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RESEARCH ARTICLE

EVALUATING COASTAL VULNERABILITY TO TSUNAMIS IN COASTAL TOWNS OF SABAH, MALAYSIA

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ABSTRACT

Malaysia is a rapidly developing country with expanding urban coastal populations, which in turn increases their vulnerability to tsunamis. This research sets out to establish the risk to Sabah's coastline of a potential tsunami threat and identify the vulnerabilities of six large coastal communities in Sabah namely, Kota Kinabalu, Kudat, Sandakan, Lahad Datu, Semporna and Tawau, to such a tsunami. Using topographical data from digital elevation models, mangrove forest distribution data from Global Mangrove Watch, as well as OpenStreetMap data, the creation of GIS maps allowed the identification of topographical vulnerabilities of these communities as well as the identification of vulnerable infrastructure with the use of GoogleEarth. This data was supplemented by information obtained from interviews with three Malaysian professionals whom possess earthquake and tsunami knowledge and experience. Vulnerable features for each community were identified and scored to provide a comparative figure. The coastal settlement identified as exhibiting the greatest vulnerability overall is Sandakan, mainly due to a lack of significant protective natural barriers, extensive low coastal elevation zones, a very dense coastal population within 1km of the coast, extensive number and size of water villages and a single route of access to and from the city. The findings of this research provide a foundation for further exploration into Sabah's coastal vulnerability to tsunamis and provides an initial focus for the Malaysian Government and other agencies involved in disaster risk reduction to direct their efforts in reducing the vulnerability of Sabah's coastal communities to a potential tsunami.

KEYWORDS

Coastal vulnerability, Tsunami vulnerability, Sabah, Malaysia, Coastal populations, Tsunami hazard risk reduction.

1. INTRODUCTION

As the world's population continues to increase, tsunamis pose an ever-increasing risk to human lives and economies around the world, with economic losses and loss of life projected to continue rising into the future, more so in the developing countries (Tucker, 2013). Earthquakes and tsunamis claimed more human lives between 1994 and 2013 than all other disasters combined at nearly 750,000 people with tsunamis being the deadliest consequence of earthquakes averaging 79 deaths for every 1000 people affected (Gonzalez-Riancho et al., 2015).

Natural disasters become disasters due to the increased vulnerability of the people and the places in which they occur (Mazurana et al., 2011). In the hope of reducing the losses from natural disasters, in 2005, Japan hosted the World Conference on Disaster Reduction in Kobe and, in succession to the Yokohama Strategy, the Hyogo Framework for Action (HFA) was adopted. The HFA placed an emphasis on reducing disaster risk, not only at a national level, but also at a local level as well as monitoring potential disaster risks and strengthening disaster preparedness (UNISDR, 2005). The HFA was later succeeded by the Sendai Framework for Disaster Risk Reduction in 2015 building on what was learned from the HFA, i.e., disaster risk reduction (DRR) requires a multi-hazard and multi-sectoral approach right down to local communities and highlighted the need for an 'action-oriented framework' that aids the identification of those disaster risks to be managed (UNISDR, 2015).

1.1 Research Rationale

Studies have highlighted the rise in exposure to tsunamis with a parallel rise in territorial vulnerability and this is explained by the increased concentration of people and critical infrastructure in coastal areas (Atillah et al, 2011; Freire et al, 2013; Tavares et al, 2017).

The Eleventh Malaysia Plan 2016-2020 emphasised preparing and planning for natural disasters as well as, identifying those communities who are at risk, yet the main emphasis was only on flooding and climate change (CFE-DM, 2019). Although research has been carried out into tsunami risk in Malaysia, and several researchers acknowledge the future risks to the country, little-to-none has been carried out on the vulnerability of Malaysia's coastal communities (Najihah et al., 2014; Mardi et al., 2017; Terry et al., 2017; Tan et al., 2017; Tongkul et al., 2020). Proactive, rather than reactive, measures are likely to significantly reduce loss of human lives in Malaysia and minimise its economic losses.

This research paper aims to evaluate coastal vulnerability in Sabah, East Malaysia, to a potential tsunami hazard. The main objectives to achieve this aim are:

- To identify the threat and impact of tsunami to the Sabah coastline

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by reviewing existing literature and interviewing disaster management (DM) academics in Malaysia;

- To evaluate the perception of a few, select professionals involved in DM or tsunami risk in Sabah;
- To use geoinformatics to map Sabah's coastline and identify those areas most vulnerable;
- To identify what measures Malaysia's government has taken or plans to take to lessen Sabah's coastal vulnerability to tsunamis.

There are a number of research questions that this research intends to answer:

- How likely is the tsunami threat to Sabah and which part of Sabah is most likely to be affected by a tsunami?
- Which communities and industries are most likely to be affected?
- What measures has the Malaysian government taken to reduce tsunami risk/vulnerability in Sabah?
- Where are the most likely geological tsunamigenic sources?
- Where is the most vulnerable topography on Sabah's coastline?
- Where are Sabah's most exposed populations and key exposed industries and infrastructure?
- What would be the extent of inundation or damage to Sabah's coastline of a potential tsunami?
- What action has the Malaysian government taken to reduce people's vulnerability to a potential tsunami?
- Are there additional measures that could be taken to further reduce Sabah's coastal vulnerability to tsunamis?

The answers to these questions are crucial if Malaysia is to protect its people whilst continuing its development efforts to become a world-leading economy. Sustainable coastal development necessitates an understanding of the impacts of potential hazards in addition to implementing appropriate risk mitigation measures - over-estimating the tsunami risk significantly increases development cost however, under-estimating it could lead to catastrophic consequences – both to life and economy (Kulikov et al., 2005).

2. LITERATURE REVIEW

2.1 Global Tsunami Vulnerability Assessment

Disaster management is pivotal in strategically minimising negative impacts on human life and economy from any disaster. Typical DM consists of four basic phases: mitigation, preparedness, response and recovery and it is the mitigation phase (pre-crisis), which mainly involves interventions designed to minimise risk and reduce the vulnerability of populations to the effects of disasters (Lettieri et al., 2009; Oktari et al., 2020). Assessing the vulnerability of coastal communities to tsunamis is usually achieved by defining particular sets of indicators according to post-tsunami reports, previous literature and the available data at the location of interest (Eckert et al., 2012; Gonzalez-Riancho et al., 2015). A group of researchers in their review on tsunami human vulnerability indicators following the Indian Ocean Tsunami (2004), Chilean Tsunami (2010) and the Japan Tsunami (2011), establish four key tsunami vulnerability indicators: 1. Exposure, 2. Warning capacity, 3. Evacuation and emergency capacity and 4. Recovery capacity (Gonzalez-Riancho et al., 2015). They also establish ten key issues, which influence the four vulnerability indicators and are themselves affected by numerous physical, economic, social and political factors (Table 1).

One group of researchers utilised two inundation scenarios (5m and 9m depths) based on historical records of past tsunamis to assess tsunami vulnerability and risk on the coastal building infrastructure of Alexandria, Egypt (Eckert et al., 2012). They state that tsunami vulnerability is a product of physical parameters (e.g., distance from the shore, altitude above sea level) and social parameters (e.g., preparedness of the society, risk perception) influencing the potential level of damage. High resolution satellite remote sensing (RS) data was used to ascertain spatial information (including building height, number of floors and generating digital elevation and digital surface models (DEMs and DSMs)), which was then analysed by a geographical information system (GIS) in assessing the physical vulnerability of the coastal region (Eckert et al., 2012). With both sites being studied in Alexandria being densely populated and highly developed, the authors concluded that risk reduction should be focused on reducing building vulnerability, e.g., identifying critical facilities at risk of being flooded or damaged, as well as implementing an early warning system (EWS) and an emergency evacuation plan (Eckert et al., 2012).

Table 1: Ten key issues expected to influence tsunami vulnerability and their influential factors within the scope of the four key indicators mentioned in the text (adapted from Gonzalez-Riancho et al, 2015).

Key Tsunami Vulnerability Issues		Influential Factors
1.	Human exposure.	Population density and coastal physical topography.
2.	Reception of a warning message.	Presence of an EWS and affected by isolated communities.
3.	Understanding the warning message.	Age, education level, language and social and institutional awareness.
4.	Mobility and evacuation speed.	Age, gender, disability and health.
5.	Safety of buildings.	Building type, materials utilised, number of floors, elevation and distance to shore.
6.	Difficulties in evacuation related to built-up environment.	Distance to safe places, road access and network, critical public infrastructure (number of people and floors).
7.	Society's coping capacity.	Health/emergency infrastructure and capacity, EWS, evacuation routes, contingency plans, local civil protection commissions.
8.	Household economic resources.	Home/health insurance, employment/income level, savings, poverty level, asset ownership (house, land, etc.).
9.	External recovery support.	Availability of utilities, access to social help networks (family, friends, institutional), access to temporary shelters and public funds.
10.	Expected impacts affecting recovery.	Human injuries, socioeconomic losses, damage to ecosystems and critical infrastructure, impact on cultural heritage.

In a study on the southwest coast of Sri Lanka, which also utilised RS in the form of light detection and ranging (LiDAR) in combination with field measurements and numerical simulations, various conclusions affecting the impact of a tsunami were drawn including:

- Rivers and canals provide a low-resistance pathway for a surge of tsunami water to travel upstream penetrating areas further inland;
- Tsunami inundation is affected by tsunami amplitude and velocity,

onshore topography and density of buildings and vegetation;

- Steep coastal terrain offers resistance and obstruction to tsunami surge, which may inadvertently worsen the tsunami's impact on neighbouring low-lying coastal terrain (Wijetunge, 2014).

Researchers in El Salvador separated a tsunami vulnerability and risk assessment into human factors, environmental factors, socioeconomic factors and infrastructure factors for both exposure and vulnerability in order to formulate a risk assessment and ultimately, identify risk reduction measures (Gonzalez-Riancho et al., 2014). However, the authors fail to discuss which aspects of these factors specifically increases or decreases El Salvador's vulnerability to tsunamis, instead concentrating more on how to formulate a risk assessment.

During tsunami vulnerability assessment of buildings in the city of Heraklion, Crete, GoogleEarth and field inspection were utilised to validate types of building obtained from census data whilst GIS mapping was used to determine the inundation zone and assess building exposure based on the 'worst-case' tsunami scenario (Triantafyllou et al., 2019). The researchers assert the assumptions that the function and structural material of buildings as well as the tsunami water depth are likely significant determinants of damage (Triantafyllou et al., 2019) – these are consistent with the results obtained (Leelawat et al., 2014). Furthermore, they draw upon work carried out in a previous study which classified building damage based on construction material and water depth indicating that even with a tsunami water depth of 2.6m, wooden constructions would suffer partial collapse – sufficient enough to necessitate complete reconstruction (Valencia et al., 2011; Triantafyllou et al., 2019).

In a recent study by a researcher which estimated tsunami inundation characteristics for three Japanese cities on Japan's west coast, physical features such as, sand dunes and port breakwaters, were found to protect areas behind them by decreasing tsunami inundation (Yamanaka, 2022). However, the latter had a similar effect to that of steep coastal terrain on tsunami surge water demonstrated in Sri Lanka in that their presence increased tsunami surge heights beyond the ports (Wijetunge, 2014; Yamanaka, 2022). Despite dunes being protective, areas behind them can still be inundated by tsunami invasion of river channels, this can be mitigated by the presence of river levees (Yamanaka, 2022).

2.2 Tsunami Risk to Sabah from the South China Sea

Malaysia is split by the South China Sea (SCS) into West (Peninsular) Malaysia and East Malaysia. Peninsular Malaysia is situated in the South-eastern part of the Eurasian tectonic plate within the western region of the Sundaland block, which is bounded to the west and south by the Sunda Subduction Zone at the Indo-Australian and Eurasian plate boundary (Figure 1) (Shuib, 2009; Shuib et al., 2017; Martin et al., 2020). The seismicity of East Malaysia is far more significant than that of the West, in particular, the region of Sabah, which is experiencing compressional stress from the SCS basin moving southeast and the Philippine plate moving northwest as well as the nearby Sulu and Celebes seas subduction zones (Figures 2 & 3) (Tongkul, 2015; 2017; Khalil et al., 2018). Most of Malaysia's coastline borders the SCS and these coastlines are potentially vulnerable to inundation from the sea but, until recently, little research on tsunami risk in the SCS had been carried out (Terry et al., 2017).

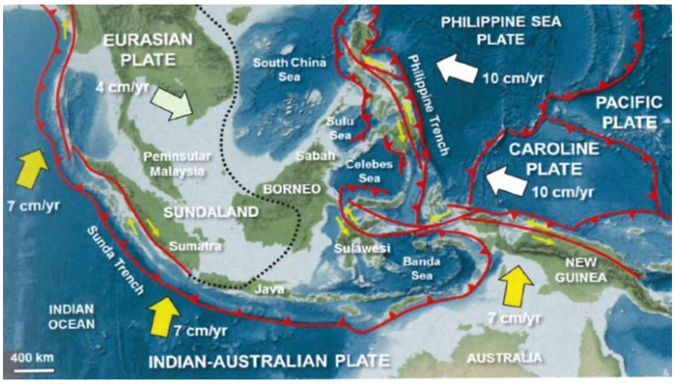

Figure 1: Major tectonic boundaries in Southeast Asia (adapted from Tongkul, 2015).

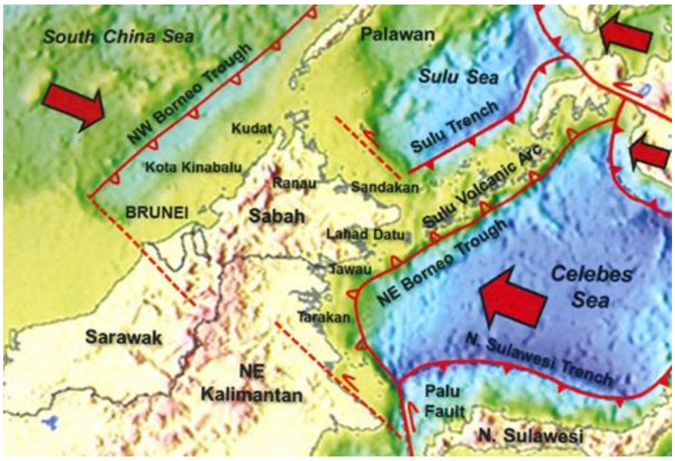

Figure 2: Map of Sabah depicting the surrounding regional active tectonic faults (Tongkul, 2015).

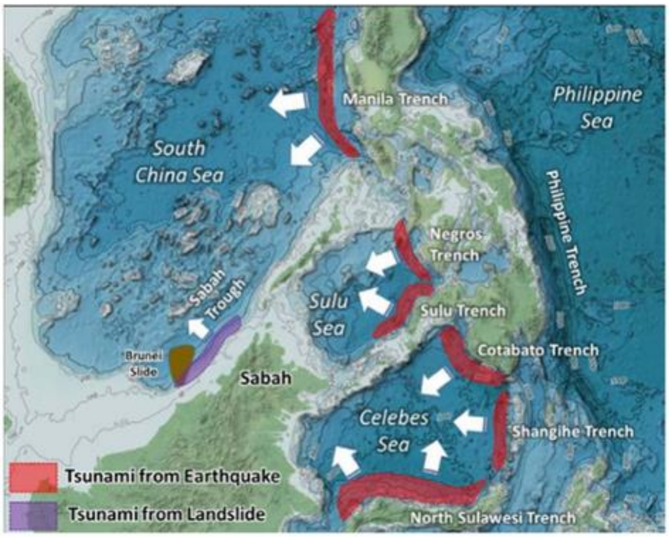

Figure 3: Map of Sabah depicting the surrounding potential tsunami sources (Tongkul et al, 2020).

The western portion of the SCS poses little risk of tsunamis to SCS coastlines; the Gulf of Thailand and the Java Sea (lying southeast of Singapore and west of Borneo Island) have no known potential tsunami sources that could affect SCS coastlines (Terry et al., 2017). By far, the source of the largest tsunami risk in the SCS, according to the literature, is from the Manila Trench – a 1500km long subduction zone extending along the western coast of the Philippines from Mindoro all the way up to Gaoxiong, Taiwan (Figure 4) – which has the potential to create a giant megathrust rupture up to MW 9.0 (Megawati et al., 2009; Abe et al., 2011; Mardi et al., 2017; Terry et al., 2017).

The maximum recorded earthquake magnitude in the SCS is Mw8.4; Figure 5 depicts large recorded SCS, Sulu and Celebes Seas earthquakes and earthquake-generated tsunamis near Sabah (Tongkul et al., 2020). One study utilised computerised simulation models to estimate the path and duration taken for a tsunami generated from the Manila Trench to reach various parts of Malaysia and associated wave heights based on varying moment magnitudes of earthquakes; their results indicated that the tsunami would take about 2 hours to reach Sabah's coast with a maximum wave height of 5.3m given a MW 9.0 earthquake. Various tsunami simulations for the SCS, Sulu Sea and Celebes Sea have been carried out by a multitude of researchers and their estimated arrival times, wave heights and run-ups have been summarised elsewhere (Tongkul et al., 2020).

Additional risk of tsunami in the SCS is speculated to arise from a possible submarine landslide from unstable continental shelf slopes but this is expected to be a much slower process than an earthquake (Terry et al., 2017). The threat to East Malaysia is from the Baram and Champion Deltas lying at the southern end of the Northwest Borneo Trough (NWBT) (Figure 4); both are experiencing a slow collapse under the weight of gravity (King et al., 2009; Terry et al., 2017). The NWBT is a deep linear trough extending approximately 500km from the Baram Line to Palawan Island, Philippines (Figure 4) (Hutchison, 2010).

It is thought that previously a mass of seabed 1200 cubic kilometres in size subsided travelling 120km across the SCS floor at the western edge of the NWBT associated with the Baram delta and has been termed the 'Brunei Slide' (Figures 3 and 4) (Tan et al., 2017). The NWBT is located in a tectonically active region, which has a high potential for seismic events; from 1930 to 1995, the region experienced seven earthquakes with a maximum magnitude of 6.0 (Hesse et al., 2010; Tan et al., 2017). One group of researchers report that an earthquake of this magnitude is sufficient to trigger a submarine landslide at the NWBT producing a tsunami that could reach the north-western coast of Sabah in less than an hour (Tan et al., 2017). In one study, wave heights for such an occurrence have been estimated by researchers to reach up to 24m in western Sabah and up to 14m in north-eastern Sarawak and such results tend to correlate closely with proposed maximum inundation depths in another study of 20.3m in Kudat (northern Sabah) and 26.1m in Kota Kinabalu, the capital of Sabah, situated on the north-western coast (Chai et al., 2014; Tan et al., 2017). The Department of Mineral and Geosciences Malaysia (JMG) also acknowledges this potential threat in their seismic threat assessment (Yan et al., 2017). Significantly lesser tsunami threats exist in the form of three volcanoes: Cu Lao Re, Gaojianshi and Hon Tro (Figure 4); the latter having erupted as recently as 1923 generating a local tsunami which affected south-eastern Vietnam (Terry et al., 2017).

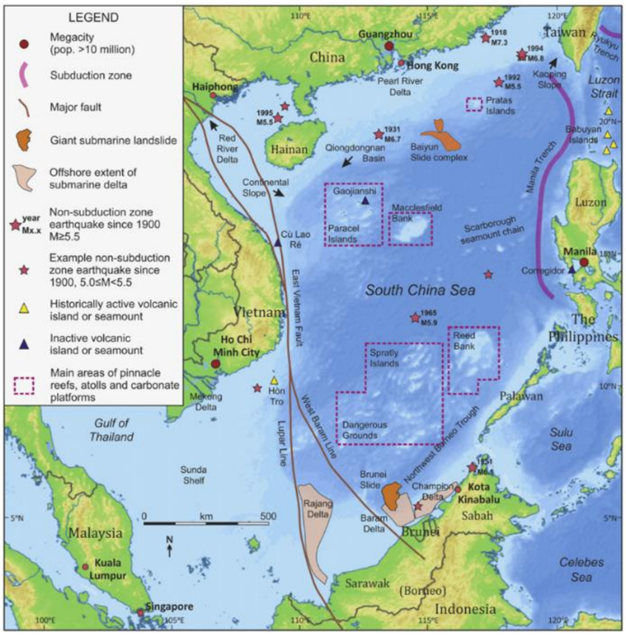

Figure 4: Detailed map of the geographical features of the SCS depicting key features and locations from the text (Terry et al., 2017).

2.3 Tsunami Risks to Sabah from the Sulu and Celebes Seas

The Sulu Sea lies to the northeast of Sabah with the Sulu Trench lying along its southern edge and joining the Negros Trench along its eastern edge (Figures 2 and 3); maximum recorded earthquake magnitude in the Sulu Sea is Mw8.3 (Tongkul et al., 2020). In 1897, a Mw8.2 earthquake north of Zamboanga, Philippines in the Sulu Sea (figure 5) created a tsunami, which resulted in 13 deaths, 14 injured and 33 destroyed houses; despite reducing in wave height from about 6-7m by the time it arrived at the eastern and northern coasts of Sabah, it was still 2m in height (Tongkul et al., 2020). Simulations by one group of researchers estimate a tsunami from the Sulu Sea could reach parts of Sabah's east coast in as little as approximately 20 minutes (Mardi et al., 2017).

The Celebes Sea lies to the southeast of Sabah with the North Sulawesi Trench lying along its southern edge and the Cotabato Trench along its eastern edge (Figures 2 and 3); maximum recorded earthquake magnitude in the Celebes Sea is Mw8.4 (Tongkul et al., 2020). In 1918, a Mw8.3 earthquake in the northern Celebes Sea (Figure 5) generated a 7.2m-high tsunami, which killed 52 people in the Philippines, had a wave height of 2m by the time it reached eastern Sabah (Tongkul et al., 2020). A 9m-high tsunami generated from a Mw8.1 earthquake from the Cotabato Trench in 1976 caused 8000 deaths, 10,000 injured people and left 90,000 homeless (Tongkul et al., 2020). More recently, the effects of a 0.2m tsunami wave created by a Mw6.8 earthquake in April 2017 were felt in south-eastern Sabah with simulations estimating the time of arrival in Sabah being roughly 2 hours after the earthquake (Tongkul et al., 2020).

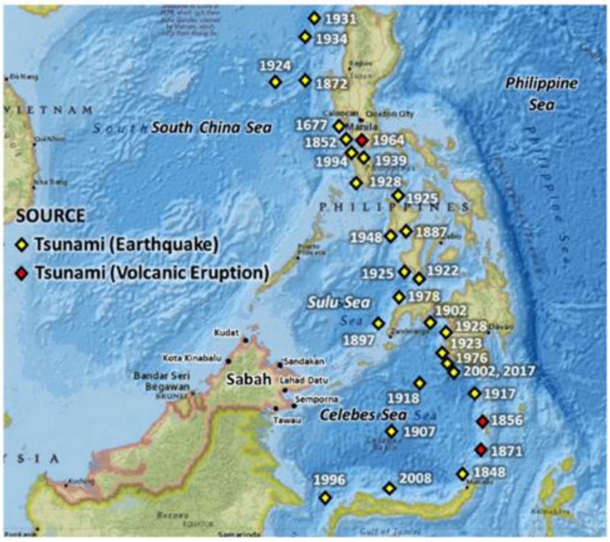

Figure 5: Historically recorded tsunamis near Sabah generated by earthquakes and volcanoes (Tongkul et al., 2020).

2.4 Physical Characteristics & Vulnerabilities of Sabah

Shallow continental shelves and deep seas surround Sabah with the continental shelf being quite wide in the SCS and Sulu Sea (around 80-200km) whereas in the southeast in the Celebes Sea it is very narrow (at approximately 20km) (Figure 6) (Tongkul et al., 2020). The coastline is fairly irregular consisting of bays and estuaries (where mangroves grow), islands and headlands; major towns are located on low-lying coastal plains ahead of hilly areas (Tongkul et al., 2020). Major coastal towns like Sandakan, Lahad Datu, Semporna and Tawau all contain numerous water villages with wooden houses built on stilts (Figure 8), this is despite evidence from the 2004 Andaman-Indian Ocean Tsunami that old timber buildings and even single brick-walled buildings collapsed in parts of West Malaysia due to the force of the waves (Ahmadun et al., 2020; Tongkul et al., 2020).

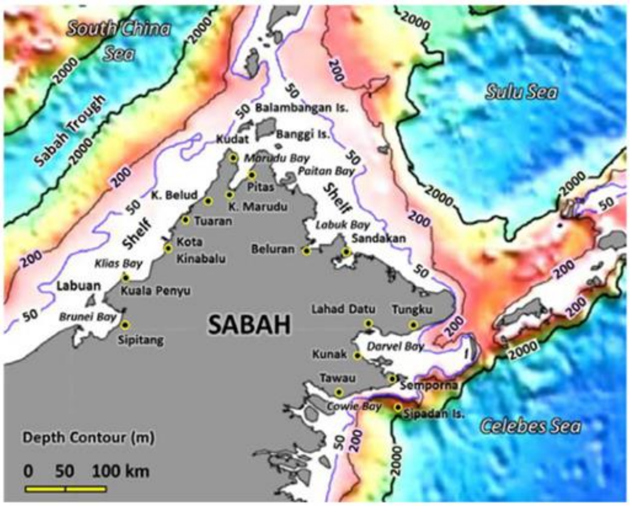

Figure 6: Key coastal towns and Sabah's coastal bathymetry with the narrowest continental shelf being in the southeast (Tawau and Semporna) (Tongkul et al., 2020).

2.5 Actions Taken Following the 2004 Andaman-Indian Ocean Tsunami

In December 2004, a powerful Mw9.3 earthquake in the Andaman Islands, 680km northwest of Kuala Lumpur, West Malaysia, struck sending tsunami waves in all directions across the Indian Ocean, some of which headed east to Malaysia taking 68 lives and injuring 300 others causing millions of dollars of damage (Lye et al., 2010; Abas et al., 2011).

In response to this disaster, the Malaysian Government set up a national tsunami early warning system (TEWS) comprising 3 components:

- Information collection (seismic stations, tide gauge stations (Figure 7) and coastal cameras);

- Processing (involving tsunami analysis, databases and seismic shakemaps);
- Dissemination (SMS, TV broadcasts, sirens (Figure 9) and emails) (Aasen et al., 2007; Lye et al., 2010; Abas et al., 2011; Ahmadun et al., 2020).

Surveys of the public following the tsunami identified a lack of awareness on tsunami hazards, which contributed to the number of casualties (Ahmadun et al., 2020). Subsequently, the Malaysian Meteorological Department (MMD) in collaboration with the National Security Council began carrying out yearly public awareness campaigns and evacuation drills at high-risk areas such as, north-west Peninsular Malaysia and east Sabah (Abas et al., 2011; Ahmadun et al., 2020). Tsunami emergency response plans (TERPs) have been developed for Langkawi Island and Penang Island in West Malaysia but also for Kudat in Sabah (Ahmadun et al., 2020). Revisions were also made to Directive No.20 and Malaysia's National Disaster Management Agency (NADMA) was established in 2015 (Ahmadun et al., 2020).

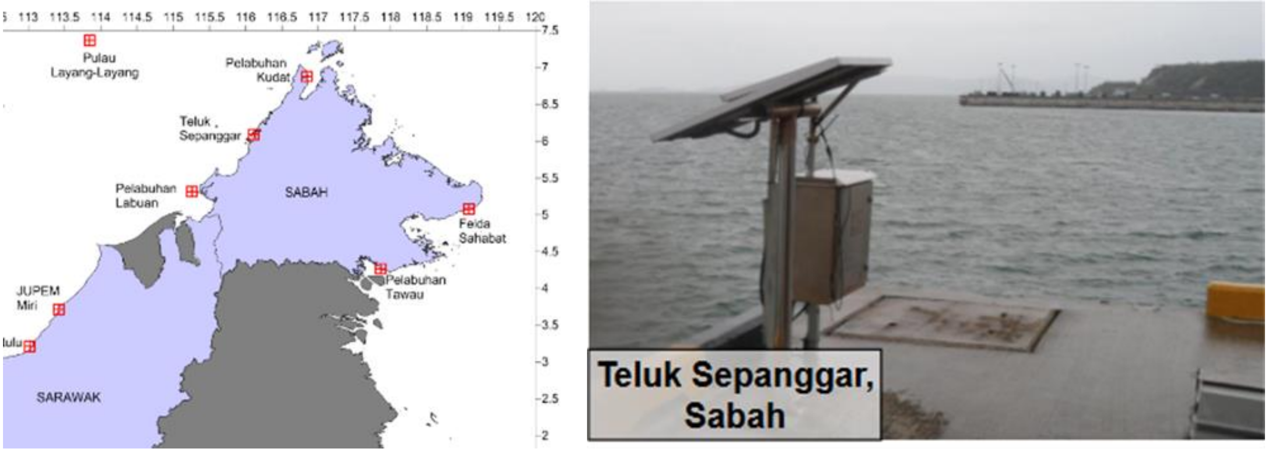

Figure 7: (Left) Map of tide gauge locations in Sabah with a photo (right) of the tide gauge at Teluk Sepanggar, Kota Kinabalu. Since 2020, 3 more tide gauges have been added including one at Sandakan and one at Semporna (Source: MMD).

Figure 8: Examples of coastal water villages in Sandakan (a) & (b) and Tawau (c) & (d) (Tongkul et al., 2020).

Figure 9: Visual depiction of tsunami sirens located in Sabah's coastal towns (Source: MMD).

3. METHODOLOGY

In order to address the research questions posed, this research utilised a combination of a review of the existing literature, semi-structured interviews (SSIs), satellite imagery and GIS mapping. In order to visually assess and depict the impact of a potential tsunami to Sabah's coastline and identify vulnerable areas and features, GIS was utilised in the form of QGIS software (due to its open-source nature) to create layers from the acquired data mentioned below by using regions of interest (ROI) shape files obtained from the Database of Global Administrative Areas (GADM). Shuttle Radar Topography Mission (SRTM) 1-ARC second data from the United States Geological Survey (USGS) Earth Explorer provided DEMs to aid in assessing topographical vulnerability and depicting differences in coastal terrain. OpenStreetMap (OSM) provided road and waterways mapping to gauge ease of accessibility/evacuation of affected populations. Use of Google Earth, which is readily accessible, allowed identification of key vulnerable urban and industrial coastal areas of interest. Global Mangrove Watch (GMW) data from the Japan Aerospace Exploration Agency (JAXA) indicated spatial mangrove forest distribution and was used to determine whether they could provide any protection from tsunamis based on their physical location relative to the urban population and infrastructure. Geospatial population data was obtained from WorldPop in order to visualise population change over a 20-year period and therefore, determine whether vulnerability had increased due to increased population density.

In addition to satellite imagery and GIS mapping, 3 SSIs were conducted online using the 'Zoom' programme to supplement the research. This was to gain first-hand, the views and opinions of native Malaysians, who are also specialists on tsunami risk in Malaysia, in particular in Sabah, as well as the current state of coastal communities – identifying vulnerable factors, understanding better the culture, lifestyle and current understanding of tsunami hazards of these communities and any preparation/interventions undertaken. SSIs were selected for the purpose of this study due to their balance of focus and direction whilst allowing for exploration of topics in greater detail due to their utilisation of open-ended questions and follow-up probes (Ayres, 2012; Jamshed, 2014; Newcomer et al., 2015). The interviewees were from the specialties of DM, geology (with published research on tsunami hazards and risks in Malaysia) and the MMD (one of the governmental departments responsible for the monitoring of earthquake and tsunami hazards in Malaysia). Due to the small number of interviews secured and because the interviews are supplementary to the mapping for the purpose of this research, sampling was not required. Interview audio for the one-to-one interviews were recorded with the consent of the interviewees as this helped to minimise omission of key points mentioned by the interviewees and thus, mitigate the unreliability of live note-taking (as highlighted in Jamshed, 2014).

GIS maps were created using QGIS for each of the six settlements consisting of OSM road and waterway layers, GMW mangrove distribution layers and DEM-derived elevation zone layers. As some key road or waterway data was missing from the OSM layers, the missing roads and waterways were added manually by the author to produce more accurate and complete road and waterway layers. WorldPop population density data was also visualised in GoogleEarth. Low coastal elevation zones (LCEZ) (elevations up to 10m) were overlayed in GoogleEarth to highlight parts of the settlements that would be more likely flooded in the event of a tsunami (especially with lower wave heights of approximately 2m) and this allowed the identification and marking of vulnerable infrastructure in each settlement's LCEZ. Once all relevant maps using the data outlined above had been created and interviews carried out, each settlement was scored between 1-3 on various criteria deemed to affect the vulnerability of the settlement, or its population, based on concepts highlighted in the literature review and interviews. A higher overall score thereby indicating greater vulnerability to that settlement and its population from a tsunami.

A number of ethical considerations were accounted for when carrying out this research as outlined below:

- That the interviewee had volunteered to participate in the interview without being coerced or bribed;
- Interviewees were able to withdraw their consent at any time or refuse to answer any particular questions;
- Data obtained from interviews would not be used against the interviewees or disclosed to their employers nor will it be used for personal use;
- Interviewees' personal identifiable details were kept confidential and finally;
- Satellite imagery was obtained legally and not used in a manner that would intrude on people's privacy or reveal their physical identity.

4. RESULTS

4.1 Mapping

A comparison of data over a 20-year period from 1996 to 2016 indicates that mangrove distribution had barely changed in 2016 compared to 1996 in all of the 6 settlements, with the main change being a marginal reduction in overall mangrove density in 2016 compared with 1996. The population density in all 6 settlements showed a significant increase over the 20-year period from 2000 to 2020, especially the 3 cities: Kota Kinabalu, Sandakan and Tawau.

4.1.1 Kudat Town

Mangrove growth in Kudat is present west of the main town and OSM map data indicates there are two main routes in and out of Kudat Town (Figure 10a). There is very little LCEZ in the area of the main town with exposed infrastructure consisting of water villages, a port, golf course and part of the airport (Figure 11a). Despite its small size, Kudat appears to be quite densely populated according to the WorldPop spatial population density data.

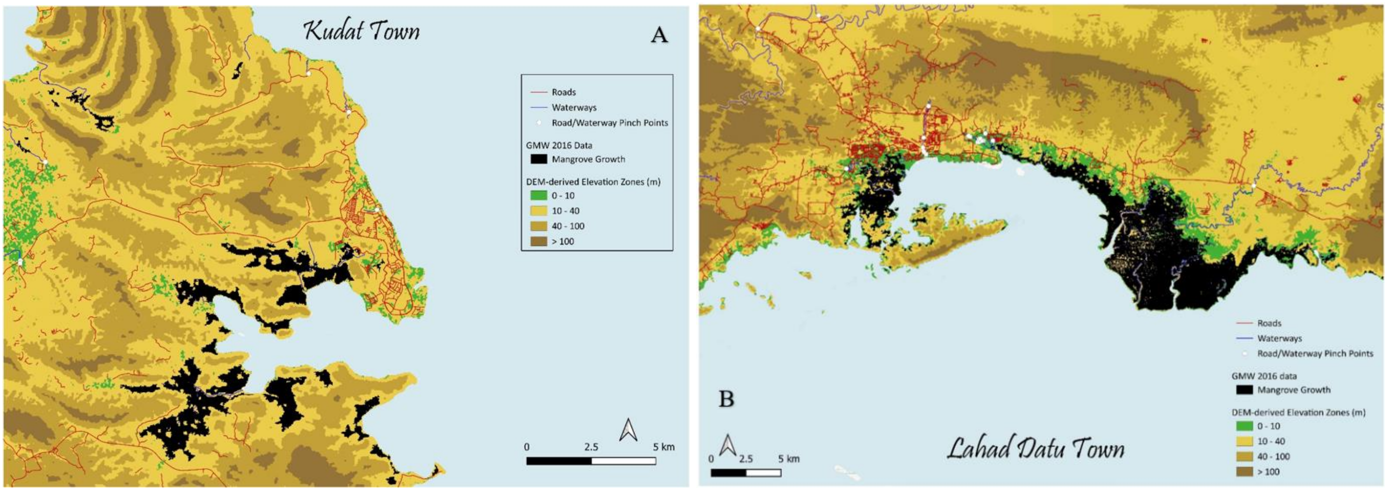

Figure 10: GIS map of Kudat Town (a) and Lahad Datu Town (b) illustrating roads, waterways, pinch points between roads and waterways and elevation zones derived from DEM data. LCEZ in green identifies the most vulnerable areas to tsunami flooding. Mangrove distribution in 2016 is depicted in black (Source: Author, using QGIS software).

4.1.2 Lahad Datu Town

The GIS map indicates multiple access routes by road in and out of the town and a fairly narrow LCEZ (Figure 10b). There are numerous road/waterway pinch-points along the eastern route into the town as well as within the town centre. The town is situated in a bay but is preceded by Sakar Island, which is more than 5km in length with elevations along the southern edge of the island exceeding 100m. The infrastructure within the LCEZ appears to be mainly residential (water villages) and partially industrial (oils refinery and container port) (Figure 11b). Mangrove forests are present in front of several of the large water villages as well as a very large mangrove forest more than 5km in length just east of the main bay. The population of Lahad Datu is fairly dense within the LCEZ.

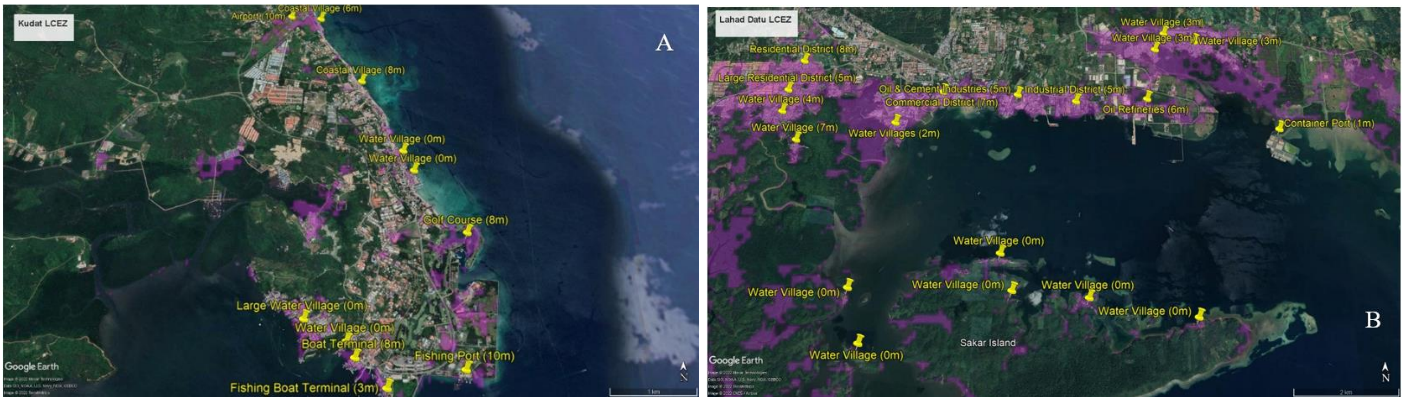

Figure 11: Kudat Town (a) and Lahad Datu (b) LCEZ (magenta shading) derived from DEM data and depicted in GoogleEarth along with the identification of key vulnerable areas and constructions (yellow pins) to tsunami flooding. (Source: Author).

4.1.3 Kota Kinabalu (city)

The GIS map for Kota Kinabalu (the capital of Sabah) (Figure 12a) shows negligible mangrove forest growth. Despite numerous pinch-points between roads and waterways, there are multiple routes into and out of the city to circumnavigate these areas. The LCEZ exists predominantly in the central and southern parts of the city. These areas contain key infrastructure, such as, ports, an airport and multiple residential districts (Figure 13) and are very densely populated. There are large water villages situated on the south-eastern tip of Gaya Island.

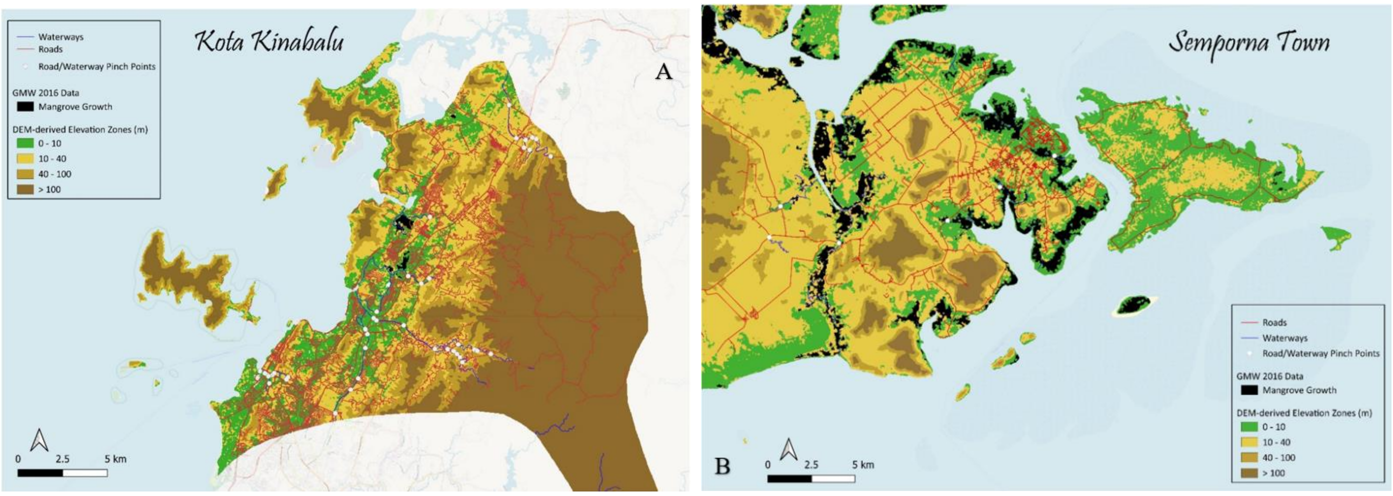

Figure 12: GIS map of the district of Kota Kinabalu (a) and Semporna town (b) illustrating roads, waterways, pinch points between roads and waterways (indicating bridges) and elevation zones derived from DEM data. LCEZ in green identifies the most vulnerable areas to tsunami flooding. Mangrove distribution in 2016 is depicted in black (Source: Author, using QGIS software).

4.1.4 Semporna Town

Semporna Town and neighbouring Bum Bum Island have abundant LCEZs but apart from Semporna Town Centre, they are fairly sparsely populated. Infrastructure within the LCEZ consists predominantly of residential districts and water villages in Semporna Town as well as numerous small water villages dotted around the entire perimeter of Bum Bum Island (Figure 14). There are narrow but extensive mangrove forests around the whole perimeter of Semporna Town but a negligible amount on Bum Bum Island (Figure 12b). A single road leads in and out of Semporna Town and lies in the LCEZ but additionally, it has a pinch-point where it exits the main peninsula.

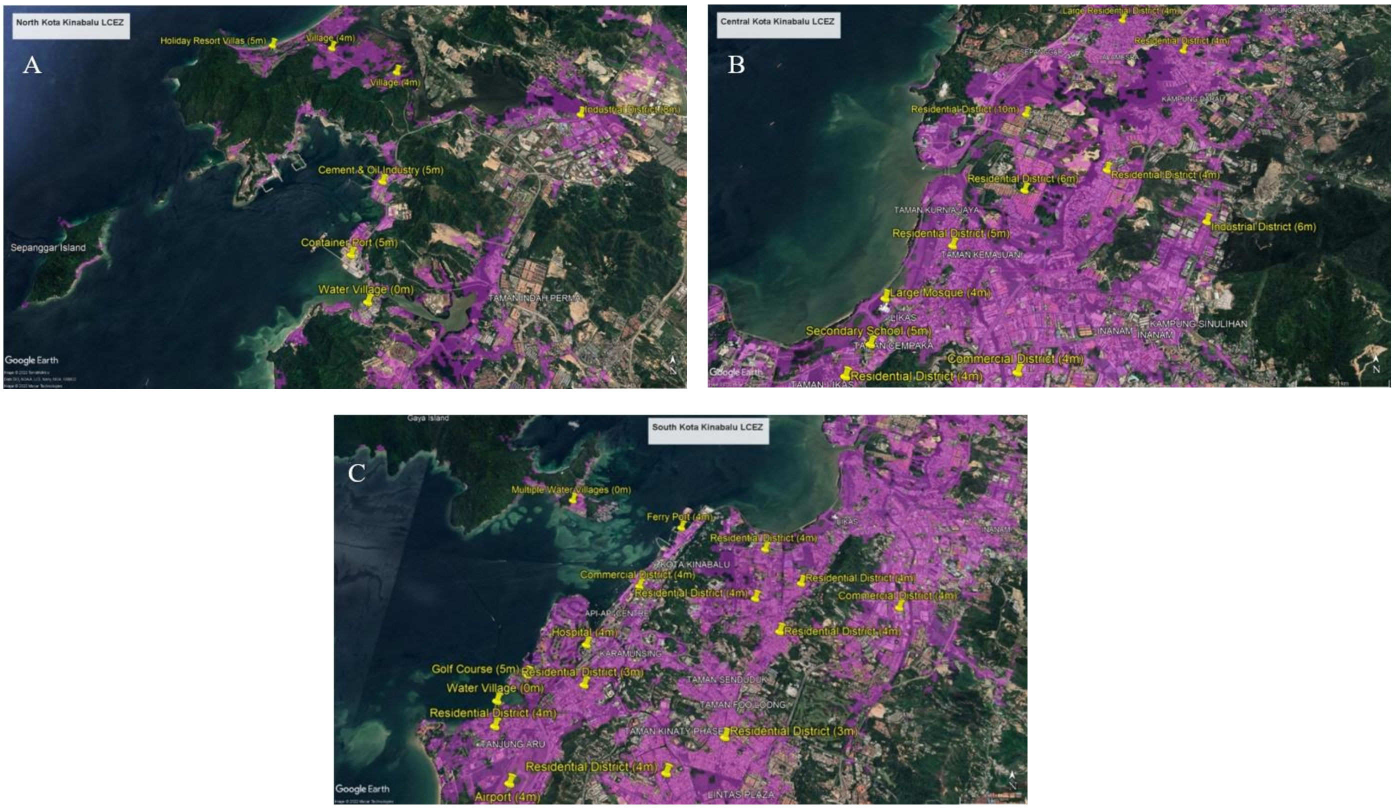

Figure 13: a) North Kota Kinabalu City LCEZ (magenta shading) derived from DEM data and depicted in GoogleEarth along with the identification of key vulnerable areas and constructions (yellow pins) to tsunami flooding. b) Central Kota Kinabalu City LCEZ and, c) South Kota Kinabalu City LCEZ. (Source: Author).

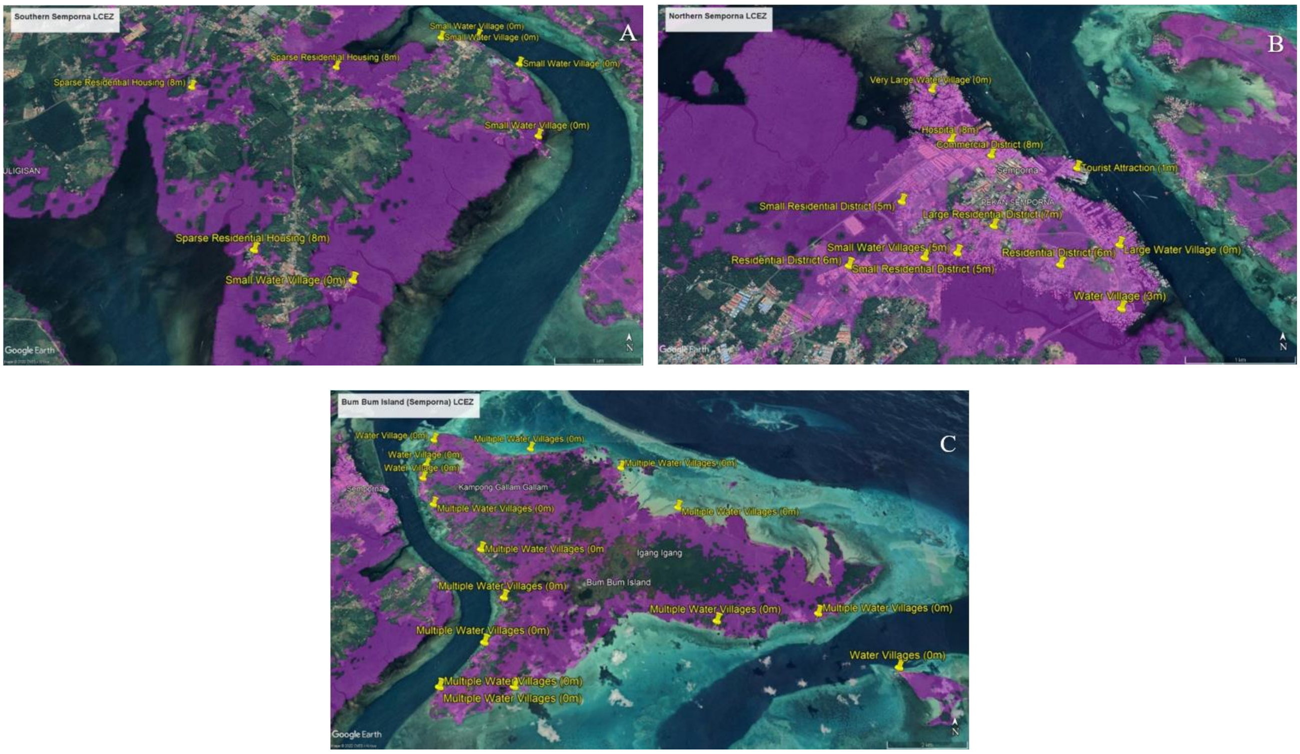

Figure 14: Semporna Town LCEZ (magenta shading) derived from DEM data and depicted in GoogleEarth along with the identification of key vulnerable areas and constructions (yellow pins) to tsunami flooding. a) Southern Semporna Town, b) Northern Semporna Town and, c) neighbouring Bum Bum Island (Source: Author).

4.1.5 Tawau (city)

The city of Tawau is very densely populated throughout the LCEZ, which is broad in the southern and eastern parts of the city. Infrastructure within the LCEZ consists of a mix of industrial, commercial and residential with numerous water villages (Figure 16). Mangrove forest distribution is mainly to the west of the city. A large island, known as Sebatik Island lies directly opposite the city with elevations >100m towards the centre of the island. There are multiple roads leading into and out of the city but there are numerous pinch-points with waterways throughout (Figure 15a).

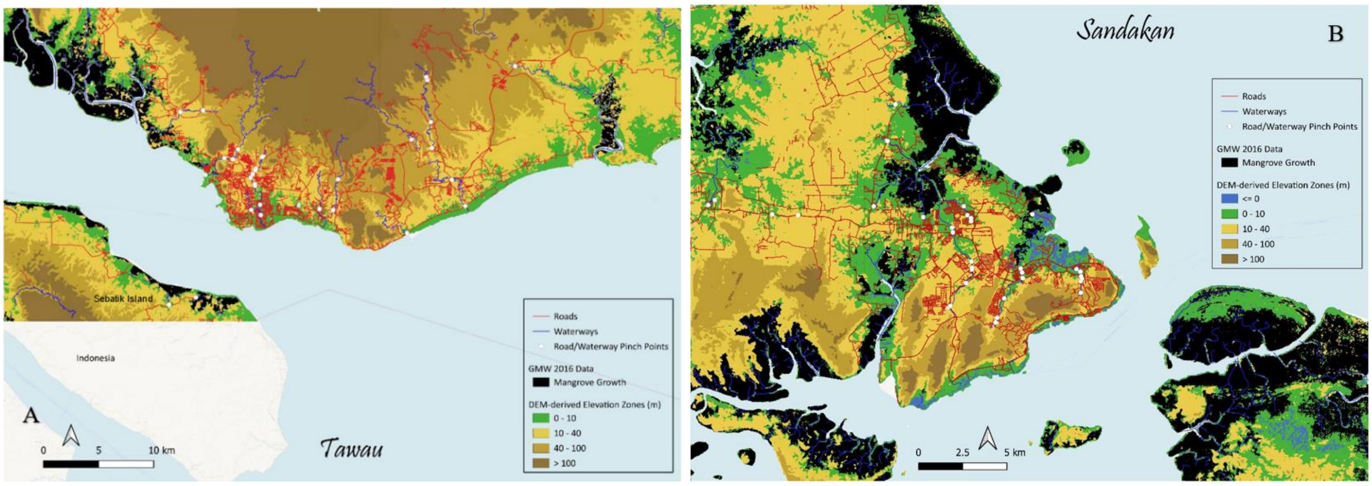

Figure 15: GIS map of Tawau (a) and Sandakan (b) illustrating roads, waterways, pinch points between roads and waterways and elevation zones derived from DEM data. LCEZ is depicted in green, whereas blue indicates sub-sea level. Mangrove distribution in 2016 is depicted in black (Source: Author, using QGIS software).

4.1.6 Sandakan (city)

Large mangrove forests are present to the north and south of the Sandakan City peninsula. Main road access to the city appears to be limited to a single point of access, like Semporna, to the west of the city of which some parts lie in the LCEZ as well as having numerous road/waterway pinch points (Figure 15b). The LCEZ in Sandakan is fairly extensive and includes abundant key infrastructure, i.e., extensive large water villages, multiple oils refineries, a container port, numerous commercial and residential districts and a hospital (Figure 17). Population density throughout the city and coastal areas is very high.

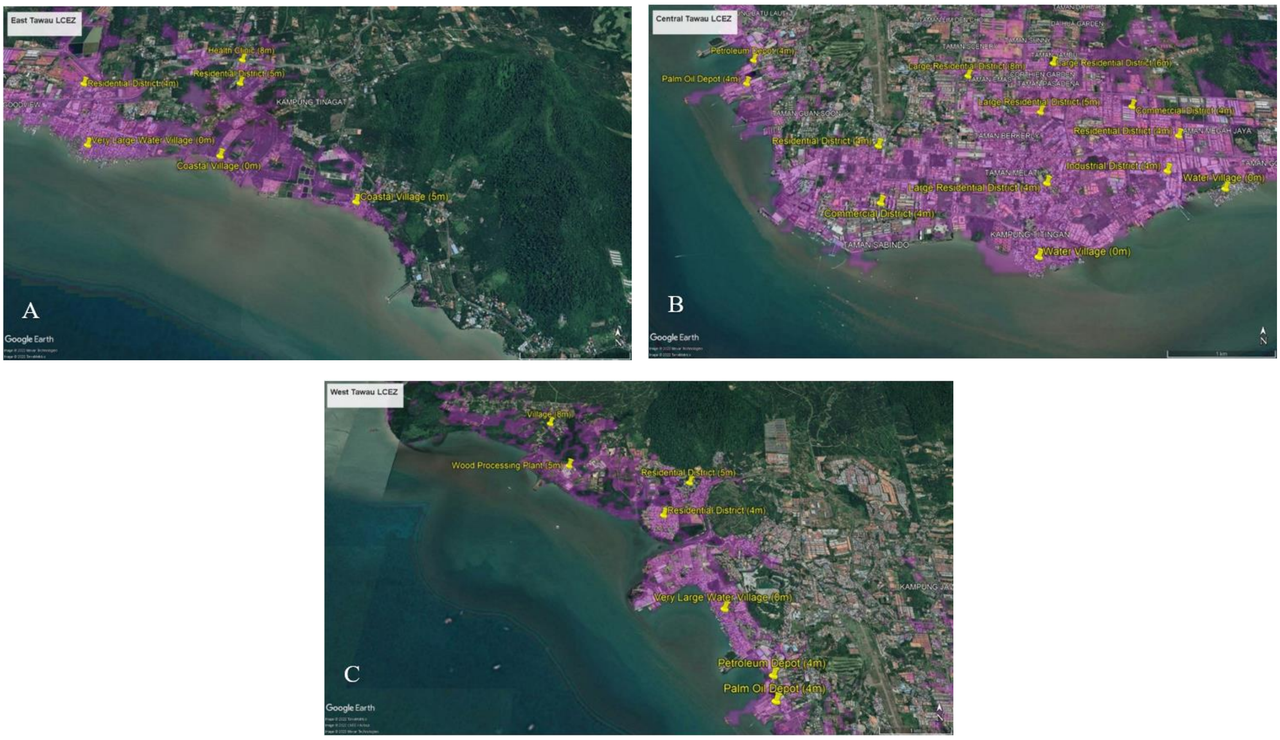

Figure 16: Tawau City LCEZ (magenta shading) derived from DEM data and depicted in GoogleEarth along with the identification of key vulnerable areas and constructions (yellow pins) to tsunami flooding. a) East Tawau City, b) Central Tawau City and, c) West Tawau City (Source: Author).

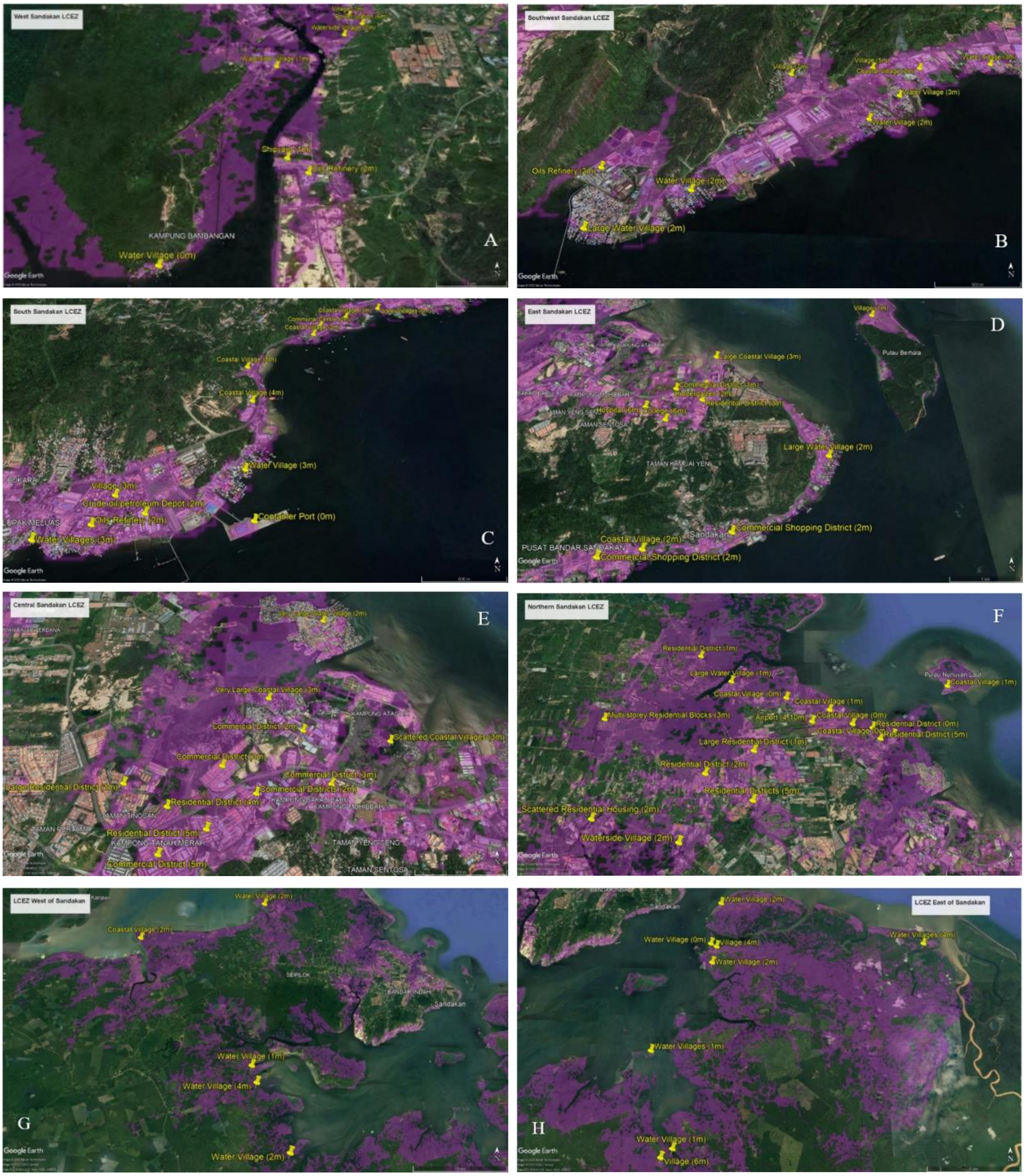

Figure 17: Sandakan LCEZ (magenta shading) derived from DEM data and depicted in GoogleEarth along with the identification of key vulnerable areas and constructions (yellow pins) to tsunami flooding. a) West Sandakan City, b) Southwest Sandakan City, c) South Sandakan City, d) East Sandakan City, e) Central Sandakan City, f) North Sandakan City, g) West Sandakan District and, h) East Sandakan District. (Source: Author).

4.2 Interviews

Unlike the geology academic and governmental meteorological officer, the DM Specialist viewed the risk of a tsunami to Peninsular Malaysia, in particular the west coast, to be greater than Sabah and also scored the risk of a tsunami higher than the other two experts at 5-6/10. The geology academic and governmental meteorological officer both felt the risk of tsunami in Malaysia was greatest to Sabah, in particular, to east and southeast Sabah. The governmental meteorological officer also mentioned about a risk of tsunami to northwest Sabah from a landslide akin to the Brunei Slide, however, the geology academic was of the opinion this would be unlikely. Additionally, the geology academic further stated that tsunami impact to northwest Sabah would be reduced by the presence of a wide continental shelf so a tsunami coming from the Manila Trench would be rapidly slowed down, becoming insignificant by the time it hit the shores of Sabah and, the island of Palawan, Philippines, would also act as a barrier.

The DM Specialist was of the opinion that communities in East Malaysia have a lower level of education and awareness of disaster risk, partly due to being more isolated and being less developed than Peninsular Malaysia and this notion was shared by the geology academic. All three professionals were aware of some form of tsunami awareness that had been given to the coastal populations of Sabah. The DM specialist felt that island communities in Peninsular Malaysia like, Penang and Langkawi, are the most vulnerable with the most vulnerable industry being tourism and the most vulnerable infrastructure being multi-storey buildings and losses being more economical. In contrast, those most vulnerable in Sabah would be coastal 'water village' communities in low-level housing with losses being more towards loss of life. Additionally, they mentioned there have been issues such as, limited access, internet, phone lines and telecommunications as well as power in these water villages.

The geology academic and governmental meteorological officer also reported that the coastal population in Sabah would experience the loss of livelihoods due to the damage and disruption to aquaculture or agriculture from a tsunami. The latter mentioned that the water village communities continue to build on the water despite guidelines advising them to build 1km away from the coast and further added that, despite seismic building codes now being implemented in Malaysia, due to the higher costs of implementing seismic building standards people don't incorporate this when building a house. Car insurance covers disasters but for houses, insurance only covers fire. However, in the event of a disaster the government provides a stipend to help people rebuild their homes (about 60,000 MYR at the time of interview).

With regards to geoinformatics, the DM Specialist was of the view that there is minimal use of geoinformatics by the government with non-governmental organisations (NGOs) being the main user. According to the governmental meteorological officer however, geoinformatics are being used in the form of tsunami databases and computed modelling. The geology academic stated that data was being bought from the USGS and the National Oceanic and Atmospheric Administration (NOAA). He was also of the opinion that the government acknowledges the risk of a tsunami in east Sabah but there are no plans to carry out any physical mitigation measures at present. The DM specialist's view was that currently, the Malaysian Government is mainly focusing on floods, flash floods and tropical storms for DRR.

The governmental meteorological officer mentioned the existence of multi-agency involvement with yearly campaigns (in collaboration with NADMA) for tsunami awareness and tsunami drills; working with public communities to simulate evacuation drills to the evacuation centres whilst testing the DM at the same time. An evacuation plan for Kudat Town in the event of a submarine landslide-generated tsunami was completed (contrary to the view of the geology academic who said there were no evacuation routes or signage for tsunamis in Sabah) but had not yet been tested at the time of interview due to delays by the Covid-19 Pandemic. The geology academic said that there are two committees in Sabah, one for earthquakes and one for tsunamis but also because of the Covid-19 Pandemic they hadn't met since 2019. Both experts did however, mention the presence of coastal sirens and cameras but that TEWS buoys in the ocean were no longer used due to the high cost of maintenance.

In order to assess and compare the vulnerability of the different coastal settlements, each settlement's maps were studied in conjunction with the responses from all 3 interviewees and scored against 10 vulnerability factors with a score of 1-3. Table 2 lists the 10 vulnerability factors and the criteria of scoring for each factor. None of the 6 coastal settlements achieved a minimum score of 10 (lowest vulnerability) nor did any achieve a maximum score of 30 (highest vulnerability). Based on this scoring, Sandakan achieved the highest vulnerability score of 25, with Semporna and Tawau close behind at 23 points followed by Kota Kinabalu with 20 points. Both Kudat and Lahad Datu achieved the lowest scores of 18.

Table 2: The list of the 10 vulnerability factors and the criteria of scoring for each factor that each of the six settlements was scored against based on analysis of the maps created from the research and results of the three interviews. (Source: Author).

Vulnerability Factor	**Settlement ►**	**Kota Kinabalu**	**Kudat**	**Sandakan**	**Lahad Datu**	**Semporna**	**Tawau**
	Criteria ▼						
Tsunami Risk	1 point = low 2 points = medium 3 points = high	2	2	3	3	3	3
Mangrove Forest Protection	1 point = high level of protection 2 points = some protection 3 points = little/no protection	3	3	2	1	2	3
Shielding Islands	1 point = settlement majority shielded 2 points = some shielding 3 points = no island barriers/minimal protection	2	2	3	1	3	3
Man-made Preparation Measures	1 point = TEWS + evacuation plans/physical defences 2 points = TEWS 3 points = No TEWS or mitigation measures	2	1	2	2	2	2
Extent of LCEZ-exposed Infrastructure	1 point = Minimal exposed infrastructure 2 points = Some exposed infrastructure 3 points = Most of the coastal infrastructure exposed	2	1	3	3	2	3
Population Density	1 point = Majority of LCEZ >500people/km^2 2 points = Majority of LCEZ >1000people/km^2 3 points = Majority of LCEZ >3000people/km^2	3	3	3	2	1	3
Extent of Water/Coastal Villages	1 point = Minimal/sparse 2 points = Moderate (size/number) 3 points = Large/extensive	1	2	3	2	3	2

Table 2(Cont.): The list of the 10 vulnerability factors and the criteria of scoring for each factor that each of the six settlements was scored against based on analysis of the maps created from the research and results of the three interviews. (Source: Author).

Access to Higher Elevation for Refuge (by foot)	1 point = 10-40km elevation zone within 1km 2 points = 10-40km elevation zone within 2km 3 points = 10-40km elevation zone >2km	2	1	1	1	2	2
Main Road Access for Evacuation & Response	1 point = >2/multiple access routes 2 points = 2 routes 3 points = single route of access to town centre	1	2	3	1	3	1
Public Awareness	1 point = tsunami drills 2 points = public tsunami education 3 points = no tsunami awareness education/campaigns	2	1	2	2	2	1
Total Points		**20**	**18**	**25**	**18**	**23**	**23**

5. DISCUSSION

5.1 Mapping

5.1.1 Kudat

The town's lower vulnerability can be attributed to the fact that it has very little LCEZ. The LCEZ it does have mainly consists of residential housing, mostly in the form of water villages. The people of Kudat however, benefit from a TERP and evacuation plan in the event of a tsunami as well as close access to higher elevations (above 10m), which drastically reduce their vulnerability. Another key factor that reduces the town's vulnerability, despite the fact it doesn't benefit from any protection from mangroves, is it is relatively protected from a tsunami originating from the Sulu Sea by the Pitas District Peninsula to the east as well as the three islands of Balambangan, Banggi and Malawali to the northeast. Balambangan island, which is north of Kudat Town, may also offer partial protection from a tsunami originating from the SCS. The protective notion of preceding islands can be likened to the protective impact of sand dunes and breakwaters to tsunamis, noted in a previous study (Yamanaka, 2022).

5.1.2 Lahad Datu

The town appears to benefit from shielding provided by Sakar Island. At ~5km across with elevations >100m, the island likely acts as a partial barrier to the bay preceding the town. Just directly to the east, the town also likely benefits from protection from a large mangrove forest (more than 5km across) that may buffer some of the tsunami's power prior to reaching the bay. Given these two factors, there remains only a narrow angle of open bay for a tsunami from the Celebes Sea to directly enter the bay of the town. The water villages that are more exposed on the east of the town are slightly protected by preceding mangrove forests. Compared to Kudat, despite both towns having small populations, Lahad Datu is more spread out therefore, its population density is significantly lower within the LCEZ, with the majority of those at-risk being residents of water villages. Due to its lower population density, high level of natural protection and narrow LCEZ, Lahad Datu Town exhibited lower vulnerability than most of the other towns.

5.1.3 Kota Kinabalu

Sabah's capital is extremely densely populated along almost the entirety of its coastline, a substantial amount of which is exposed in the LCEZ. The LCEZ consists of numerous densely-packed residential districts indicating that the population at risk is very high in this area as well as other critical infrastructure such as, the airport and the ferry port. Gaya Island being fairly large (~7.5km in length) and mostly high elevation (>100m) likely offers some protection to parts of the city's coast from a tsunami arriving from the direction of the Manila Trench. However, the large water village on the southern tip of Gaya Island would be extremely vulnerable to a tsunami but high elevations on Gaya Island may provide its population with some temporary refuge. With numerous areas of high elevation around the LCEZ, there are several potential areas of refuge. Additionally, multiple routes out of the city would aid evacuation attempts.

5.1.4 Semporna

Semporna is a more sparsely populated small coastal town and therefore, large areas of its LCEZ are sparsely populated in the south. The northern central part of the town is where the population density is higher, including a huge water village (at least 1.5km across), of which the majority lies in the LCEZ. Neighbouring Bum Bum Island is relatively flat and dotted with water villages around its perimeter making it very vulnerable to a tsunami. Several extremely shallow islands southeast of Semporna Town may help to weaken a tsunami from the Celebes Sea but, asides from a thin perimeter of mangrove forests, Semporna lacks significant protection from an on-coming tsunami. The bay to the south of the town may act to funnel a tsunami further inland. Like Sandakan, Semporna also only has one main road leading out of the peninsula that could be prone to a bottleneck in the event of an evacuation. Additionally, the road itself may be partially flooded as it has a pinch-point in the LCEZ so the tsunami may be funnelled via the waterway to flood this road.

5.1.5 Tawau

The city of Tawau is very densely populated with virtually all of the eastern half of the city centre lying within the LCEZ consisting mainly of dense residential districts. This area also has a waterway that may help to funnel tsunami waves further inland flooding surrounding residential districts as well as inundating roads as there are several pinch-points along this waterway. The LCEZs in the western and eastern parts of the city each contain a very large water village (>1km across), which would be highly vulnerable to a tsunami from the Celebes Sea. Sebatik Island does however, provide some protection depending on the angle of the in-coming tsunami. Dense mangrove forests lie to the west of the city deeper in the bay and wouldn't provide any protection to the city from a tsunami. Like Kudat Town, the people of Tawau have benefitted from tsunami drills, which likely will increase their awareness of tsunamis. Tawau's vulnerability could be considered moderate-high.

5.1.6 Sandakan

The city of Sandakan received the highest vulnerability score indicating that out of the six settlements evaluated, Sandakan is the one that exhibits the most vulnerability to a tsunami. This is based on the fact that the risk of tsunami from the Sulu Sea is quite high – a view favoured by the geology academic and governmental meteorological officer. Its substantial mangrove forests are located either side of the main city, to the north and the southeast and therefore, with the exception of a small mangrove forest in the northern part of the city providing some protection to neighbouring residential districts, provide very little protection from an on-coming tsunami unless it arrives at an angle from the north or the south. Due to the lack of significant physical barriers (man-made or natural islands), a tsunami arriving perpendicular to Sandakan would have little resistance before crashing into the shores of the city and infiltrating the neighbouring bay area to the south inundating the surrounding low-lying mangrove forests and numerous water villages. Berhala Island, albeit approximately 3.5km in length and located just to the east of the city, would likely be partially inundated and also likely to redirect most of the tsunami either side of the island to continue onwards towards the main city. Sandakan has a very dense population with extensive and large coastal water villages and important industry (such as oils refineries and a container port) in the LCEZ. These factors, when combined with the possibility of only 20 minutes evacuation time (based on the estimates in a previous study in 2017) and a single access route leading out of the city likely to lead to gridlocks, vastly increase Sandakan's vulnerability in the event of a tsunami from the Sulu Sea (Mardi et al., 2017). One positive factor however, that helped to reduce Sandakan's vulnerability score was its access to higher elevations to seek refuge. In the west, south and eastern parts of the city, in particular, higher elevations are fairly easily accessible being less than 1km from the coast and may likely serve as the quicker and safer option rather than evacuation, immediately following reception of a TEWS message given the likely short onset of arrival of a tsunami from the Sulu Sea.

5.2 Interviews

Apart from consolidating tsunami risk to parts of Sabah, the interviews allowed for a great insight into the status of the population's awareness to tsunami threats and the actions and approaches being taken by the Malaysian Government. The governmental meteorological officer corroborated that which has been mentioned in previous literature about the Malaysian Government carrying out yearly tsunami awareness campaigns as well as public tsunami drills, adding that the awareness campaigns also teach about the protective benefit of mangrove forests from a tsunami (Abas et al., 2011; Ahmadun et al., 2020). The geology academic however, was of the impression that tsunami awareness by the government to the general public was carried out every 3-4 months and that this still was not frequent enough – their argument being that the government are only reaching a small percentage of the population. The geology academic is themself involved with an academic institution in carrying out outreach educational programmes in local schools raising awareness of tsunamis every 2-3 months, however, due to the Covid-19 Pandemic as well as a lack of financial funding, this had been put on hold at the time of interview.

What is particularly interesting is that the Kudat TERP and evacuation routes are based on a submarine landslide-generated tsunami rather than an earthquake-generated tsunami from the Manila Trench in the SCS or the Negros or Sulu Trenches in the Sulu Sea. This possibly indicating that as far as the Malaysian Government is concerned, the threat and potential consequences of a submarine landslide-generated tsunami are seen to be greater than an earthquake-generated tsunami. This is contrary to the opinion of the geology academic interviewed in this research who was of the view that landslide-generated tsunami, from a landslide akin to that of the Brunei Slide, is unlikely and that most of these types of landslides occur 'bit-by-bit' rather than a huge mass giving way at one specific time.

The geology academic mentioned that with northwestern Sabah having a wide continental shelf, a tsunami travelling from the Manila Trench would be rapidly slowed down and likely insignificant by the time it reached Sabah. This somewhat correlates with other research carried out in 2018, which found that tsunami run-up at the shore was higher after traversing deeper continental shelves than shallow continental shelves irrespective of the continental slope gradient (Naik and Behera, 2018). This suggests that tsunamis that travel over deeper continental slopes retain more energy therefore, leading to higher run-up. If this is the case, then the impact of a tsunami in Tawau or Semporna could be significantly greater due to them having a very narrow shallow continental shelf and this would likely need to be factored into their vulnerability status.

A salient point that arose from the interviews was that of the apparent divide in development between West and East Malaysia that was touched upon by the geology academic and DM specialist. The former described the divide as a 20–30-year development gap in West Malaysia's favour and therefore, the people's awareness and education to disasters is also more advanced compared to Sabah's population, especially given Peninsular Malaysia's experience of the 2004 Andaman-Indian Ocean Tsunami. It is uncertain however, if the development gap and less experience of tsunami disasters alone would be a sufficient enough excuse to explain peoples' persistence of living in water villages in Sabah, especially in Sandakan, even despite the presence of guidelines that advise people to build houses 1km away from the coast. Research carried out in 2011 has indicated that tsunami wave heights of 2.6m are sufficient to induce partial collapse of wooden structures necessitating rebuilding and with projected wave heights of approximately 2m for tsunamis that could impact Sabah, it is very possible that these wooden water village houses on stilts could suffer partial collapse (Valencia et al., 2011). Furthermore, it is unclear whether the government stipend for rebuilding after a disaster extends to those in water villages who build against the guidelines, possibly further increasing their vulnerability. The existence of issues regarding limited access to the villages, internet, phone lines and telecommunication as well as power raises the question of how effective would a TEWS be to people living in these water villages? A question worthy of further research given the scope and size of the population living in water villages in east and southeast Sabah and one, that would have a heavy impact on the vulnerability of these populations.

5.3 Limitations of the Research

The foundations of this research are based on a LCEZ of up to 10m which would be adequate for approximate tsunami wave heights of 2m. However, if new research were to highlight the likelihood of higher wave heights (e.g., those expected from a submarine landslide-generated tsunami like the Brunei Slide) than the estimates of vulnerability for the towns evaluated in this research would be deemed inaccurate based on the currently defined LCEZ. In such a scenario, the LCEZ range would need to be increased accordingly and then reapplied to each town in order to reassess the extent of the LCEZ and exposed infrastructure.

Another limitation of this research is the impact on aquaculture has been overlooked. Aquaculture, described by the geology academic as a 'million-dollar industry' due to its export demand, plays a huge role in the livelihoods of the local coastal people in Sabah. This is not something that can be easily identified and monitored using mapping unless one can first identify the style, nature and location of the aquaculture farming in order to identify what to look for when viewing satellite imagery. This may require physically visiting these areas to see first-hand as well as gathering data from local farmers to gain a better understanding of the impact of a potential tsunami on the industry and the locals' livelihoods. The caveat is, for the people to open-up aquaculture farming, mangroves have to be destroyed (as was mentioned by the geology academic). The question then is, which of the two increases the population's vulnerability more, destruction of mangrove forests by the local population or the destruction of aquaculture by a tsunami?

5.4 Significance of the Research

By drawing on ideas on tsunami vulnerability factors described in existing literature and by utilising a combination of GIS mapping and specialist interviews, this research has been able to successfully answer the research questions posed at the start of the paper and these are summarised in table 3. This research has identified key factors that lead to increased tsunami vulnerability in six of Sabah's main coastal settlements and which of these coastal settlements are most at risk and which exhibits the most vulnerability based on these factors. The findings of this research provide a foundation for further exploration into Sabah's coastal vulnerability to tsunamis and provides an initial focus for the Malaysian Government and other agencies involved in DRR to direct their efforts in reducing the vulnerability of Sabah's coastal communities to a potential tsunami, particularly in Sandakan, Semporna and Tawau.

Table 3: A summary outlining the answers to the research questions posed by this research. (Source: Author).

Research Question	Answer
How likely is the tsunami threat to East Malaysia and which part of Sabah is most likely to be affected by a tsunami?	There is a credible risk of tsunami to Sabah from the SCS, Sulu and Celebes Seas with the greatest impact likely to afflict east or southeast Sabah.
Which communities and facilities are most likely to be affected?	Water village communities, coastal residential areas, commercial districts as well as oil processing plants, ports and aquaculture farms are the most likely communities and industries affected.
What measures has the Malaysian government taken to reduce tsunami risk/vulnerability in Sabah?	Coastal sirens, cameras, seismic stations and tide gauges combine to form a TEWS in order to reduce tsunami risk to coastal populations.
Where are the most likely geological tsunamigenic sources?	Earthquakes of approximately magnitude 8.5 or greater from the Manila Trench, Negros Trench, Sulu Trench, Cotabato Trench, Shangihe Trench and North Sulawesi Trench.
Where is the most vulnerable topography on Sabah's coastline?	Semporna and Sandakan have the most vulnerable topography.
Where are Sabah's most exposed populations and key exposed industries and infrastructure?	Sandakan is the most exposed and vulnerable coastal settlement in Sabah.
What would be the extent of inundation or damage to Sabah's coastline of a potential tsunami?	With an estimated wave height of ~2m, inundation is likely to be less than 1km with the greatest damage being the destruction to water villages as well as the inundation of residential districts and coastal industries, like oils refineries.
What action has the Malaysian government taken to reduce people's vulnerability to a potential tsunami?	Public awareness and education campaigns, as well as tsunami evacuation drills have been carried out to try and reduce people's vulnerability to a tsunami.
Are there additional measures that could be taken to further reduce Sabah's coastal vulnerability to tsunami?	The greatest measure that would reduce coastal communities' vulnerability to tsunami hazard in Sabah would be to relocate the population living in wooden water villages to more suitable reinforced concrete or brick housing away from the shore, preferably avoiding the LCEZ.

6. CONCLUSION

Researching the existing literature and carrying out specialist interviews identified a legitimate tsunami risk to the coast of Sabah. By utilising freely available GIS software and spatial data, coastal settlements in Sabah could be mapped to identify their tsunami vulnerability based on the risk identified. Drawing upon earlier research into tsunami vulnerability factors and attributing a score based on these factors, this research identified Sandakan as Sabah's most vulnerable coastal settlement to a potential tsunami, which, in Sandakan's case, would arise from the Sulu Sea. Given these findings, Sandakan should be prioritised in terms of tsunami DRR.

RECOMMENDATIONS

Future research would benefit from numerical and simulated tsunami modelling to more accurately estimate run-up and inundation on Sabah's coast. This would in turn, more accurately determine LCEZ and what elevations would be required to be classed as safe for refuge. This should allow for a more thorough evaluation of a town's vulnerability to tsunamis. Additionally, research into the recovery capacity of responding agencies in these settlements as well as exploring in more detail, their demographics (e.g., the number of minors, the number of physically disabled and the number of car owners) for the purpose of analysing ease of evacuation would, yet further increase, the accuracy of the tsunami vulnerability assessment.

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DATA AVAILABILITY

ROI shape files were obtained from https://gadm.org/ from GADM. DEMs from USGS EarthExplorer were obtained from https://earthexplorer.usgs.gov/. GMW data from JAXA was obtained from https://www.eorc.jaxa.jp/ALOS/en/dataset/gmw_e.htm. Population density data from WorldPop was obtained from https://hub.worldpop.org/project/categories?id=18.

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