Selecting tailored risk indicators for assessing Marine Heat Wave risk to the Fisheries sector in Vanuatu

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Executive Summary

This report presents key finding on "Selecting tailored risk indicators for assessing Marine Heat Wave risk to the Fisheries sector in Vanuatu" conducted as part of the Van CISRDP (Climate Information Services for Resilient Development in Vanuatu) / Van-KIRAP (Vanuatu Klaemet blong Redy, Adapt mo Protekt) project.

Increased frequency and severity of Marine heat wave (MHW) events, resultant of climate change, is concerning for vulnerable communities around the world. In Vanuatu, communities are predicted to be at high risk to MHW impacts in the future. A critical sector at risk in Vanuatu is Fisheries, which vitally supports food security and livelihoods. To sustain local communities, MHW risk to Vanuatu Fisheries must be extensively explored. Tailored risk assessment is recognised as a key method for informing on MHW risk. In this study, the first two steps in a tailored MHW risk assessment methodology are addressed: indicator selection and weighting. A combined process, utilising both a literature review and participatory survey, was implemented to select indicators appropriate for examining MHW risk to Vanuatu Fisheries.

To conduct the participatory component of this study, a survey was employed to collect both qualitative and quantitative data. A survey workshop was held at the Vanuatu Fisheries Department in Port Villa, Vanuatu on the 11th of October 2022. During this workshop, detailed information about the survey was presented to staff of the Vanuatu Fisheries Department. A survey was distributed to participants across all Vanuatu provinces over a two-week period from the 11th of October to the 28th of October 2022. All participants were sourced through networks of the Vanuatu Fisheries Department. A total of 12 completed surveys were collected. Survey participants were of a range of ages, genders and located across various Vanuatu provinces (3 from Penama, 4 from Shefa, 4 from Malampa, and 1 from Tafea).

A user-informed weighting scheme was developed based on survey results. Sea Surface Temperature (SST), Coral bleaching, and Chlorophyll-a concentration were selected as appropriate hazard indicators. Terrestrial-based food and income generation, Fishing skills and technology, Fishery fish diversity/fishery flexibility and Primary production of commercial fisheries were selected for the vulnerability index. Seagrass population/C content, Coral Habitat Health/Crown of Thorns Prevalence, Crab stock health and Fish mortality/fish stock health were the selected exposure indicators. The selected indicators, along with their specific weights, are recommended for use to conduct a tailored MHW risk assessment for Vanuatu Fisheries. Such an assessment is likely critical for informing local decision-makers of high-risk areas and can aid in increasing the resilience of the Fisheries sector.

1. Introduction

1.1 Marine Heat Waves pose a critical threat to the Pacific Small Island Developing State of Vanuatu

Vanuatu is a Small Island Developing State (SIDS) in the Pacific which is particularly exposed to natural hazard events like marine heat waves (MHWs), resultant of heightening climate change (Shultz et al. 2016; Jackson et al. 2017). MHWs have several definitions within literature; here we define a MHW as a spatial area with prolonged extreme warm sea surface temperature (SST), persisting for days to months (Frölicher and Laufkötter 2018). The impacts of such events can be detrimental to marine ecosystems and key industries like Fisheries (Hobday et al. 2016). This is of particular concern for Vanuatu communities, as they commonly rely on coastal and ocean resources (Holbrook et al. 2022) but have low adaptive capacity to MHW impacts due to their geography, level of economic development, limited resources, and physical isolation (Spickett et al. 2013; Jackson et al. 2017).

The processes that result in the build-up, persistence, and conclusion of MHW events across the Pacific Ocean are not widely understood. Generally, extreme ocean temperatures that occur during MHWs throughout the Pacific are driven by the following: air-sea heat fluxes, horizontal and vertical advection of heat (Holbrook et al. 2022), and climate phenomena like the El Niño Southern Oscillation (ENSO) (Frölicher and Laufkötter 2018; Gupta et al. 2020), the Interdecadal Pacific Oscillation (IPO), the North Pacific Gyre Oscillation (NPGO) and Pacific Decadal Oscillation (PDO) (Holbrook et al. 2022). ENSO notably affects the climate of countries like Vanuatu, throughout the tropics and subtropics, as an irregular periodic variation in SSTs and winds. It consists of three phases: El Niño (commonly known as the warm phase), Neutral phase and La Niña (commonly known as the cool phase). El Niño is generally associated with an increase in MHW events in the central and eastern Pacific Ocean and a decrease in MHW occurrences throughout the western Pacific. Driven by such factors, MHW events across the Pacific have many detrimental impacts on Pacific SIDS like Vanuatu.

1.2 Marine Heat Waves threaten the vital Fisheries sector in Vanuatu

A key sector in Vanuatu that is under threat from MHW occurrence is Fisheries. The Fisheries sector is critical to Vanuatu communities as it provides a major source of food and nutrition security and is important for the livelihood of locals. In previous MHWs across the world, Fisheries have been consistently reported as experiencing harsh impacts. Dunstan et al. (2018) highlights that these impacts are felt over long-time scales. Such impact on Fisheries is particularly linked to the ecological destruction caused by MHWs (Ainsworth et al. 2019).

Recently observed MHWs in 2011 and 2015/2016, which occurred across Australia and the Pacific, have demonstrated the extensive ecological impacts of MHWs, particularly on marine organisms and ecosystems services (Stubbs et al. 2020). The bleaching of corals and mortality of other key species is particularly concerning for Vanuatu, as this directly threatens the prosperity of Fisheries. The risk of MHW-induced coral mortality and key species death was highlighted by the 2015/2016 El Niño-driven MHW which significantly impacted Vanuatu (Holbrook et al. 2022). This event caused the mass coral bleaching and mass mortality of key fish species (Ainsworth et al. 2019). This decreased fishery production; both the marine ecosystems and fisheries industry is yet to recover (Barbeaux et al. 2020).

Decreased capacity of Vanuatu Fisheries is expected to have subsequent effects on the Health sector. A study by Savage et al. (2011) investigating the vulnerability of the Health sector to climate extremes, found that disasters and hazard events like MHWs causes additional demands on the Vanuatu health system. Participants described that the Vanuatu health system is already overburdened; with the additional pressures associated with disaster events, like MHWs, the health system will struggle to deal. Due to its fragility, the Health sector is heavily dependent upon other sectors, like Fisheries (Spickett et al. 2013). As the Fisheries sector is likely to be negatively impacted during and after a MHW event, the Health sector is expected to suffer linked impacts (Holbrook et al. 2022). With MHW prevalence expected to increase under heightening climate change, it is critical that the associated impacts of MHWs on Fisheries in Vanuatu are further investigated and resilient preparedness strategies are constructed (Frölicher and Laufkötter 2018).

1.3 Risk management of Marine Heat Wave impacts on Fisheries is critical to the resilience of Vanuatu communities

To ensure overall Vanuatu community resilience, MHW risk to Fisheries must be extensively explored, and effective management strategies should be employed (Eriksson et al. 2017). Effective and resilient MHW risk management requires two key components: proactivity and suitability (Holbrook et al. 2022). Proactivity entails managing a MHW risk situation prior to the occurrence of a MHW event, rather than responding to a MHW after it has become a crisis (Aitkenhead et al. 2021). Suitability is the level of appropriateness that MHW management strategies have for local application in vulnerable places. A MHW risk management strategy focused on risk to Fisheries would be suitable if it could be independently implemented by local stakeholders and/or communities. Additionally, MHW risk management must focus on both the ecological and human risk posed by MHW's (Jackson et al. 2017; Ainsworth et al. 2019). Barbeaux et al. (2020) explains that suitable Fisheries risk management strategies should address the specific physical, biological, economic, and social interactions among the affected fishery-related components of the target ecosystem, including humans. Currently, MHW risk management strategies in Vanuatu are inadequate (Hobday et al. 2016).

There are no management strategies specific to MHW risk in place for Vanuatu Fisheries presently. Limited MHW preparedness efforts are considered through climate monitoring via ocean monitoring buoys and climate projections, and through the establishment and management of Marine Protected Areas (MPAs) (Pascal 2011). Although Eriksson et al. (2017) state that MPAs have the potential to reduce the vulnerability of Fisheries and increase climate change resilience in fishing communities, there is no definitive evidence for Vanuatu that MPAs have increased Fisheries resilience to MHWs specifically. Therefore, it is unlikely that either the current climate monitoring/projections, or use of MPAs in Vanuatu, can be considered as Fisheries specific or resilient MHW risk management tools (Sutherland et al. 2019).

To increase the capacity of Vanuatu communities to implement resilient MHW risk management strategies, MHW risk knowledge must first be expanded (Eriksson et al. 2017). Risk knowledge addresses the patterns and trends in natural hazards, and the vulnerabilities that exist in a given area from which disaster risk can arise (De León et al., 2007). Risk knowledge is a concept that has been explored previously in Pacific SIDS like Vanuatu for hazards like tropical cyclones, droughts, and floods. However, risk knowledge for MHWs remains limited (Frölicher and Laufkötter 2018). MHW risk knowledge specific for the Fisheries sector in Vanuatu is further underexplored (Jackson et al. 2017).

1.4 Efficient Marine Heat Wave risk assessments are critical to resilient risk management

A key method, recognised by disaster risk management studies, to increase risk preparedness and expand risk knowledge is effective risk assessment (Aitkenhead et al. 2021; Frölicher and Laufkötter 2018). Marine heat wave risk assessments assess the ecological, societal and climatic threat of MHWs in a specified area (Frölicher and Laufkötter 2018). Specifically, efficient MHW risk assessments would examine the three core aspects of disaster risk: hazard, vulnerability, and exposure. In this instance, hazard refers to the climatic disruptions that occur during a MHW event that have potential to damage livelihoods, resources, and/or the environment in each area. Vulnerability considers the degree to which livelihoods, resources, and/or the environment is open to being affected by or unable to cope with negative impacts when a MHW event occurs (Kouwenhoven 2013). Finally, exposure encompasses the total populations, its livelihoods, resources, and environmental factors in each area where a MHW event may occur (Kouwenhoven 2013).

Risk assessments can either be static or dynamic. Dynamic MHW risk assessment includes the spatial and temporal components of MHWs (Aubrecht et al. 2013). This is done through the incorporation of historic, periodically updated, and simulated indicator data. In dynamic risk assessment, the three core components of MHW risk are considered equally: hazard, vulnerability, and exposure. Although recognised as more robust for informing resilient risk management, dynamic MHW risk assessments are not common (Giardino et al. 2018). Most previous MHW risk assessments conducted globally have been static (Giardino et al. 2018). Static risk assessments describe risk factors only for a distinct temporal and spatial scale, usually only including one or two of the three core components of risk (commonly hazard and/or vulnerability) (van Riet 2012). Risk assessment literature commonly recommends dynamic rather than static assessment (Samhouri et al.2021; van Riet 2012). MHW risk is dynamic in both space and time, thus an effective MHW risk assessment would be dynamic.

Along with being dynamic, it has been recognised that effective MHW risk assessments must be tailored (Asare-Kyei et al. 2014; Twomlow et al. 2022). A tailored MHW risk assessment would be specific for estimating MHW risk in a particular area and outputs user-specific information (Rufat et al. 2015). The selection of contextually specific risk indicators, and development of a user-informed indicator weighting scheme, is seen as the first step to a tailored risk assessment methodology (Twomlow et al. 2022; Agliata et al. 2021). The inclusion of local expert and user input during the indicator selection and weighting process can critically identify the most relevant hazard, vulnerability and exposure indicators that specifically consider the climatic, socio-economic, and geographic characteristics of the area being assessed (Rufat et al. 2015). Whilst presenting a user-centred design framework for disaster risk visualisation, Twomlow et al. (2022) highlight that the perspectives of end-users are critical for tailored selection of disaster risk indicators.

A promising technique for incorporating end-users into risk assessment is through participatory research. As explained by Aitkenhead et al. (2023), “this technique includes collaboration with stakeholders in a capacity building process as well as consideration of local peoples and expert observations into knowledge systems”. The usability of participatory research for efficient MHW risk assessment is demonstrated by Jackson et al. (2017) in their study of climate risk in Emae Island, Vanuatu. A multitude of participatory research methods was used to identify potential indicators of climate risk and to gather qualitative data for such indicators: semi structured interviews, informal discussions, and participatory hazard mapping. Notably, this inclusion of end-users through participatory research, for tailored indicator selection, has been commonly omitted from not only MHW risk assessment in Vanuatu, but also from global studies (Asadzadeh et al. 2015).

Furthermore, for efficiency in MHW risk assessment, literature emphasises the importance of incorporating ecological and human indicators, rather than one or the other (Frölicher and Laufkötter 2018). Ideally, a MHW risk assessment focused on Fisheries in Vanuatu would consider the relationship between ecological and human MHW impacts that pose a risk to the Fisheries sector (Frölicher and Laufkötter 2018). Globally, risk assessments commonly lack this approach, which limits current understanding of the risk MHWs pose to individual organisms, ecosystems, and their socioeconomic services (Frölicher and Laufkötter 2018).

1.5 Key knowledge gaps in studies conducting Marine Heat Wave risk assessment

Marine heat wave risk knowledge and risk management is widely underexplored across Pacific SIDS, with little to no investigations focusing on Vanuatu. Currently, many knowledge gaps exist for efficient MHW risk assessment in Vanuatu, as well as for the specific risk posed to Fisheries in Vanuatu. The small number of studies assessing MHW risk across Vanuatu are not focused on the Fisheries sector, and widely omit the following aspects of efficient risk assessment methodology: dynamic inclusion of hazard, vulnerability, and exposure indices (Frölicher and Laufkötter 2018), the tailored selection and weighting of MHW risk indicators (Asadzadeh et al. 2015), and the inclusion of ecological and human focused indicators to holistically explore MHW risk (Frölicher and Laufkötter 2018). Table 1 identifies such knowledge gaps that are evident in previous risk assessment studies performed for MHWs in Vanuatu.

Table 1. Key knowledge gaps identified in previous studies assessing MHW risk in Vanuatu.

Study	Description	Evident gaps in risk assessment efficiency
Major et al. 2021	An evaluation of issues with climate change adaption in island settlements using case studies and general perspectives on adaption. Six island settlements were used as case studies: Cocos Islands (Australia), Shishmaref (USA), Broad Channel (USA), Samsø (Denmark), Ciutadella de Menorca (Spain), and Port Vila (Vanuatu). Climate change impacts, including MHW impacts, are described and assessed, including the adaptions and capacity within each of the six case study countries. The following indicators were considered in the assessment: access, cost, governance, and cultural, historical, and ecological preservation.	-Does not focus on fisheries sector -Does not incorporate the dynamic assessment of hazard, vulnerability, and exposure indices -Indicator selection and weighting is not tailored
Pedersen Zari et al. 2019	To assess and respond to the risks of natural hazards like MHWs in Port Vila Vanuatu, this study developed a methodology for urban ecosystem-based adaption (EbA) in SIDS. EbA methodology considers the importance of symbiotic relationships between sociocultural and ecological systems when hazard impacts are present. The study found that in Port Vila, Vanuatu: -adaption planning must put local people at the forefront, using a participatory research. - EbA methodology must be multidisciplinary and iterative. - EbA must be developed holistically, focusing on socio-ecological systems.	-Does not focus on fisheries sector -Does not incorporate the dynamic inclusion of hazard, vulnerability, and exposure indices -Indicator selection and weighting is not tailored
Kaly and Pratt 2000	This study included the development of an Environmental Vulnerability Index (EVI) to natural hazards like MHWs for Fiji, Samoa, Tuvalu, and Vanuatu. EVI indicator data was collected, and provisional results were calculated for the study countries to identify their environmental vulnerabilities. As part of this study the following was conducted: -rigorous peer review was obtained -the model and indicators were refined -a mechanism for the collection of data was developed -preliminary results were calculated for Fiji, Samoa, Tuvalu, and Vanuatu -criteria and a workplan for testing and refining the index to make it internationally acceptable were developed The results of this study were concluded to demonstrate the potential of the EVI for identifying which countries are environmentally vulnerable in a general sense. It was recommended that further research is required to test the model and indicators using a larger set of countries. Additionally, it is stated that improvement is required in the following areas: peer review process, scoring and weighting factors, improving response process to EVI results, and collecting EVI data and operationalise the index	-Does not focus on fisheries sector -Does not incorporate the dynamic inclusion of hazard, vulnerability, and exposure indices -Indicator selection is not tailored -Only considers ecological impacts, rather than a cohesive assessment of both ecological and human impacts
Bell et al. 2013	This study focused on a fisheries risk assessment to climate change-induced natural hazards like MHWs. The research was conducted for Pacific Island countries and territories, including Vanuatu. Risk was assessed specifically for tuna species, which are critical to the fisheries industry in Pacific Island countries and provide a key source of food. The impacts posed by natural hazards were examined and priority adaptations to reduce the threats to oceanic fisheries were proposed.	-Does not incorporate the dynamic inclusion of hazard, vulnerability, and exposure indices - Indicator selection and weighting is not tailored
Jackson et al. 2017	In this study, and adapted framework for Emae Island, Vanuatu is developed to understand the climactic vulnerability of Emae communities. This study considered vulnerability as a function of exposure, and physical and social susceptibility. It examined risk for the current day, as well as incorporating historical data. Although this study defines the hazard, vulnerability, and exposure components of risk differently, it does consider all three, and it considers risk on various temporal scales. Therefore, this study includes elements of dynamic risk assessment. To investigate community risk to hazards and the indicators that could be used to identify this specifically in Emae Island, discussions were held with locals. This ensured tailored indicator selection. Locals identified the following critical	-Does not focus on fisheries sector - Only considers human impacts, rather than a cohesive assessment of both ecological and human impacts

	determinants of risk: -water availability -groundwater availability -lack of evacuation centres -road susceptibility -infrastructure vulnerability -access to resources Results showed that Emae Island communities are highly exposed and susceptible to hazards, but also have high levels of resilience. It was concluded that the adapted framework developed allowed a holistic picture of disaster vulnerability to emerge for Emae Island.	
SPREP and CSIRO 2021	In this project by SPREP and CSIRO, NextGen extreme sea level and marine heat wave projections are being applied across Vanuatu to monitor the hazard component of MHW risk. This monitoring is targeted at examining the risk to fisheries specifically. Results are to be used to understand hotspots and areas of high and low risk in Vanuatu. Additionally, critical nursery areas that are less vulnerable to MHW impacts are identified for the establishment of MPAs, which are intended to allow fish stocks to recover in adjacent high-risk areas once a coral bleaching event occurs.	-Does not incorporate the dynamic inclusion of hazard, vulnerability, and exposure indices -Indicator selection and weighting is not tailored -Only considers ecological impacts, rather than a cohesive assessment of both ecological and human impacts.

Overall, Table 1 shows that the most prominent knowledge gaps in MHW risk assessment studies for Vanuatu are the dynamic inclusion of hazard, vulnerability and exposure indices and the tailored selection of indicators. It is essential to address such gaps in the future. Further study should also address the Fisheries sector and consider both the ecological and human impacts of MHWs.

1.6 Aims and objectives

Accordingly, this study aims to establish a foundation for efficient MHW risk assessment in Pacific SIDS, specifically for the highly vulnerable country of Vanuatu. This study addresses the critical knowledge gaps previously identified by establishing a process of tailored indicator selection for a fisheries specific MHW risk assessment.

Specifically, it is intended that this study:

- establishes the first step towards an efficient MHW risk assessment for Fisheries in Vanuatu.
- adopts participatory methods to inform the selection of tailored hazard, vulnerability, and exposure indicators, including both ecological and human impact indicators, to be used in a MHW risk assessment for Fisheries in Vanuatu, as well as to determine if data is available for selected indicators on dynamic temporal and spatial scales.
- utilises locals' perspectives to develop a weighting scheme for the selected hazard, vulnerability and exposure indicators based on their importance for indicating risk to Fisheries in Vanuatu.

This study is a critical first step for developing an efficient MHW risk assessment specific to the vital Fisheries sector in Vanuatu. Such an assessment has the potential to inform local decision-makers of priority areas and can guide risk management strategies to improve community resilience.

2 Methodology

2.1 Study area: Vanuatu

Vanuatu is a Small Island Developing State (SIDS) located in the South Pacific Ocean, consisting of approximately 80 islands (refer to Figure 1) (Spickett et al. 2013). The islands that make up Vanuatu span a land area of 12,335 km^2. The land ranges from rugged mountains and high plateaus to rolling hills and low plateaus. Much of Vanuatu is coastal, with offshore coral reefs a key characteristic of the country (Spickett et al. 2013). The climate in Vanuatu is tropical with two clear seasons: a warm, wet season and a cool, dry season (Spickett et al. 2013). The climatic conditions of Vanuatu tend to change on a yearly basis, mainly influenced by ENSO (Frölicher and Laufkötter 2018; Gupta et al. 2020). The variable climatic conditions experienced in Vanuatu often accumulate to natural hazard events like tropical cyclones, drought, and marine heat waves (Frölicher and Laufkötter 2018; Gupta et al. 2020). There are several key sectors that drive the Vanuatu economy, including Agriculture, Fisheries, and Tourism. Such sectors heavily support the countries food security (Holbrook et al. 2022). With a history of malnutrition, food security is critical to the resilience of Vanuatu communities (Spickett et al. 2013).

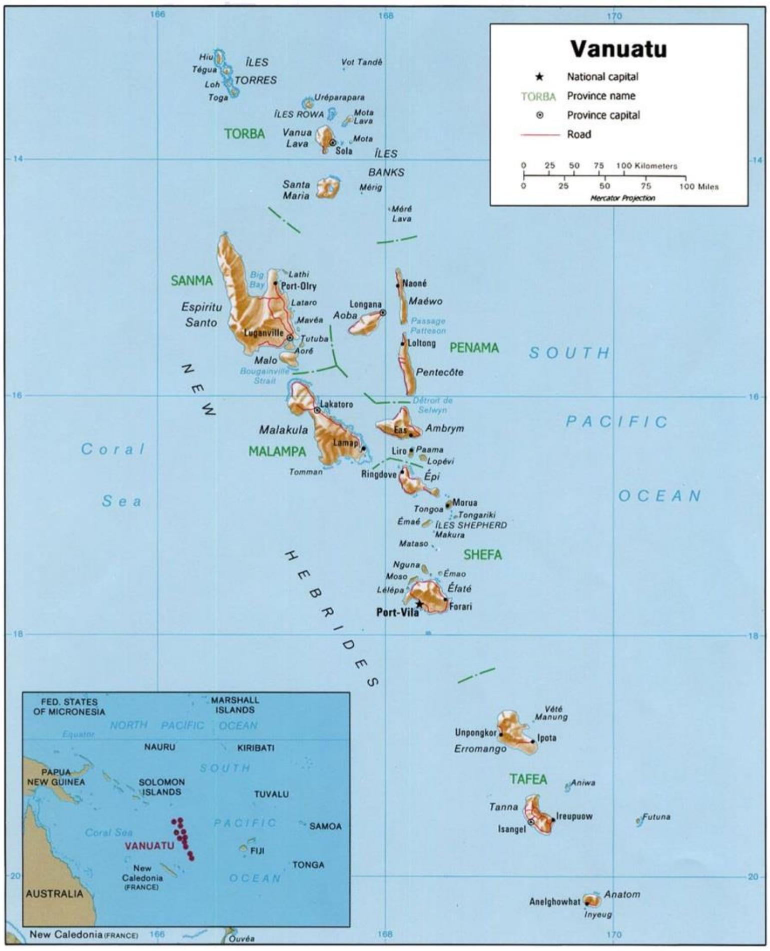

Figure 1. Administrative map of Vanuatu displaying the six provinces of Vanuatu: Malampa (capital: Lakatoro), Penama (capital: Saratamata), Sanma (capital: Luganville), Shefa (capital: Port Vila), Tafea (capital: Isangel), and Torba (capital: Sola) (Nations Online Project 2015).

2.2 Study design

The methodology developed in this study uses best practice techniques to achieve an efficient first step in a MHW risk assessment for Fisheries in Vanuatu (refer to Figure 2). This first step includes the tailored selection and weighting of dynamic hazard, vulnerability, and exposure indicators for MHW risk to Fisheries in Vanuatu, holistically incorporating both ecological and human indicators. End-user perspectives are incorporated in the indicator selection and weighting process through participatory methodology in the form of surveys. It is important to note that in this study, indicators that include dynamic data on both temporal and spatial scales are prioritised over static indicators.

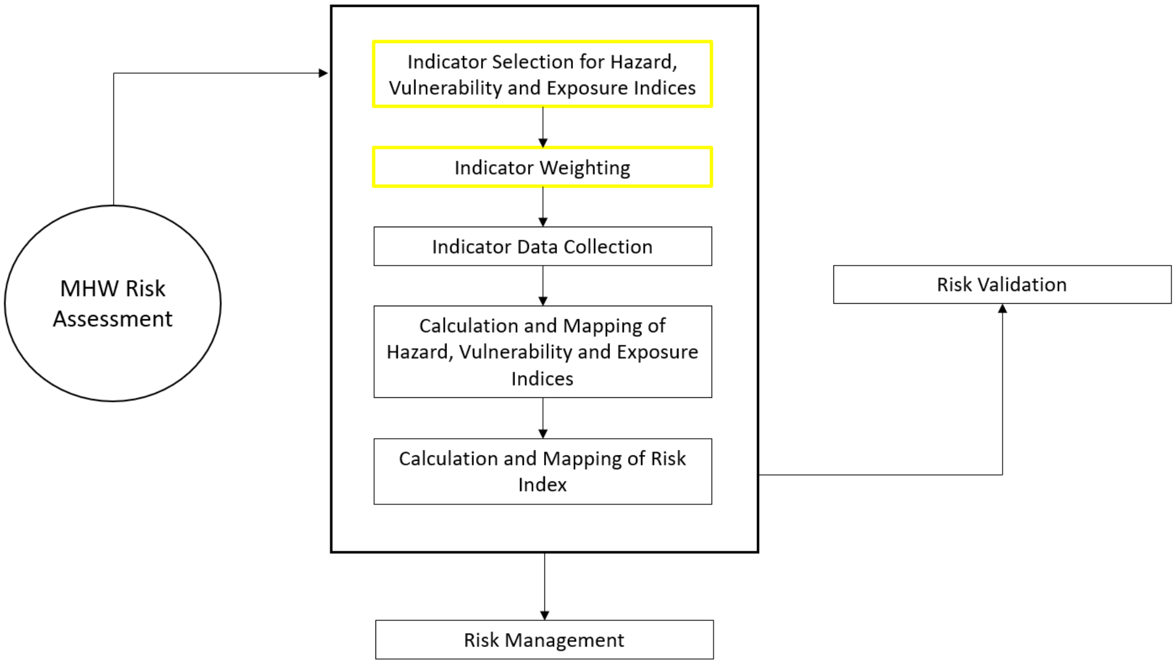

Figure 2. The key steps involved in MHW risk assessment methodology. The steps addressed in this paper are highlighted in yellow. This figure is adapted from Wang et al. (2011).

The methodology used here to complete this first step in a MHW risk assessment for Fisheries in Vanuatu is three-part:

1. A literature review was conducted to determine a list of potentially relevant hazard, vulnerability, and exposure indicators to be used in the Fisheries specific MHW risk assessment for Vanuatu.
2. Participatory research was conducted through the development and distribution of a survey; it was completed by local Vanuatu participants, who are/were involved in the Fisheries industry, to inform the tailored selection of MHW indicators.
3. An appropriate indicator weighting scheme for selected indicators was formulated based off survey responses.

2.2.1 Part 1: Literature Review- Investigation of Potential Indicators

A literature search was conducted to gather a list of potentially useful indicators to use in the MHW risk assessment for Vanuatu Fisheries. Sources relaying information on past studies that have used hazard, vulnerability and/or exposure indices to determine MHW risk in similar study areas were examined. Criteria for the inclusion and exclusion of sources to be analysed were developed based on the relevance to this study (refer to Table 2). The search parameters used for the literature investigation are listed in Table 3. Most searches were conducted using the database Google Scholar, due to the wide availability of relevant sources. ScienceDirect, Springer Link and Wiley Online Library were used for additional searches. A filtered date range of 2000-2022 was used in each search, to increase relevancy of sources (studies before 2000 are likely to be irrelevant to current MHW risk assessment practices).

Overall, a total of 23 sources (Caputi et al. 2016; Chandrapavan et al. 2019; Cheung and Frölicher 2020; Ainsworth et al. 2008; Holbrook et al. 2022; Le Nohaïc et al. 2017; Eriksson et al. 2017; Sammarco et al. 2006; Obura 2001; Sen Gupta et al. 2020; Lee and Park 2019; Barbeaux et al. 2020; Roberts et al. 2019; Taves et. al 2022; Green et al. 2021; Bellotti et al. 2018; Kim et al. 2014; Lam et al. 2020; von Biela et al. 2019; Spickett et al. 2013; Suryan et al. 2021; Frölicher and Laufkötter 2018; Arias-Ortiz et al. 2018) were analysed. Each indicator mentioned by the sources, as well as key points provided in each source were recorded. Based on the literature review, a list of potential hazard, vulnerability, and exposure MHW indicators to be used for the Vanuatu Fisheries assessment was developed. This list was further refined depending on the following criteria before being included in the survey: (i) The indicator is appropriate for the climatic, socio-economic and/or geographic characteristics of Vanuatu, specifically in the context of the Fisheries sector; (ii) Data is available for Vanuatu, and (iii) Data is of a high spatial and temporal resolution (at least on the regional scale in Vanuatu and spans at least 10 years).

Table 2. Inclusion and exclusion criteria for the selection of sources to be used in the literature investigation to find potentially useful MHW indicators.

Criteria for inclusion	**Criteria for exclusion**
Literature in English	Literature in other languages
Mention of specific hazard, vulnerability and/or exposure indicators	Vague mention of hazard, vulnerability and/or exposure indicators
Mention of assessing MHWs specifically, rather than using indicators to examine other hazard events	No mention of MHWs specifically and/or used indicators to assess other similar/dissimilar hazard events
The way in which indicators were used to assess MHW risk/impacts is described in detail	Vague or no description of how indicators were used to assess MHW risk or relevant impacts
Study area has similar climatic/socioeconomic or geographic features to Vanuatu	Indicators discussed are highly specific to assessing MHW risk to a certain species/feature that is not at all relevant to Vanuatu, or to an area that is very dissimilar to Vanuatu
Publicly available government/relevant organisation documents, Journal articles, review articles and book chapters	Restricted access books/book chapters, journal/ review articles, and grey literature other than relevant organisation documents (meteorological organisation documents), for example newspaper articles

Table 3. Search parameters used to gather sources for the literature investigation to gather a list of potential indicators.

Database	**Search Parameters**	**Result**
Google Scholar	1st search: "Marine Heat Wave" AND "risk assessment" AND "indicator" Filtered date from 2000 onwards 2nd search: "Marine Heat Wave" AND "risk" AND "hazard" OR "vulnerability" OR "exposure" Filtered date from 2000 onwards 3rd search:	1st search: 136 items found, 3 Included, 133 Excluded 2nd search: 765 items found, 10 Included, 89 Repeated, 663 Excluded 3rd search: 1300 items found, 2

	"marine heatwave" AND 'impact' AND 'fish' AND 'risk' AND 'indicator' Filtered date from 2000 onwards 4th search: "climate" AND "hazard" AND "vulnerability" AND "risk" AND "temperature" AND "Vanuatu" AND "health impact" AND "malnutrition" Filtered date from 2000 onwards 5th search: “marine heatwave" AND "warming ocean" AND "resilience" AND "impact" AND "coral reef" Filtered date from 2000 onwards 6th search: "marine heatwave" AND "increased SST" AND "impact" AND "nutrients" Filtered date from 2000 onwards	Included, 716 Repeated, 582 Excluded 4th search: 46 items found, 1 Included, 5 Repeated, 40 Excluded 5th search: 132 items found, 1 Included, 53 Repeated, 78 Excluded 6th search: 24 items found, 1 Included, 0 Repeated, 23 Excluded
ScienceDirect	1st search: "Marine Heat Wave" AND indicator AND vulnerability Filtered date from 2000-2022 2nd search: "Vanuatu" AND “food security” AND "indicator" Filtered date from 2000-2022	1st search: 56 items found, 1 Included, 3 Repeated, 52 Excluded 2nd search: 208 items found, 1 Included, 2 Repeated, 205 Excluded
Springer Link	1st search: "Marine Heat Wave" AND indicator AND exposure Filtered date from 2000-2022	1st search: 42 items found, 1 Included, 6 Repeated, 35 excluded
Wiley Online Library	1st search: Marine Heat Wave AND risk indicator AND Pacific Island Filtered date from 2000-2022	1st search: 96 items found, 3 Included, 129 Excluded, 2 Repeated

2.2.2 Part 2: Participatory Methodology - Survey Development and Distribution

To conduct the participatory component of the methodology, a survey was employed to collect both qualitative and quantitative data. The survey was designed with the intention of participants selecting indicators they believe are most appropriate for assessing MHW risk to Fisheries in Vanuatu. The survey was limited to seven main questions and was to be filled out in approximately 20 minutes, to lessen survey fatigue (Jackson et al. 2017). Most questions were ranking-style questions to inform the tailored selection of hazard, vulnerability, and exposure indicators, and to inform on the weights that should be applied to each indicator. As this is a scientifically complex topic, and survey participants were not required to have a science background, sufficient information on the topic and intention of the study was provided at the beginning of the survey. Refer to Appendix A for the full survey. Refer to Appendix B for ethics approval information. As part of human ethics requirement, a consent form was distributed prior to participant inclusion in the study. Refer to Appendix C for a copy of the consent form.

To further ensure the smooth rollout of survey, and that the content would be understood, a survey workshop was held at the Vanuatu Fisheries Department in Port Villa, Vanuatu on the 11th of October 2022. During this workshop, a team from the Australian Bureau of Meteorology presented information to staff of the Vanuatu Fisheries Department. The presented content included an overview of the study, and a step-by-step synopsis of each survey question.

The consent form and survey were distributed to participants across all Vanuatu provinces over a two-week period from the 11th of October to the 28th of October 2022. These were distributed to the Fisheries staff who attended the workshop, as well as their colleagues who could not attend, and other relevant fisheries stakeholders via email. All participants were sourced through networks of the Vanuatu Fisheries Department. A total of 12 completed surveys were collected. Survey participants were of a range of ages, genders and located across various Vanuatu provinces (3 from Penama, 4 from Shefa, 4 from Malampa, and 1 from Tafea). Although the sample size is relativitley small, this study is novel with no similar data collected for this study's focus, so results are still seen as meaningful (Asadzadeh et al. 2015).

Data from each survey question was analysed in Microsoft Excel. To investigate the trends in the data for the indicator ranking questions (Questions 4, 5 and 6) several statistical tests were performed. Firstly, test assumptions were checked by plotting the data distribution on boxplots. All assumptions were met, thus the tests proceeded. The statistical tests performed were used determine if there was signficiant differences between how the potetnail indicators for each index (hazard, vulnerability and exposure) were ranked in terms of importance. Firstly, an ANOVA: Single Factor test was conducted for Question 4 results, to assess if significant differences were present between the rankings given to each potential hazard indicator: SST, Coral bleaching/mortality, and Chlorophyll-a concentration. The test statistic (F-value), degrees of freedom and p-value were recorded. This test was repeated for Question 5 and 6 results, to assess differences between potential vulnerability and exposure indicators respectively. If signficant differences were found, further statistical tests were performed to find how potential indicators differed from one another. For Question 4 results, an F-test was performed to determine if there was signficiant variance between ranking given to SST versus Coral bleaching/mortality, SST versus Chlorophyll-a conentration, and Coral bleaching/mortality versus Chlorophyll-a concentration. The F-value (test statistic), degrees of freedom and the p-value indicating the level of marginal significance within the test, were recorded. Students T-test's (assuming equal or unequal variance, depending on F-test findings) were then performed to analyse if significant differences were evident between SST versus Coral bleaching/mortality, SST versus Chlorophyll-a conentration, and Coral bleaching/mortality versus Chlorophyll-a concentration. The t-value (test statistic), degrees of freedom and p-value were recorded. These sets of tests were repeated to analyse results of questions 5 and 6. All statistical tests used $\alpha = 0.05$.

2.2.3 Part 3: Development of Indicator Weighting Scheme

A weighting scheme was developed following a rank-ordering weighting method (Asare-Kyei et al. 2014) informed by Questions 4-6 of the participatory research survey. Firstly, a list of confirmed indicators was compiled for each of the hazard, vulnerability and exposure indices based on survey results. Secondly, a weight between 0 and 1 was assigned to each indicator in each of the three indices. These weights were made to reflect the rankings given to each indicator by survey participants. Weights closer to 1 reflect high importance and relevance and those closer to 0 reflect comparatively low importance and relevance. Overall, it was ensured that indicator weights for each index would equal 1 (e.g. in the hazard index, if all indicator weights were added it would equal 1).

3 Results

3.1 Part 1: Literature Review- Investigation of Potential Indicators

23 sources (Caputi et al. 2016; Chandrapavan et al. 2019; Cheung and Frölicher 2020; Ainsworth et al. 2008; Holbrook et al. 2022; Le Nohaïc et al. 2017; Eriksson et al. 2017; Sammarco et al. 2006; Obura 2001; Sen Gupta et al. 2020; Lee and Park 2019; Barbeaux et al. 2020; Roberts et al. 2019; Taves et. al 2022; Green et al. 2021; Bellotti et al. 2018; Kim et al. 2014; Lam et al. 2020; von Biela et al. 2019; Spickett et al. 2013; Suryan et al. 2021; Frölicher and Laufkötter 2018; Arias-Ortiz et al. 2018) were analysed. From this analysis a list of indicators, used in previous MHW risk assessment studies, was formed. Previously used hazard indicators included: Sea Surface Temperature (SST) anomalies; Coral bleaching/mortality; Chlorophyll-a concentrations; Marine heatwave cumulative intensity (MHCI) value; Water column nutrient status (Table 4). Previously used vulnerability indicators included: Terrestrial-based food and income generation; Fishing skills and technology; Human malnutrition; Fish nutritional value; Disease prevalence; Fishery fish diversity/fishery flexibility; Primary production of commercial fisheries; occupational multiplicity (Table 4). Previously used exposure indicators included: Market access; Physical capital (e.g. infrastructure, water tanks and strong dwellings); Seagrass population/C content in seagrass; Coral habitat health/crown of thorns prevalence; Crab stock health; Fish mortality/fish stock health (Table 4). An overview of the literature analysis, including descriptions of each of these indicators, is provided in Table 4.

Table 4. Key information found in the literature review, including a list of previously used MHW risk indicators, definitions of each indicator and descriptions of how each indicator was used.

Index	Indicator	Past Investigation Description
Hazard	Sea-Surface Temperature (SST) anomalies	SST has been used in most studies investigating MHWs as SST can indicate the occurrence of this hazard. High SSTs continue to be associated with the occurrence of MHWs. • In an investigation of the MHW event which impacted the Midwest coast Australia during the austral summer of 2010/11, Caputi et al. (2016) explain that SST anomalies of 2-5°C above normal climatology were associated with the occurrence of the MHW. • Chandrapavan et al. (2019) further explain that this 2011 Western Australian MHW was driven by a very strong La Niña event and SSTs were raised by up to 5°C between November 2010 and March 2011. • Cheung and Frölicher (2020) examined the potential impact of heightened SST in the Pacific Ocean and found that high SST was associated with changes in abundance and distributions of significant fish species. These impacts are commonly evident when a MHW occurs. • Currently, the Vanuatu National Weather Service outlines the association of SST with MHW occurrence and recommends actions to reduce the impacts of a MHW event when SST rises. In the Vanuatu Climate Outlooks the following recommendations are made for when SST is above normal: - build low huts near beaches to cool off - encourage sun safe behaviour for tourists - do not remove branches from trees nearby - heavily mulch flower beds - provide shade tents and cooling stations for tourists - use structural of mechanical aid - avoid areas of unfavourable weather conditions - fishing practices must adapt to fish distribution shifts.
	Coral bleaching/mortality	Previous studies outline that coral bleaching/mortality can indicate the occurrence of a MHW event. When a MHW develops, SST increases, and coral bleaching/mortality commonly occurs. Bleaching occurs in response to high SST as thermal stress causes a dissociation of coral-dinoflagellate symbiosis which makes coral tissues whiten (Ainsworth et al. 2008). • In an investigation of MHWs in the tropical western and central Pacific Ocean region, Holbrook et al. (2022) observed that moderate/strong MHW events had various associated impacts including coral bleaching. • Le Nohaïc et al. (2017) conducted coral health surveys during the austral summer of

		2016 in four bioregions along the WA coast; it was reported that an El Niño-related MHW caused a regional-scale mass bleaching event in WA. It was also demonstrated that even heat-tolerant corals, from reef environments that naturally experience extreme thermal variability, are threatened by MHWs. • Eriksson et al. (2017) sought to understand community impacts from natural disasters in the different provinces of Vanuatu. Focus group discussions were held at different sites across Vanuatu to gauge the impacts communities experienced from hazard events. Coral mortality was a key impact noted by communities. • Sammarco et al. (2006) further explains the link between MHW events and coral bleaching. It was determined that high SST in MHW events was associated with severe bleaching. • In an examination of interspecific patterns of bleaching, mortality, and recovery of corals on reefs in Kenya, Tanzania, Mozambique, and Madagascar for one year after the 1997–98 El Niño, Obura (2001) found that coral species varied in responses to thermal stress. However, all coral species underwent some degree of bleaching and reality. One major group of species underwent severe bleaching followed by 100% mortality and the other major group experienced graduated bleaching with pale tissue and low-to-moderate mortality (Obura 2001). • Currently, the Vanuatu National Weather Service outlines the association of coral bleaching/mortality with MHW occurrence and recommends actions when coral bleaching/mortality occurs. A coral bleaching alert is issued via climate outlooks, describing the level of coral bleaching expected for a future period. If coral bleaching levels are above normal, the National Weather Service recommends the following: • reduce stormwater and fertiliser runoff - avoid using herbicides and pesticides - work with government to move towards renewable energy - for tourism operators nearby coral, provide extensive education to tourists on how to avoid damaging coral reefs - when anchoring boats, avoid anchoring near places with coral reefs - tour boats to avoid releasing greywater discharge or other water pollutants that can be damaging to marine environments - encourage offshore fishing to alleviate stressors in the lagoon (for lagoon fisheries specifically).
	Chlorophyll-a concentrations	Past studies have revealed an association between MHW occurrence and changes in Chlorophyll-a concentrations. MHWs have tended to coincide with reduced chlorophyll-a concentration at low and mid-latitudes (Sen Gupta et al. 2020). Chlorophyll-a concentration indicates the abundance and biomass of phytoplankton in the ocean. It is the main pigment used by phytoplankton to capture light energy and convert that energy into biomass. Concentrations are useful for monitoring the trophic status, water quality and photosynthetic rate of marine environments. Phytoplankton populations and thus chlorophyll-a concentrations are influenced by SST, with high SSTs in MHW events commonly associated with a reduction in chlorophyll-a concentration and phytoplankton abundance, however there are some cases that have recorded increase in chlorophyll-a concentration during MHWs. • Lee and Park (2019) investigated the relationship between MHW events and Chlorophyll-a concentration in the East China Sea from 2016-2018. An ocean colour sensor at a geostationary orbit (Geostationary Ocean Color Imager; GOCI), was used to examine this relationship. It was observed that when a MHW event occurred, chlorophyll-a concentration decreased. This was attributed to the fact that increased SST enhances the stratification in the upper ocean surface layer. Strong stratification results in the weak upwelling and limited supply of nutrients from the deep to the surface (Lee and Park 2019). Limited nutrient supply in turn limits phytoplankton growth and abundance, resulting in reduced chlorophyll-a concentrations. • Currently, the Vanuatu National Weather Service outlines the association of chlorophyll a concentration with MHW occurrence and recommends actions when chlorophyll a concentration change. Chlorophyll concentration is monitored and if it is found to be above the normal level, it is recommended that: - Offshore fisheries will likely have higher stocks for smaller pelagic fish - Higher risks of lagoon fish disease, so offshore fishing should be encouraged - Nutrient runoff should be limited

		- Monitor for algal blooms - Lagoon fisheries should target high chlorophyll regions for crown of thorns starfish management activities
	Marine heatwave cumulative intensity (MHCI) value	MHCI value is used to measure for MHWs. This value defines a heatwave as 5 days or more with daily mean SSTs greater than the 90th percentile of the 1 January 1983 through 31 December 2012 time series (Barbeaux et al. 2020). • When examining winter MHW occurrence, Barbeaux et al. (2020) MHCI was used as an indicator of hazard conditions associated with MHWs.
	Water column nutrient status	Water column nutrient status is commonly related to SST, resulting in it being a commonly used indicator of MHW events. • When investigating high and anomalous water temperature in 2013 over South Australia, Roberts et al. (2019) collected water samples to assess water column nutrient status. It was determined that nutrient levels were impacts by the change in temperature. • An investigation of MHWs from 2013-2016 determined that there was increased stratification of the water column during MHW events which resulted in "shoaling of the winter mixed layer and a decrease in nutrient re-supply to the euphotic zone" (Taves et al. 20220). Results highlighted that during marine heatwave events a shallower mixed layer in the water column reduces the transport of essential nutrients to the surface layer (Taves et al. 20220).
Vulnerability	Terrestrial-based food and income generation	The fisheries industry provides staple food and sources of livelihood in Pacific Island countries; if a MHW occurs and the fisheries industry is negatively impacted, communities must have a terrestrial-based source of food and income to survive (Eriksson et al. 2017). Thus, if terrestrial-based food income and generation is limited, a community is likely more vulnerable to experiencing negative impacts from MHWs. Securing a sustainable supply of food and income is recognised as a critical priority for nutrition security in the face of natural hazard occurrence in Pacific SIDS (Eriksson et al. 2017). • A study by Eriksson et al. (2017) sought to understand the role of fish for Pacific Island communities during disasters and recovery from associated impacts. It was found that a significant decrease in terrestrial-based food and income generation capacity generally caused increased reliance on marine resources to cope. It was concluded that that fisheries management is of critical focus for disaster preparedness and relief strategies in Pacific SIDS communities.
	Fishing skills and technology	Fisheries is a critical industry to Pacific Island communities; thus, fisheries sustainability is a priority for natural hazard management. Increasing the fishing skills and technology within Pacific Island communities is key for reducing vulnerability and increasing the adaptive capacity of communities to deal with the impacts of natural hazard events like MHWs (Eriksson et al. 2017). • Eriksson et al. (2017) state that "lack of fishing skills and technology …reduced the capacity for marine resources to support recovery". Eriksson et al. (2017) held focus group discussion at ten sites throughout Shefa, Tafea, Malampa and Sanma provinces in Vanuatu. It was noted that lack of fishing skills and technology in communities limited the capacity for marine resources to support resilience in the face of natural hazard events. • Green et al. (2021) conducted a global meta-analysis investigating adaptive capacity of small-scale fishing case studies from 20 countries. Results displayed that adaptive responses within communities only occurred where learning and knowledge regarding fishing practices was expanded.
	Human malnutrition	Pacific SIDs like Vanuatu are at high risk of malnutrition from the associated impacts of climate change-induced disasters on food supply (Bellotti et al. 2018). If malnutrition is already prevalent in a community, this would mean that the community would be more vulnerable to the likely effects of MHWs. • Kim et al. (2014) explain that extreme weather events like MHWs facilitate malnutrition. • In a review by Lam et al. (2020), the effects of climate change on tropical marine fisheries were investigated, with particular focus on the socio-economic impacts to tropical nations, and potential adaptation strategies. It was concluded that rapid climate change and increased occurrence of MHWs will result in acidification and deoxygenation in marine ecosystems. Consequently, the maximum catch potential of

		tropical fish stocks is projected to decline by up to 40% by the 2050s under the RCP8.5 emissions scenario (Lam et al. 2020). Climate-driven decreases in fisheries production and changes to fish species composition will result in heightened vulnerability of Pacific SIDS with limited adaptive capacity, including increased human malnutrition and other detrimental health impacts (Lam et al. 2020).
	Fish nutritional value	MHWs are often associated with a reduction in the nutritional value of key fish species (von Biela et al. 2019). If the nutritional value of key fish species within communities is already diminished, then the community would be more vulnerable to MHW impacts. • In an investigation of a MHW event that occurred in Alaska during 2015-2016, von Biela et al. (2019) noted declines in the nutritional value of a key fish species, sand lance, indicating that energy transfer from lower trophic levels to predators via sand lance may have been disrupted during the MHW event. To investigate this, data on the nutritional value (length, energy density, and whole-body energy) of sand lance was collected during in cool (2012-2013) years, and increasingly warm (2014-2016) years. It was concluded that the energy flow disruption within the pelagic food web associated with the MHW event caused population declines/breeding failures in predator species throughout the Gulf of Alaska (von Biela et al. 2019).
	Disease prevalence	In Pacific SIDS, natural disasters such as MHWs are commonly associated with changes in disease prevalence. An increase in health problems resultant of changes in water-borne diseases, malnutrition/food security and food-borne diseases is likely when a MHW occurs in Pacific SIDS (Spickett et al. 2013). Thus, if a community is already suffering from elevated disease prevalence, it would be highly vulnerable to the health effects of MHW events. • Spickett et al. (2013) used a Health Impact Assessment (HIA) framework as a basis to consider the health impacts likely to be caused by climate change affects in Vanuatu. The health risks associated with climate change driven hazard events were assessed and a range of potential adaptive responses appropriate for Vanuatu were proposed. The HIA process that was carried out included the stakeholder participation; stakeholders included a wide range of representatives from various sectors (Spickett et al. 2013). Stakeholders provided input, during focus groups, into the knowledge of potential health impacts and adaptation strategies. It was concluded that health problems that may be affected by natural hazard events resultant of climate change in Vanuatu include vector-borne diseases (eg. malaria, dengue fever, etc.), respiratory disease, water-borne diseases, malnutrition/food security, food-borne diseases and non-communicable diseases (Spickett et al. 2013).
	Fishery fish diversity/fishery flexibility	Past investigation commonly notes that the level of fish diversity in fisheries/ the flexibility of fisheries is indicative of how vulnerable a community is to MHW impacts (Green et al. 2021; Frölicher and Laufkötter 2018). Fisheries diversity and flexibility is linked to the vulnerability of communities to MHW impacts, and the adaptive capacity of communities for responding to MHW events. If fisheries are more diverse and flexible, communities are likely to have decreased vulnerability, and increased adaptive capacity for dealing with MHW impacts. Thus, fishing industries must remain flexible and adopt adaptive management frameworks to support sustainability, manage uncertainty and respond to climate change impacts (Chandrapavan et al. 2019). • To expand evidence on linking theoretical measures of adaptive capacity to community and household responses, Green et al. (2021) conducted a global meta-analysis examining adaptive capacity and human responses to change in small-scale fishing case studies. It was determined that adaptive responses at the local level were only present when communities had diversity and flexibility. Overall, it was concluded that fisheries portfolio diversification is important for livelihood resilience in resource-dependant coastal communities (Green et al. 2021). • Frölicher and Laufkötter (2018) note that MHWs can cause adverse impacts on the political and socio-economic sector as they commonly affect aquaculture and important fishery species. It was observed that the MHW event in the northwest Atlantic in 2012 caused “altered fishing practices and harvest patterns, price collapses of important fisheries and ultimately to intensified economic tensions between nations” (Frölicher and Laufkötter 2018). If the fishing industries were able to be flexible in such a situation, this may have resulted in adaptation to the MHW impacts, and the fishing industries could have been sustained during the event.
	Primary production of commercial	Primary production of commercial fisheries is noted as being linked the level of community vulnerability to MHW events (Suryan et al. 2021. This is because MHWs commonly affect fish

	fisheries	species negatively and are seen to limit the production of commercial fisheries. Therefore, if the primary production of commercial fisheries is low prior to a MHW event, then a MHW is likely to reduce production to a critical level. • Suryan et al. (2021) explored the 2014–2016 northeast Pacific marine heatwave in the Gulf of Alaska and the affect that it had on fisheries. An analysis of the primary production to commercial fisheries and nearshore intertidal to offshore oceanic domains demonstrated decreased primary production in fisheries and sudden changes throughout marine food web trophic levels, with many trophic responses being long-term (lasting up to 5 years after the onset of the MHW).
	Occupational multiplicity	Occupational multiplicity is the diversity of occupations of locals within a community. If a community has high occupational multiplicity, then adaptive capacity is increased and vulnerability to hazard events is decreased (Green et al. 2021). If there is not a strong reliance on only one occupation, when a disaster occurs that might affect one industry more dominantly (e.g drought and agriculture, MHWs and fisheries, etc.), the community can still function and maintain livelihood resilience. • Green et al. (2021) displayed that adaptive responses to climate change impacts only occurred when communities had diversity and flexibility in where livelihoods were sourced. Occupation multiplicity was considered important in small-scale fishing communities as it is important for sustaining livelihoods in resource-dependant coastal communities when faced with climate impacts (Green et al. 2021).
Exposure	Market access	Limited access to market in communities is commonly associated with higher exposure to the negative impacts of MHWs. Management of the fisheries industry, and increased access to market in communities is critical for disaster resilience in the future. • Eriksson et al. (2017) explain that "limited market access in many sectors of the community reduced the capacity for marine resources to support recovery". It has been seen that when a community has limited access to assets, they are of increased vulnerability to negative impacts when a MHW event occurs (Green et al. 2021). • In their analysis, Green et al. (2021) show that adaptive responses to climate impacts at the local community level were present only when the community had sufficient access to assets.
	Physical capital (e.g. infrastructure, water tanks and strong dwellings)	Having high physical capital (e.g. infrastructure, water tanks and strong dwellings) is strongly linked to disaster preparedness, and is observed to reduce the exposure that communities have to negative impacts when natural hazards occur (Eriksson et al. 2017). • A study by Eriksson et al. (2017) sought to understand the role of fish for Pacific SIDS communities during natural hazard events and when recovering from such events. It was determined that high physical capital is key for disaster preparedness and can improve community resilience.
	Seagrass population/C content in seagrass	In the pacific, coastal marine ecosystems tend to rely on seagrass populations seagrass is a foundation species upon which many other species rely on seagrass for food and habitat. Seagrass also provides a key ecosystem service- carbon sequestration. Seagrass populations convert harmful dissolved carbon dioxide into useful vegetative biomass (Arias-Ortiz et al. 2018). If a coastal marine ecosystem has a strong seagrass population then it can function adequately, however, if seagrass populations are limited the ecosystem may function insufficiently and is further exposed to negative impacts from natural hazards like MHWs (Arias-Ortiz et al. 2018). • In an investigation of seagrass stocks in Shark Bay, Western Australia during the 2010/2011 MHW (Arias-Ortiz et al. 2018) used field studies and satellite imagery to estimate that 36% of Shark Bay's seagrass meadows were damaged following the MHW. It was proposed that this damage caused the harmful release of a significant amount of CO_2 into the atmosphere. Arias-Ortiz et al. (2018) concluded that an increase in MHW prevalence in the future will threaten seagrass systems, making the conservation of seagrass ecosystems essential to avoid adverse feedbacks not only on marine coastal systems, but also on the climate system. • In a similar investigation of the 2010/2011 MHW that affected the Midwest coast of Australia, Caputi et al. (2016) examine the major impact of MHWs on seagrass/algae and invertebrate fisheries. It was illustrated that the MHW event had a major effect on the marine ecosystem, predominantly due to changes in seagrass/algae populations (Caputi et al. 2016).
	Coral habitat	The health of coral habitats in the coastal marine ecosystems around Pacific SIDS is key to

	health/crown of thorns prevalence	MHW exposure. If coral habitats are healthy then it is less likely that the marine ecosystem will experience harsh impacts from MHWs. The prevalence of crown of thorns starfish is linked to the health of coral habitats; its occurrence can indicate declining health of corals and the overall ecosystem. • When investigating an extreme MHW along the midwest coast of Australia in the 2010/11 austral summer, Caputi et al. (2016) determined the effects of the MHW on coral habitats. It was found that the event had a major effect on the marine ecosystem with changes to coral habitats. • Eriksson et al. (2017) found that in the context of MHWs in Vanuatu, crown-of-thorns outbreaks were commonly linked to coral mortality and increased exposure of coral systems to the negative affects of disasters.
	Crab stock health	Crab stock health (crab abundance, distribution, recruitment, etc.) is linked to the level of exposure a marine ecosystem has to the negative impacts of MHWs (Chandrapavan et al. 2019). MHWs are known to detrimentally affect crab stocks, if the health of crab stocks was already reduced, the effects experienced in MHW events could be critical. • Chandrapavan et al. (2019) investigated the relationship between crab stocks and MHW events using a case study of the 2011 MHW in Western Australia. Commercial catch and effort data, crab abundance data was collected, and SST data was obtained across nine sites inside Shark Bay, Western Australia. The relationship between crab stocks and SST data was examined (Chandrapavan et al. 2019). The 2011 Western Australian MHW, driven by a very strong La Niña event, raised SSTs significantly. It was found that this led to several crab mortality events and recruitment impairment of commercially important crab species in Shark Bay (Chandrapavan et al. 2019). As a result, there was a fishery closure in 2012 to allow for crab stock recovery. The Shark Bay fishery only returned to full recovery status in 2018, a significant time after the MHW event (Chandrapavan et al. 2019).
	Fish mortality/fish stock health	When a marine heat wave event occurs, fish stocks are known to undergo ecological changes, with usual impacts including the mortality of certain fish species (Cheung and Frölicher 2020). If fish stocks are already reduced in a marine area than it is likely that the adverse impacts experienced from MHWs will cause fish stocks to be at a critical low. If fish stocks are unhealthy and reduced, then it is expected that they will have a low rate of recovery after the conclusion of a MHW event. This is particularly important as long-term increases in water temperatures will increase the frequency of marine heatwave events and the fisheries stocks would have less time for recovery (Chandrapavan et al. 2019). • When examining the impact that the 2010/2011 Western Australian MHW had on fisheries, Caputi et al. (2016) illustrated the significant affect on marine ecosystems and fish stocks. Fish kills and the southern extension of the range of certain tropical species were associated impacts found from the MHW. It was also seen that recovery rates of fish stocks after the conclusion of the MHW were influenced by the following factors: - species near their upper temperature range and/or sensitive to warming temperatures - spatial overlap between the warming event and species distribution - whether spawning stock was affected to the point of recruitment impairment - life-cycle duration of invertebrate (or habitat) species affected and management intervention • Caputi et al. (2016) recommend that fisheries manage such impacts through “an early identification of temperature hot spots, early detection of abundance changes (preferably using pre-recruit surveys), and flexible harvest strategies which allow a quick response to minimize the effect of heavy fishing on poor recruitment to enable protection of the spawning stock”. • Holbrook et al. (2022) document the impacts MHWs have in Pacific Island Countries like Fiji, Samoa, and Palau, highlighting that moderate to strong MHW events are associated with fish mortality. • In their study examining the northeast pacific 2013-2015 MHW, Cheung and Frölicher (2020) found that fish stock biomass decreased during the MHW and the biogeography of fish stocks shifted significantly.

Out of the previously used indicators found, their applicated to assessing MHW risk in Vanuatu, specifically for the Fisheries sector was assessed. Table 5 shows the decided applicability of each previously used indicator.

Table 5. Previously used MHW indicators found in the literature review, their data availability and likely applicability for use in a MHW risk assessment for Vanuatu Fisheries.

Index	Indicator	Appropriate to the climatic, socio-economic and/or geographic characteristics of Vanuatu, specifically focused on the fisheries sector?	Data Available for Vanuatu?	What is the spatial and temporal resolution of the data?	Likely applicable for Vanuatu Fisheries MHW Risk Assessment?
Hazard	Sea-Surface Temperature (SST) anomalies	Yes	Yes- from NOAA and COSPAAC Pacific Ocean Portal	Satellite-based monitoring: NOAA High-resolution Blended Analysis of Daily SST and Ice. Data is from Sep 1981 and is on a 1/4 deg global grid.	Yes
	Coral bleaching/mortality	Yes	Yes-from NOAA and ArcGIS online and COSPAAC Pacific Ocean Portal	The NOAA Coral Reef Watch (CRW) daily global 5km satellite coral bleaching Degree Heating Week (DHW) product presented here shows accumulated heat stress, which can lead to coral bleaching and death. The scale ranges from 0 to 20 °C-weeks. The DHW product accumulates the instantaneous bleaching heat stress, measured by CRW's Coral Bleaching HotSpot, during the most recent 12-week period. It is directly related to the timing and intensity of coral bleaching. Significant coral bleaching usually occurs when the DHW value reaches 4 °C-weeks. By the time the DHW value reaches 8 °C-weeks, severe, widespread bleaching is likely and significant mortality can be expected.	Yes
	Chlorophyll-a concentrations	Yes	Yes- NASA MODIS and COSPAAC Pacific Ocean Portal	This algorithm returns the near-surface concentration of chlorophyll-a (chlor_a) in mg m-3, calculated using an empirical relationship derived from in situ measurements of chlor_a and blue-to-green band ratios of in situ remote sensing reflectances (Rrs). Implementation is contingent on the availability three or more sensor bands spanning the 440 - 570 nm spectral regime. The algorithm is applicable to all current ocean color sensors. The chlor_a product is included as part of the standard Level-2 OC product suite and the Level-3 CHL product suite.	Yes

	Marine heatwave cumulative intensity (MHCI) value	No	No publicly available data was found for this indicator	N/a	No, there is no data and it is not as accurate as SST and other hazard indicators.
	Water column nutrient status	Yes	Yes, for a limited time period- Cefas (Centre for Environment Fisheries and Aquaculture Science Centre for Environment Fisheries and Aquaculture Science) Vanuatu Water Quality Dataset - 2016-2018	Only from 2016-2018 and focused on Port Villa. Dataset supporting a baseline assessment of marine water quality around Vanuatu, South Pacific. As part of the Commonwealth Marine Economies Programme, water quality measurements were collected over three years in the coastal waters around the island of Efate, and on one occasion around the island of Tanna. Observations focus on Port Vila (Efate), which is the main urbanised area on the Island. Key water quality parameters are presented (salinity, temperature, turbidity and total suspended solids, light attenuation, dissolved oxygen, chlorophyll and phaeophytin, and nutrients) which represent part of a larger research program on water quality, human health and habitat mapping. Please see the downloadable methods file for information on sampling and analysis.	No, data is too limited.
Vulnerability	Terrestrial-based food and income generation	Yes	Yes- SPREP and Griffith University, and limited data available from The Vanuatu HIES	Data for 2006, 2010 and 2019 for Vanuatu provinces from HIES.	Yes
	Fishing skills and technology	Yes	Yes- Australian Aid Province Skills Plan	Data for each province, looking at what skills are required for employees in the fisheries sector, and how many people require training in such skills. Data from 2015-2018.	Yes
	Human malnutrition	Yes	Yes- Available from the Household Nutrition Analysis by the Food and Agriculture Organisation aswell as the Demographic and Health Survey by the Vanuatu Ministry of	Data available for the 2013 and 2015 year, on the provincial and national scale.	Yes

			Health, Vanuatu National Statistics Office, the Secretariat of the Pacific Community.		
	Fish nutritional value	Yes	Yes- Available from the 2007 FAO Food Balance Sheet as well as from the Food and Agriculture Organization of the United Nations	2007 yearly data available on the national scale for Vanuatu. 2019-2020 yearly data is also available on the national scale.	Yes
	Disease prevalence	No- not relevant to Fisheries specifically, only relevant for the community as a whole	Yes- available for only certain diseases (e.g heart and kidney diseas) from the The Global Burden of Diseases, Injuries, and Risk Factors Study	Limited data available for the 2019 year on the national scale.	No
	Fishery fish diversity/fishery flexibility	Yes	Yes- Some monitoring sites around Vanuatu	Mean Fish Density per 100m2 in each region from CRISP SOUTH-WEST PACIFIC STATUS OF CORAL REEFS REPORT 2007.	Yes
	Primary production of commercial fisheries	Yes	Yes- available from the National Fishery Sector Overview for Vanuatu conducted by the Food and Agriculture Organization of the United Nations.	Data is provided on the yearly scale from 2003-2010. Data is on the national scale for Vanuatu.	Yes
	Occupational multiplicity	No- not relevant to Fisheries industry in Vanuatu specifically, as it would not inform on spatial differences in MHW risk as occupational demographics are highly similar across most Vanuatu communities.	Yes- limited data available from The Vanuatu HIES	Data for 2006, 2010 and 2019 for Vanuatu provinces.	No

Exposure	Market access	No- not specifically relevant to the exposure of the fisheries industry in Vanuatu	Yes- limited data available from The Vanuatu HIES	Data for 2006, 2010 and 2019 for Vanuatu provinces.	No
	Physical capital (e.g. infrastructure, water tanks and strong dwellings)	No- not relevant to MHWs specifically, rather just generally relevant to disaster risk overall across Pacific SIDS	Yes- only for some physical capital like water tanks. From the Water Safety Plans Programme- Vanuatu	Data for water tanks and water sources available for 2006.	No
	Seagrass population/C content in seagrass	Yes	Yes- Seagrass-Watch global seagrass observing network	Seagrass-Watch global seagrass observing network (established in 1998) accurately monitors the status and trends in seagrass condition. The network has conducted over 5700 assessments at 408 sites across 21 countries, involving thousands of dedicated participants.	Yes
	Coral habitat health/crown of thorns prevalence	Yes	Yes- from the Pacific Regional Environment Programme	Crown of thorns data and coral health available for various reefs around Vanuatu, data is available for 2017.	Yes
	Crab stock health	Yes- Coconut crab is an important subsistence and commercial resource for communities in Vanuatu	Yes- for provinces and fisheries across Vanuatu from Vanuatu National Coconut Crab Fishery Management Plan and Pacific Regional Environment Programme.	Available for 1983 to 2013 and specific fisheries level is the most local level available for data. Only for Coconut Crab.	Yes
	Fish mortality/fish stock health	Yes	Yes- in some areas around Vanuatu.	Mean Fish Density per 100m2 in each region from CRISP SOUTH-WEST PACIFIC STATUS OF CORAL REEFS REPORT 2007.	Yes

The final list of applicable indicators, that have potential for inclusion in the Vanuatu MHW risk assessment are listed in Table 6. These are the indicators that were assessed in the participatory research survey.

Table 6. Potential risk indicators gathered from literature review results.

Index	**Indicator for potential inclusion in the index**
Hazard	SST Coral bleaching/mortality Chlorophyll-a concentration
Vulnerability	Terrestrial-based food and income generation

	Fishing skills and technology Human malnutrition Fish nutritional value Fishery fish diversity/fishery flexibility Primary production of commercial fisheries
Exposure	Seagrass population/C content in seagrass Coral habitat health/crown of thorns prevalence Crab stock health Fish mortality/fish stock health

3.2 Part 2: Participatory Research-Survey Results

3.2.1 Participant Demographics

Survey participants were of a wide range of demographics. Most participants were fisheries staff rather than local community members or local fisherpersons (Appendix D). Participants were aged from 20 to 50, with the majority being in a twenty to thirty-five age bracket (Appendix E). The gender of participants was varied, with half of the participants being female and the other half male (Appendix F). Four out of the six Vanuatu provinces were represented, with most participant being from either Malampa or Shefa province (Appendix G).

3.2.2 Survey Questions 1-3

When asked which potential hazard indicators they would want included in a MHW risk assessment for Vanuatu fisheries, all 12 participants selected SST, Coral Bleaching and Chlorophyll-a concentration. When considering the list of potential vulnerability indicators, all participants deemed Terrestrial (land)-based food and income generation, Fishing skills and technology, Fishery fish diversity/fishery flexibility, and Primary production of commercial fisheries, as valid for inclusion in the MHW risk assessment for Vanuatu fisheries. Whereas, for human malnutrition and fish nutritional value several participants (4 and 3 respectively) declared that they would exclude them from the MHW risk assessment. Reasons given for the exclusion of these indicators included:

- "Human malnutrition is not a currently a vulnerability indicator for most Vanuatu communities as yet, but it will be with elevating climate change impacts in the near future. Then it could be included." (P2)
- "I do not think fish nutritional value is something to assess in the vulnerability index for marine heatwave risk assessment. There are other factors that may cause reduction in the nutritional value of a fish." (P6)
- "Fish is not the only source of protein. There are a lot of other sources of protein." (P7)
- "The two indicators are excluded because most communities in Vanuatu now consume canned food and processed fish, and rely more on processed food than fresh seafood so the indicator will be less effective." (P11)
- "There are other factors that can cause human malnutrition and reduction in fish nutritional value. For example, human malnutrition in Vanuatu will highly likely to be caused by the impacts of cyclones. As for the reduction in fish nutritional value, chemical runoffs could be a cause of that. So these two indicators will not be reliable." (P12)

As with the potential hazard indicators, all survey participants deemed that they would include each of the potential exposure indicators listed (which were Seagrass population, Coral Habitat Health/Crown of Thorns Prevalence, crab stock health and fish mortality/fish stock health).

3.2.3 Survey Questions 4-6

Most participants (83%) ranked SST as the 1st (most important) hazard indicator (Figure 3). 58% of participants ranked coral bleaching as 2nd, while 25% ranked it as 3rd and 17% ranked it as 1st (Figure 4). 58% of participants ranked Chlorophyll-a concentration as 3rd (least important), with the rest ranking it as 2nd (Figure 5). The most common ranking combination was SST as 1st, Coral bleaching as 2nd, and chlorophyll as 3rd (with 58% of participants giving this combination).

The ANOVA test displayed that these differences between the rankings of each of the hazard indicators were significant (f_2=10.81, p=0.0002). When assessing the variance in rankings between hazard indicators, no significant variance was detected in any hazard indicator set: SST vs Coral Bleaching (f_{11}=1.35, p=0.31), SST vs Chlorophyll-a concentration (f_{11}=2.28, p=0.09), and Coral Bleaching vs Chlorophyll-a concentration (f_{11}=1.68, p=0.20). Students t-test (assuming equal variance) results showed that there were significant differences between indicator rankings for each set of hazard indicators: SST vs Coral Bleaching (t_{22}=-2.53, p=0.009), SST vs Chlorophyll-a concentration (t_{22}=-4.64, p=<0.0001), and Coral bleaching vs Chlorophyll-a concentration (t_{22}=-2.05, p=0.03).

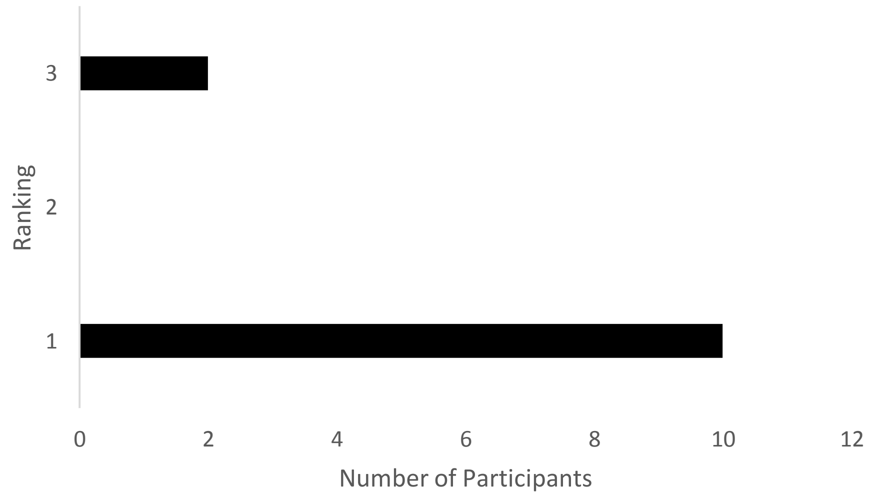

Figure 3. Bar graph showing the participant-given ranks for SST (as part of responding to survey Question 4).

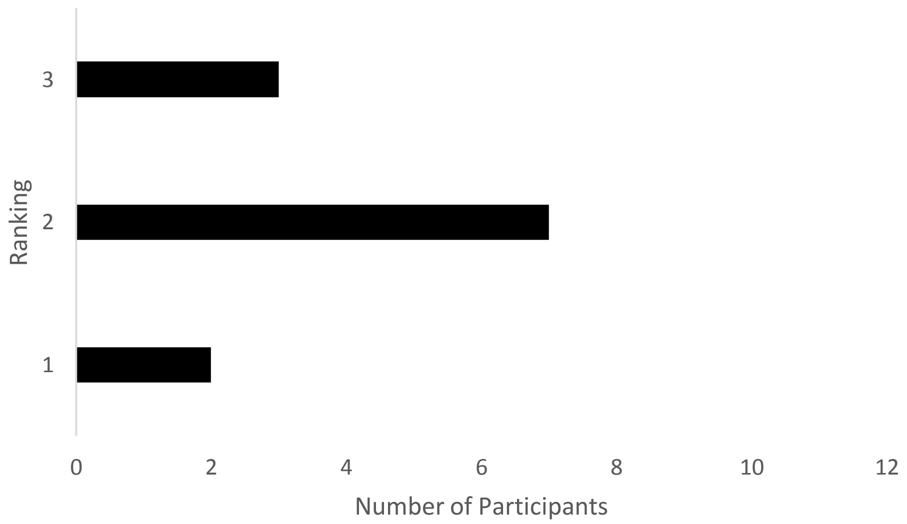

Figure 4. Bar graph showing the participant-given ranks for Coral bleaching (as part of responding to survey Question 4).

Figure 5. Bar graph showing the participant-given ranks for Chlorophyll-a concentration (as part of responding to survey Question 4).

The most common rank given to Terrestrial-based food and income generation was 1^{st} (42% of participants allocated this rank) (Figure 6). The most common rank given to Fishery fish diversity/fishery flexibility was 2^{nd} (33% of participants allocated this rank) (Figure 7). The indicator which most participants ranked as 3^{rd} was Primary production of commercial fisheries (33% of participants ranked this indicator as 3^{rd}) (Figure 8). The indicator which many participants ranked as 4^{th} was Fishing skills and technology (42% of participants gave this ranking) (Figure 9). Human malnutrition and Fish nutritional value were the two indicators commonly ranked the least (50% of participants gave Human malnutrition a rank of 6^{th} and 33% chose it as 5^{th}, whilst 42% of participants ranked Fish nutritional value as 5^{th}) (Figures 10 and 11). In the ANOVA test results, significant difference was found between the rankings given to each of the potential vulnerability indicators (f_5=5.85, p=0.0001).

When assessing the variance in rankings, no significant variance was detected in the following sets of vulnerability indicators: Terrestrial-based food and income generation vs Human malnutrition (f_{11}=2.23, p=0.10), Terrestrial-based food and income generation vs Fish nutritional value (f_{11}=1.42, p=0.28), Terrestrial-based food and income generation vs Fishery fish diversity/fishery flexibility (f_{11}=2.48, p=0.07), Terrestrial-based food and income generation vs Primary production of commercial fisheries (f_{11}=1.84, p=0.16), Fishing skills and technology vs Human malnutrition (f_{11}=0.77, p=0.34), Fishing skills and technology vs Fish nutritional value (f_{11}=0.49, p=0.13), Fishing skills and technology vs Fishery fish diversity/fishery flexibility (f_{11}=0.86, p=0.40), Fishing skills and technology vs Primary production of commercial fisheries (f_{11}=0.64, p=0.23), Human malnutrition vs Fish nutritional value (f_{11}=0.64, p=0.23), Human malnutrition vs Fishery fish diversity/fishery flexibility (f_{11}=1.11, p=0.43), Human malnutrition vs Primary production of commercial fisheries (f_{11}=0.82, p=0.38), Fish nutritional value vs Fishery fish diversity/fishery flexibility (f_{11}=1.74, p=0.18), Fish nutritional value vs Primary production of commercial fisheries (f_{11}=1.29, p=0.34), and Fishery fish diversity/fishery flexibility vs Primary production of commercial fisheries (f_{11}=0.74, p=0.31). Only one vulnerability indicator set displayed significant variance: Terrestrial-based food and income generation vs Fishing skills and technology (f_{11}=2.88, p=0.05). When the students t-test was performed for this indicator, the test assumed equal variance. In the t-tests performed for all other vulnerability indicator combinations, unequal variance was assumed.

Students t-test results showed that there were significant differences between indicator rankings for most sets of potential vulnerability indicators. Significant differences were found between the following indicators: Terrestrial-based food and income generation and Fishing skills and technology (t_{18}=-1.39, p=0.09), Terrestrial-based food and income generation and Human malnutrition (t_{22}=-3.43, p=0.001), Terrestrial-based food and income generation and Fish nutritional value (t_{22}=-1.92, p=0.03), Fishing skills and technology and Human malnutrition (t_{22}=-2.81, p=0.005), Fishing skills and technology and Fishery fish diversity/fishery flexibility (t_{22}=2.38, p=0.01), Fishing skills and technology and Primary production of commercial fisheries (t_{22}=2.03, p=0.03), Human malnutrition and Fishery fish diversity/fishery flexibility (t_{22}=4.95, p=<0.0001), Human malnutrition and Primary production of commercial fisheries (t_{22}=4.44, p=0.0001), Fish nutritional value and Fishery fish diversity/fishery flexibility (t_{22}=2.80, p=0.005) and Fish nutritional value and Primary production of commercial fisheries (t_{22}=2.51, p=0.01). For the remaining sets of potential vulnerability indicators (Fishing skills and technology and Fish nutritional value, Human malnutrition and Fish nutritional value, Fishery fish diversity/fishery flexibility and Primary production of commercial fisheries, Terrestrial-based food and income generation and Fishery fish diversity/fishery flexibility, and Terrestrial-based food and income generation and Primary production of commercial fisheries), no significant differences were evident (t_{22}=-0.86, p=0.20; t_{22}=1.51, p=0.07; t_{22}=-0.15, p=0.44; t_{22}=0.37, p=0.36; t_{22}=0.24, p=0.41 respectively).

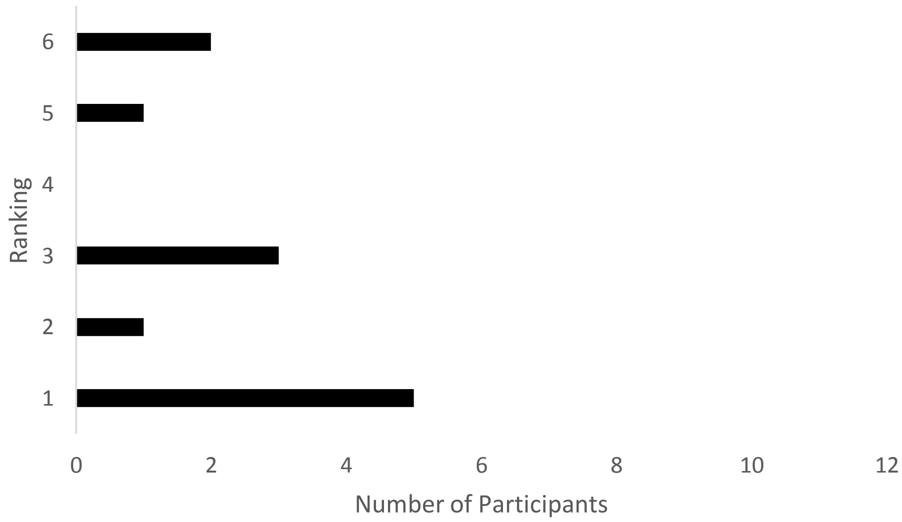

Figure 6. Bar graph showing the participant-given ranks for Terrestrial Based Food Generation (as part of responding to survey Question 5).

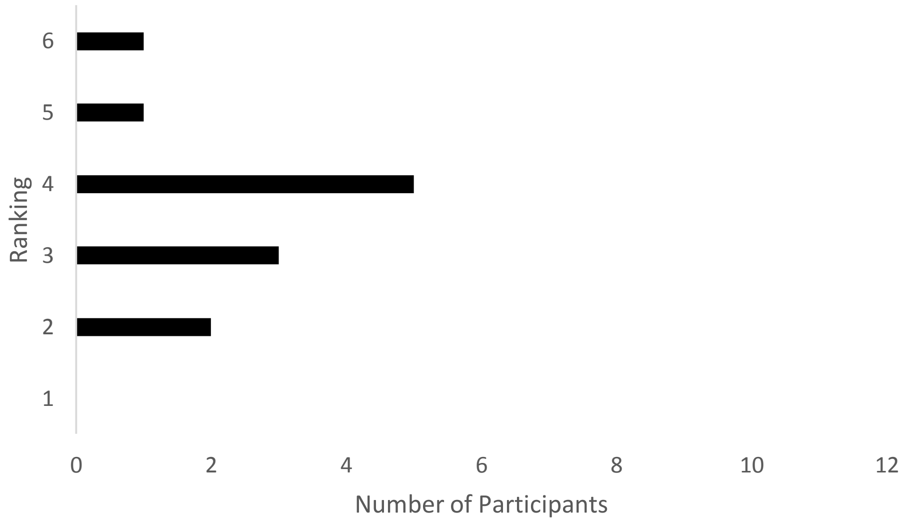

Figure 7. Bar graph showing the participant-given ranks for Fishing Skills and Technology (as part of responding to survey Question 5).

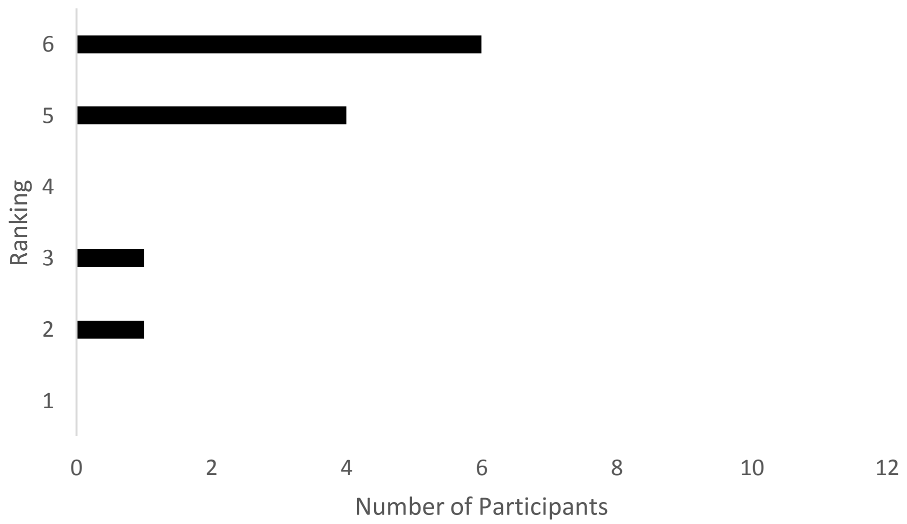

Figure 8. Bar graph showing the participant-given ranks for Human Malnutrition (as part of responding to survey Question 5).

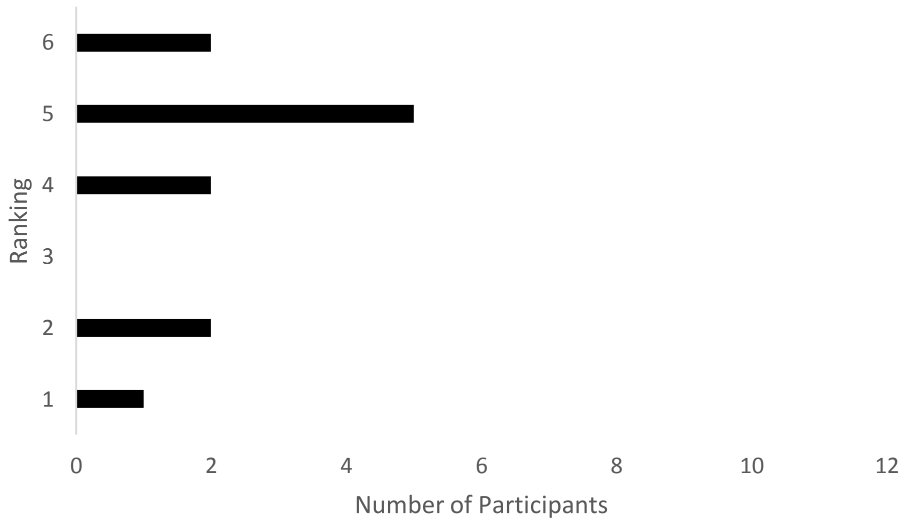

Figure 9. Bar graph showing the participant-given ranks for Fish Nutritional Value (as part of responding to survey Question 5).

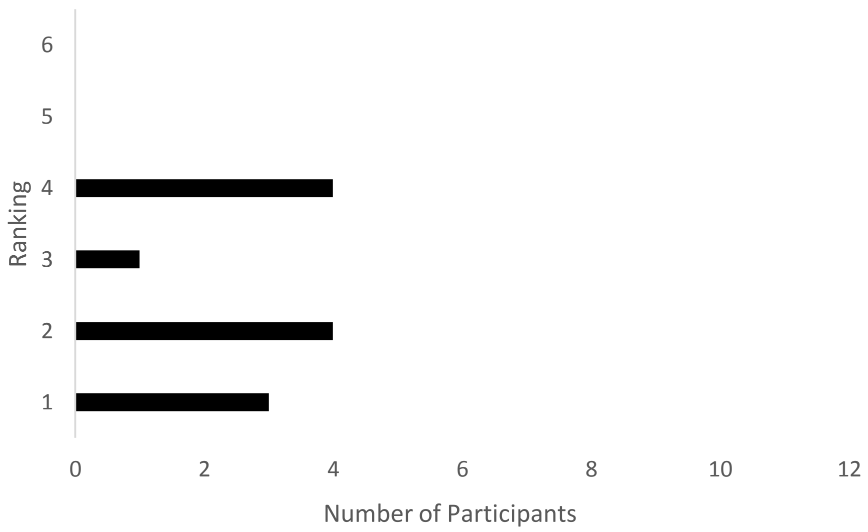

Figure 10. Bar graph showing the participant-given ranks for Fishery Fish Diversity (as part of responding to survey Question 5).

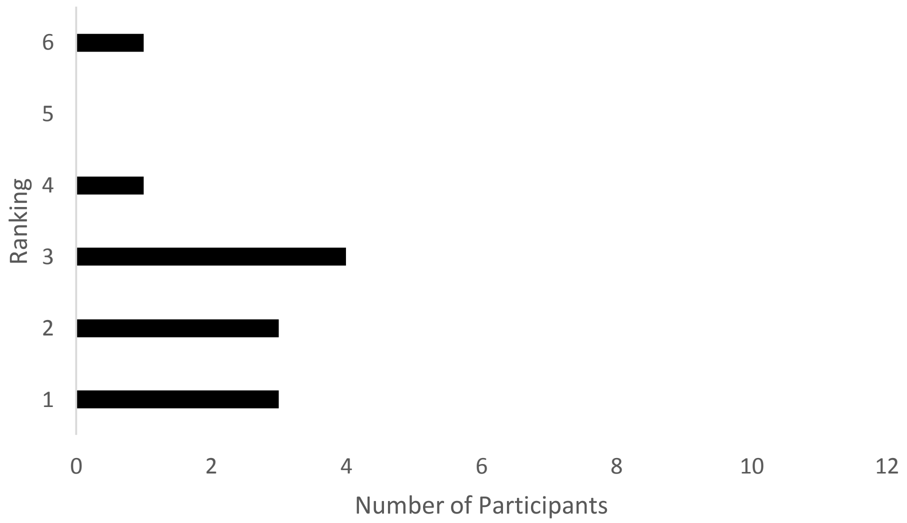

Figure 11. Bar graph showing the participant-given ranks for Primary Production of Commercial Fisheries (as part of responding to survey question 5).

Participants commonly ranked Seagrass population/C content as a highly important exposure indicator (50% rated it as 1st, and 44% ranked it as 2nd) (Figure 12.). Coral habitat health/crown of thorns prevalence was ranked by the majority (58%) of participants as 2nd out of the four exposure indicators (Figure 13.). Most participants (67%) ranked the Fish mortality/fish stock health indicator as 3rd, and all participants ranked Crab stock health as 4th (Figures 14 and 15.). ANOVA results show that there is significant difference between these rankings given to the exposure indicators (f_3=28.26, p=<0.0001).

Significant variance was found between the rankings in all indicator pairs that included crab stock health (Seagrass population and Crab stock health (f_{11}=65535, p=0.00), Coral habitat health and Crab stock health (f_{11}=65535, p=0.00), Crab stock health and Fish mortality/fish stock health (f_{11}=0.00, p=0.00)). When the t-test was performed for these indicator pairs, a t-test assuming unequal variance was conducted. Whereas no significant variance was found between the rankings of Seagrass population vs Coral habitat health (f_{11}=1.35, p=0.31), Seagrass population vs Fish mortality/fish stock health (f_{11}=0.75, p=0.32), and Coral habitat health vs Fish mortality/fish stock health (f_{11}=0.55, p=0.17). For these indicators, a t-test assuming equal variance was performed.

A significant difference was found between the rankings of each set of exposure indicators, except for two pairs. No significant difference was evident between the ranks given to Seagrass population vs Coral habitat health (t_{22}=-0.84, p=0.20), and the ranks given to Coral habitat health vs Fish mortality/fish stock health (t_{22}=-1.54, p=0.07). The ranks given to Seagrass population vs Crab stock health were significantly different (t_{11}=-10.38, p=<0.0001), along with Seagrass population vs Fish mortality/fish stock health (t_{22}=-2.18, p=0.02), Coral habitat health vs Crab stock health (t_{11}=-10.79, p=<0.0001), and Crab stock health vs Fish mortality/fish stock health (t_{10}=5.87, p=<0.0001).

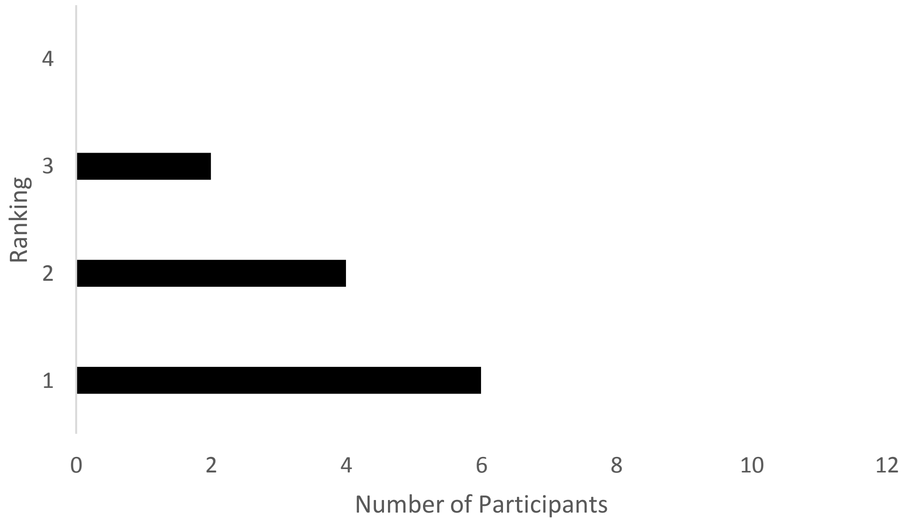

Figure 12. Bar graph showing the participant-given ranks for Seagrass/C content (as part of responding to survey Question 6).

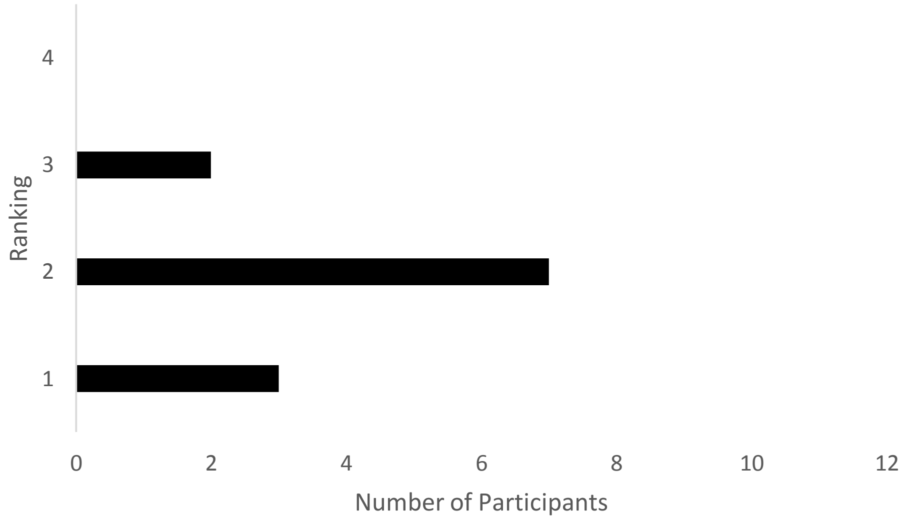

Figure 13. Bar graph showing the participant-given ranks for Coral habitat health (as part of responding to survey Question 6).

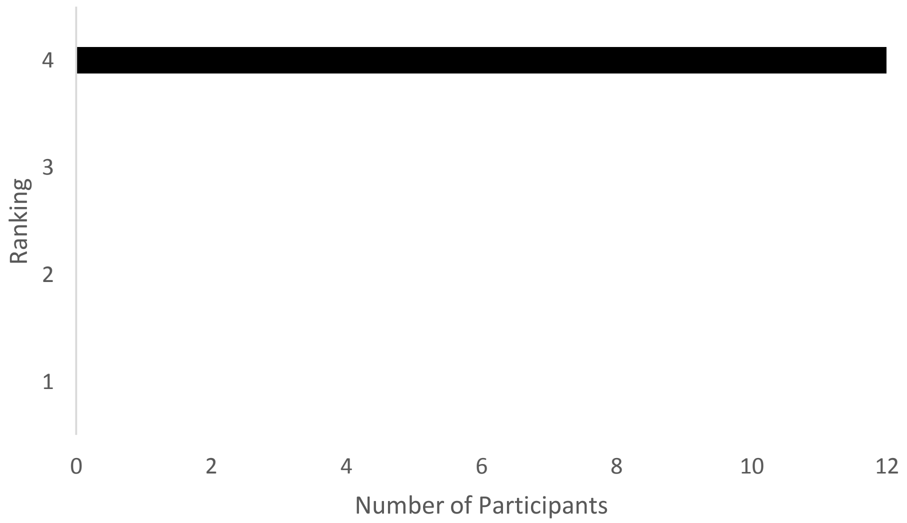

Figure 14. Bar graph showing the participant-given ranks for Crab stock health (as part of responding to survey Question 6).

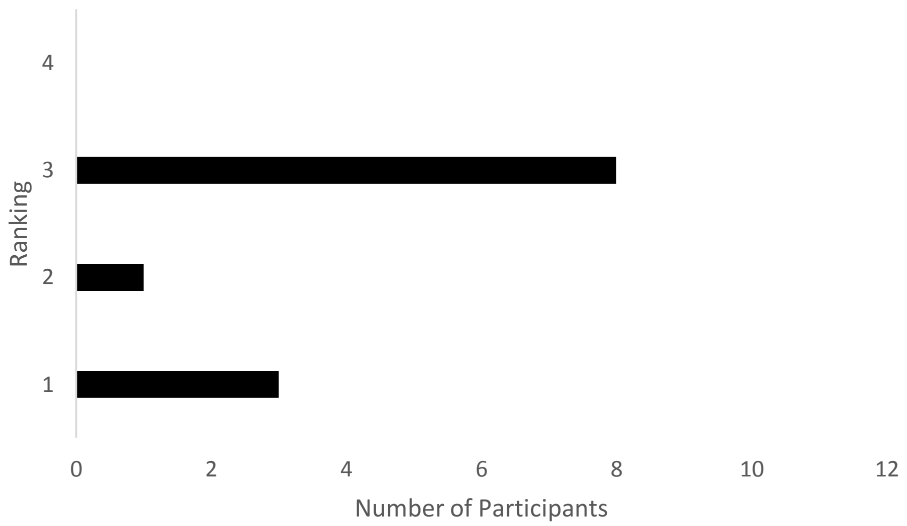

Figure 15. Bar graph showing the participant-given ranks for Fish mortality (as part of responding to survey Question 6).

3.2.4 Survey Question 7

No other indicators were suggested for the vulnerability and exposure indices; however, some suggestions were made for the hazard index. Participants suggested the following indicators for the MHW hazard index:

- Ocean acidification indicator
- Tropical cyclone indicator
- Heavy rainfall indicator
- Rainfall (precipitation) indicator

3.3 Part 3: Developed Weighting Scheme

Based on survey results, the following indicators are confirmed for inclusion in the hazard index: SST, Coral Bleaching, Chlorophyll-a Concentration. Confirmed vulnerability indicators include the following: Terrestrial (land)-based food and income generation, Fishing skills and technology, Fishery fish diversity/fishery flexibility, and Primary production of commercial fisheries. The exposure indicators to be included in the risk assessment are Seagrass population/C content, Coral Habitat Health/Crown of Thorns Prevalence, crab stock health and fish mortality/fish stock health. Thus, all potential hazard and exposure indicators selected in the literature review were confirmed for use by the participatory research survey. Whereas, two potential vulnerability indicators selected from the literature review (Human Malnutrition and Fish Nutritional Value), were unconfirmed for use by survey participants, and are therefore not to be included in the MHW risk assessment for Vanuatu Fisheries.

The confirmed indicators are listed in Table 7, along with the proposed weights assigned based on survey results. In the hazard index, it was suggested that SST was a more important indicator compared to Coral Bleaching and Chlorophyll-a concentration. For vulnerability indicators, it was seen that Fishing skills and technology was of least importance compared to Terrestrial (land)-based food and income generation, Fishery fish diversity/fishery flexibility, and Primary production of commercial fisheries. Likewise, crab stock health was suggested as the least important exposure indicator, compared to Seagrass population/C content, Coral Habitat Health/Crown of Thorns Prevalence, and fish mortality/fish stock health.

Table 7. Proposed Risk Index Composition and Suggested Weights to be applied to each Hazard, Vulnerability, and Exposure indicator.

Index	Indicator	Final Rank	Proposed Weight
Hazard	SST	1	0.50
	Coral Bleaching	2	0.30
	Chlorophyll-a Concentration	3	0.20
Vulnerability	Terrestrial (land)-based food and income generation	1	0.35
	Fishing skills and technology	4	0.10
	Fishery fish diversity/fishery flexibility	2	0.30
	Primary production of commercial fisheries	3	0.25
Exposure	Seagrass population/C content	1	0.35
	Coral Habitat Health/Crown of Thorns Prevalence	2	0.30
	crab stock health	4	0.10
	fish mortality/fish stock health	3	0.25

4 Discussion

4.1 Selected indicators for the proposed MHW risk assessment- informed by the literature review and participatory research survey

4.1.1 Selected Hazard Indicators

SST is a MHW hazard indicator commonly used in past MHW risk research around the globe (Caputi et al. 2016; Cheung and Frölicher 2020; Cheung and Frölicher 2020). For the Vanuatu context, SST data is available as a space-based monitoring product, on a wide spatial (0.25 degree grid) and temporal (1981-present) scale. It has been demonstrated in past disaster risk studies (Aitkenhead et al. 2022; Kuleshov et al., 2020; Blauhut, 2020) that space-based monitoring products are essential for hazard monitoring, with spaced-based observations being increasingly accurate compared to ground-based observations (Chua et al. 2020). Furthermore, SST is seen as a hazard indicator with the ability to indicate specific hazard impacts to the Vanuatu Fisheries sector. SST has been commonly linked with fish species ranges and abundances (Cheung and Frölicher 2020). Due to the reliability of SST data, and its relevance to indicating MHW hazard impacts on the Fisheries industry, it was considered a potentially useful MHW hazard indicator to be assessed in the participatory survey. As expected, participants confirmed SST as a useful hazard indicator and recommended it be included in the MHW risk assessment for Vanuatu Fisheries.

Coral bleaching/mortality has similarly been commonly recognised in the past as a reliable MHW hazard indicator (Holbrook et al. 2022; Le Nohaïc et al. 2017; Obura 2001). The link between this indicator and MHW hazard impacts have long been described to be of ecological importance. Coral is a critical foundation species for Vanuatu marine ecosystems; its abundance is critical to the ecosystem's resilience in response to a MHW event (Smale et al. 2019). The Vanuatu Fisheries sector is reliant upon ecosystem services, so a coral bleaching/mortality indicator could be vital to informing on fisheries risk (Frölicher and Laufkötter 2018). As an important ecological indicator relevant to fisheries, with a wide range of spaced-based data available, coral bleaching/mortality was included as a potential hazard indicator to be assessed in the participatory survey. Survey participants recognised the importance of this indicator, and recommended it be included in the hazard index for the proposed MHW risk assessment.

Many global studies have suggested the usefulness of Chlorophyll-a concentrations as a MHW hazard indicator (Sen Gupta et al. 2020; Houk and Raubani 2010), however no previous studies conducted within Pacific SIDS, assessing MHW risk, have included this indicator. Although not yet proven as useful in Pacific SIDS, this indicator was chosen to be included for analysis in the participatory survey. This was due to its strong link to MHW impacts, specifically for marine ecosystems and fisheries, and wide availability of space-based observational data (Sen Gupta et al. 2020). Several fisheries-specific impacts can be indicated by chlorophyll-a concentrations. Depending on the region, varied Chlorophyll-a concentrations can change fish sizes in fishery stocks, increase risk of disease in fish, increase likelihood of algal blooms and/or crown of thorns outbreaks (Houk and Raubani 2010). As all survey participants recommended Chlropohyll-a concentrations as a hazard indicator for the proposed MHW risk assessment, it is expected to be useful in highlighting MHW risk to ecosystems and fisheries in Vanuatu.

4.1.2 Selected Vulnerability Indicators

Terrestrial (land)-based food and income generation was selected as a vulnerability indicator, with literature suggesting its usefulness (Eriksson et al. 2017) and survey participants unanimously confirming its applicability for this study. This is a key indicator that has the potential to provide insight into the pressure that may be applied to the Fisheries industry, if a MHW was to occur in Vanuatu. Vanuatu communities rely heavily on fisheries as a key food and income source. Verdone and Seidl (2012) explain that artisanal and subsistence fisheries are especially critical to the livelihoods and economic of rural communities in Vanuatu. Approximately 80% of Vanuatu's population live in rural areas, with over 66% of these people vitally relying on marine resources to reach income and nutritional needs (Verdone and Seidl 2012). The other major industry supporting the nutritional and income needs of Vanuatu communities is the land-based agricultural sector (Langford 2022). If a MHW occurs in Vanuatu, communities will be increasingly threatened if terrestrial (land)-based food and income generation cannot support local need. Due to its relevance to indicating risk to fishing communities in Vanuatu, and the fact that data is readily available for the intended research scale (Household Income and Expenditure Survey (HIES)), this is an ideal indicator of MHW vulnerability in Vanuatu.

Similarly, the primary production of commercial fisheries is described as critical by literature sources (Suryan et al. 2021) and is seen as an important indicator of MHW vulnerability by survey participants. MHWs have been consistently linked to direct impacts on fish species key to commercial fishery production around the world (Barbeaux et al. 2020; Suryan et al. 2021). Barbeaux et al. (2020) emphasises that globally, long-term ocean warming will significantly decrease marine production up to 20%. Smale et al. (2019) elaborates that MHW events will specifically restructure entire ecosystems and severely damage the provision of marine goods and services in the future. The production of fisheries in Vanuatu is no exception to this predicted damage, with the production of commercial fisheries in Vanuatu already being proven as unstable during previous disaster events. For example, commercial fisheries were significantly damaged in 2015 by Tropical Cyclone (TC) Pam. The estimated physical damage for the overall Fisheries sector in Vanuatu following TC Pam, was around 268 million Vatu (Dunstan et al., 2018). Given the link between primary production of commercial fisheries in Vanuatu to the impacts of MHWs, primary production of commercial fisheries is likely a highly valuable MHW vulnerability indicator for Vanuatu. Furthermore, data is accessible through the National Fishery Sector Overview for Vanuatu, conducted by the Food and Agriculture Organization of the United Nations. Thus, increasing the indicator's usability.

Although not a widely explored MHW indicator, fishing skills and technology was not only recognised by the literature sources as useful but was confirmed as an important MHW vulnerability indicator by survey participants. This is not surprising as recent investigations into disaster risk for fisheries in Pacific SIDS have noted critical links between the level of fishing skills and technology in a community, and the extremity of impacts on the Fisheries industry in those places (Eriksson et al. 2017; Green et al. 2021). For example, impacts seen across Pacific SIDS, including Vanuatu, during TC Pam were increased for the Fisheries industry if there was a reduced range of fishing skills and rudimentary technology were used. Eriksson et al. (2017) elaborate for the specific context of Vanuatu after TC Pam. It is explained that lack of fishing skills and technology across Vanuatu communities reduced the capacity for marine resources to support recovery after the disaster event. Thus, a key lesson learnt from TC Pam for Vanuatu and surrounding Pacific SIDS was the need to strengthen fishing skills and technology (Eriksson et al. 2017). Gillet (2011) explains that in response to TC Pam, education opportunities related to fisheries were increased in Pacific SIDS to "introduce or adapt exotic fishing techniques or technology…and to expose local fishermen to these innovations with the aim of improving the productivity, economic efficiency, safety or comfort of fishing operations".

Another key factor strongly linked to the disaster risk of fishing communities in Vanuatu, is the diversity of fish used in fisheries/the overall flexibility of fisheries (Green et al. 2021; Frölicher and Laufkötter 2018). Consequently, fishery fish diversity/fishery flexibility was explored in this study as a vulnerability indicator for MHW risk to Vanuatu Fisheries. It was consistently noted throughout the literature review that reduced diversity and flexibility of fisheries commonly results in increased vulnerability of fishing communities to MHW impacts (Chandrapavan et al. 2019; Green et al. 2021; Frölicher and Laufkötter 2018). This may be due to the direct relationship between fishery diversity and flexibility and the adaptive capacity of the fishing communities; at the small-scale fishery, community level adaptive responses generally only occur in situations where diversity and flexibility is present (Green et al. 2021). Furthermore, the ecological resilience of marine ecosystems commonly relies on fish diversity as it increases the range of response to damages and magnifies the chances of species compensating for one another (Bernhardt and Leslie 2013). Survey results confirmed these literature findings, with all participants noting that fishery fish diversity/fishery flexibility would be a useful MHW vulnerability indicator for Vanuatu.

4.1.3 Selected Exposure Indicators

Seagrass population/C content in seagrass is a highly appropriate indicator for MHW exposure, specifically when assessing exposure to Fisheries in Vanuatu. This indicator was suggested by literature review sources to be a valuable MHW exposure indicator (Arias-Ortiz et al. 2018; Caputi et al. 2016); this was confirmed by all participants in the survey. Importantly, seagrass populations support marine ecosystems around Vanuatu through providing food and shelter for other key species (like marine turtles and dugongs) as well as providing a key ecosystem service- carbon sequestration (Arias-Ortiz et al. 2018). When a MHW occurs, seagrass populations can be damaged, posing a significant risk to the overall marine ecosystem upon which the Fishery industry relies (Caputi et al. 2016). Nguyen (2021) explains the potential damages that can be caused to seagrass populations during MHWs, stating that "warming alters seagrass distribution causing massive die-offs in some seagrass populations, whilst also causing tropicalization and migration of temperate species". It is likely that seagrass population/C content in seagrass can provide integral insight into the severity of impacts from MHWs, subsequently indicating on the level of exposure fisheries have to such impacts.

Coral habitat health/crown of thorns prevalence is another factor that is likely vital to indicating the exposure of Vanuatu fisheries to the impacts of MHWs. This is suggested by both the literature review and survey results. Differing from coral bleaching/mortality, which is seen as a MHW hazard indicator, coral habitat health/crown of thorns prevalence indicates the overall health of coral systems, rather than indicating solely on coral death. The health of coral systems prior to MHW occurrence can alter the severity of impacts that might be experienced by the overall marine ecosystem, and Fishery industry, as well as play a role in the recovery process after a MHW (Eriksson et al. 2017). Like seagrass meadows, coral reefs support diversity of marine species that provide critical resources for coastal communities in Vanuatu, along with specifically supporting species of concern like marine turtles (Lovell et al. 2004). In turn, prosperous marine ecosystems underpin the Fisheries industry. Bell et al. (2019) highlight that extreme warming events are highly likely to be destructive to coral reef habitats that underpin small-scale, coastal fisheries in the Pacific. Such changes to coral reef habitats are predicted to impact harvest from small-scale coastal fisheries in the Pacific by approximately 20% by 2050 under the RCP8.5 emissions scenario (Bell et al. 2019).

Fish mortality/fish stock health is recognised by several literature sources as a potentially useful MHW exposure indicator (Caputi et al. 2016; Chandrapavan et al. 2019; Cheung and Frölicher 2020; Holbrook et al. 2022); survey participants also noted its value. Healthy fish stocks are critical to the society and economy of Vanuatu, with communities dependent on fish for food security and economic livelihoods (Asch et al. 2018). The threat of damaging MHW impacts on important fish species across Vanuatu (e.g. tuna) is therefore of high concern (Bell et al. 2019). High ocean temperatures can negatively impact life stage duration, growth rates and energetic demand rates of fish species (Chandrapavan et al. 2019). As a result, the distribution of fish species can be seriously altered (Caputi et al. 2016). This can cause detrimental changes to fish species composition and regional reductions in the catch potential of fisheries throughout Vanuatu (Holbrook et al. 2022). In their study investigating the impact that MHWs have on fish stocks, Cheung and Frölicher (2020) demonstrated that MHWs can decrease the biomass and cause shifts in the biogeography of fish stocks. These changes in fish stocks were noted as heightened: "With MHWs, we project a doubling of impact levels by 2050 amongst the most important fisheries species over previous assessments that focus only on long-term climate change" (Cheung and Frölicher 2020).

Another key marine species that is critical in supporting the lives of local Vanuatu fishing communities is the crab. Specifically, coconut crabs (*Birgus latro*) are noted as a species key to the livelihoods of Vanuatu fisher people (Warrick 2011). In Vanuatu, coconut crab populations are spread throughout the country. The main populations exist in the Banks/Torres islands, Santo/Malo, and Maewo islands in the north, and in Erromango Island in the south (Lovell et al. 2004). On these islands, coconut crabs form an important part of local income (Warrick 2011). Lovell et al. (2004) notes that the "sale of coconut crabs is sometimes the only income earning possibility for the inhabitants of some of the remote islands". Extreme weather events like MHWs have been known impact crab populations and subsequently reduce fishery crab stocks (Caputi et al. 2019; McNamara et al. 2021). High marine temperatures can affect the development, size, and distribution of coconut crabs (Hamasaki et al. 2009). Due to the significance of crab stocks for Vanuatu fishing communities, and the fact that all survey participants declared that crab stock health should be included as part of the MHW exposure index for this study, crab stock health is likely a suitable MHW exposure indicator for Vanuatu.

4.2 Excluded indicators- informed by the literature review and participatory research survey

Marine heatwave cumulative intensity (MHCI) value was found to be a hazard indicator used in past MHW risk assessment studies (Barbeaux et al. 2020). However, it was deemed as an inappropriate indicator for potential use in the MHW risk assessment for Vanuatu Fisheries. This was due to reported inaccuracies for MHW monitoring, and limited data availability across Vanuatu. MHCI has been known to have seasonal biases (Kajtar et al. 2021); a similar indicator that is recognised as a more accurate alternative is SST anomaly (Kajtar et al. 2021). Similarly, water column nutrient status was listed by sources as indicative of MHW occurrence, alluding to its usefulness of a MHW hazard indicator (Roberts et al. 2019; Taves et al. 20220). However, the literature review did not find any source which explicitly mentioned its use as a hazard indicator in a previous MHW risk assessment methodology. It's underexplored nature, and the fact that there is no data available for such an indicator across Vanuatu, mean that it is not appropriate for potential use in the Vanuatu fisheries risk assessment.

Disease prevalence has been used as a MHW vulnerability indicator in previous studies (Spickett et al. 2013). Although there is data available, and its usefulness for indicating community-level vulnerability to MHWs in Vanuatu has been proven by Spickett et al. (2013), it was not included as a potential vulnerability indicator in the participatory survey. This was because it does not specifically inform on MHW risk to Fisheries, rather it is indicative of MHW risk to the Health sector. Another vulnerability indicator excluded as a potential vulnerability indicator in the participatory research survey was occupational multiplicity. This indicator was listed by sources in the literature review as a previously used MHW vulnerability indicators (Green et al. 2021). It's relevance to MHW risk on fisheries is noted by Green et al. (2021) "occupation multiplicity was considered important in small-scale fishing communities as it is important for sustaining livelihoods in resource-dependant coastal communities when faced with climate impacts". However, in Vanuatu occupational demographics are consistently similar across communities. Locals are commonly employed in the Fisheries, Agriculture, and/or Tourism industry (Verdone and Seidl 2012). This indicator is not likely to provide insight into the spatial dynamics of MHW risk to Fisheries across Vanuatu, so its usability in the MHW risk assessment for Vanuatu Fisheries is limited.

In the literature review, it was found that several sources mentioned Human malnutrition as an important MHW vulnerability indicator (Belloti et al. 2018; Kim et al. 2014; Lam et al. 2020). Globally, it is recognised that extreme weather events like MHWs threaten food security, subsequently impacting the supply of nutrition to local populations (Bellotti et al. 2018). However, for the context of Vanuatu, not all locals may view Human malnutrition as an effective MHW vulnerability indicator. This was suggested in the survey results, with several participants opting to exclude Human malnutrition from the vulnerability index in this study. This may have been because human malnutrition is more closely related to the indirect impacts MHWs could pose for the Health sector in Vanuatu, rather than the direct impacts MHWs are predicted to have on the Fisheries sector (Lam et al. 2020). Additionally, participants reasoned that Human malnutrition is more of an appropriated vulnerability indicator for other natural hazards like TCs, rather than MHWs. Due to the uncertainty around the relevance of this indicator to a fisheries focused MHW risk assessment in Vanuatu, it was not included in the final selection of risk indicators. Further investigation is required to determine the reasoning behind local's exclusion of this indicator from a potential MHW vulnerability index.

Similarly, for Fish nutritional value, literature review results suggested that it would be a relevant indicator to use in a MHW risk assessment for Vanuatu (von Biela et al. 2019). However, survey results contradicted this, with several participants advising to exclude Fish nutritional value from the proposed MHW risk assessment for Fisheries in Vanuatu. The main reason for this being that there are other factors that affect Fish nutritional value; it not solely linked to MHW impacts (Farmery et al. 2020). Furthermore, Fish nutritional value may not be as relevant to the MHW vulnerability of

Vanuatu communities nowadays, as communities have transitioned from a reliance on fresh seafood to more processed, canned food (Charlton et al. 2016).

Market access is an exposure indicator that has been used in previous MHW risk assessment studies (Eriksson et al. 2017). Past studies have marked that there is a significant link between market access and MHW exposure “limited market access in many sectors of the community reduced the capacity for marine resources to support recovery” (Eriksson et al. 2017). However, in Vanuatu, a MHW will unlikely influence how accessible a market is as it is not likely to affect transportation to or from markets. A MHW would be more likely to affect the types of foods available at markets (Pacific Community 2019). To investigate this factor of risk, an indicator more specific to measuring food insecurity in Vanuatu would be appropriate, like primary production of fisheries or terrestrial-based food generation (Holbrook et al. 2022).

The potential for physical capital (e.g. infrastructure, water tanks and strong dwellings), to be an effective disaster exposure indicator for Pacific SIDS is noted by Eriksson et al. (2017). However, Eriksson et al. (2017) discussed the importance of this indicator in the context of all natural hazard events that are known to impact Pacific SIDS like Vanuatu, rather than in the context of MHWs specifically. The intended risk assessment for Fisheries in Vanuatu is to be highly tailored to assessing MHW risk, so trusted indicators that have been proven useful in past MHW-specific risk assessment studies must be used. Therefore, although noted as a likely important disaster exposure indicator in the literature review, physical capital was not selected to be a potential MHW risk indicator for examination in the participatory survey.

4.3 Proposed Index: Composition and Weighting Scheme

Informed by participant rankings, the proposed hazard index has SST weighted the most (0.50), Coral bleaching weighted second (0.30), and Chlorophyll-a concentration the least (0.20). This is an expected result as SST has been historically recognised as a core factor to MHW occurrence (Mohamed et al. 2022). It is highlighted in studies like Frölicher and Laufkötter (2018) and Holbrook et al. (2022) that SST has been a factor consistently used to define MHWs. Therefore, it is likely that SST is the most important indicator of MHW. Although coral bleaching and Chlorophyll-a have been linked to the occurrence of MHWs by many past studies (Fordyce et al. 2019; Perkins et al. 2022; Mohanty et al. 2021; Noh et al. 2022; Le Grix et al. 2021; Thoral et al. 2022), there is still some argument around their direct link to MHW hazard. Correlations have been found with MHW occurrence and Coral bleaching (Mohanty et al. 2021), but direct causation has not been explicitly proven (Fordyce et al. 2019). Additionally, Coral bleaching can occur from thermal stress not necessarily associated with a MHW event (Perkins et al. 2022). Similarly, it has been noted that changes in chlorophyll-a concentrations can be associated with the occurrence of a MHW (Noh et al. 2022; Le Grix et al. 2021), but the occurrence of a MHW does not always affect Chlorophyll-a concentrations (Sen Gupta et al. 2020; Thoral et al. 2022).

For the vulnerability index, Terrestrial (land)-based food and income generation was weighted the greatest, with Fishery fish diversity/fishery flexibility and Primary production of commercial fisheries weighted slightly less, and Fishing skills and technology weighted the least. In terms of MHW risk to fishing communities, Terrestrial (land)-based food and income generation is likely the most important indicator of vulnerability. Besides fisheries food and income generation, Terrestrial (land)-based food and income generation is the major method by which communities can maintain food security and local livelihoods (Langford 2022). The three other vulnerability indicators are directly linked to the vulnerability of the Fisheries sector itself. Fishery fish diversity/fishery fish flexibility is consistently noted in previous studies as key to fishery resilience (Green et al. 2021). It is also commonly explained that Primary production of commercial fisheries needs to be high enough to cope during and after a MHW event. Thus, these two indicators can be described as important with it appropriate to have them weighted similarly. Disparately, Fishing skills and technology has only been noted by some studies investigating MHW vulnerability (Eriksson et al. 2017; Green et al. 2021). As it has not been widely explored in the context of MHW vulnerability, it is logical to weight this indicator the least. In the future, if evidence for its usability in the MHW risk context, more weight could be applied to Fishing skills and technology.

In the exposure index, Seagrass population/C content was weighted the greatest based on survey ranks. Coral habitat health/crown of thorns prevalence and Fish mortality/fish stock health were then similarly weighted as second greatest and third greatest respectively. Crab stock health was deemed less important by survey participants and was therefore weighted the least. It is reasonable to weight fish mortality/fish stock health and crab stock health as third and fourth greatest; although fish species and crabs are important to Vanuatu fisheries, the industry does not solely rely on them. The Vanuatu Fisheries industry is highly diverse, utilising a range of species (mollusc species, lobsters, fish species, coconut crabs, Sea cucumbers, turtles, etc.) (Amos 2007).

It is unexpected that seagrass population/C content was weighted more than Coral habitat health/crown of thorns prevalence. Coral reef habitat dominates the coastline of Vanuatu; there is over 1200km^2 of coral reef along the coast of Vanuatu. Coral reef habitats critically support socio-economic services for Vanuatu communities and vitally underpin the Fisheries industry. They also provide critical habitat for species of concern like marine turtles. Thus, coral reef habitat has been noted as essential to the resilience of Vanuatu communities (Naviti and Aston 2000). Seagrass meadows are also prevalent around Vanuatu, supporting several key species and providing important ecosystem services (Lincoln et al. 2021). However, the total area covered by seagrass meadows is currently unknown. Due to the domination of coral habitat around Vanuatu, it was expected that coral habitat health/crown of thorns prevalence would be weighted the greatest out of all MHW exposure indicators. A possible reason for seagrass population/c content in seagrass being ranked higher than coral habitat health/crown of thorns prevalence is its vitality to dugong species (McKenzie et al. 2021). Seagrass meadows are critical habitat for dugongs. These animals play an important role in maintaining coastal ecosystems, are culturally significant in Vanuatu, and are utilised by the Fisheries industry across Pacific SIDS (McKenzie et al. 2021). Dugongs are globally vulnerable (IUCN red list). Without healthy seagrass populations, dugongs would likely become extinct, having destructive impacts on the overall marine ecosystem.

4.4 Review of Methodology

4.4.1 Indicator selection methods

The tailored selection of indicators is generally observed through assessing indicator appropriateness to the unique characteristics of a study area, as well as how indicators can address user needs. In a report on Ecosystem and Socio-economic Resilience Analysis and Mapping for Vanuatu, Mackey et al. (2017) similarly discussed the appropriateness of the risk indicators which were used in their disaster risk assessment of Vanuatu coral reef systems. Hazard indicators were appropriate if they measured the specific hazard being investigated, and if data was available for smaller spatial scales (Mackey et al. 2017). Ecological hazard indicators were also mentioned as important. For vulnerability indicators, it was deemed that they were appropriate if they indicated on the factors that influence community vulnerability to the loss of ecosystem services, and if indicator data was available at the community level to provide insight into community level sensitivity and coping capacity (Mackey et al. 2017). Exposure indicators were appropriate if they informed on how the socio-ecological system of the study area is geographically exposed to the hazard investigated, and if data was available across temporally diverse time scales (including seasonal and future time scales) (Mackey et al. 2017). Much like Mackey et al. (2017), when deeming indicators appropriate for potential inclusion in the Vanuatu fisheries MHW risk assessment it was intended that indicator selection would include ecological and human indicators, indicators with sufficient data availability (particularly at the community level) and are specific to assessing risk to the overall Fisheries industry in Vanuatu as well as local fishing communities.

In disaster risk assessment methodology, the appropriateness of indicators is commonly determined according to expert or local opinion and academic views (Wafiy Adli Ramli et al. 2021). This is conducted with two common methods: indicator selection through literature review or participatory method. The first method is common among previous disaster risk assessments (Wafiy Adli Ramli et al. 2021; Aminur Rahman Shah et al. 2020; Yang Ying Chan et al. 2019). Chan et al. (2019) used a three-phase methodology to construct a disaster risk model, specifically focusing on health indicators. The first phase of the methodology included utilising a literature review to select relevant indicators for the development of the health vulnerability index. Although it has been recognised that this method can produce tailored selection of indicators to the geographic, socioeconomic, and climactic characteristics of a study area, it does not specifically consider tailored selection of indicators for user needs as well (Wafiy Adli Ramli et al. 2021). This is where participatory method is helpful; user needs are considered when indicator selection includes surveying and/or interviewing users to determine appropriate risk indicators (Jackson et al. 2017). In this study, these two methods were combined to select MHW risk indicators appropriate for the climatic, geographic, and socio-economic characteristics of Vanuatu, as well as for user needs (specifically for locals involved in fisheries) (Asare-Kyei et al. 2014; Twomlow et al. 2022).

The indicator selection methodology use in this study did have some limitations. Only 24 sources were able to be examined in the literature review. Ideally, a larger body of literature would be used. However, as MHW risk assessment in Pacific SIDS is a relatively new study field, there is not a strong body of literature that fit the source criteria. The literature review outlined many MHW risk indicators previously used across global studies to assess MHW hazard, vulnerability, and exposure. Out of these indicators, some were limited in their data availability and thus, were excluded as potential indicators to be assessed in the participatory research stage of the methodology. Limited data availability is a common obstacle seen in disaster risk assessment studies across Pacific SIDS (Aitkenhead et al 2023; Kuruppu and Willie 2015).

4.4.2 Indicator weighting methods

The indicator weighting method used in this study was locally informed rank-based weighting. This a commonly used indicator weighting method for disaster risk assessment studies (Meza et al. 2021). Wang et al. (2011) describe this method of locally informed rank-base weighting as a semi-quantitative approach that is widely used. The benefits of this method include simplicity, accounting for data scarcity, and effectiveness on regional scales. A potential downfall is that weights will be subjective. This downfall does not likely impact the results of our study; local judgement is often based off of years of experience and knowledge which can be highly informative (Papathoma-Köhle et al. 2019).

The specific methodological process used in this study follows that of Asare-Kyei et al. (2014). In a West African multi-hazard risk assessment, Asare-Kyei et al. (2014) indicator weights were informed by ranking indicators, specifically considering each sub-component of their methodological framework. The list of indicators to be ranked was formed through literature assessment determining commonly used risk indicators. A participatory approach was employed to confirm the use of and rank risk indicators in the West Africa context. Relevant stakeholders (including farmers) that have felt the affects of natural hazard events were consulted in the participatory stage of Asare-Kyei et al.'s (2014) study.

This approach was seen to produce a comprehensive list of indicators, with appropriate weightings (Asare-Kyei et al. 2014). As our study aims to similarly build a MHW risk framework with tailored indicators and appropriate indicator weightings, it is reasonable to follow such a methodology. However, the participatory method that informed our weighting scheme could be limited by the small sample size. Only 12 participants completed the survey which contributed to the development of indictor weights.

4.5 Research Significance

This study included the development of a tailored indicator selection and weighting methodology. This is the first step in the development of an effective MHW risk assessment for Vanuatu Fisheries. Such studies are scarce across Pacific SIDS, with MHW risk assessment remaining a relatively new topic of study (Frölicher and Laufkötter 2018). In this study, significant effort was made to address the key knowledge gaps widely omitted from MHW risk assessment studies globally, as well as in Vanuatu specifically (Frölicher and Laufkötter 2018). In many past studies, aspects of effective risk assessment are commonly lacking: dynamically including hazard, vulnerability, and exposure indices; tailoring the selection and weightings of indicators; and holistically incorporating both ecological and human indicators into risk indices (Asadzadeh et al. 2015).

This study addressed these knowledge gaps in the following ways:

- **Dynamic inclusion of tailored hazard, vulnerability and exposure indicators**

  The proposed risk index includes three hazard indicators, four vulnerability and four exposure indicators. It is believed that the relatively small number of indicators is beneficial in this study context. This is because the study intends to be highly specific rather than general. Many past disaster risk studies using an extended number of risk indicators have been generalised rather than tailored (Frischen et al. 2020). Tailored risk assessments are ideal to ensure the presentation of accurate and relevant risk information for a specific area (Asare-Kyei et al. 2014; Twomlow et al. 2022). Although a reduced number of indicators is used here to increase the specificity of the risk index, it is believed that the overall index is still holistic and encompasses multiple aspects of hazard, vulnerability, and exposure of Vanuatu Fisheries. Not only was the composition of the risk index intended to be highly tailored to the context of Vanuatu Fisheries MHW risk, but the proposed weights also given to each selected indicator was informed by local users to ensure specificity to Vanuatu communities (Twomlow et al. 2022).

- **Incorporation of ecological and human risk**

  A diverse range of vulnerability and exposure indicators have been used in global MHW risk assessment studies, with most assessments having a human-based focus or an ecological focus (Major et al. 2021; Galli et al. 2017). In this assessment, a focus on both human-based and ecological vulnerability was considered. To incorporate human-based risk, Terrestrial (land)-based food and income generation, Fishing skills and technology, Fishery fish diversity/fishery flexibility and Primary production of commercial fisheries were included as vulnerability indicators. To inspect ecological risk, Seagrass population/C content, Coral Habitat Health/Crown of Thorns Prevalence, Crab stock health and Fish mortality/fish stock health were chosen as exposure indicators.

Furthermore, few studies have specifically focused on MHW risk to Pacific SIDS fisheries (Frölicher and Laufkötter 2018). It is important to develop specific risk indices for each of the key sectors in a vulnerable area. In doing so, index results can be increasingly informative and aid key sectoral decision makers to prepare for and respond to a MHW event (Cheung and Frölicher 2020). In a study region that has many major sectors that should be assessed, a risk index should be develop for each specific sector. In Vanuatu, Fisheries are a key sector along with Agriculture and Tourism. MHW impacts on Fisheries have already been noted across the world, but they remain underexplored in Pacific SIDS like Vanuatu (Holbrook et al. 2022). Our study provides an initial exploration into MHW risk on Fisheries in Vanuatu, building a foundation for future studies to expand MHW risk knowledge for Fisheries in Vanuatu (Holbrook et al. 2022).

4.6 Study Conclusions and Further Steps

This study aimed to begin the process of tailored MHW risk assessment for Vanuatu fisheries. Pacific SIDS like Vanuatu have been identified as some of the most vulnerable regions in the world to climate change impacts, including the increased occurrence of MHW events. However, MHW risk in general is underexplored across Pacific SIDS, as well as the specific risk to key sectors. This study implemented the most efficient methodological processes available to complete two crucial first steps in an effective MHW risk assessment methodology for Fisheries in Vanuatu: indicator selection and weighting. However, some limitations of this study must be addressed in future studies. For example, an increased number of Vanuatu locals should be consulted to further inform on indicator selection.

Overall, this study produced a user-centered list of tailored hazard, vulnerability, and exposure indictors, along with their specific weights, which are recommended for use in the completion of a MHW risk assessment. It is intended that future steps follow on from this study to conduct a tailored MHW risk assessment for Vanuatu Fisheries using the indicators selected and weighting scheme developed here. Critical next steps include data collection, index calculation, index mapping and validation. A finalised, effective MHW risk assessment for Fisheries has the potential to inform local decision-makers of priority areas in Vanuatu and can guide the development of risk management strategies to improve local community and fishery resilience.

5. Appendices

Appendix A. A copy of the survey distributed to Vanuatu locals for this study.

Survey for 'Selecting indicators to assess the risk of negative impacts from Marine Heat Waves on fisheries in Vanuatu'

This research is conducted by Isabella Aitkenhead (with Royal Melbourne Institute of Technology (RMIT) and the Australian Bureau of Meteorology) -isabella.aitkenhead@bom.gov.au

Survey Background Knowledge

Please read the following information before completing the survey questions

Definitions of key terms

- **Marine Heat Wave Risk Assessment**: Marine heat wave risk assessments analyse the risk of marine heat waves causing negative effects in a particular area.
- **Marine Heat Wave Risk**: Marine heat wave risk is the probability of harmful consequences, or expected losses resulting from interactions between three elements: hazard, exposure, and vulnerability.
- **Hazard Index**: Measures the possible future occurrence of marine heat wave events. The hazard index includes different indicators of such hazard information.
- **Vulnerability Index**: Measures the likelihood of exposed factors within an area to suffer negative impacts when marine heat waves occur. The vulnerability index is made up of different indicators of such vulnerability information.
- **Exposure Index**: Measures exposed aspects of the total population, its livelihoods, and assets in an area in which marine heat waves may occur. The exposure index is calculated from different indicators of such exposure information.

List of potential indicators considered for this survey

Index	Potential indicators	Indicator Description
Hazard	Sea Surface Temperature (SST) anomalies	Sea surface temperature (SST) has been used in most studies investigating marine heat waves as a hazard indicator. High SSTs continue to be associated with the occurrence of marine heat wave events.
	Coral bleaching/mortality	Coral bleaching/mortality is a marine heat wave hazard indicator for the warmest months of the year, as it can indicate the occurrence of a marine heat wave event. When sea surface temperature increases, a marine heat wave can develop, and coral bleaching/mortality commonly occurs.
	Chlorophyll-a concentrations	Past studies have revealed an association between marine heat wave occurrence and changes in Chlorophyll-a concentrations, so chlorophyll-a concentration has been used in many studies as an indicator of marine heat wave hazard. Chlorophyll-a concentration indicates the amount of phytoplankton in the ocean. It is the main pigment used by phytoplankton to capture light energy and convert that energy into biomass. Marine heat wave events have tended to coincide with reduced chlorophyll-a concentration at low and mid-latitudes.
Vulnerability	Terrestrial (land)-based food and income generation	This is a marine heat wave vulnerability indicator. The fisheries industry provides staple food and sources of livelihood in Pacific Island countries; if a marine heat wave occurs and the fisheries industry is negatively impacted, communities must have a land-based source of food and income to survive. If land-based food income and generation is limited, a community is likely more vulnerable to experiencing negative impacts from marine heat waves.

	Fishing skills and technology	This is a marine heat wave vulnerability indicator. Fisheries is a critical industry to Pacific Island communities, so fisheries sustainability is a priority for disaster risk management. Increasing the fishing skills and technologies within Pacific Island communities is key for reducing vulnerability and increasing the capacity of communities to deal with the impacts of marine heat waves.
	Human malnutrition	This is a marine heat wave vulnerability indicator. Pacific countries like Vanuatu are at high risk of malnutrition from food insecurity caused by climate change impacts. If malnutrition is already high in a community, this would mean that the community would be more vulnerable to the likely effects of marine heat waves.
	Fish nutritional value	This is a marine heat wave vulnerability indicator. Marine heat waves are often associated with a reduction in the nutritional value of key fish species. If the nutritional value of key fish species within communities is already low, then the community would be more vulnerable to marine heat wave impacts.
	Fishery fish diversity/fishery flexibility	Fisheries diversity and flexibility is linked to the vulnerability of communities to marine heat wave impacts, and the capacity of communities to respond well to marine heat wave events. If fisheries are more diverse and flexible, communities are likely to be less vulnerable.
	Primary production of commercial fisheries	Primary production of commercial fisheries is noted as being linked to the level of community vulnerability for marine heat wave events. This is because marine heat waves commonly affect fish species negatively and are seen to limit the production of commercial fisheries. If the primary production of commercial fisheries is low prior to a marine heat wave event, then it is likely to reduce fisheries production to a critical level.
Exposure	Seagrass population/C content in seagrass:	This is a marine heat wave exposure indicator. In the pacific, coastal marine ecosystems tend to rely on seagrass populations. Seagrass is a foundation species, and many other species rely on seagrass for food and habitat. Seagrass also provides a key ecosystem service- carbon sequestration. Seagrass populations convert harmful dissolved carbon dioxide into useful vegetative biomass. If a coastal marine ecosystem has a strong seagrass population then it can function adequately, however, if seagrass populations are limited the ecosystem may function insufficiently and is further exposed to negative impacts from marine heat waves.
	Coral habitat health/crown of thorns prevalence	This is a marine heat wave exposure indicator. The health of coral habitats in the coastal marine ecosystems around Vanuatu is key to marine heat wave exposure. If coral habitats are healthy, then it is less likely that the marine ecosystem will experience harsh impacts from marine heat waves. The number of crown of thorns starfish in the ecosystem is linked to the health of coral habitats; its occurrence can indicate declining health of corals and the overall ecosystem.
	Crab stock health	This is a marine heat wave exposure indicator. Crab stock health (crab abundance, distribution, recruitment, etc.) is linked to the level of exposure a marine ecosystem has to the negative impacts of marine heat waves. Marine heat waves are known to negatively affect crab stocks. If the health of crab stocks was already reduced, the effects experienced by marine ecosystems during marine heat wave events could be critical.
	Fish mortality/fish stock health	This is a marine heat wave exposure indicator. When a marine heat wave event occurs, fish stocks are known to undergo ecological changes, with usual impacts including the death (mortality) of certain fish species. If fish stocks are already reduced in a marine area than it is likely that the negative impacts experienced from marine heat waves will cause fish stocks to be at a critical low. If fish stocks are unhealthy and reduced, then it is expected that they will have a low rate of recovery after the end of a marine heat wave event.

Participant Details

Please provide the following details

Province:

Age:

Gender:

Stakeholder group (fisher person, fisheries staff, and/or local community member):

Survey Questions

Please answer the following survey questions

Question 1- For the **hazard** index, what potential indicators would you include? *Choose from the hazard index section in the table above*

Indicators to include	Indicators to exclude

If there are indicators you have excluded, why is this?

Question 2- For the **vulnerability** index, what potential indicators would you include? *Choose from the vulnerability index section in the table above*

Indicators to include	Indicators to exclude

If there are indicators you have excluded, why is this?

Question 3- For the **exposure** index, what potential indicators would you include? *Choose from the exposure index section in the table above*

Indicators to include	Indicators to exclude

If there are indicators you have excluded, why is this?

Question 4- If each potential **hazard indicator** was included in the hazard index, how would you rank them in terms of weighting (weighting= how much they contribute to the hazard index compared to other indicators)?

1st being the hazard indicator weighted the most and 3rd being the least

Potential Hazard Indicators	**Rank**
Sea-Surface Temperature (SST) anomalies	
Coral bleaching/mortality	
Chlorophyll-a concentrations	

Question 5- If each potential **vulnerability** indicator was included in the vulnerability index, how would you rank them in terms of weighting (weighting= how much they contribute to the vulnerability index compared to other indicators)?

1st being the vulnerability indicator weighted the most and 6th being the least

Potential Vulnerability Indicators	**Rank**
Terrestrial-based food and income generation	
Fishing skills and technology	
Human malnutrition	
Fish nutritional value	
Fishery fish diversity/fishery flexibility	
Primary production of commercial fisheries	

Question 6- If each potential **exposure** indicator was included in the exposure index, how would you rank them in terms of weighting (weighting= how much they contribute to the exposure index compared to other indicators)?

1st being the exposure indicator weighted the most and 4th being the least

Potential Hazard Indicators	**Rank**
Seagrass population/C content in seagrass	
Coral habitat health/crown of thorns prevalence	
Crab stock health	
Fish mortality/fish stock health	

Question 7- Are there any additional indicators that you know of that we should consider? *Please list any other potential indicators, and what index (hazard, vulnerability, or exposure) they should be considered for*

Administrative Questions

Please answer the following administrative questions

Would you be willing to participate in further related research? (If yes, you are consenting to being contacted by the researcher in the future)

Would you like a copy of the research results sent to you via email? (If yes, please include the email address you would like to receive this at)

Appendix B. Notice of Approval for RMIT Human Ethics Application regarding this study.

RMIT UNIVERSITY

STEM College
College Human Ethics Advisory Network (CHEAN)
Email: humanethics@rmit.edu.au
Tel: [61 3] 9925 4620

Notice of Approval

Date:	**5 October 2022**
Project number:	**25578**
Project title:	**Selecting indicators to assess the risk of negative impacts from Marine Heat Waves on fisheries in Vanuatu**
Risk classification:	**Negligible/Low**
Chief investigator:	**Professor Suelynn Choy**
Status:	**Approved**
Approval period:	From: **05/10/2022** To: **06/10/2025**

The above application has been approved by the RMIT University CHEAN as it meets the requirements of the *National Statement on Ethical Conduct in Human Research* (NHMRC, 2007).

Terms of approval:

1. **Responsibilities of chief investigator**
   It is the responsibility of the above chief investigator to ensure that all other investigators and staff on a project are aware of the terms of approval and to ensure that the project is conducted as approved by CHEAN. Approval is valid only whilst the chief investigator holds a position at RMIT University.
2. **Amendments**
   Approval must be sought from CHEAN to amend any aspect of a project. To apply for an amendment, use the request for amendment form, which is available on the HREC website and submitted to the CHEAN secretary. Amendments must not be implemented without first gaining approval from CHEAN.
3. **Adverse events**
   You should notify the CHEAN immediately (within 24 hours) of any serious or unanticipated adverse effects of their research on participants, and unforeseen events that might affect the ethical acceptability of the project.
4. **Annual reports**
   Continued approval of this project is dependent on the submission of an annual report. Annual reports must be submitted by the anniversary of approval of the project for each full year of the project. If the project is of less than 12 months duration, then a final report only is required.
5. **Final report**
   A final report must be provided within six months of the end of the project. CHEAN must be notified if the project is discontinued before the expected date of completion.
6. **Monitoring**
   Projects may be subject to an audit or any other form of monitoring by the CHEAN at any time.
7. **Retention and storage of data**
   The investigator is responsible for the storage and retention of original data according to the requirements of the *Australian Code for the Responsible Conduct of Research* (R22) and relevant RMIT policies.
8. **Special conditions of approval**
   Nil.

In any future correspondence please quote the project number and project title above.

Yours faithfully,

Dr Lauren Saling
Chair, STEM College Human Ethics Advisory Network

Cc	Student Investigator/s:	Miss Isabella Aitkenhead
	Other Investigator/s:	Dr Chayn Sun

Appendix C. A copy of the consent form distributed to all survey participants prior to their involvement in the survey, as per RMIT Human Ethics requirements.

Research description and consent form

Research Project Title: Selecting indicators to assess the risk of negative impacts from Marine Heat Waves on fisheries in Vanuatu

Researcher details: Isabella Aitkenhead is the primary researcher conducting this research. Isabella is a HDR student for RMIT, working in partnership with the Australian Bureau of Meteorology and collaborating with the Secretariat of the Pacific Regional Environment Programme.

Researcher contact:

Email- isabella.aitkenhead@bom.gov.au

Phone- 0401811509

Project description

Aim:

This research aims to gain the perspective of Vanuatu locals and fisheries stakeholders, through surveys, on the selection of indicators to be used in a marine heat wave risk assessment for Vanuatu fisheries. It is intended that participation of Vanuatu people will increase the specificity of chosen marine heat wave risk indicators and the validity of the risk assessment.

Why is this research important?

Small Island Developing States (SIDS) in the Pacific, like Vanuatu, are exposed to natural hazard events like marine heat waves (MHWs). The impacts MHWs in the Pacific have been proven to be destructive to marine ecosystems and key industries like fisheries. This is of concern for Vanuatu, as the country has a strong reliance on coastal and ocean resources and a low capacity to cope with the negative impacts associated with MHWs. Current efforts to manage MHW impacts in Vanuatu are not enough. To increase effective management of MHWs, it is critical that the associated impacts of MHWs on Vanuatu are investigated and MHW risk knowledge is expanded.

Risk knowledge includes knowledge on three components: hazard, vulnerability, and exposure. The hazard component describes the possible future occurrence of MHW events. Exposure is the total population, its livelihoods, and assets in an area in which MHWs may occur. Vulnerability is the likelihood of exposed factors to suffer negative impacts when MHW events occur.

A technique for investigating MHW risk knowledge, which has the potential for application in Vanuatu, is MHW risk assessment. A MHW risk assessment would analyse the risk of MHWs in a particular area through the production of a MHW risk index. The MHW risk index would be produced from combining a hazard index, vulnerability index and exposure index.

MHW risk assessments are vital to indicating the most at-risk places to MHWs that are of priority for improved risk management. However, for such a risk assessment to be effective, the indicators that are selected to inform the hazard index, vulnerability index and exposure index must be tailored to the area of study and must be accurate for assessing risk proactively on a local level. Consultation with local people and key stakeholders allows for the appropriate selection of indicators.

Therefore, seeking the advice of Vanuatu locals and fisheries sector stakeholders is vital to the development of an effective MHW risk assessment for fisheries in Vanuatu, which will in turn be critical for informing effective risk management of MHWs in Vanuatu communities in the future.

What is required of participants?

You will be required to fill out a 20-30min (approximately) survey. To aid in your completion of this survey, you will also be required to attend a workshop at the Vanuatu meteorological and geohazard department in Port Vila, Vanuatu (date TBD). You will be required for a 1-hour session on (date TBD). You must then submit the completed survey within two weeks following the workshop, to the researcher via email. The survey will ask your opinion on different marine heat wave risk indicators, specific to fisheries in Vanuatu. All relevant terms, and the indicators discussed will be described at the beginning of the survey. You may also ask any questions of the researchers at the workshop. The results of this survey are intended to aid in the development of a tailored marine heat wave risk assessment for Vanuatu fisheries. Results will be reported through a published research paper and can be sent to participants upon request.

Risks and Benefits to Participants:

- By undertaking this survey, you may be at risk to triggering negative feelings or memories that you associate with disaster events. By discussing MHWs we are talking about a disaster event, and previous experiences you may have with natural disaster events may affect how you react to the survey content. Throughout the survey process, if this does occur you are welcome to take a break at any time, and you can fill out the survey slowly within a two-week period. Additionally, if you wish to discontinue and participate no further in this research, that is also completely fine. If you require support throughout the survey process, please contact the researcher via phone or email and they will help in any way that they can.
- As the survey is asking about complex scientific indicators, there is possibility for confusion. The information provided in the survey is intended to be as easily understandable as possible, however, if you have any questions or confusion you will be able to ask them in the workshop, or if you have questions following the workshop please contact the researcher, and they will assist you with resolving this.
- To further ensure participants are protected throughout the research process, all survey results that are reported will be de-identified.
- It is believed that this project will be greatly beneficial to the fisheries sector and local communities in Vanuatu, as it will contribute to increasing resilience to MHWs. This benefit is likely to outweigh the minor risk of this project, but it is intended that Vanuatu locals will be consulted consistently throughout the research project to ensure that this is the case. Consultation with Vanuatu locals will be carried out throughout the project using existing networks with Vanuatu locals who are employed in the Secretariat of the Pacific Regional Environment Programme, which works in partnership with the Australian Bureau of Meteorology to improve disaster risk reduction in Pacific Small Island Developing States.

Informed consent

Once you have read the above information, please indicate if you are willing to participate in this research by completing the statement below.

I *please insert your name here* agree to participate in the research project 'Selecting indicators to assess marine heat wave risk to the fisheries sector in Vanuatu' by attending the survey workshop and filling out the provided survey to the best of my ability, and consent to the following:

- Receiving the research survey via email or in person
- Attending the workshop in Port Vila, Vanuatu via online methods or in person
- If completing the survey in Bislama, having your survey results translated to English for the data analysis phase
- Analysis and reporting of survey response (in a non-identifiable manner)
- Publishing of survey results (in a non-identifiable manner) in a research paper

Signed:

X ______________________

Signature

____

Date:

Appendix D. The number of participants for each stakeholder group the study considers.

	Stakeholder group			
	Fisheries Staff	Local Community Member	Local Fisherperson	Other
Number of Participants	10	2	0	0

Appendix E. Summary of survey participant gender.

	Gender

	Female	Male	Other
Number of Participants	6	6	0

Appendix F. Age ranges of survey participants.

	Age						
	Twenty to Twenty-five	Twenty-five to Thirty	Thirty to thirty-five	Thirty-five to forty	Forty to Forty-five	Forty-five to fifty	Above Fifty
Number of Participants	4	3	3	1	0	1	0

Appendix G. The number of survey participants from each of the six provinces in Vanuatu.

	Province					
	Malampa	Penama	Sanma	Shefa	Tafea	Torba
Number of Participants	4	3	0	4	1	0

6. Declarations and Ethics Statements

This study required ethics approvals as human ethics research was conducted. Vanuatu locals participated in a participatory survey which contributed to the results of this study. Human Ethics was approved through the ethics committee at RMIT University. The data used in this study was open-sourced data gathered from public databases. Spaced-based observation data underwent transformation from what is publicly available. This data may be available upon reasonable request.

7. Acknowledgements

This study was conducted as part of the Van CISRDP (Climate Information Services for Resilient Development in Vanuatu) / Van-KIRAP (Vanuatu Klaemet blong Redy, Adapt mo Protekt) project. Authors express sincere gratitude to colleagues from the Climate Risk and Early Warning Systems (CREWS) team at the Australian Bureau of Meteorology for their helpful advice and guidance.

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