance (e.g. coastal revegetation versus sea walls); utilising sound land-use planning approaches, and implementing and enforcing ecosystem-related development policy documents*	This research provides information on mangrove loss which can be utilised while proposing future revegetation/restoration processes. The vulnerability map of mangroves to shorelines predicts the possible risk in revegetation in those areas.
PO (7.5.2) Mitigation and REDD+	*developing and strengthening planning and legal frameworks to avoid damage to high carbon natural resources and ecosystems (e.g. mangroves, coral reefs and sea grasses)*	This study provides information spatial extents of mangroves for planning framework to avoid damage to mangrove areas and identifies possible mangrove areas with higher probabilities of damage

6.4 Recommendations

The accuracy of this research was limited by the absence of ground truth validation. Future research in monitoring mangroves for Vanuatu should highly consider inclusion of ground truth validation. High resolution Sentinel 2 data and LiDAR data for elevation for a more accurate mangrove assessment can be used for future monitoring of mangroves in Vanuatu. The vulnerability modeling for mangroves in Vanuatu will also need a more exhaustive study at local scales and involvement of indigenous knowledge to develop better models in a Vanuatu context. It is important to include governance and policy parameters like the land lease state and presence of conservation management like protected areas along with geomorphology and ecological parameters of the mangroves. InVest is a software that models for habitat risk and vulnerability which may also be used to assess mangrove areas. A portion of this study was limited do the level of processing and analysis. Google Earth Engine is another tool that uses cloud processing to analyse large amounts of data.

Chapter 7: Conclusion

This research is a good example of integrated approach of mangrove conservation using contemporary remote sensing and GIS tools and socio-economic and ecological data over large temporal and spatial scales. The overall aim of this research was to conduct national level mangrove monitoring for the country of Vanuatu to provide baseline mangrove estimates for the country and identify mangrove areas of conservation interest. This was successfully achieved by developing a set of objectives that were focussed on understanding the change in mangrove cover in Vanuatu over 16 years and developing a vulnerability model using influential drivers of change for mangroves.

The first research question was addressed by delineating current mangrove areas using Landsat 8 OLI data for the epoch of 2016-2017 and Landsat ETM+ data for the epoch of 2001-2003 using a supervised classification approach using software like ENVI 5.4, Arc GIS Ver10.2 and Arc GIS Pro. To ensure accurate and high-quality results, the Landsat data was put through multiple levels of pre-processing that involved corrections for the atmospheric influences at sensor and surface. The maximum likelihood algorithm used in the study provided higher accuracy to detect mangroves over other land use/ land cover classes. The results revealed that currently 1987.56 ha of mangrove forests are present nationally and the mangrove area was lost by around 58% since 2000. Islands previously assumed to not have mangroves have been identified to have small patches of mangroves. NDVI analyses showed that mangroves in 2001-2003 epoch had higher NDVI values than in 2016-2017. The results of this study also updated the mangrove areas mapped by UNEP that are currently available for Vanuatu. To aid with conservation and policy planning, a data repository of delineated mangrove areas was created at the area council level which is available online for information and capacity sharing.

The second research question that aimed to identify vulnerable mangrove areas was answered by developing a vulnerability criterion after identifying top change drivers and modeling it spatially using Arc GIS. The top drivers of change were identified as mangrove exploitation for fuelwood in rural areas, coastal development and tourism and climate change related sea level rise and damage from cyclones. The vulnerability model revealed 39% of mangroves in Vanuatu are highly vulnerable. A detailed council level record of vulnerable mangroves was created for future conservation measure and research which is also available online at ___. It was important to identify the possible use of the results for Vanuatu within a sustainable development context. Thus, a review of five National Policy and Vision plans for Vanuatu was conducted and target objectives identified for the policies where the results or the framework of this study will be relevant.

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Personal Communication

Baereleo Rolena Tavue. Expert mangroves Vanuatu. Department of Environmental protection and Conservation, Vanuatu. Email and skype conservations. May 2017.

Sritharan Shakthi. Expert GIS, GIS Head for Wildlife Trust of India. Telephonic conversation. 20 May 2017.

Chapter 9: Appendix

Appendix A List of datasets that can be used for future studies of mangroves in Vanuatu

Data type	Data Source	Availability	Data format	Resolution
Landsat 7 ETM+/LANDSAT 8 Sentinel 2 DEM SRTM NDVI	USGS Earth Explorer	Free & Available	GEOTIFF	15-30m
LiDAR DEM DSM Contours Canopy Height model Foliage cover model Coincident aerial photography	Vanuatu Globe Google-created by Australian AID	Available for Efate, Malekula and Espiritu Santo. Need to acquire from department	GEOTIFF	2-10m
Global mangrove datasets	SEDAC-Giri et al 2013 from Temporal range-1993-2003	Free & Available all islands	kmz	30 m
Aerial Photography	Department of Land surveys (2007)	Need to acquire from department	Unknown	
Vegetation map	Department of Forestry 2011	Need to acquire	JPEG	NA
Ground truth data	IUCN Oceania	Free & Available for Efate and Aniwa	XML	GPS locations
ALOS-2PALSAR	Sentinel Japan	Free & Available	JPEG	3-10m

Appendix B Landsat image characteristics of data analysed

LANDSAT_SCENE_ID	Date Acquired	Data type	Collection Category	Sensor	Path	Row	Cloud Cover	Land Cloud Cover
LC80800732017273LGN00	30/Sep/17	L1TP	t1	OLI_TIRS	80	73	10.08	10.34
LC80800742017273LGN00	30/Sep/17	L1TP	T1	OLI_TIRS	80	74	6.66	7.53
LC80820702017271LGN00	28/Sep/17	L1TP	T1	OLI_TIRS	82	70	2.55	4.77
LC80820712017271LGN00	28/Sep/17	L1TP	T1	OLI_TIRS	82	71	1.45	0.71
LC80820692017271LGN00	28/Sep/17	L1TP	t1	OLI_TIRS	82	69	24.77	5.99
LC80790742017170LGN00	19/Jun/17	L1TP	T2	OLI_TIRS	79	74	3.38	1.19
LC80810702017104LGN01	14/Apr/17	L1TP	t1	OLI_TIRS	81	70	8.26	1.96
LC80810712017024LGN01	24/Jan/17	L1TP	t1	OLI_TIRS	81	71	10.27	26.63
LC80810722017024LGN01	24/Jan/17	L1TP	t1	OLI_TIRS	81	72	12.87	25.2
LC80830692016276LGN01	2/Oct/16	L1TP	t1	OLI_TIRS	83	69	2.67	2.1
LE70820702003081EDC00	22/Mar/03	L1TP	T1	ETM+	82	70	10	29
LE70790742003044EDC00	13/Feb/03	L1GT	T2	ETM+	79	74	10	11

LE70810702003042EDC00	11/Feb/03	L1TP	T1	ETM+	81	70	3	1
LE70810712003042EDC00	11/Feb/03	L1TP	T1	ETM+	81	71	3	8
LE70830692003008EDC00	8/Jan/03	L1GT	T2	ETM+	83	69	6	16
LE70800732003003EDC00	3/Jan/03	L1TP	T1	ETM+	80	73	6	35
LE70800742002096EDC00	6/Apr/02	L1GT	T2	ETM+	80	74	24	45
LE70800722002080EDC00	21/Mar/02	L1GT	T2	ETM+	80	72	11	0
LE70820692001219EDC00	4/Aug/01	L1TP	T1	ETM+	82	69	31	1
LE70810722001116EDC01	4/26/2001	L1TP	T1	ETM+	81	72	7	20
LE70820712001107EDC00	17/Apr/01	L1TP	T1	ETM+	82	71	4	9

Appendix C Mangrove forest area by area council in Vanuatu in 2003

OBJECTID	**Area Council**	**Province**	**Mangrove Area ha**
1	South East Ambrym	Malampa	58239
2	East Ambae	Penama	16767
3	West Tanna	Tafea	44307
4	Middle Bush Tanna	Tafea	891
5	South West Tanna	Tafea	27297
6	South Tanna	Tafea	13932
7	Whitesands	Tafea	74925
8	North Tanna	Tafea	14013
9	North Erromango	Tafea	79704
10	South Erromango	Tafea	35397
11	Vermali	Shefa	28836
12	Aneityum	Tafea	73386
13	Futuna	Tafea	1053
14	Aniwa	Tafea	324
15	Makimae	Shefa	86994
16	Tongariki	Shefa	2592
17	North Tongoa	Shefa	4455
18	South Epi	Shefa	47547
19	Vermaul	Shefa	106110
20	Varisu	Shefa	14985
21	Paama	Malampa	26892
22	North Ambrym	Malampa	51597
23	West Ambrym	Malampa	130572
24	North West Malekula	Malampa	94527
25	North East Malekula	Malampa	67797
26	Central Malekula	Malampa	743742
27	South East Malekula	Malampa	130491
28	South Malekula	Malampa	632043
29	South West Malekula	Malampa	160866
30	South Pentecost	Penama	53865
31	Central Pentecost 2	Penama	28512
32	Central Pentecost 1	Penama	11016
33	North Pentecost	Penama	15471
34	South Ambae	Penama	40176
35	West Ambae	Penama	42039
36	North Ambae	Penama	13527
37	North Maewo	Penama	49815
38	South Maewo	Penama	57186
39	West Santo	Sanma	63018
40	South Santo	Sanma	98658
41	South East Santo	Sanma	89262
42	East Santo	Sanma	106758
43	North Santo	Sanma	110160
44	Canal - Fanafo	Sanma	120204

45	North West Santo	Sanma	78813
46	East Malo	Sanma	71118
47	West Malo	Sanma	18711
48	Torres	Torba	208008
49	Mota	Torba	3483
50	Motalava	Torba	130734
51	Ureparapara	Torba	4293
52	Gaua	Torba	33372
53	North Efate	Shefa	124254
54	Eton	Shefa	296298
55	Pango	Shefa	23004
56	Ifira	Shefa	324
57	Nguna	Shefa	42768
58	Emau	Shefa	14175
59	Malorua	Shefa	147987
60	Port Vila	Shefa	49410
61	Luganville	Sanma	11907
62	Vanua Lava	Torba	235872
63	Mele	Shefa	33939
64	Erakor	Shefa	56862
65	Eratap	Shefa	153576
66	Merelava	Torba	8181