Architecting SatCom-Enabled Early Warning Systems in Indonesia

by

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Abstract

Indonesia lies within the Ring of Fire, making the country highly prone to geophysical disasters such as earthquakes and tsunamis, in addition to weather-related disasters such as floods, landslides, and wildfires. One effective way to reduce the risk of getting hit by these natural disaster hazards is through the deployment and operation of early warning systems. Early warning systems are generally responsible for two things: identifying the hazard precursors and delivering the warning in a timely manner. In both of these functions, wireless communication plays a critical role. Terrestrial communication, however, is often compromised when a disaster hits. Satellite communication (SatCom) offers a promising alternative not only for warning transmission, but also precursor detection from the thousands of disaster monitoring sensors deployed. It enables the placement of such sensors in remote areas, often closer to the source of the hazards. This thesis uses system architecture concepts to evaluate the pros and cons of the various terrestrial and satellite communication technologies in the context of early warning systems and suggest the best architecture for each use case. Based on the results of the analysis, satellite L-band, S-band, amateur radio, and newer technologies such as satellite LPWAN and GSM can provide significant benefits in terms of performance and cost. Additionally, the benefit of combining technical development and community engagement are highlighted for a sustainable early warning system. Findings from this thesis are hoped to provide the relevant government agencies in Indonesia and other countries with similar challenges for disaster risk reduction.

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List of Abbreviations

AAWS	Agroclimate Automatic Weather Station
AHP	Analytic Hierarchy Process
APRS	Automatic Packet Reporting System
ARG	Automatic Rain Gauge
ASRS	Automatic Solar Radiation Station
AWS	Automatic Weather Station
BGAN	Broadband Global Area Network
BIG	*Badan Informasi Geospasial* (Geospatial Information Agency)
BMKG	*Badan Meteorologi, Klimatologi, dan Geofisika* (Meteorological, Climatological, and Geophysical Agency)
BNPB	*Badan Nasional Penanggulangan Bencana* (National Disaster Management Agency)
BPBD	*Badan Penanggulangan Bencana Daerah* (Municipal Disaster Management Agency)
BPPT	*Badan Pengkajian dan Penerapan Teknologi* (Agency for the Assessment and Application of Technology)
BPS	*Badan Pusat Statistik* (Statistics Indonesia)
BRG	*Badan Restorasi Gambut* (Peatland Restoration Agency)
CBT	Cable-based Tsunameter
CCTV	Closed-circuit Television
DIBI	*Data Informasi Bencana Indonesia* (Disaster Database of Indonesia)
DVB	Digital Video Broadcasting
EM-DAT	Emergency Events Database
ESDM	*Kementrian Energi dan Sumber Daya Mineral* (Ministry of Energy and Mineral Resources)
EVDT	Environment – Vulnerability – Decision – Technology
FDRS	Fire Danger Rating System
GEO	Geostationary Orbit
GITEWS	German-Indonesian Tsunami Early Warning System
GNSS	Global Navigation Satellite System
GSM	Global System for Mobile Communications
InaCORS	Indonesian Continuously Operating Reference Station

InaOFS	Indonesian Ocean Forecasting System
InaTEWS	Indonesian Tsunami Early Warning System
IoT	Internet of Things
IP	Internet Protocol
ITU	International Telecommunication Union
KLHK	*Kementrian Lingkungan Hidup dan Kehutanan* (Ministry of Environment and Forestry)
KOMINFO	*Kementrian Komunikasi dan Informatika* (Ministry of Communication and Informatics)
LAPAN	*Lembaga Penerbangan dan Antariksa Nasional* (National Institute of Aeronautics and Space)
LEO	Low Earth Orbit
LIPI	*Lembaga Ilmu Pengetahuan Indonesia* (Indonesian Institute of Sciences)
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
MAGMA	Multiplatform Application for Geohazard Mitigation and Assessment in Indonesia
NB-IoT	Narrow Band Internet of Things
ORARI	*Organisasi Radio Amatir Republik Indonesia* (Indonesian Amateur Radio Organization)
POLRI	*Kepolisian Negara Republik Indonesia* (Indonesian National Police)
PRIMS	Peatland Restoration Information and Monitoring System
PVMBG	*Pusat Vulkanologi dan Mitigasi Bencana Geologi* (Center for Volcanology and Geological Hazard Mitigation)
SatCom	Satellite Communication
SDG	Sustainable Development Goals
SIPALAGA	*Sistem Pemantauan Air Lahan Gambut* (Peatland Water Level Monitoring System)
SLA	Service Level Agreement
SMS	Short Message Service
SPARTAN	*Sistem Peringatan Kebakaran Hutan dan Lahan* (Forest and Peatland Fire Warning System)
SVN	Stakeholder Value Network
TCWC	Tropical Cyclone Warning Center
TNI	*Tentara Nasional Indonesia* (Indonesian National Army)
UHF	Ultra High Frequency
ULF	Ultra Low Frequency
VHF	Very High Frequency
VSAT	Very Small Aperture Terminal

Chapter 1

Introduction

> *“No siren, no warning: Indonesians caught unawares by devastating tsunami”*
>
> *– Reuters, October 2018*

The above news headline refers to the six-meter tsunami crashing the city of Palu in late September 2018, causing thousands of deaths and severe infrastructure damages [1] [2]. It’s easy to accuse the government for a complete lack of technology. But in fact, the Meteorological, Climatological and Geophysical Agency (BMKG) was already operating a number of early warning sensors and issued a text-message warning. Unfortunately, the earthquake traveled faster than expected, knocking down the cell tower and the electricity before the text-message could ever make it.

1.1 Motivation

It would be unfair to completely blame the severe damage from the Palu Tsunami on the early warning system, because many people in Palu Bay also lack the preparedness or education on how to react when the earthquake struck. However, it is clear that Indonesia’s early warning system has a lot to improve.

Indonesia lies within the Ring of Fire, making the country highly prone to geophysical disasters such as earthquakes, volcanic eruptions, and tsunamis, in addition to weather-related disasters. The National Disaster Management Agency (BNPB) recorded a dramatically increasing trend in natural disasters, with 3,814 events, 6 million people evacuated and a total loss of more than 4.5 billion USD just in the year 2019 alone [3].

The Palu Tsunami story is just one of the many examples where terrestrial communication fails. The most common and popular terrestrial communication is cellular network. Cell towers are prone to natural disasters for two reasons: they are tall, and they require electricity to work. Although the government has imposed a regulation including technical specifications such as structural integrity and power backup availability since 2009 [4], more than a thousand cell towers in Palu went out of service as the earthquake hit [5].

This kind of incidents poses a question of whether satellite communication (SatCom) can provide a promising alternative, especially whenever cell towers are out of service. Besides warning transmission, there are thousands of disaster monitoring sensors such as seismometers, tsunami buoys, and weather stations that can take advantage of SatCom for data collection. SatCom enables the placement of such sensors in remote areas, closer to the source of the natural disaster hazards.

In early 2019, the National Institute of Aeronautics and Space (LAPAN) published a conceptual mission design called the Nusantara Early Warning System, which since then has been integrated into Indonesia's National Research Priority 2020-2024 [6] [7] [8]. The proposed system shall be a Low Earth Orbit (LEO) communication satellite constellation flying along the equator, providing 24/7 coverage for before, during, and post-disaster purposes. This constellation aims to be a store-and-forward platform for many of the disaster monitoring sensors deployed all over the country in addition to backup voice communication repeater. Based on LAPAN's preliminary analysis, locally developing and operating such a constellation would save more than 120 million USD of foreign exchange reserves every year when compared to using foreign satellite services.

Just in the last one year, SatCom technology has seen a number of breakthroughs including satellite-based Low Power Wide Area Network (LPWAN) and Global System for Mobile Communications (GSM) that have been prominent for terrestrial Internet of Things (IoT) and mobile cellular applications. These innovations are promising to form a better and cost-effective early warning system. Section 2.3.2 describes these in further detail.

This thesis aims to examine the pros and cons of satellite vs terrestrial communication in the context of early warning systems and suggest a number of communication architectures that would fit the various disaster monitoring and warning delivery requirements not only in terms of performance, but also cost-effectiveness. Additionally, this thesis aims to discuss how engaging the local community to develop, operate, and maintain such a complex system locally can give long-run technological, economic, and social benefits. It is hoped that the results from this study will provide BMKG, BNPB, LAPAN and other agencies with insights in further leveraging SatCom for disaster risk reduction toward a more sustainable Indonesia; in line with the United Nations Sustainable Development Goals.

1.2 Scope

There are various kinds of natural disasters in Indonesia and they come with various spatial and temporal characteristics. Therefore, it is unlikely to find a one-size-fits-all kind of communication solution for all of these disasters. The author decided to cover all natural disasters as defined and classified by the National Disaster Management Agency (BNPB) [9] [10] to demonstrate a breadth of case studies discussing the various strategies catered toward each natural disaster. Other disasters such as epidemics, transport accidents, industrial accidents, and terrorisms are considered out of scope. The natural disasters that are within the scope of this study are:

1. Earthquakes
2. Volcanic activities

3. Tsunamis (with or without earthquakes)
4. Landslides
5. Floods (coastal, fluvial, or pluvial)
6. Droughts
7. Tidal waves and erosions
8. Storms and whirlwinds
9. Wildfires

All of the natural disasters mentioned above are either geophysical, meteorological, or climatological in nature. The spatial and temporal characteristics such as the distribution throughout the country and the seasonality of these disasters are discussed further in detail in Section 2.1.

From a communication perspective, an early warning system generally consists of two parts: *upstream*, i.e. the collection of environmental parameters to be used for modeling risks and making forecasts; and *downstream*, i.e. the generation and dissemination of the calculated risk information, forecasts, and early warnings.

There are several methods to collect environmental parameters, but in general they can be categorized into *in-situ monitoring* and *remote sensing*. In-situ monitoring refers to the measurement of parameters on site, whereas remote sensing is the measurement of parameters without making physical contact by measuring the object's reflected and/or emitted radiation at a distance. Another way to categorize data collection methods is by the location of the sensors: *terrestrial* (including land and sea), *airborne*, and *spaceborne*. For all the natural disasters mentioned above, a combination of all those methods is not uncommon. However, this study has an emphasis on terrestrial sensors (in-situ or remote) that can take advantage of wireless communication to transmit its data. There can also be many ways to disseminate risk information and early warnings, but this thesis focuses on wirelessly transmitted information as the scope of the study.

Lastly, this study primarily focuses on the communication function of an early warning system. The effectiveness of the science behind the models, the choice of sensors, the spatial placement and the sampling interval is beyond the scope of this study. This research assumes that those parameters are determined by the relevant stakeholders..

1.3 System Definition

As mentioned in the previous section, an early warning system consists of upstream and downstream components. The upstream component includes the sensor, the onsite data handling, and the wireless communication link, which consists of an onsite transmitter, a receiver at the operations center, an air interface, and any packet forwarder in between the air interface (satellite or cell tower with IP gateway). The downstream component includes the risk analysis software running at the operations center, the information output device located at areas at risk, and the wireless communication link, which consists of a transmitter at the operations center, a receiver attached to the output device, an air interface, and any packet forwarder in between the air interface (satellite, radio or cell tower). An overview of the system is visualized in Figure 1-1 and more information can be found in Section 2.2 and Section 2.3.

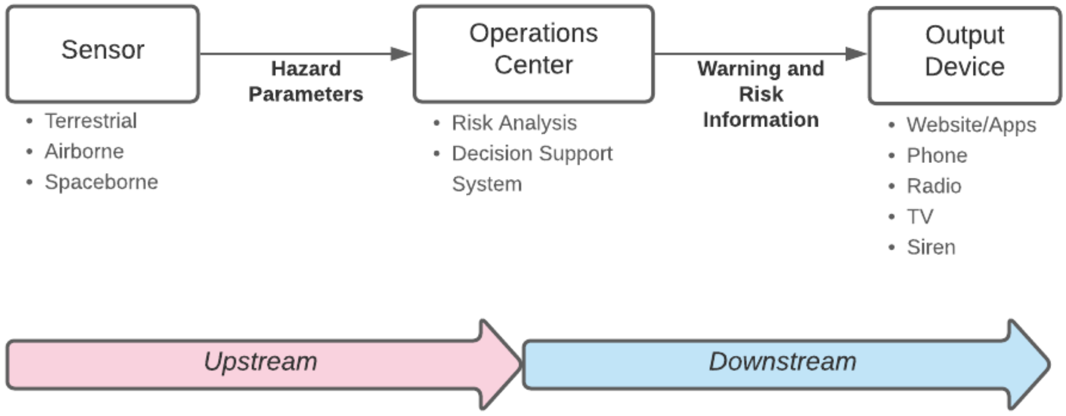

Figure 1-1: Overview of a generic early warning system for natural disasters

1.4 Research Framework

The research started with attempting to understand the natural disaster context in Indonesia through literature review and conversation with subject matter experts, who usually work for organizations that are involved in natural disaster management, i.e. the stakeholders. Once the stakeholders are identified, further stakeholder analysis was done to identify their needs and desired outcomes from an early warning system. This analysis also includes mapping of the relationships among the stakeholders and this information is visualized in the form of a *stakeholder value network* (SVN) diagram. All information was obtained through literature review, one-on-one meetings, and group discussions with members of the stakeholders.

From the beginning it has been identified that communication is an important problem and the main interest of the study, therefore, the research focuses only on two system functions: upstream communication and downstream communication. These two functions fundamentally define the system architecture, and hence are considered as *architectural decisions*.

Finally, this study uses a standard hierarchical decision-making framework to evaluate the pros and cons and select which communication technology/architecture would be best for each use case. The framework includes the use of *weighted morphological matrix* to rank the options and *analytic hierarchy process* (AHP) to determine the weights based on the author's technical knowhow, literature review and inputs from the stakeholders.

The research framework as a whole is referred to as *System Architecture Framework* and is described in further detail in Section 2.5. In addition, an integrated framework called the *Environment-Vulnerability-Decision-Technology (EVDT) Framework* is used as an overarching reference in transforming stakeholder needs into the desired technology design (the core of this thesis) and how the resulting technology then informs human decision making for sustainable development. This framework which was originally proposed by the Space Enabled Research Group at the MIT Media Lab is described in further detail in Section 2.6.

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Chapter 2

Literature Review

This chapter aims to thoroughly describe the important information needed to determine suitable communication architectures for Indonesia's network of hazard monitoring sensors and early warning systems. It includes the characteristics of the various natural disasters in Indonesia, the current early warning systems in place, and both state-of-the-art and emerging wireless communication technologies. The chapter ends with an explanation of the academic theories and frameworks used throughout this study.

2.1 Natural Disasters in Indonesia

As mentioned briefly in Chapter 1, Indonesia lies within the Ring of Fire and is home to various geophysical, hydrometeorological, and climatological disasters. It is considered as one of the most disaster-prone countries, given its high exposure to various natural hazards and considerable socio-economic vulnerabilities. Djalante et al. mentioned that the interaction between an increasing population, largely uncontrolled urbanization, and economic development in high-risk areas without proper consideration of the social and environmental impacts, has led to high disaster and climate-related vulnerability and risk in Indonesia [11].

It is the fourth most populous country in the world with more than 250 million people and according to Statistics Indonesia (BPS), is projected to reach more than 300 million in 2035 [12]. Although economically largest in South East Asia, inequality remains high in Indonesia.

In March 2020, its Gini Ratio is 0.393 in urban areas and 0.317 in rural areas, where 0 means total equality and 1 means total inequality [13].

In terms of climate, there are two seasons in Indonesia: wet season that typically runs from October to April and dry season that runs from April to October. Between the two seasons, there is a transition period that is locally known as *pancaroba*. During this *pancaroba* "season", storms and whirlwinds tend to be more intense. The two seasons in Indonesia happen as a result of the annual Monsoons that travel between Asia and Australia.

The National Disaster Management Agency (BNPB) recorded a dramatically increasing trend in natural disasters, with 3,814 events, 6 million people evacuated and a total loss of more than 4.5 billion USD just in the year 2019 alone [3]. BNPB's historical record of all disasters can be found in its Disaster Database of Indonesia (DIBI) [10]. An international disaster database called the Emergency Events Database (EM-DAT), compiled from various sources including the United Nations and national governments, also showed an increasing trend [14]. Figure 2-1 to Figure 2-5 show the statistics of natural disasters in Indonesia from different points of view. It should be noted that for a disaster event to be recorded in EM-DAT, it has to fulfill at least one of these three criteria: 10 or more people deaths, 100 or more people affected/injured/homeless, and declaration by the country of a state of emergency and/or an appeal for international assistance.

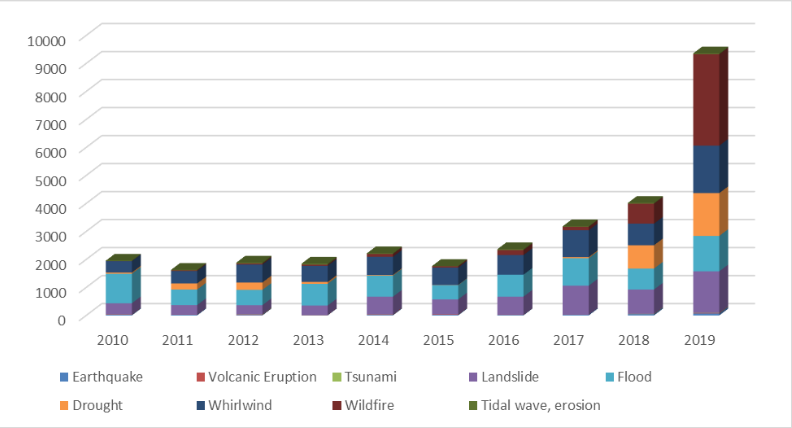


Figure 2-1: Number of natural disaster events in Indonesia from 2010 to 2019.

Source: BNPB DIBI [10]

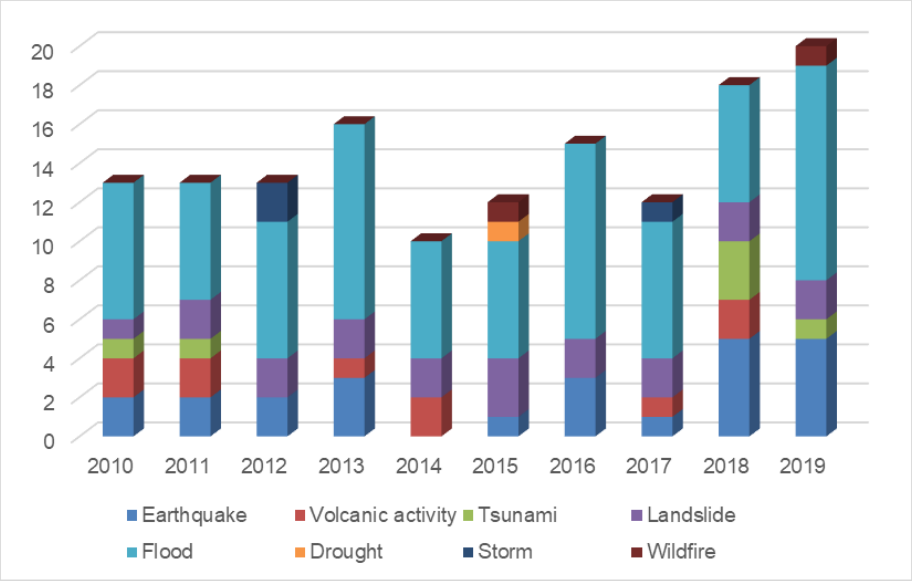


Figure 2-2: Number of natural disasters in Indonesia from 2010 to 2019 as recorded in EM-DAT [14]

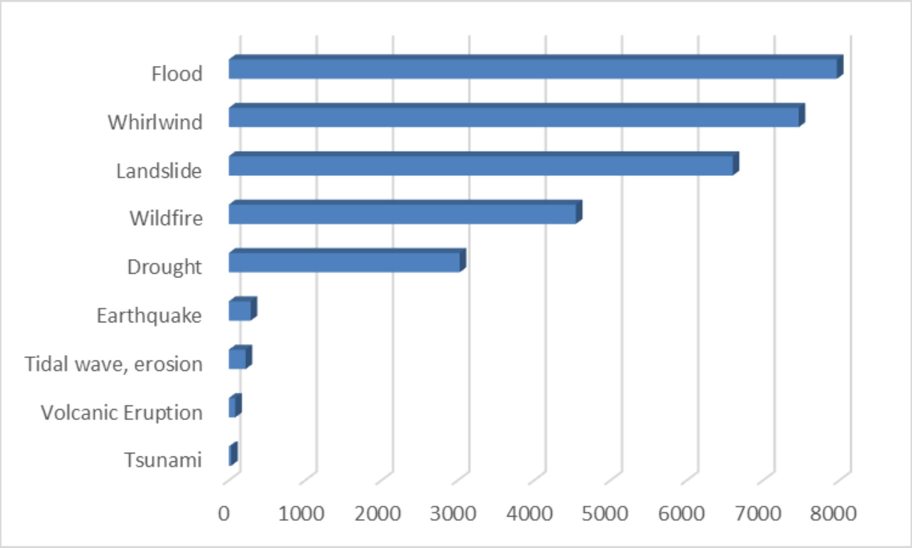


Figure 2-3: Various types of natural disasters in Indonesia from 2010 to 2019, sorted by number of events. Source: BNPB DIBI [10]

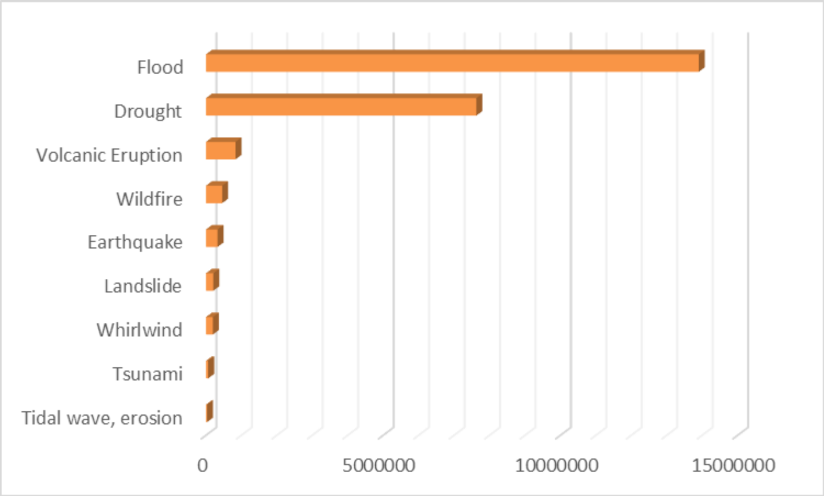


Figure 2-4: Various types of natural disasters in Indonesia from 2010 to 2019, sorted by total number of people affected. Source: BNPB DIBI [10]

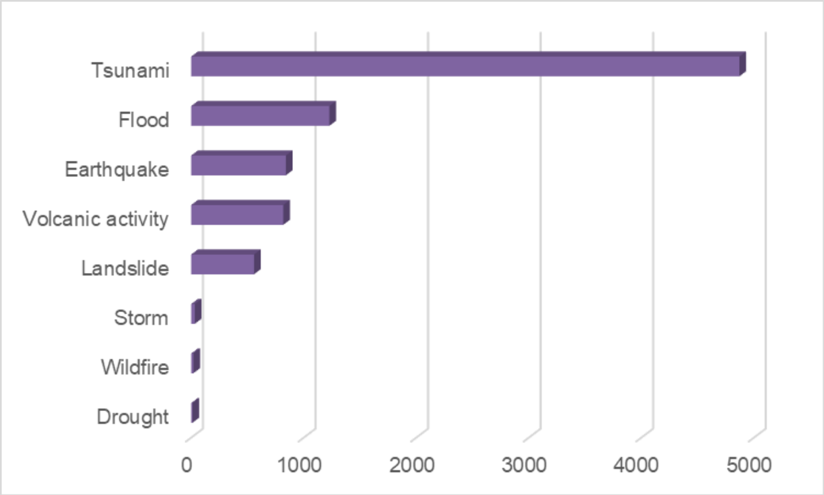


Figure 2-5: Various types of natural disasters in Indonesia from 2010 to 2019, sorted by total number of deaths as recorded in EM-DAT [14]

Based on various sources including BNPB and EM-DAT from the course of 2010 to 2019, a summary of all the natural disasters in Indonesia is created based on their spatial and temporal characteristics as well as the resulting impact [10] [14]. The summary can be seen in Table 2-1. In general, the natural disasters that are most frequent and affect the greatest number of people are those that are seasonal and theoretically more predictable. These include floods, storms, landslides, droughts, and wildfires. Conversely, the natural disasters that are more random in nature occur rarely but are the deadliest. These include earthquakes, volcanic activities, and tsunamis.

Table 2-1: Summary of natural disasters in Indonesia and their characteristics (2010-2019)

Natural Disaster	**Spatial Characteristics**		**Temporal Characteristics**			
	Location	**Radius**	**Seasonality**	**Frequency**	**Lead Time**	**Duration**
Earthquake	More often in West, South, and East	Up to hundreds of km	Random	27/year	A few secs to a few mins	A few secs to several mins
Volcanic eruption	More often in South and North East	Up to tens of km	Random	8/year	Hours to days	Several mins to weeks
Tsunami	More often in North West and South	Up to hundreds of km	Random	3/year	A few mins to a few hours	Less than an hour
Landslide	All over the country, but worst in Java	Up to several km	Wet Season and Transition Period	683/year	Mins to days	A few mins to hours
Flood (coastal, fluvial, pluvial)	All over the country, but worst in Java	Up to several km	Wet Season and Transition Period	740/year	Hours to days	A few hours to days
Drought	All over the country, but worst in Central Java	Up to hundreds of km	Dry Season	298/year	Hours to days	Days to months
Whirlwind	More often in North West and South	Up to a few km	Wet Season and Transition Period	747/year	Secs to mins	A few mins
Wildfire	More often in Kalimantan and Southern half of Sumatera	Up to tens of km	Mostly Dry Season	462/year	Hours to days	A few days to a few weeks
Tidal wave, erosion	More often in North West and South	Up to several km	Up to monthly	22/year	Hours to days	A few hours

2.2 Early Warning System

An important concept to understand in dealing with natural disasters is that disasters will only happen if there are people or valuable assets involved. If the people or assets are resilient enough to the natural hazards, there could be no disasters either. This is the fundamental theory of disaster risk. Disaster risk is a product of three independent components: hazard, exposure, and vulnerability [15]. *Hazard* is the likelihood of a destructive phenomenon at a certain location and time; *exposure* is the number of lives and assets exposed to a hazard; and *vulnerability* is the likelihood that the lives and assets will be damaged when exposed to a hazard. Establishing an early warning system is one way to increase preparedness and reduce vulnerability.

Other ways to increase preparedness and reduce vulnerability are educating the local at-risk communities on how to anticipate and respond to hazardous events such as earthquakes, tsunamis, and extreme weathers [16]. These include establishing evacuation procedures and preparing emergency supplies. Another way to reduce risk is by prevention, i.e. reducing exposure by relocating people and valuable assets away from a hazardous area. Lastly, another way to reduce risk is by mitigation, which is an action of reducing vulnerability and/or the source of the hazard itself so as to limit the disaster impact. This includes constructing flood defenses, planting trees to stabilize slopes, and cloud seeding to control precipitation.

According to the United Nations Office for Disaster Risk Reduction (UNDRR) or formerly called United Nations International Strategy for Disaster Reduction (UNISDR), a complete and effective early warning system comprises four key elements: risk knowledge, monitoring and warning service, dissemination and communication, and response capability [17]. Refer to Figure 2-6. These key elements are in line with our definition of early warning system from the communication perspective introduced in Chapter 1. The upstream component provides hazard monitoring service and hence support risk knowledge, whereas the downstream component generates warnings and disseminates risk information. As mentioned in Chapter 1, hazard monitoring can be either in-situ or remote.

RISK KNOWLEDGE

Systematically collect data and undertake risk assessments

Are the hazards and the vulnerabilities well known?

What are the patterns and trends in these factors?

Are risk maps and data widely available?

MONITORING & WARNING SERVICE

Develop hazard monitoring and early warning services

Are the right parameters being monitored?

Is there a sound scientific basis for making forecasts?

Can accurate and timely warnings be generated?

DISSEMINATION & COMMUNICATION

Communicate risk information and early warnings

Do warnings reach all of those at risk?

Are the risks and warnings understood?

Is the warning information clear and useable?

RESPONSE CAPABILITY

Build national and community response capabilities

Are response plans up to date and tested?

Are local capacities and knowledge made use of?

Are people prepared and ready to react to warnings?

Figure 2-6: Key elements of early warning systems according to UNDRR, adapted from [17]

Works on wireless sensor-based early warning systems have been ongoing around the world for more than a decade. Past literatures highlight the benefit of wireless communication infrastructure and the importance of choosing the right technology (e.g. frequency and protocol). In the Philippines, Mercado and team designed a flood early warning system combining low-cost rain gauges and water level sensors for the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA). His work managed to save 60% of cost or 300,000 USD compared to an imported solution and has been replicated for other natural disasters such as landslides, tsunamis, and storm surges [18].

Basha and Rus from MIT Computer Science and Artificial Intelligence Laboratory (CSAIL) deployed a field experiment for wireless sensor-based river flood early warning system in Honduras that entailed nine site visits over three and a half years [19] [20]. The project used three low-cost sensors: rain gauge, water level, and air temperature, which data were then transmitted over 900 MHz and 144 MHz terrestrial radio. Their work showed great promise through its potential for scalability. Benefits identified include autonomous monitoring even in the middle of the night and during a hurricane. Some challenges were also highlighted, including the need for extra security from vandalism and the need for engaging local communities and NGOs when solely relying on the government is not a good idea.

Valente de Almeida and Vieira presented a forest fire early warning system based on differential optical absorption spectroscopy (DOAS) consisting of 13 remote stations in the north of Portugal [21]. The Forest Fire Finder (FFF) system was developed by the NOVA University of Lisbon and NGNS-IS Ltd. to autonomously detect smoke columns day and night up to 15 km away. The system has been able to register hundreds of fire events.

Kodera et al. evaluated the performance of Japan Meteorological Agency's earthquake early warning system utilizing approximately 1,070 seismometers throughout the country [22]. The system has proven to be fast and highly accurate, with a lapse time of less than 5.3 seconds in 11 out of 14 cases. In the United States, an earthquake early warning system called the ShakeAlert has been developed for the highest risk areas in the West Coast states of California, Oregon, and Washington. Kohler et al. identified seismometer and GNSS sensors operated by the Advanced National Seismic System (ANSS) for ShakeAlert [23]. To provide a robust earthquake early warning system for the West Coast region, up to 1,675 seismic stations would be needed, as close as 5 km apart from each other [24]. A heterogenous network combining radio, cellular, commercial internet, and satellites was proposed to introduce path diversity and minimize single points of failure in data delivery. Strauss and Allen did a study to quantify the benefits and costs of the same earthquake early warning system for the West Coast region [25]. Based on the research, saving three lives would already save enough money to pay for 1 year of the system's operation, hence the clear benefits over costs.

The above literatures highlight two things in common: implementation of an effective early warning system is capable of saving lives and money, and autonomous wireless technology improves that further by saving the time to respond and continuously providing information without human limitations.

2.2.1 Early Warning System in Indonesia

Early warning systems are not new for Indonesia either. After the deadly 2004 Indian Ocean Tsunami that killed more than 200,000 people in Indonesia, a national tsunami early warning system has been developed. Development on both remote and in-situ sensing based hazard monitoring have also been progressing to better model and forecast natural disaster hazards beyond tsunamis and earthquakes. This section describes the various early warning systems in Indonesia that are already operational or under development.

2.2.1.1 Tsunami and Earthquake

A national tsunami early warning system called the Indonesia Tsunami Early Warning System (InaTEWS) was developed quite immediately after the 2004 Indian Ocean Tsunami. Indonesia sought international partnerships, including from Germany, China, Japan, France, USA, and UNESCO [26]. In Spring 2005, Germany's contribution through the German Indonesian Tsunami Early Warning System (GITEWS) project was officially signed and started [27]. InaTEWS was completed and inaugurated by the Indonesian president toward the end of 2008 and has issued 23 tsunami warnings within 5 minutes on average by the end of 2019 [28]. With several hundred million US dollars of funding and hundreds of research publications, the system is probably one of the most state-of-the-art tsunami early warning systems in the world.

InaTEWS was designed to provide a first tsunami early warning in less than 5 minutes after an earthquake. This was done using a network of seismometers to provide the location, depth and magnitude of the earthquake and GNSS reference stations to provide crustal deformation within the 5 minutes limit. Once the early warning is issued, sea surface height measurements with a network of tide gauges and buoys are used to either confirm or cancel the tsunami warning. Figure 2-7 shows an overview of InaTEWS.

Today, InaTEWS' suite of sensors comprises 372 seismometers (with 39 more by 2020) operated by the Meteorological, Climatological, and Geophysical Agency (BMKG) and the Center for Volcanology and Geological Hazard Mitigation (PVMBG), 529 accelerometers and 400 intensity meters operated by BMKG, 237 GNSS reference stations (with 193 more by 2024) called the Indonesian Continuously Operating Reference Station (InaCORS) operated by the Geospatial Information Agency (BIG), 159 tide gauge stations (with 110 more by 2024) also operated by BIG, and 4 buoys (with 9 more by 2021) and 2 cable-based tsunameters (CBT) (with 3 more by 2021) operated by the Agency for the Assessment and Application of Technology (BPPT) [29] [30] [31]. Figure 2-8 until Figure 2-12 shows how the sensors are spatially distributed throughout the country.

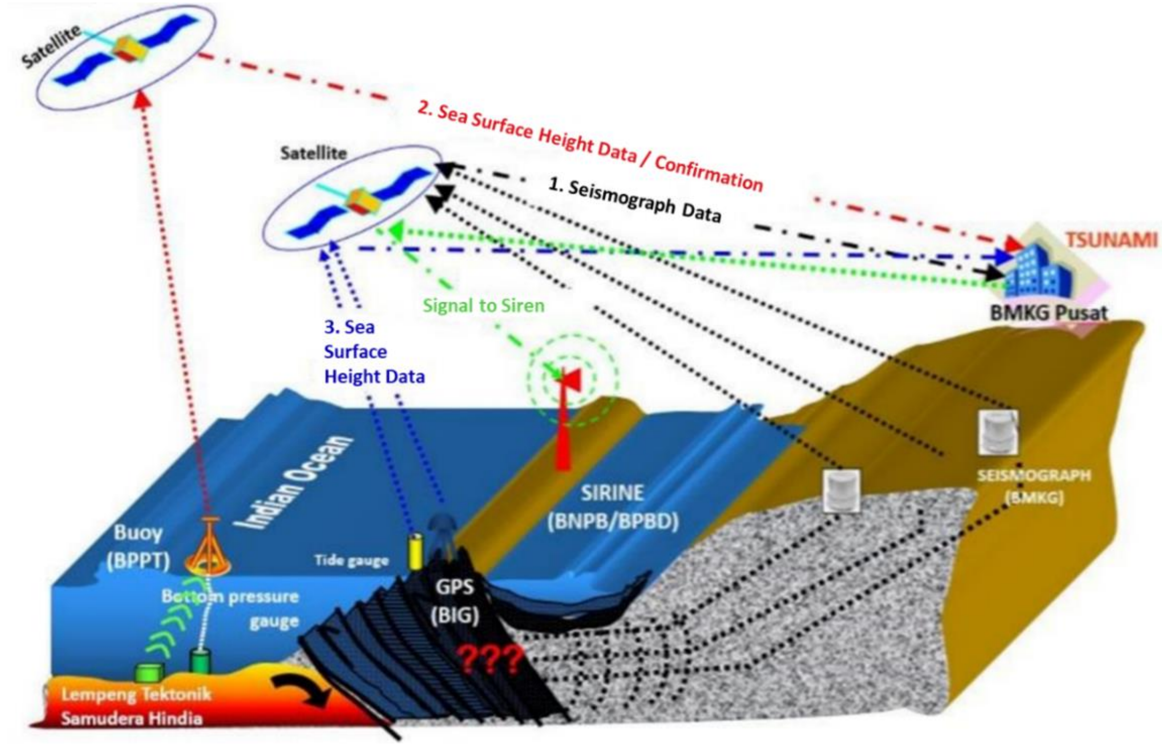


Figure 2-7: Overview of InaTEWS [26]

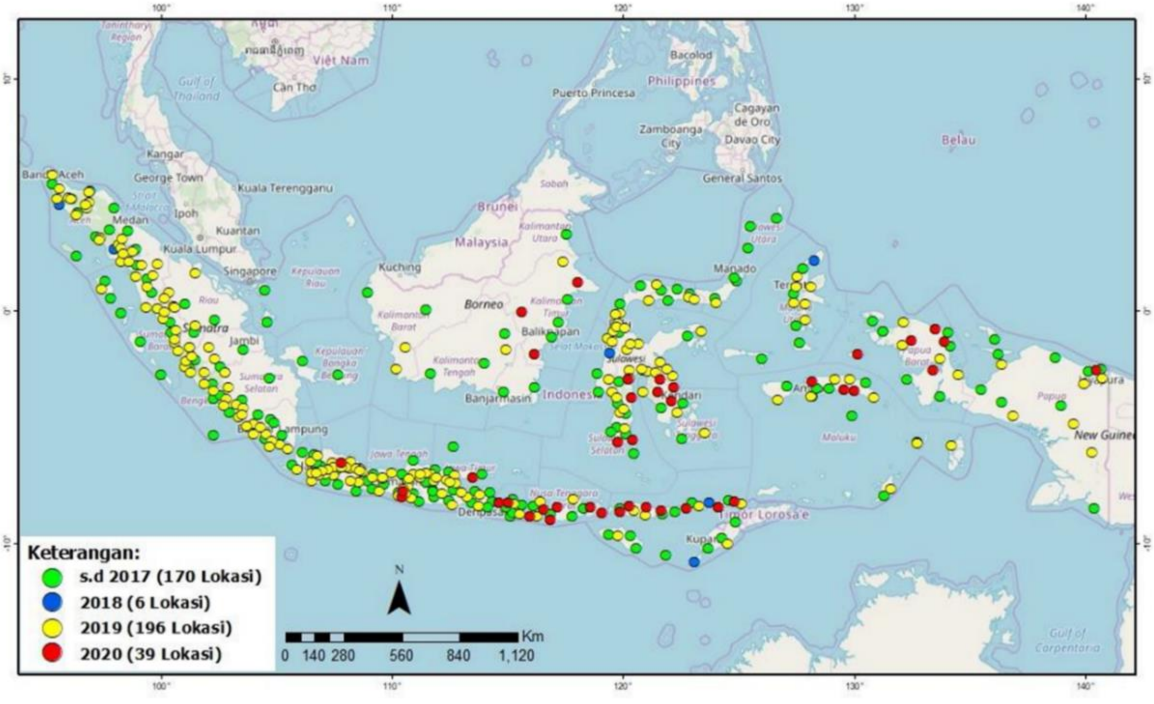


Figure 2-8: InaTEWS' network of seismometers [29]

Figure 2-9: InaTEWS' network of accelerometers and intensity meters [29]

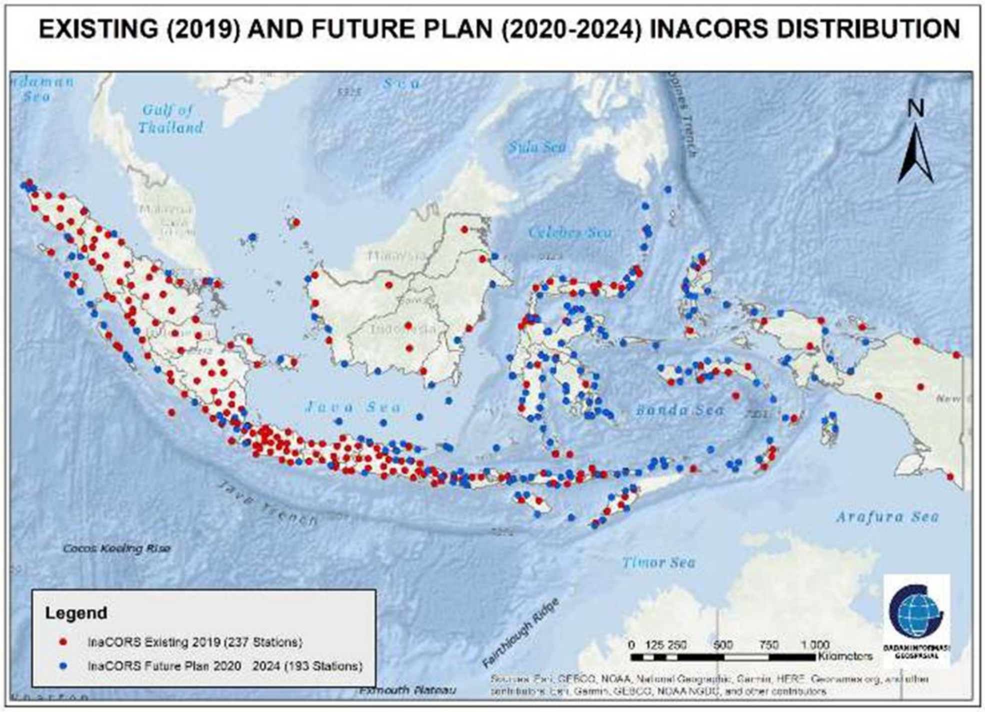


Figure 2-10: InaCORS' network of GNSS reference stations utilized in InaTEWS [30]

http://nrtk.big.go.id/

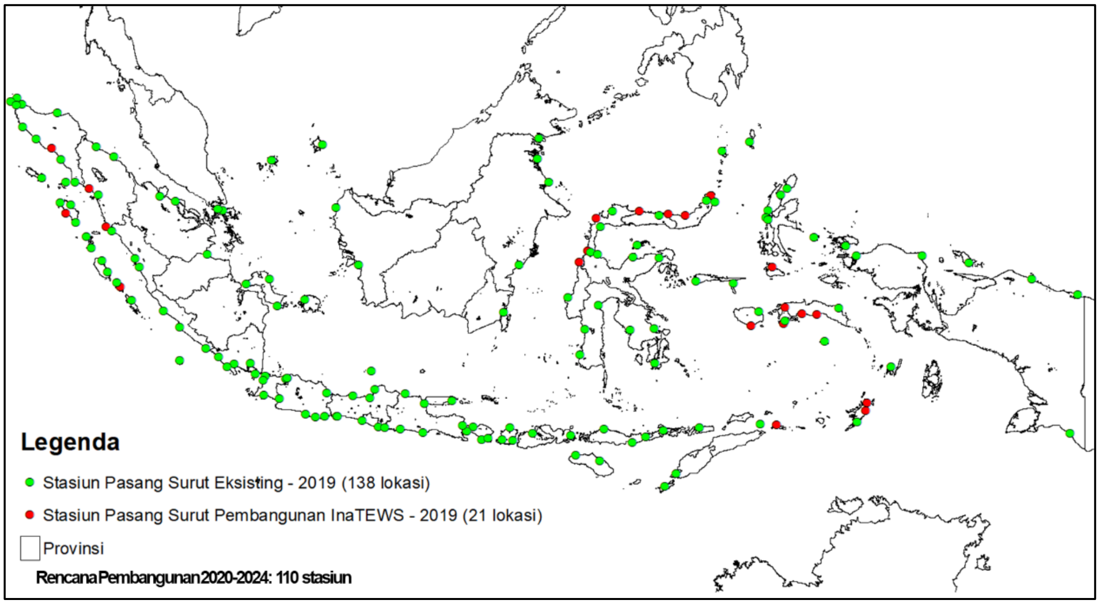


Figure 2-11: InaTEWS' network of tide gauges [30]

http://tides.big.go.id:8888/deskripsi/

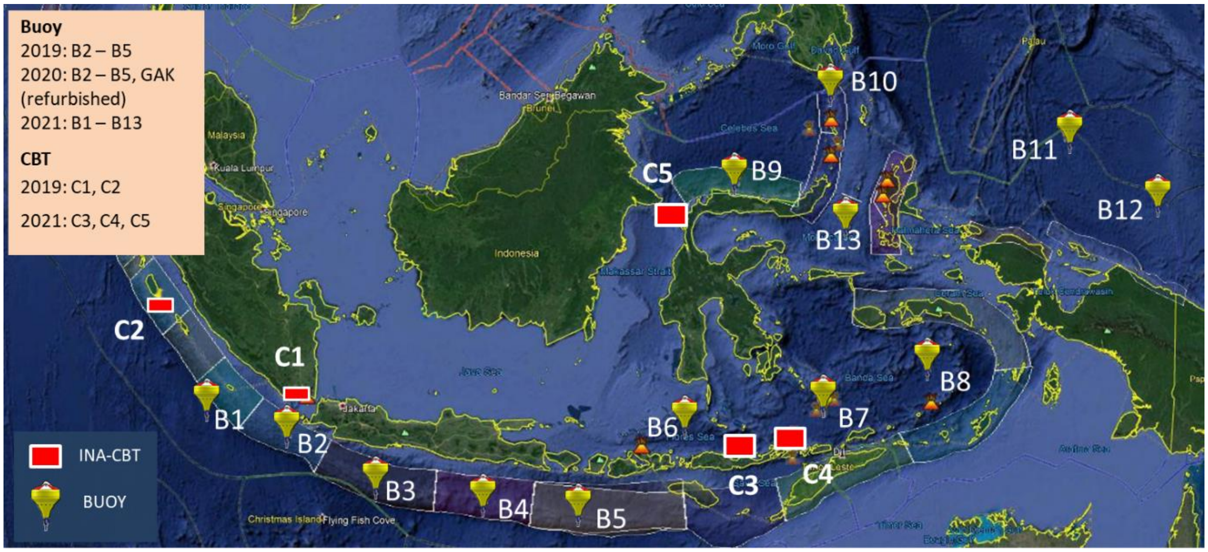


Figure 2-12: InaTEWS' network of surface buoys and cable-based tsunameters (INA-CBT), adapted from [31]

InaTEWS' upstream communication architecture relies primarily on C-Band (4-8 GHz) VSAT, Inmarsat's satellite L-Band (1-2 GHz), and cellular GSM terrestrial network whenever possible. For GITEWS' tide gauges, Inmarsat BGAN is used as a primary communication because of the low amount of data (about 150 kByte of uncompressed data per hour) [32]. It was noted in [32] that using BGAN for the seismic stations for primary communication would have increased the bandwidth cost by a factor of 100 because the seismic stations generate about 10 kbit/s of traffic. For the C-Band VSAT SatCom, there are various providers found in literature review: Telkom-2 and Palapa-D satellites owned and operated by Indonesian companies and the Libra and Reftek systems using satellite services such as Intelsat [26] [32] [33] [34]. It is also mentioned in [32] that using Iridium's L-Band SatCom system was too expensive. However, today the buoys built by BPPT are using Iridium's network [31]. Lastly, terrestrial communication over cellular GSM is widely used for BIG's network of GNSS reference stations and tide gauge stations. Table 2-2 summarizes the upstream communication architecture of most InaTEWS sensors found from various sources.

Table 2-2: Summary of InaTEWS upstream communication architecture

Sensor	**Communication Service(s)**	**Data Sampling and Transmission Specifications**	**References**
Seismic Station	C-Band VSAT	20 - 100 Hz sampling rate, 10 kbit/s transmit rate	[32] [35] [36]
GNSS Station	GSM, L-Band Iridium, C-Band VSAT	Tens of Bytes of data, 1 Hz sampling rate, 5 secs transmit interval	[30] [37] [38]
Tide Gauge Station	GSM, L-Band Inmarsat BGAN, C-Band VSAT	Hundreds of Bytes of data, 1 - 5 mins sampling interval, 1 - 5 mins transmit interval (normal), 5 secs interval (streaming mode)	[30] [32] [39] [40]
Surface Buoy	L-Band Iridium	Tens of Bytes of data, 15 mins transmit interval (normal), Real-time (streaming mode)	[31] [41]
Cable-based Tsunameter	Fiber Optic Cable	Real-time	[31]

For downstream communication, the strategy of InaTEWS is to disseminate warnings and risk information over as many media as possible and to transmit the information to both the public and the local officials. In the warning chain, the officials involved are local disaster management officials called BPBD, the local police (POLRI) and the national armed forces (TNI). Figure 2-13 shows an overview of the chain [42].

The most effective method of warning transmission is believed to be SMS over the cellular network. However, there are many other channels and devices such as sirens, TV, FM radio, amateur radio, and the internet through email, BMKG's website, social media, and smartphone application. Most of these devices rely on terrestrial communication network, however some home TVs and local officials like the BPBD utilize the Digital Video Broadcasting (DVB) or VSAT [43] [44]. BPBD officials receiving the warning through DVB/VSAT are responsible for controlling the sirens [45].

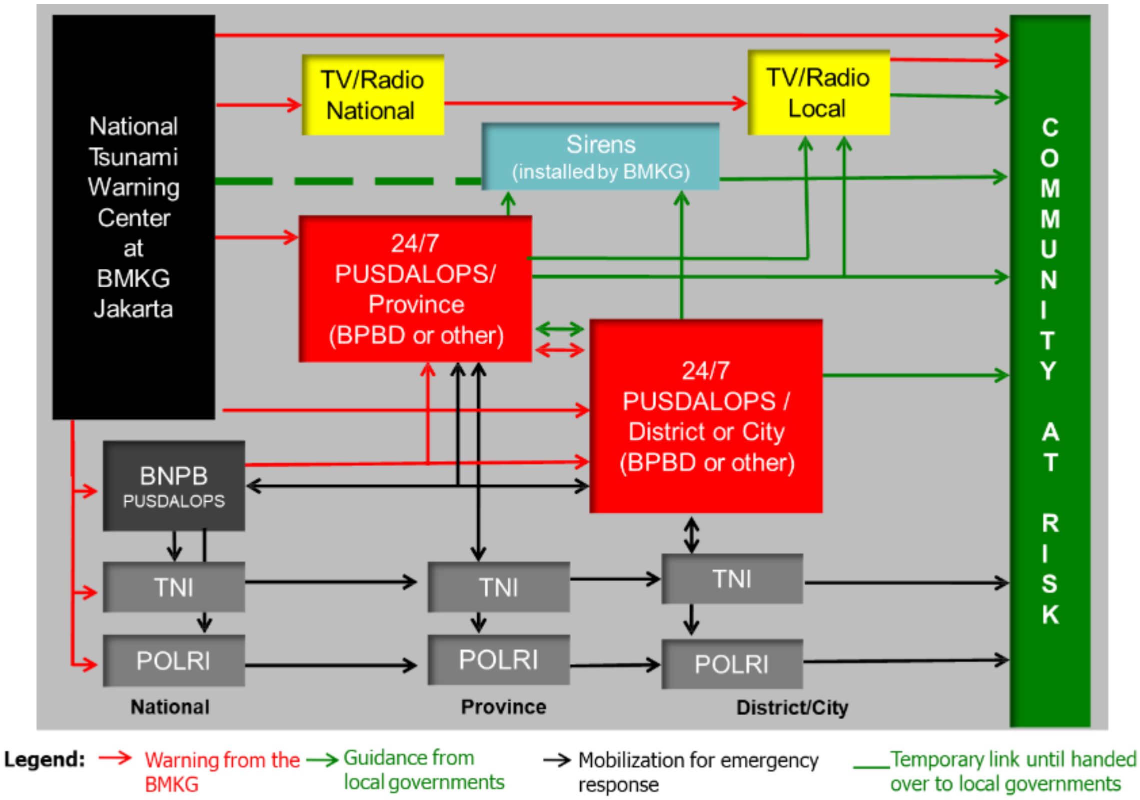


Figure 2-13: InaTEWS warning chain [42]

Despite some of the successes stories of InaTEWS, the Palu Tsunami in 2018 was a big hit because for one, the dissemination network failed even though the warning was generated. The cell tower was not earthquake-proof and the DVB-based warning receiver system's power backup was not functioning and its antenna is prone to misalignments. But even if the communication system had worked well, the tsunami would still have been fatal. Unlike the usual tsunamis that take 20 - 40 minutes to travel to the coastline, the Palu Tsunami arrived in less than 10 minutes [2] [45]. Additionally, the prediction of the tsunami height from InaTEWS was lower than the actual event. This is because the tsunami was triggered by a submarine landslide, and none of world's tsunami early warning systems were designed for that. The Sunda Strait Tsunami in December 2018 was completely undetected because the tsunami originated from an underwater volcanic landslide.

Due to those limitations, BMKG is aiming to upgrade InaTEWS to issue a first warning within 2 minutes [29]. Additionally, a new non-tectonic tsunami early warning system is being developed to be integrated into InaTEWS. The system would include coastal HF radars in addition to the tide gauges, buoys, and cable-based tsunameters [29] [46] [47] [48].

2.2.1.2 Volcanic Activity

Out of 127 active volcanoes in Indonesia, 69 are continuously monitored by the Center for Volcanology and Geological Hazard Mitigation (PVMBG), a part of the Ministry of Energy and Mineral Resources (ESDM). PVMBG has since 2015 developed a volcanic activity information system to provide risk information, early warnings, and actionable recommendations to the general public and important institutions such as AirNav Indonesia and the National Disaster Management Agency (BNPB). The system is called Multiplatform Application for Geohazard Mitigation and Assessment in Indonesia (MAGMA) and a screenshot of its web application can be seen in Figure 2-14 [49].

Figure 2-14: MAGMA web application [49]

https://magma.esdm.go.id/

MAGMA’s data sources include satellite and drone-based imagery and a network of terrestrial instruments such as seismometers and CCTV cameras. Additionally, it combines information from the Meteorological Climatological and Geophysical Agency (BMKG) to provide risk information related to earthquakes and ground movements that can cause landslides. It also lets the general public to participate in reporting any of those geological disasters through its app.

2.2.1.3 Hydro-Meteorological Disaster

BMKG provides information and services related to hydro-meteorological disasters through its website [50] [51]. These include information related to extreme weather such as heavy rain, lightning, strong wind, hail, whirlwind, extreme temperature, and bad visibility [52]. The website also provides information about the tropical cyclone and how it affects the weather in the country through the Tropical Cyclone Warning Center (TCWC), although Indonesia is generally not along the trajectory of tropical cyclones.

For its hydro-meteorological services, BMKG utilizes various sources of data. Continuous satellite weather monitoring is provided through the Japanese Himawari-8 geostationary satellite. Images are updated every 10 minutes [53]. Additionally, BMKG operates a network of terrestrial sensors including weather radars, automatic weather stations (AWS), automatic rain gauges (ARG), automatic solar radiation systems (ASRS), and human-operated weather and climatological stations.

Until 2019, there are 41 weather radar stations throughout the country and BMKG plans to add more as can be seen in Figure 2-15 [54] [55]. BMKG’s weather radar stations work in either S-Band, C-Band, or X-Band and output reflectivity data of around 4-7 MBytes for 10 minutes, depending on the radar’s coverage [55]. According to a survey by the World Meteorological Organization (WMO), communication rates between 64 and 256 kbit/s is the most commonly used [56].

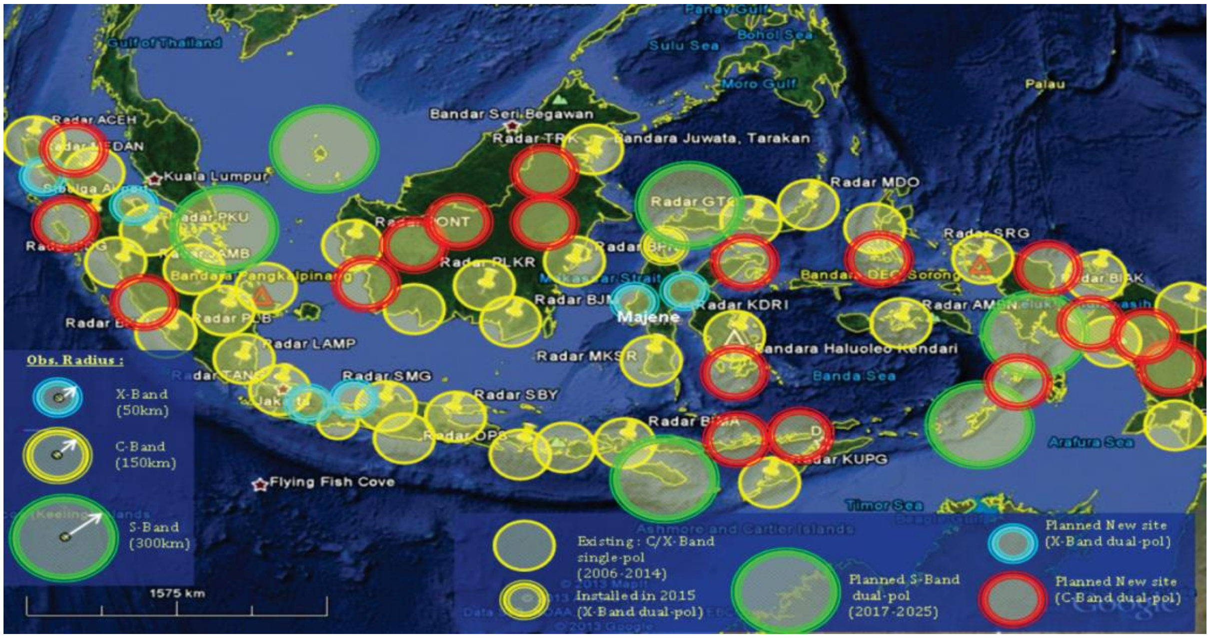


Figure 2-15: BMKG's network of weather radar stations [55]

Based on its automatic weather station web application, BMKG currently operates 325 automatic weather stations (AWS), 105 agroclimate automatic weather stations (AAWS), 649 automatic rain gauges (ARG), and 26 automatic solar radiation stations (ASRS) throughout the country [57] [58] [59]. These stations operate at an interval of 10 minutes and transmit from a few to tens of bytes of data on each interval [57] [60] [61]. Most of these stations use the GSM network, but recently a study on utilizing Low Power Wide Area Network (LPWAN) by BMKG's communication network department seems to be promising for the automatic rain gauges [61]. Figure 2-16 shows BMKG's network of automatic weather-related stations.

BMKG also provides other products and services, such as for maritime transportation through its Indonesia Ocean Forecasting System (InaOFS) that delivers wave predictions every three hours with a grid resolution of 27 km [62] [63], and air quality through its network of meteorological and climatological stations that monitor multiple parameters including PM10, PM2.5, SO_2, NO_2, suspended particulate matters (SPM), and greenhouse gases (GHG) [33] [64].

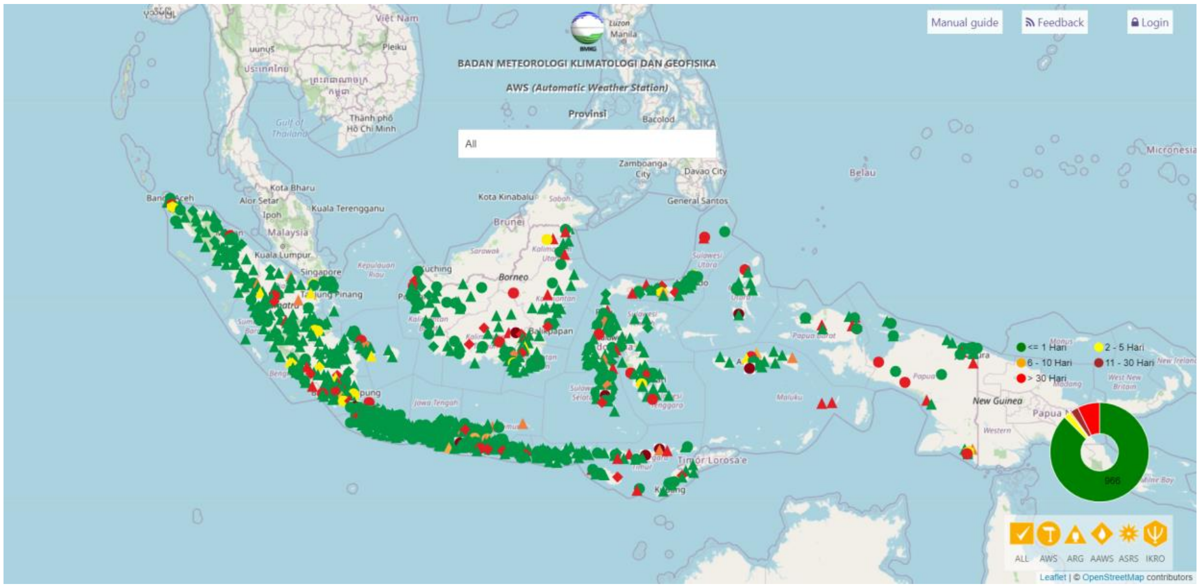


Figure 2-16: BMKG's network of automatic weather stations [57]

http://202.90.198.206/aws/

2.2.1.4 Wildfire and Drought

Information on wildfire in Indonesia is provided on SiPongi, a system led by the Ministry of Environment and Forestry (KLHK) with support from BMKG, LAPAN, BNPB and BPPT [65] [66]. Early detection of wildfire is currently done through three methods: satellite imagery, fire lookout towers, and thermal or CCTV cameras. The major source of data is satellite imagery and is provided daily from TERRA/AQUA, SNPP, NOAA20, and LANDSAT8.

Meteorology-based fire danger rating system (FDRS) called the Ina-FDRS has also been undergoing development by BPPT, in cooperation with BMKG and KLHK [67] [68]. It was piloted in peatland fire-prone area in the Southern Sumatra province using 12 automatic weather stations and Himawari-8 satellite imagery [69]. BMKG gives its contribution through its forest and peatland fire warning system (SPARTAN) that provides daily drought code, fine fuel moisture code, duff moisture code, build up index, initial spread index, and fire weather index [70]. BMKG also utilizes its network of weather stations to observe and forecast droughts [71].

Figure 2-17: KLHK's SiPongi wildfire information system [65]

http://sipongi.menlhk.go.id/

Due to the urgency of peatland fires, the Indonesian president created a new agency called the Peatland Restoration Agency (BRG) to restore 2 million hectares of peatland ecosystem in seven high-risk provinces together with KLHK [72]. These provinces are Jambi, Riau, Southern Sumatra, West Kalimantan, South Kalimantan, Central Kalimantan, and Papua. Within first few years of its inauguration, the agency has launched the Peatland Restoration Information and Monitoring System (PRIMS) that provides the latest status of the peatland and its restoration [73], and the Peatland Water Level Monitoring System (SIPALAGA) that uses a network of in-situ sensors to record the peatland's water condition near real time [74]. By November 2019, together with BPPT, BRG has installed 172 stations that measure water level, soil humidity, rainfall, ambient temperature and humidity, and wind velocity [75] [76]. These in-situ sensor data are recorded every 10 minutes and transmitted over GPRS every hour. Transmission over SMS is also available at some stations. Over SMS, the data are collected for the whole day period for transmission once a day.

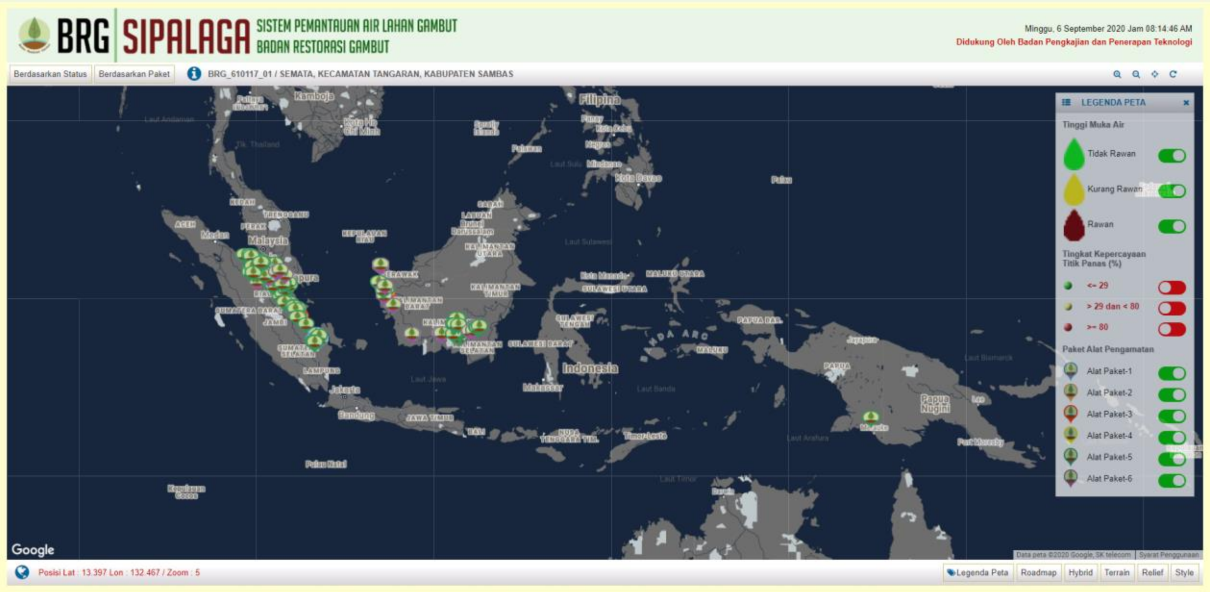


Figure 2-18: BRG's peatland water level monitoring system (SIPALAGA) [74]

https://sipalaga.brg.go.id/

2.2.2 Common Challenges and Areas for Improvement

As described in the previous section, there are thousands of sensors and warning devices requiring remote and reliable connectivity. Comparing with higher income countries like Japan and the United States, it is only logical that the number of devices will grow. Communication availability is often taken for granted and many projects lack a thorough consideration and strategy when in fact it is actually the backbone of all activities. A recent study by Sufri et al in 2019 examined the progress in Aceh's early warning system since the 2004 Indian Ocean Tsunami and identified that a robust and reliable infrastructure for hazard precursor monitoring and warning dissemination to be one of the key areas for a successful early warning system [77]. Yulianto et al also highlighted communication network infrastructure as the main source of problems in natural disasters in Indonesia, including the one in Palu in 2018 [78]. This communication technology gap is not unique to Indonesia, as also identified by academics from Sri Lanka and India [79] [80]. The issue is heightened especially in low- and middle-income countries alike, where government budget for continuous operation and maintenance like telecommunication subscription is required. It is therefore important to optimize the design of communication technology for early warning systems for both reliability and cost-effectiveness.

2.3 Wireless Communication Technologies

Both for collecting data and disseminating information, wireless communication is a vital part. For many cases in the past, it can even be the single cause of failure. Therefore, it is crucial to select the wireless communication technology through comprehensive evaluation over multiple criteria.

2.3.1 Cellular

By Q3 2019, the Ministry of Communications and Informatics (KOMINFO) reported that 99.16%, 96.34%, and 97.51% of residential areas in Indonesia are covered by 2G, 3G, and 4G, respectively [81]. In terms of land area coverage, 2G, 3G, and 4G covers 69.27%, 46.11 %, and 52.28%, respectively, noting that Indonesia is 24% land and 76% water, with 1,899,753 km^2 land area and 8,063,601 km^2 total area. This cellular coverage is done through an estimated 95,556 cell towers in Q3 2019 [82].

Additionally, cellular Low Power Wide Area Network (LPWAN) NB-IoT was first commercialized in 2018 and has since covered up to 35 cities in August 2020 [83] [84] [85]. Figure 2-19 gives a visualization of cellular coverage in Indonesia by Telkomsel, the largest provider in the country and Table 2-3 summarizes the coverage and performance of existing and upcoming cellular technologies in Indonesia.

Preparation on 5G deployment in Indonesia has been ongoing. However, there are some issues regarding the frequency spectrum that is suggested by the International Telecommunication Union (ITU) because quite a significant part of it has been an important spectrum for satellite telecommunication in Indonesia [86]. According to [87], an optimistic scenario will allow 5G spectrum in Indonesia to be secured by 2022, whereas in a wait and respond scenario 5G has to wait as long as 2024.

Figure 2-19: Crowdsourced coverage data of Telkomsel 2G, 3G, and 4G in Indonesia. [88]

https://www.nperf.com/id/map/ID/-/5119.Telkomsel/signal/

Table 2-3: Summary of existing and upcoming cellular technologies in Indonesia

Technology	**Land Coverage**	**Land and Sea Coverage**	**Residential Coverage**	**Throughput**	**Reference**
2G	69.27%	16.32%	99.16%	< 144 kbit/s	[81] [89] [90]
3G	46.11%	10.86%	96.34%	< 14.4 Mbit/s	
4G	52.28%	12.32%	97.51%	< 100 Mbit/s	
NB-IoT	35 out of 514 cities are deployed as of 2019			< 159 kbit/s	[85] [91]
5G	Still under evaluation, might be deployed in 2022/2024			< 10 Gbit/s	[86] [87]

2.3.2 Satellite Communication (SatCom)

Communication satellites can generally be categorized by their orbit and frequency band. The higher the frequency, the higher throughput, but the more vulnerable it becomes to rain and cloud. Additionally, the higher the frequency, generally the more directional the device antenna has to be to account for signal losses. They can also either be owned and operated by local companies or by foreign companies who have obtained the necessary licenses and landing rights from the Ministry of Communication and Informatics (KOMINFO).

Quite a wide range of applications and markets exist, from satellite TV, news broadcasting, voice, backhaul for cellular, maritime services, military services, and data connectivity. The most popular frequency for SatCom in Indonesia is probably the C-Band (4-8 GHz). It has been mainly used for TV broadcasting and data connectivity over VSAT. Due to the nature of the Indonesian archipelago, one research in 2014 estimated that 35 out of 45 million households in Indonesia have no alternative to satellites to receive television [92]. The same literature also reported an estimated number of 124,561 C-Band VSAT terminals were being used across the country, mainly from the banking and retail market. InaTEWS also uses C-Band VSAT terminals for both data collection and warning dissemination. C-Band players in Indonesia include both local and international companies, such as Telkom, Pasifik Satelit Nusantara (PSN), Indosat, Bank Rakyat Indonesia (BRI), JSAT from Japan, and SES from Luxembourg. Figure 2-20 shows an example of a satellite C-Band footprint over Indonesia from PSN's Nusantara Satu satellite.

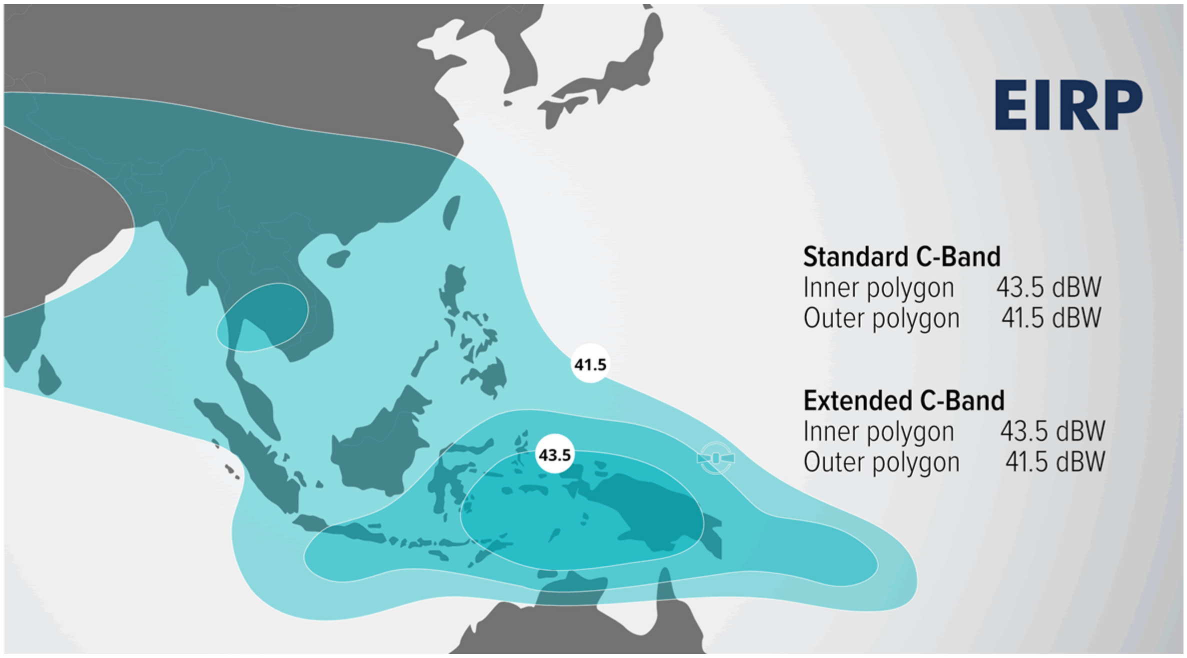


Figure 2-20: PSN's Nusantara Satu C-Band coverage [93]

Satellite L-Band (1-2 GHz) is widely used around the world for mobile satellite services, i.e. applications that require connectivity while moving. In Indonesia, this frequency is dominated by Inmarsat's geostationary satellite, Iridium's network of low earth orbit (LEO) satellites, and Thuraya's geostationary satellite. Applications include voice, text, and machine-to-machine (M2M) connectivity. One example is an international pilot project funded by the UK Space Agency that was run from 2017 to 2019 to connect 200 Indonesian small fishing vessels for tracking and basic SMS communication over Inmarsat's L-Band satellite [94]. As mentioned in Section 2.2.1.1, InaTEWS has also benefited from L-Band connectivity from both Inmarsat and Iridium.

Ku-Band (12-18 GHz) has also started to pick up in the last few years in Indonesia. Telkom 3S satellite launched in 2017 and PSN Nusantara Satu launched in 2018 provide high throughput satellite (HTS) connectivity for satellite-based internet in remote areas with speeds up to 10 Mbit/s and latency of 500 to 900 ms using a fixed 97-cm VSAT dish antenna [95] [96]. Ka-Band (27-40 GHz) has not been popular in Indonesia due to its vulnerability to rain and cloud. However, technology has improved, and rain fade may not be a significant issue anymore. KOMINFO's Telecommunication and Information Accessibility Agency (BAKTI) partners with a consortium led by PSN will launch a Ka-Band very high throughput satellite (VHTS) with a capacity of 150 Gbit/s to deliver satellite internet to 145,000 areas in the country including 90,000 schools and 40,000 hospitals starting in 2023 [97] [98]. Based on speed test data of Ka-Band satellite internet in the US such as ViaSat and HughesNet, the speed averages at 30+ Mbit/s and can reach up to 100 Mbit/s in certain areas [99] [100] [101].

One satellite from the Indonesia's space agency (LAPAN) called LAPAN-A2/ORARI has also been actively used by the Indonesian Amateur Radio Organization (ORARI). The satellite flies in the equatorial orbit and passes over Indonesia 14 times a day, with up to 14 minutes time window for each pass. During and after a major disaster, the satellite provides voice and text communication over its onboard UHF/VHF voice repeater and automatic packet reporting system (APRS). It has been a good alternative when a disaster takes the cellular network down because the satellite design allows radio amateurs to use a handheld transceiver with a low gain portable antenna as demonstrated during the Palu Tsunami and Lombok Earthquake disasters in 2018 [102]. LAPAN's latest satellite constellation project which is planned to launch in the next few years aims to host store-and-forward payloads for Indonesia's disaster monitoring sensors [6] [7] [8]. Extensive study is ongoing to determine which frequency bands and protocols are suitable for this purpose. Additionally, the constellation is hoped to host voice repeaters similar to the LAPAN-A2 satellite. With such an equatorial constellation, 24/7 emergency communication will be possible.

SatCom in the past year has seen a number of breakthroughs. Satellite-based Low Power Wide Area Network (LPWAN), for example, have been demonstrated by Lacuna Space over the LoRaWAN protocol and by Skylo technologies over the NB-IoT protocol [103] [104]. Another breakthrough came from Lynk, who successfully demonstrated a text message from low earth orbit to an unmodified Android phone over GSM [105] [106]. Another important breakthrough came from the broadband realm. SpaceX's first phase of its Starlink constellation launched this year managed to deliver 100 Mbit/s of internet with less than 30 ms latency over Ku/Ka-Band [107]. All these new technologies offer promising opportunities for early warning systems. Table 2-4 summarizes existing and upcoming SatCom technologies in Indonesia.

Table 2-4: Summary of existing and upcoming SatCom technologies in Indonesia

Technology	**Time to Market**	**Throughput**	**Reference**
VHF, UHF	Operational	$<$ 9.6 kbit/s	[108] [109]
L-Band	Operational	$<$ 492 kbit/s	[110] [111] [112]
S-Band	Prospective	$<$ 290 kbit/s	[113]
C-Band	Operational	$<$ 2 Mbit/s	[34] [92] [114] [115]
Ku-Band	Operational	$<$ 20 Mbit/s	[95] [96] [116]
Ka-Band	Prospective	$<$ 100 Mbit/s	[99] [100] [101] [107]
LPWAN (Sub-GHz)	Prospective	$<$ 20 kbit/s	[117] [118]
GSM (Sub-GHz)	Prospective	SMS	[106]
Amateur Radio (VHF/UHF)	Operational	Voice and $<$ 9.6 kbit/s data	[102]

2.4 Sustainable Development Goals

The term sustainable development is widely accepted as “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [119]. All United Nations Member States, including Indonesia, has adopted the 17 Sustainable Development Goals (SDGs) since 2015, as reflected in the country’s National Medium-Term Development Plan (RPJMN) 2015-2019 and 2020-2024 [120] [121].

One of the goals is SDG#11 “Make cities and human settlements inclusive, safe, resilient and sustainable” which is only possible by successfully implementing disaster risk reduction (DRR) [122]. This thesis aims to extensively refer and reflect from principal narratives such as those described in the Sendai Framework for Disaster Risk Reduction [123] and the 2030 Agenda for Sustainable Development [124]. In the Sendai Framework, for example, the use of multi-hazard early warning systems, hazard-monitoring telecommunication systems, and space-based technologies and related services are stated as ways to reduce disaster risks.

According to the Sendai Framework, in addition to SDG#11, there are nine other goals with 25 targets that are related to disaster risk reduction [125]. These SDGs are highlighted in Figure 2-21.

Figure 2-21: Sustainable Development Goals contributed by disaster risk reduction

2.5 System Architecture Framework

The main framework of this thesis utilizes a system architecture framework that the author has learned and experienced from the MIT System Design and Management program and from practitioners of system architecture at MIT, including Dr. Ed Crawley, Dr. Bruce Cameron, Dr. Eric Rebentisch, Dr. Bryan Moser, Dr. Olivier de Weck, and Dr. Danielle Wood. Most of what is discussed in this framework are described in Dr. Danielle Wood's lecture notes titled "Systems Architecture as a Modeling Tool to Analyze and Design Space Activities in Emerging Nations" and detailed in the System Architecture textbook by Crawley et al. and the Art of Systems Architecting by Rechtin and Maier [126] [127] [128].

The theory of system architecture has a wide variety of applications. Hassan, de Weck, and Springmann used system architecture to formulate a multiobjective design optimization of a product line for commercial communication satellites [129]. James, a student of Crawley, used system architecture to develop an improved framework of Concept of Operations for the Department of Defense (DoD) with a Search and Rescue system case study [130].

The system architecture framework has also been used in analyzing cross-disciplinary, socio-technical issues. For example, Wood used it to examine the effectiveness of capacity building in developing countries through international collaborative satellite development projects [131]. Kazansky, Wood, and Sutherlun used system architecture framework to analyze the components of a malaria early warning system and evaluate the role of satellite remote sensing in such a system [132]. The literatures mentioned above show some examples of how the system architecture framework can be adapted to a wide range of systems and can be particularly effective in analyzing complex problems involving not only technical, but also political, social, and economic factors.

At the heart of this framework is *system thinking*, which is "thinking about a question, circumstance, or problem explicitly as a system – a set of interrelated entities". There are generally four tasks in system thinking: (1) identifying the system, its form and function; (2)

identifying the entities of the system and the system boundary and context; (3) identifying the relationships among the entities and at the boundary of the system; and (4) identifying the emergent properties of the system based on the function of the entities and their functional interactions.

The challenge of creating effective early warning systems is a complex sociotechnical issue. Simply building such a system without understanding the social, economic, and political context and without involving the people or organizations who will use or be affected by the system will result in a waste or even fatality. Therefore, the framework starts with understanding the natural disaster context in Indonesia through literature review and conversation with stakeholders or subject matter experts who work with the stakeholders.

Figure 2-22 shows an overview of the system architecture framework used in this research. In general, stakeholders can be categorized into *primary stakeholders*, *secondary stakeholders*, and *tertiary stakeholders*. Primary stakeholders are the main persons or organizations who make decisions to shape the system. Secondary stakeholders are the ones who influence the decisions of the primary stakeholders, often because they provide some part of the system. Tertiary stakeholders are also called the beneficiaries of the system; they are the ones who are affected by the system the most.

When designing a system, it would be best to engage all categories of stakeholders to understand their needs and constraints. A need may be defined as a necessity, an overall desire, or a wish for something that is lacking. Stakeholder needs might directly specify a component of the system, but most often they are expressed as desired attributes of the system, e.g. better, faster, cheaper. Stakeholder needs might not be aligned, and it is the role of the system architect(s) to manage the complexity of these needs. Section 3.1 shows a result of stakeholder analysis for early warning systems in Indonesia.

Once the needs and desired outcomes are identified, system architects should ask the question “what activities (or functions) should my system do to contribute to these desired outcomes?”. This is the stage where system architects translate those needs into functional requirements of the system, i.e. what kind of attributes should those functions have such that they will successfully achieve what is desired. There are numerous functions that can contribute to a successful early warning system. However, this research focuses only on two: upstream communication for data collection and downstream communication for information/warning dissemination. Desired attributes of communication include how much data can be transmitted in a single transmission and how fast can they be transmitted. More details can be found in Section 3.2.

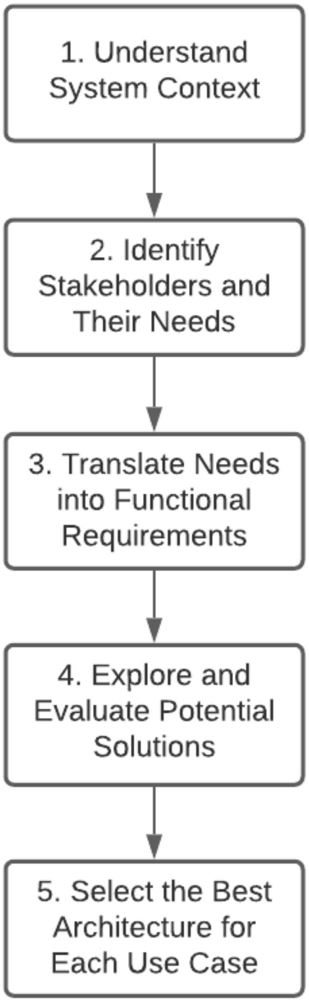


Figure 2-22: Overview of the System Architecture Framework, adapted from [128] [127]

The last step is to explore existing and prospective solutions, evaluate them according to the desired attributes, and finally select the best solution (or architecture). This study focuses only on two system functions but examines different natural disaster contexts. Each disaster has its own stakeholders and the best communication architecture for one may not be the best architecture for the other. However, opportunities for resource sharing and integration should be identified and pursued. To evaluate the pros and cons of each architecture, a standard hierarchical decision-making framework is used, which includes *weighted morphological matrix* to rank the options and *analytic hierarchy process* (AHP) to determine the weights [133]. For this study, the weights are determined based on the author's technical knowhow, literature review, and inputs from the stakeholders.

2.6 EVDT Framework

A baseline modeling framework to capture and integrate environment, societal impact, human decision-making, and technology domains was introduced by the Space Enabled Research Group at the MIT Media Lab led by Dr. Danielle Wood. Colloquially called the Environment-Vulnerability-Decision-Technology (EVDT) framework, it was developed to overcome important challenges that lie at the intersections of the four domains so that the user can better inform human-decision making for sustainable development [134] [135]. The framework is shown in Figure 2-23.

As mentioned in the paper by Reid, Zeng, and Wood, each component in the EVDT framework is referred to as submodels. The Environment submodels seek to capture the behavior of natural phenomena. In the case of this study, the natural phenomena are the natural hazards in Indonesia, from earthquakes to extreme rainfall and prolonged dry season. The Human Vulnerability & Societal Impact submodels seek to simulate and predict the degree of impact of some policy or phenomena on a set of people. In the case of natural disasters, the submodels would include the number of people and assets potentially exposed to the natural hazards and the level of vulnerability of those people and assets, e.g. in terms of health and financial conditions. The Human Decision-Making submodels seek to simulate and predict the decisions made by an individual or a group of humans. In Indonesia, the decision makers around early warning systems include BMKG, BNPB, KLHK, BIG, ESDM, LAPAN, LIPI, BPPT, the president, and the local authorities. Lastly, the Technology Design submodels seek to simulate engineered artifacts and assist in the design process. The work of this thesis essentially aims to contribute in this Technology Design submodel, specifically in terms of the communication architecture of the early warning systems.

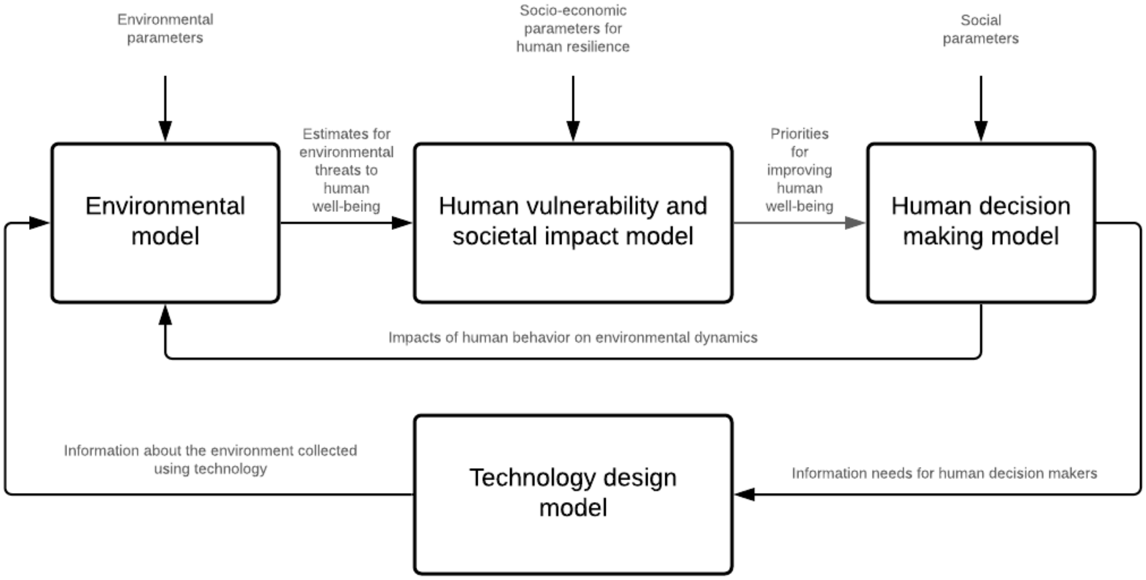


Figure 2-23: Overview of the Environment-Vulnerability-Decision-Technology (EVDT) Framework [134] [135]

The same research paper also highlighted two real-life examples of how the framework helped in integrating the challenges in the four domains. In the first case study, the environmental and socioeconomic impacts from an uncontrolled growth of water hyacinths in Benin were investigated and the corresponding solutions were proposed. The EVDT model helped in informing the selection of the hyacinth harvesting location, the creation of a new policy design, the impact estimation of the harvests, and the identification of feasible architectures for new remote sensing satellite design.

In the second case study, the impact of sea level rise and urban expansion on a mangrove ecosystem in Rio de Janeiro was investigated. The EVDT model was used to capture a wide variety of biological behaviors of the mangrove forests that occur in response to certain environmental changes. Additionally, the model could help evaluate urban planning policies in Rio de Janeiro including urban expansion rates, transportation infrastructures, and more sophisticated restriction policies on land use conversion.

2.7 Critique of Literature

One objective of the literature review in this study is to understand and evaluate the historical and current status of the natural hazards in Indonesia as well as the early warning systems that are in place. The goal of this thesis is not to design early warning systems from scratch, but rather evaluate and propose the state-of-the-art technologies to consider when expanding or upgrading those systems for data collection and warning transmission.

It was not easy to obtain a detailed information about the technical requirements and specifications of each early warning system from the public domain. Obtaining formal data from the primary stakeholders was considered but was not pursued in the interest of completion time of this thesis. However, as can be seen in the previous sections, the literatures manage to provide a pretty good grasp on the operational aspects of the various early warning systems. Although higher fidelity information would make the analysis better, the collected data are useful enough for making an analysis that will be shown in the next chapter.

Another objective of the literature review is to find any previous efforts in optimizing the performance and cost of an early warning system's communication technology. Most literatures describe about a newly designed early warning system for a specific natural disaster, e.g. flood, earthquake, or wildfire. These kinds of literature usually come from the field of engineering, mostly software or instrumentations related. Most academic literatures propose new designs that are tested in a small scale or one-off field test setting, but there are some describing systems that are actually deployed at the state or national level. InaTEWS has been the longest-operating early warning system in Indonesia involving multiple international partners and as such its literatures have also been the most mature. One academic literature that is strongly related to this thesis comes from Angermann et al. in 2010 who described the communication architecture of a large part of InaTEWS when it was deployed for the first time [32]. Since then, however, there is no academic literature that specifically evaluates the historical performance and operations of such architecture and how to improve. There are a number of recent publications evaluating the operations of Indonesia's tsunami early warning system, but they mostly come from authors with social science background. These literatures are successful in identifying which areas requiring attention and improvement, and communication technology is often mentioned as one of them. However, to actually propose a solution, it is crucial that researchers with the relevant technical background work on this issue. There is a lot of reliability and cost implications in choosing the right communication technology, especially as the population and valuable infrastructure grows, and more sensors will have to be deployed to better protect the vulnerable country from the various kind of natural disasters. The next chapter will provide a technical analysis to address the aforementioned communication needs for tsunami early warning system and beyond.

Chapter 3

Analysis and Results

This chapter shows the analysis processes and results that are manifested through literature review, stakeholder engagement, and evaluation of existing and prospective wireless communication technologies for the purpose of early warning systems in Indonesia.

3.1 Stakeholders in Indonesia's Natural Disaster Management

There are quite many stakeholder names mentioned in Chapter 2, but this section aims to summarize all of them in one stakeholder value network (SVN) diagram shown in Figure 3-1. It should be noted that for different types of natural disasters there are different stakeholders involved. However, this diagram combines all of them and categorizes them according to their main roles.

The primary stakeholders include the Meteorological Climatological and Geophysical Agency (BMKG), the Center for Volcanology and Geological Hazard Mitigation (PVMBG), the Ministry of Environment and Forestry (KLHK), and the Peatland Restoration Agency (BRG). They are the ones who have the responsibility to provide natural hazard information to the public, which is why they are also the ones who manage most of the data and operate most of the sensors. It is not uncommon to see collaboration among them in terms of data sharing.

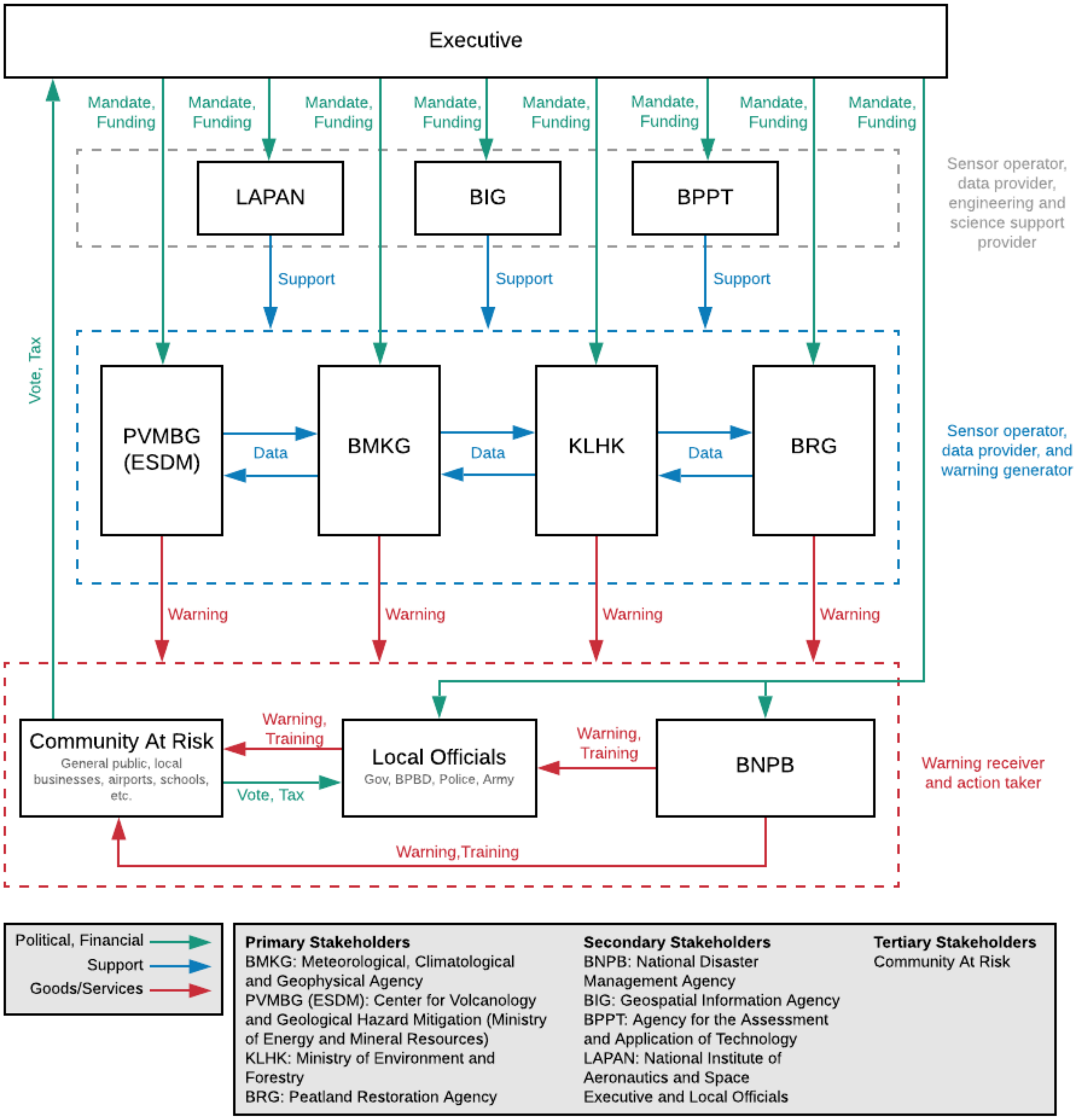


Figure 3-1: Stakeholder Value Network (SVN) diagram showing the stakeholders of early warning systems in Indonesia

There are several types of secondary stakeholders in the context of early warning systems in Indonesia. The first one is governmental institutions who are responsible to take further action when hazard or risk information is available. They are the National Disaster Management Agency (BNPB) and the local officials living together with the community at risk, including the mayor office, the police force, the armed forces, and the municipality-level disaster management officials called BPBD. Their roles cover all stages, from before, during and after a disaster. Pre-disaster, they are in charge of identifying and educating the community at risk. When a disaster hits, they also help in locating and evacuating the people at risk on top of forwarding the warnings. Once a disaster is over, they help the local community to recover and rebuild infrastructures.

The second secondary stakeholder type is governmental institutions who can support the primary stakeholders through providing data such as the National Institute of Aeronautics and Space (LAPAN) and the Geospatial Information Agency (BIG). These data include reference maps and satellite imagery of fire hotspots and atmospheric conditions. Not included in the diagram is other data providers such as international data providers and Statistics Indonesia (BPS).

The third type is institutions who support the primary stakeholders through engineering and/or scientific services. These include the Agency for the Assessment and Application of Technology (BPPT) who create and operate tsunami buoys for InaTEWS. In addition to BPPT, there are more governmental and non-governmental institutions that are not shown in the diagram such as universities, the Indonesian Institute of Sciences (LIPI), and businesses acting as engineering product or service suppliers.

The fourth type shown in the diagram is the President of the Republic of Indonesia and his/her team who provides the mandate and the funding to all the governmental agencies and local authorities mentioned above.

The fifth secondary stakeholder type is not shown in the diagram, but they are the communication provider for both the upstream data collection and the downstream warning dissemination. These include internet service providers, mobile network operators, TV and radio broadcasters, satellite communication (SatCom) service providers, and the Indonesian

Amateur Radio Organization (ORARI). LAPAN actually also belongs to this group because they provide backup voice communication over LAPAN-A2 and their satellite constellation program aims to provide communication links for sensor data collection.

Lastly, the tertiary stakeholders are the community at risk. They include people and institutions that can potentially be affected by disasters without significant active role in the context of early warning systems. These are schools, local businesses, airports, seaports, and everyone else that can be categorized as the general public. Although they do not play an active role in designing an early warning system, it is important that they are regularly trained on how to respond to a warning. Some of them, such as schools, can even play an important role in this case. The United Nations Office for Disaster Risk Reduction (UNDRR) also recommends that an effective early warning system should be a people-centered early warning system. This means directly involving those most likely to be exposed to hazards in both the establishment and operation of the early warning systems.

3.2 Stakeholder Needs and Technical Requirements

The focus of this thesis, as mentioned before, is only on two functions: upstream communication for remotely located terrestrial sensor data collection and downstream communication for dissemination of risk information and warnings.

During a discussion with fellows from the Research and Development Department and the Communication Network Department of BMKG, the needs for communication technology in early warning systems can be summarized in an analogy captured in the meeting: “If people are only riding motorcycles, should we build them highways?” This is to say that the communication technology and bandwidth should be properly selected according to the size and speed required of the data to be transmitted. This applies for both upstream and downstream communication.

Such requirement is no surprise to the world of telecommunication. The same requirement applies to any kind of communication, including our phone internet plan. We might not want to use a data plan that provides us too much capacity if we are not going to use it because we are paying for that extra. A special requirement for an early warning system's communication, though, comes from the fact that it has to withstand whatever natural hazards affecting it, from strong winds to earthquakes. During a disaster such as an earthquake or flood, electricity will also be shut down. This means that some form of power backup is required to maintain the functionality of the communication system. Table 3-1 summarizes the stakeholder needs and technical requirements for upstream and downstream communications of an early warning system.

Table 3-1: Summary of stakeholder needs and the corresponding technical requirements

No	Stakeholder Needs or Problems	Corresponding Technical Requirements
1	"We want to pay bandwidth only as much as our sensors use it. We don't want any wasted resources"	The chosen upstream communication technology shall provide just-enough bandwidth as required by the sensors
2	"There is no cellular signal on that site"	The chosen upstream communication technology shall work in areas where there is no cellular network
3	"For weather stations, Iridium and Inmarsat are too expensive for us"	The chosen upstream communication technology shall be more cost-effective than Iridium or Inmarsat for weather stations
4	"Once the earthquake struck the cell tower, people couldn't receive our warning text messages"	The chosen downstream communication technology shall not be vulnerable to earthquakes
5	"When the electricity is down, the siren is not useable"	The chosen downstream communication technology shall have a power backup and use as little power as possible
6	"The siren's satellite dish antenna is easily disturbed by an earthquake. Once misaligned, the warning would not be received"	The chosen downstream communication technology's antenna shall not be vulnerable to earthquakes
7	"Deploying ground-based sensors is expensive. Plenty of them would be needed. Moreover, the monthly connectivity price will be expensive. Maintenance will also be expensive"	The chosen upstream communication technology's terminal and connectivity price shall be affordable. Additionally, the terminal shall be free from maintenance as much as possible

3.3 Evaluation of Wireless Communication Technologies

In Chapter 2, both cellular and satellite communication technologies have been surveyed and described. In this section, all the relevant wireless communication technologies for both upstream and downstream communication will be compared and evaluated according to the criteria mentioned previously in Table 3-1. Figure 3-2 shows a general picture of wireless communication-based early warning systems in Indonesia.

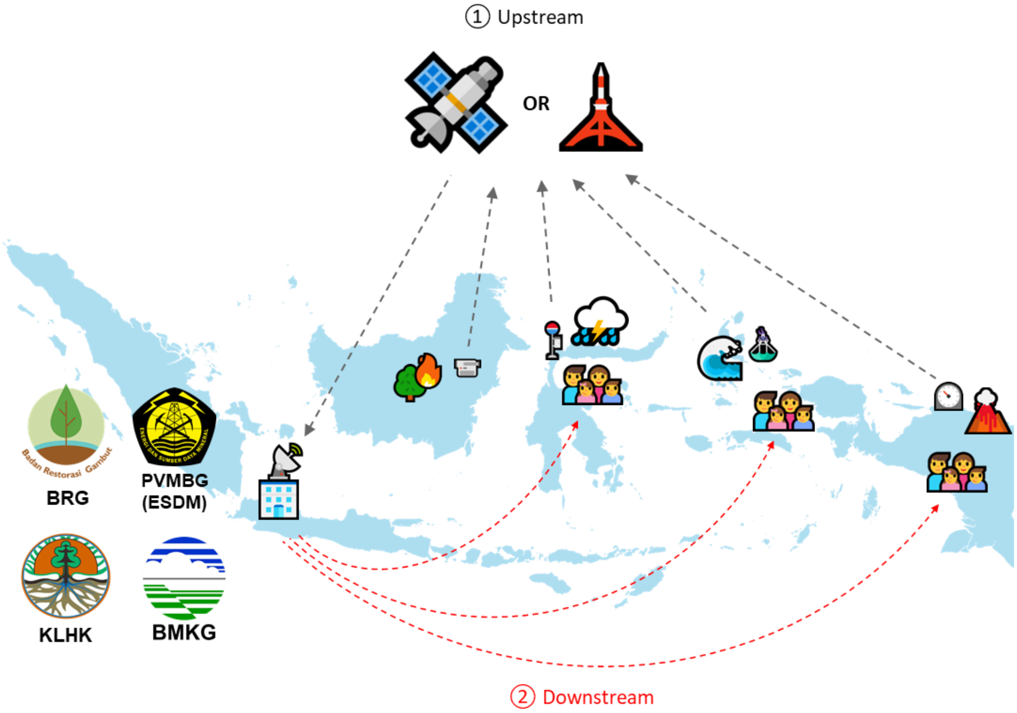
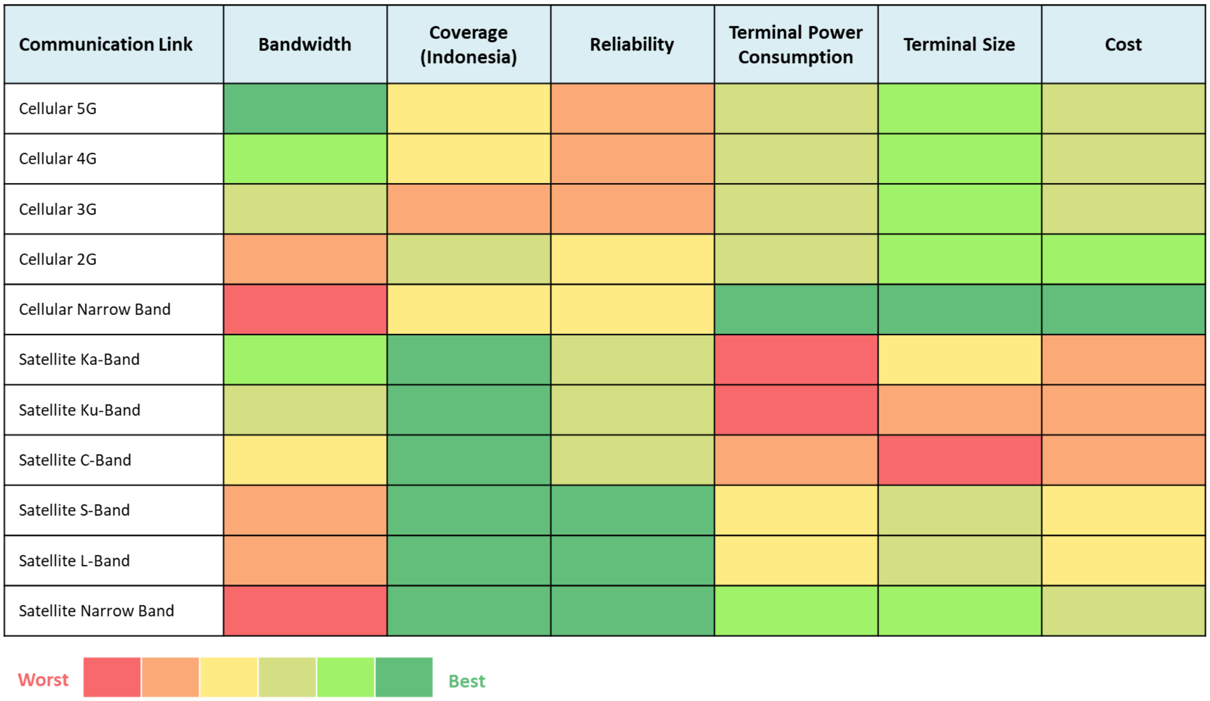


Figure 3-2: Overview of wireless communication-based early warning systems in Indonesia

3.3.1 Upstream

Table 3-2 shows a comparison of all the cellular and satellite communication technologies for sensor data collection across six levels (red, orange, yellow, lime green, light green, and dark green) with red being worst and dark green being best. At this stage of comparison, the following statements are true for a better communication link: larger bandwidth, larger coverage, higher reliability, lower terminal power, smaller terminal size, lower terminal maintenance, and lower cost. Additionally, the colors in the table should only be relatively compared within the respective columns. For example, the yellow color for bandwidth should not be compared with the yellow color for terminal size. Latency is not factored in this table because it is considered not critical and mostly depends on which orbit the satellites are located. For GEO satellites, the latency is typically more than 500 milliseconds, whereas for LEO satellites and cellular network the latency is typically lower than 50 milliseconds.

Table 3-2: Comparison of wireless communication technologies for upstream



Communication Link	Bandwidth	Coverage (Indonesia)	Reliability	Terminal Power Consumption	Terminal Size	Cost
Cellular 5G	🟩	🟨	🟧	▨	🟢	▨
Cellular 4G	🟢	🟨	🟧	▨	🟢	▨
Cellular 3G	▨	🟧	🟧	▨	🟢	▨
Cellular 2G	🟧	▨	🟨	▨	🟢	🟢
Cellular Narrow Band	🟥	🟨	🟨	🟩	🟩	🟩
Satellite Ka-Band	🟢	🟩	▨	🟥	🟨	🟧
Satellite Ku-Band	▨	🟩	▨	🟥	🟧	🟧
Satellite C-Band	🟨	🟩	▨	🟧	🟥	🟧
Satellite S-Band	🟧	🟩	🟩	🟨	▨	🟨
Satellite L-Band	🟧	🟩	🟩	🟨	▨	🟨
Satellite Narrow Band	🟥	🟩	🟩	🟢	🟢	▨

Worst 🟥 🟧 🟨 ▨ 🟢 🟩 Best

Notes:
- Assuming full coverage for satellite (GEO or LEO constellation) and full deployment of cellular narrow band on existing 4G cell towers
- Reliability is a factor of service level agreement and resilience against natural disasters (antenna directionality and cell tower's vulnerability)
- Satellite C-Band, Ku-Band, and Ka-Band operating in LEO require motorized directional antenna and might further affect reliability
- Cost includes one terminal and its subscription fee. It is not normalized against data size or throughput

It has to be noted that SatCom in the comparison table includes both GEO and LEO satellites and full coverage over Indonesia is assumed, even for new technologies that are not available at the time of this writing. For new cellular technologies such as narrow band and 5G, it is assumed that the coverage will reach as much as the current mainstream 4G.

Reliability is a factor of service level agreement (SLA) and resilience against natural disasters. In general, SatCom is able to provide higher SLA due to less congestion compared to cellular network. Resilience against natural disasters depends on the antenna directionality and cell tower's vulnerability. In general, the higher the frequency the more directional the antenna becomes in order to offset the higher free space path loss. This can be seen especially in C-Band, Ku-Band and Ka-Band VSATs. L-Band, S-Band, narrow band and cellular devices are designed for mobile, moving object applications, hence the generally omnidirectional antenna. Although cellular device antennas are not directional, cellular network has an extra vulnerability component, which is the cell tower or also known as the base transceiver station (BTS). To increase the reliability of cellular network, the cell towers must be structurally resilient against strong winds and earthquakes and they must have enough power back up in case of power outage. Not taken into consideration in the reliability component is the use of motorized directional antenna for LEO satellite-based VSATs such as Starlink, which potentially cause more vulnerability compared to fixed directional antenna for GEO satellites.

Terminal (modem plus antenna) power consumption and size is a function of the wireless technology's frequency, the distance to the receiver, and the receiver's sensitivity and size. In the case of cellular technology, the receiver means the cell tower and in the case of satellite technology, the receiver is the satellite. Narrow band including low power wide area network (LPWAN) technology is superior in terms of power consumption and size due to its small bandwidth. In the highest frequency realm (C-Band, Ku-Band, and Ka-Band), the terminal power consumption and the size are almost inversely proportional.

Lastly, the cost used as comparison is the cost of a single terminal with its subscription fee. It is not normalized against data size or throughput and it does not factor in economy of scale. To calculate and compare in terms of the total cost of ownership (TCO), a more in-depth investigation is required.

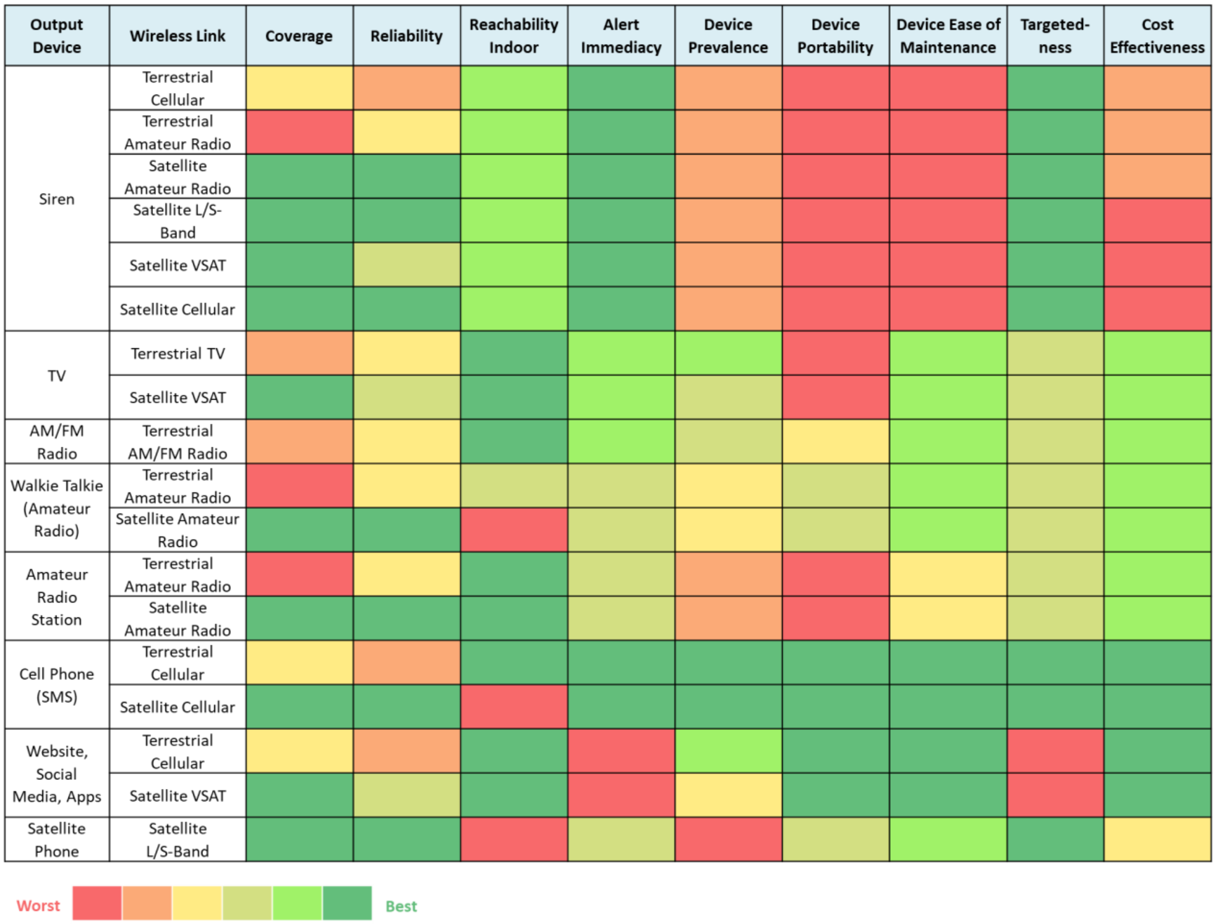
As surveyed in Chapter 2, there are various sensors for various kinds of natural disasters that come with different requirements. For each of the sensor, the next step is to select the best technology according to the sensor's data (text or image), the reliability requirement or risk tolerance, cost, power availability, etc. as stated in Table 3-2. This is further discussed in Section 3.4.1.

3.3.2 Downstream

Table 3-3 shows a comparison of all the terrestrial and satellite communication technologies for warning and information dissemination across six levels (red, orange, yellow, lime green, light green, and dark green) with red being worst and dark green being best. Additionally, the colors in the table should only be relatively compared within the respective columns. For example, the yellow color for coverage should not be compared with the yellow color for reliability. These criteria are weighted in Section 3.4.2. Bandwidth is not included in this table because each wireless technology listed is tied to the respective output device. Additionally, latency is not factored in this table because it is considered not critical and mostly depends on which orbit the satellites are located. For GEO satellites, the latency is typically more than 500 milliseconds, whereas for LEO satellites and cellular network the latency is typically lower than 50 milliseconds.

It has to be noted that SatCom in the comparison table includes both GEO and LEO satellites and full coverage over Indonesia is assumed, even for new technologies that are not available at the time of this writing, such as 24/7 satellite amateur radio. Satellite L/S-Band includes existing mobile satellite services such as Iridium, Globalstar, Inmarsat, and Thuraya, as well as prospective technology such as LAPAN's constellation. The notion of satellite cellular is limited to text-based transmission like what Lynk's satellite GSM has demonstrated over SMS. For the purpose of disseminating information, satellite coverage might not have a huge advantage over terrestrial, because the areas where people live are mostly covered by terrestrial network.

Table 3-3: Comparison of wireless communication technologies for downstream



Output Device	Wireless Link	Coverage	Reliability	Reachability Indoor	Alert Immediacy	Device Prevalence	Device Portability	Device Ease of Maintenance	Targeted-ness	Cost Effectiveness
Siren	Terrestrial Cellular	🟨	🟧	🟩	🟢	🟧	🟥	🟥	🟢	🟧
	Terrestrial Amateur Radio	🟥	🟨	🟩	🟢	🟧	🟥	🟥	🟢	🟧
	Satellite Amateur Radio	🟢	🟢	🟩	🟢	🟧	🟥	🟥	🟢	🟧
	Satellite L/S-Band	🟢	🟢	🟩	🟢	🟧	🟥	🟥	🟢	🟥
	Satellite VSAT	🟢	▨	🟩	🟢	🟧	🟥	🟥	🟢	🟥
	Satellite Cellular	🟢	🟢	🟩	🟢	🟧	🟥	🟥	🟢	🟥
TV	Terrestrial TV	🟧	🟨	🟢	🟩	🟩	🟥	🟩	▨	🟩
	Satellite VSAT	🟢	▨	🟢	🟩	▨	🟥	🟩	▨	🟩
AM/FM Radio	Terrestrial AM/FM Radio	🟧	🟨	🟢	🟩	▨	🟨	🟩	▨	🟩
Walkie Talkie (Amateur Radio)	Terrestrial Amateur Radio	🟥	🟨	▨	▨	🟨	▨	🟩	▨	🟩
	Satellite Amateur Radio	🟢	🟢	🟥	▨	🟨	▨	🟩	▨	🟩
Amateur Radio Station	Terrestrial Amateur Radio	🟥	🟨	🟢	▨	🟧	🟥	🟨	▨	🟩
	Satellite Amateur Radio	🟢	🟢	🟢	▨	🟧	🟥	🟨	▨	🟩
Cell Phone (SMS)	Terrestrial Cellular	🟨	🟧	🟢	🟢	🟢	🟢	🟢	🟢	🟢
	Satellite Cellular	🟢	🟢	🟥	🟢	🟢	🟢	🟢	🟢	🟢
Website, Social Media, Apps	Terrestrial Cellular	🟨	🟧	🟢	🟥	🟩	🟢	🟢	🟥	🟢
	Satellite VSAT	🟢	▨	🟢	🟥	🟨	🟢	🟢	🟥	🟢
Satellite Phone	Satellite L/S-Band	🟢	🟢	🟥	▨	🟥	▨	🟩	🟢	🟨

Worst 🟥 🟧 🟨 ▨ 🟩 🟢 Best

Notes:
- Assuming full coverage for satellite (GEO or LEO constellation, including LAPAN's constellation)
- Reliability is a factor of service level agreement and resilience against natural disasters (antenna directionality and terrestrial base station's vulnerability)
- Alert immediacy means how immediate can a general person notice a warning message from the device
- Device portability is a factor of size, weight and battery operability
- Targeted-ness means how targeted the warning message can be, without disrupting others that are not at risk
- Cost means the cost that the government must pay for the extra infrastructure and communication service fee

Reliability is a factor of service level agreement (SLA) and resilience against natural disasters. In general, SatCom is able to provide higher SLA due to less congestion compared to terrestrial network. Resilience against natural disasters depends on the antenna directionality and the terrestrial base station's vulnerability. In general, the higher the frequency the more directional the antenna becomes in order to offset the higher free space path loss. This is why VSAT antennas are directional whereas other satellite technologies in the table like satellite L/S-Band, satellite amateur radio, and satellite cellular are generally omnidirectional. Although terrestrial antennas are generally not directional, terrestrial network has an extra vulnerability component, which is the base station. To increase the reliability of terrestrial network, the base stations must be structurally resilient against strong winds and earthquakes and they must have enough power back up in case of power outage. Not taken into consideration in the reliability component is the use of motorized directional antenna for LEO satellite-based VSATs such as Starlink, which potentially cause more vulnerability compared to fixed directional antenna for GEO satellites.

Because warnings have to reach everyone, an important criterion to include is whether the warning can reach people indoors. Satellite network is generally unable to be captured from inside a building, unless the antenna is mounted on the roof like satellite TV or satellite amateur radio station. Some other criteria considered are alert immediacy, device prevalence, device portability, device ease of maintenance, targeted-ness, and cost effectiveness.

Alert immediacy is the estimated time required for a general person to notice the warning alert from the corresponding device. It depends on a number of things, including whether the device is active, whether the device is in the vicinity of the person at risk, and how fast can the alert spread to others.

Device prevalence means how common such device is. A prevalent device is more likely to reach more people. For example, a cell phone is significantly more prevalent than an amateur radio walkie talkie that is usually only owned by the amateur radio community. Device portability is a factor of the device's size, weight and battery operability. Unsurprisingly, a device that is prevalent, portable, and easy to maintain like the cell phone has a significant advantage.

Targeted-ness of a warning can be quite a major factor especially when it comes to determining which area should be evacuated and which area can continue its activity normally. The National Disaster Management Agency (BNPB) is responsible for estimating such a risk and certain warning output device can help to achieve targeting the right group of people.

Lastly, the cost used as comparison at this stage is the cost that the government must pay for the extra infrastructure and communication service fee. For devices with existing infrastructure such as cell phones and TVs, there will not be too much cost. The next step is to weigh each criterion shown in Table 3-3, calculate the overall score for each technology, and rank them based on their scores. This is further discussed in Section 3.4.2.

3.4 Selected Architectures

Various wireless communication technologies have been evaluated and compared against each other over multiple criteria. It is now time to select which technology would be best for each use case.

3.4.1 Upstream

Table 3-4 shows a list of existing and prospective terrestrial sensors for monitoring various natural hazards throughout the Indonesian archipelago. Columns with N/A mean the data is not available at the time of writing. For the purpose of comparison among the sensors, the transmit size is represented as multiples of powers of 10 Bytes. Additionally, information about data compression is unknown, although it is likely that the numbers already involve some form of on-site data processing or compression. For example, the transmission of videos over the compressed format of H.264 is very common. Putting more computation on site would save more communication bandwidth.

Table 3-4: Summary of existing and prospective terrestrial-based natural hazard monitoring sensors in Indonesia

Sensor	**No. of Sensors**	**Locations**	**Estimated Transmit Size**	**Transmit Interval**
Seismometer	411+	Figure 2-8	x 10^2 Bytes	Streaming (10 kbit/s)
Accelerometer	529+	Figure 2-9	x 10^1 Bytes	N/A
Intensity Meter	400+	Figure 2-9	x 10^1 Bytes	N/A
GNSS Receiver	430+	Figure 2-10	x 10^1 Bytes	5 secs
Tide Gauge	269+	Figure 2-11	x 10^2 Bytes	5 mins or 5 secs
Tsunami Surface Buoy	13+	Figure 2-12	x 10^1 Bytes	15 mins or streaming
Coastal HF Radar	3+	Coasts	x 10^5 Bytes	N/A
Weather Radar	66+	Figure 2-15	x 10^6 Bytes	10 mins
Automatic Weather Station	325+	Figure 2-16	x 10^1 Bytes	10 mins
Agroclimate Automatic Weather Station	105+	Figure 2-16	x 10^1 Bytes	10 mins
Automatic Rain Gauge	649+	Figure 2-16	x 10^1 Bytes	10 mins
Automatic Solar Radiation Station	26+	Figure 2-16	x 10^1 Bytes	10 mins
Peatland Water Level Monitoring System	172+	Figure 2-18	x 10^1 Bytes	1 hour
Thermal Imager	N/A	Forests, peatlands	x 10^3 Bytes (640 x 480, H.264)	0.03-0.1 secs (10-30 frame/s)
CCTV Camera	N/A	Volcanoes, forests, peatlands, etc.	x 10^3 Bytes (640 x 480, H.264)	0.03-0.1 secs (10-30 frame/s)

3.4.1.1 Weather Radar and Coastal HF Radar

As can be seen in Table 3-5, the sensor that requires the highest bandwidth is the weather radar and coastal HF radar. This is because of the nature of the measurement that captures a wide area. Figure 3-3 shows BMKG’s typical weather radar setup and Figure 3-4 shows a coastal HF radar setup. In order to retrieve these radar measurements wirelessly, a minimum bandwidth of hundreds of kbit/s is required. This can be achieved by 3G or greater for cellular and L-Band or greater for SatCom. BMKG’s weather radars today are mostly human operated from an office located right inside the building where the weather radar is mounted on [31]. Therefore, they are likely to be connected to the internet over cable or cellular, especially when there is no concern of transmission losses or delays. When considering to deploy weather radars in remote area, however, SatCom might be the only option. For a fully automated or remotely operated radar, C-Band VSAT should be enough and economical. However, for a radar operated manually on site, more internet data is likely to be needed for the personnel so Ku-Band or Ka-Band might be the best and most economical option.

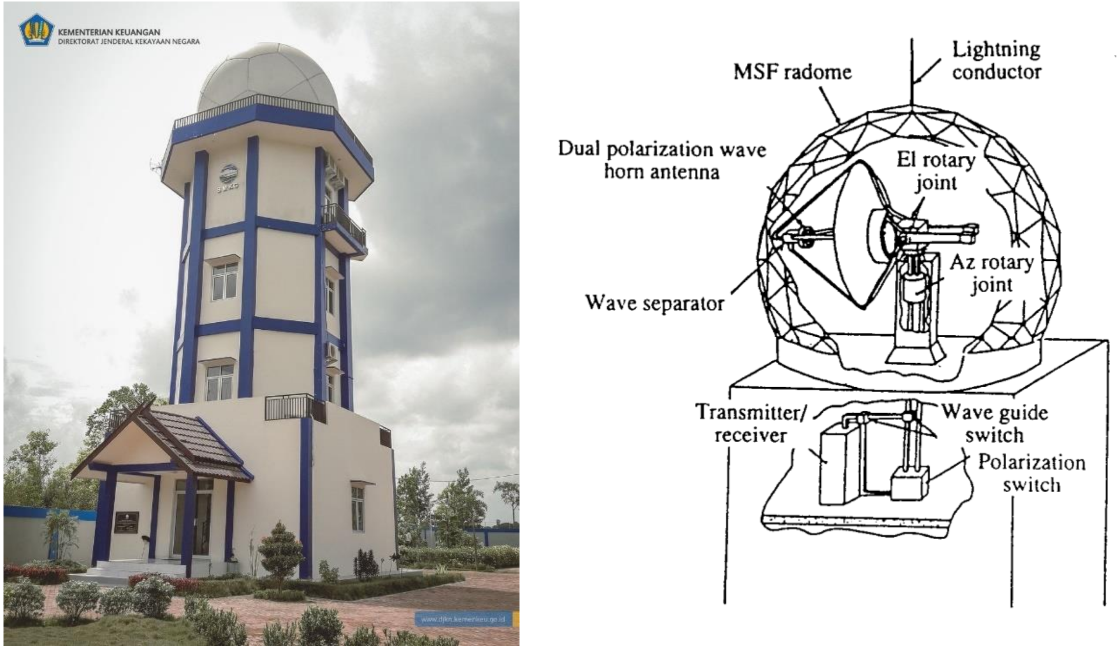


Figure 3-3: A typical BMKG weather radar station (left) [136] and
a view inside a weather radar's radome (right) [137]

Coastal HF radars are often used in the field of oceanography. However, they have also been used for tsunami early warnings as well. In Indonesia, there are not many coastal HF radars yet, but more are expected to be deployed in the coming years to help in detecting non-tectonic tsunamis as mentioned in Chapter 2. For detecting potential tsunamis, a high transmit rate is expected, especially when a certain event like receding water is triggered. Additionally, the wireless transmission might not want to rely on the cellular network even if the signal normally reaches the coasts, unless the nearby cell towers are certified to be earthquake-proof. This is why for coastal HF radars, SatCom might be preferable especially L-Band or S-Band because of their less directional antenna. According to a manual for real-time quality control of HF radar surface current data written by the US National Oceanic and Atmospheric Administration (NOAA), a communication link of 128 kbit/s should be enough although a 10 Mbit/s or greater connection would be best [138]. For such a high-speed internet connection, Ku-Band or Ka-Band would be required. Table 3-5 shows a summary of the recommended wireless technologies.

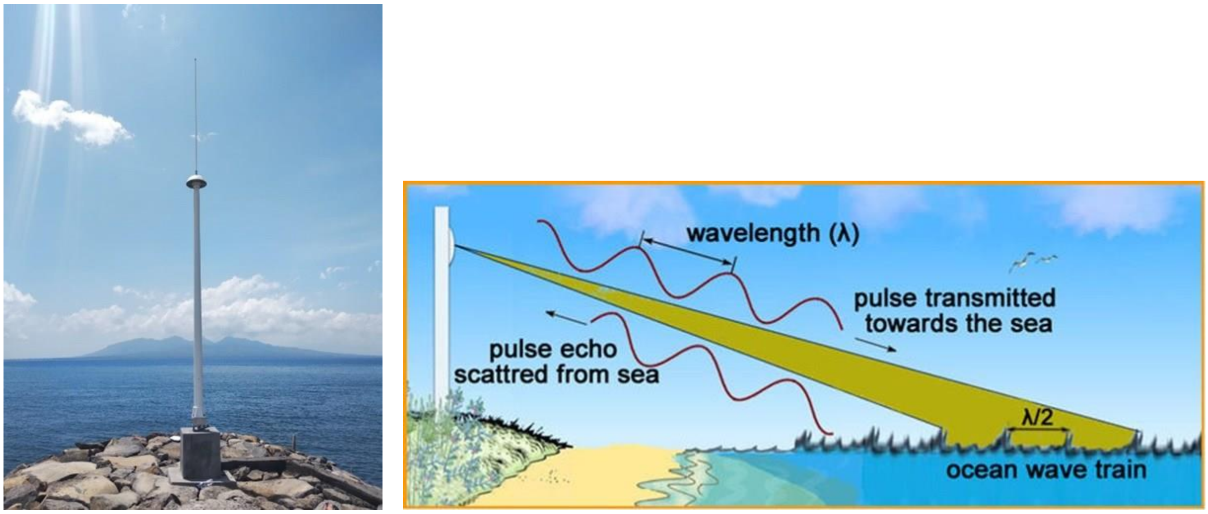


Figure 3-4: A coastal HF radar mounted in Indonesia (left) and a diagram showing how a coastal HF radar works (right) [139]

3.4.1.2 Thermal Imager and CCTV Camera

The sensors requiring the second highest bandwidth are the thermal imagers and CCTV cameras for wildfire and volcano monitoring. A thermal imager is essentially a camera that can measure heat by detecting infrared radiation in the 7-14 µm range day or night [140]. When mounted on fire lookout towers, they can be an effective option to detect wildfires early. Similar to a normal CCTV camera, it outputs videos of a certain resolution, frame rate, and compression configuration. According to literature review on computer vision-based fire detection, frame rate of 10 to 30 frame/s and resolution of more than 320 x 240 are expected [141] [142] [143] [144]. Additionally, popular thermal imagers for fire detection output 640 x 480 resolution [145] [146]. In order to transmit such data with H.264 format wirelessly, a bit rate of at least 500 kbit/s should be expected for a single camera. Therefore, at least a 3G connection for cellular or C-Band for satellite is required. Whenever available, cellular 3G/4G/5G network should be the first choice because it will be more economical than satellite communication at C-Band or higher frequency. Figure 3-5 shows a wireless fire detection setup by IQ FireWatch, a system with higher resolution of 1280 x 1024 and multiple spectra, currently deployed in eleven countries [147].

Figure 3-5: A wireless computer vision-based fire detection system by IQ FireWatch [148]

Similarly, CCTV cameras for volcano monitoring should use 3G/4G/5G network whenever available. In areas where cellular network is not available, satellite C-Band or higher should be considered. In the case where the frame rate can be reduced, L-Band or S-Band might also suffice. Figure 3-6 shows a picture of a wireless CCTV owned by PVMBG.

Figure 3-6: A wireless CCTV operated by PVMBG under maintenance [149]

3.4.1.3 Seismometer

The next sensor with the third highest bandwidth requirement is the seismometer. Figure 3-7 shows a seismic station operated by BMKG with a C-Band VSAT antenna. As described in the literature review in Chapter 2, seismometers operated by BMKG and PVMBG have quite a high sampling rate of 20-100 Hz and generate about 10 kbit/s of streaming traffic. At such a bandwidth requirement, the satellite L-Band or S-Band should be an ideal solution because of the less directional (hence less prone to earthquake) antenna. Cellular network should only be pursued if the nearby cell towers are certified to be earthquake proof.

It was mentioned in the GITEWS paper written in 2010, however, that using L-Band service such as BGAN or Iridium back then was too expensive hence the choice of C-Band VSAT [32]. According to a research paper benchmarking seismometer networks around the world, Indonesia is recommended to have around 750 to 2,500 seismic stations [150]. For new deployments, the cost of using L-Band or S-Band as compared to C-Band or higher should be further investigated, especially because directional antennas are more vulnerable to earthquakes which might affect the data transmission during critical times.

Figure 3-7: A typical seismic station operated by BMKG [26]

3.4.1.4 Tide Gauge, GNSS Station, Accelerometer, Intensity Meter

The next sensor is the tide gauges operated by BIG, which typically look like what is shown in Figure 3-8. These tide gauges currently use either C-Band VSAT, L-Band BGAN, and/or cellular 2G to transmit the hundreds of Bytes of data containing a radar gauge, pressure gauge, and a stilling well-connected shaft encoder [30] [32] [39] [40]. With such a small amount of data and manageable refresh rate, the satellite LPWAN would be more affordable when available. This option would also be a more reliable option compared to the C-Band VSAT that is currently being used in many of the tide gauge stations for the same reason of antenna direction vulnerability.

Figure 3-8: BIG's typical tide gauge station with a C-Band VSAT antenna, solar panels and radar gauge hanging by the roof [151]

The same argument is replicable for the accelerometers, intensity meters, and the GNSS stations. All these sensors output very small amount of data and they are critical for the tsunami early warning system. Therefore, satellite LPWAN should be preferable than cellular LPWAN due to the extra potential point of failure at the cell tower. Figure 3-9 shows a couple of typical GNSS stations operated by BIG.

Figure 3-9: BIG's GNSS reference stations [152]

3.4.1.5 AWS, AAWS, ARG, ASRS, Peatland Water Level Monitoring

For the automatic weather stations (AWS), agroclimate automatic weather stations (AAWS), automatic rain gauges (ARG), automatic solar radiation stations (ASRS), and the peatland water level monitoring system, the tolerance for data losses and delays is not as low as the sensors for InaTEWS. Therefore, whenever available, cellular LPWAN might be preferable over satellite LPWAN to save costs.

Figure 3-10: BMKG's automatic weather station (left) [153] and

BRG's peatland water level monitoring system (right) [76]

3.4.1.6 Tsunami Surface Buoy

Finally, the tsunami surface buoys should consider using satellite LPWAN when such service is available due to the very low data size. It would save costs compared to the currently used L-Band Iridium service. Unfortunately, the cell towers are too far from the surface buoy sites for them to be an alternative.

Figure 3-11: BPPT's tsunami surface buoy with its Iridium antenna [154]

Table 3-5 summarizes the recommended wireless technologies for all the sensors mentioned above. An important assumption here is that all the sensors are assumed to be deployed in separate sites. It might be common to co-locate some of the sensors and in this case, the bandwidth requirements have to be combined. Additionally, backup communication is not currently considered although it might be desirable, as in the case of the tide gauges developed by the GITEWS project [39]. When choosing a certain wireless communication technology, the continuity of such technology should also be considered. Phasing out of older technologies such as 2G might be inevitable.

Table 3-5: Summary of recommended wireless technologies for upstream

Sensor	**Recommended Wireless Technology**			
	1st Choice	**2nd Choice**	**3rd Choice**	**4th Choice**
Seismometer	L/S-Band	C-Band*	Ku/Ka-Band	3G / 4G / 5G
Accelerometer	Satellite LPWAN	L/S/C-Band	Cellular LPWAN	2G
Intensity Meter	Satellite LPWAN	L/S/C-Band	Cellular LPWAN	2G
GNSS Receiver	Satellite LPWAN	L/S/C-Band	Cellular LPWAN	2G*
Tide Gauge	Satellite LPWAN	L/S/C-Band*	Cellular LPWAN	2G*
Tsunami Surface Buoy	Satellite LPWAN	L/S-Band*		
Coastal HF Radar	L/S-Band	C-Band	Ku/Ka-Band	3G / 4G / 5G
Weather Radar	3G / 4G / 5G	Ku/Ka-Band	C-Band	
Automatic Weather Station	Cellular LPWAN	Satellite LPWAN	2G*	L/S-Band
Agroclimate Automatic Weather Station	Cellular LPWAN	Satellite LPWAN	2G*	L/S-Band
Automatic Rain Gauge	Cellular LPWAN	Satellite LPWAN	2G*	L/S-Band
Automatic Solar Radiation Station	Cellular LPWAN	Satellite LPWAN	2G*	L/S-Band
Peatland Water Level Monitoring System	Cellular LPWAN	Satellite LPWAN	2G*	L/S-Band
Thermal Imager	3G / 4G / 5G	C-Band	Ku/Ka-Band	
CCTV Camera	3G / 4G / 5G	C-Band	Ku/Ka-Band	

* means currently used technology

3.4.2 Downstream

Wireless communication technology can help in disseminating information in generally two ways: (1) concise and time-critical, and (2) elaborate and less time-critical. For time-critical applications like tsunami and earthquake early warnings, alerts are usually made as concise and as clear as possible to save the time to react. However, elaborate information is also important for the community at risk, the local officials, and even people outside the risk area to understand what might be happening. Once a disaster event is over, this information is also very important for public learning and for improving the early warning system.

SatCom can play a vital role in delivering time-critical alerts, due to its nature of not having to rely on any intermediary stations like the cell towers. Power outage and earthquakes are sources of vulnerability for cell towers. In Section 3.3.2, various output devices and wireless communication technologies for delivering alerts have been compared among various criteria. In this section, these technologies will be scored and ranked against each other. Before that, however, because each criterion might not be equally important, the first step would be to assign weights to these criteria. The analytic hierarchy process (AHP) is one way to do that. Figure 3-12 shows the decision-making hierarchy. The first tier is the objective, second tier is the criteria, third tier is the wireless communication link, and fourth tier is the output devices.

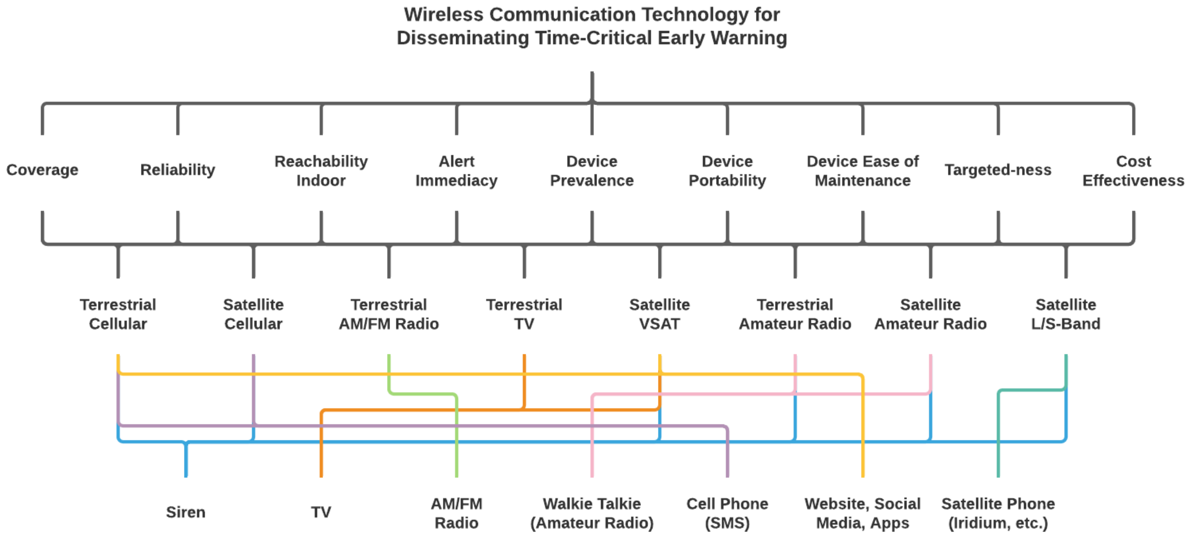


Figure 3-12: Hierarchy for choosing downstream wireless communication technology

First, a pair-wise comparison matrix is made to assess the relative importance among the criteria as shown in Table 3-6. Each cell is read as “How important is row x with respect to column y”. The scale used is the same as was proposed in the original AHP paper, i.e. 1 (equal importance), 3 (moderate importance), 5 (strong importance), 7 (very strong importance), 9 (extreme importance), and 2, 4, 6, 8 for intermediate values. The weights are obtained by solving the principal eigenvector of the matrix and then normalizing the result. Finally, the overall scores of each technology are calculated according to the weights. The consistency ratio of the matrix in Table 3-6 is 0.049, which satisfies the recommended value of less than 0.10.

Table 3-6: Relative importance of wireless communication criteria and the resulting weights

	Coverage	**Reliability**	**Reachability Indoor**	**Alert Immediacy**	**Device Prevalence**	**Device Portability**	**Device Ease of Maintenance**	**Targeted-ness**	**Cost Effectiveness**	**Weight**
Coverage	1	1/5	1/5	1/5	1/5	1	1/3	3	3	4.72%
Reliability	5	1	1	1	1	7	3	7	7	20.25%
Reachability Indoor	5	1	1	1	1	5	3	7	5	18.67%
Alert Immediacy	5	1	1	1	5	5	3	7	7	24.13%
Device Prevalence	5	1	1	1/5	1	3	3	5	3	14.42%
Device Portability	1	1/7	1/5	1/5	1/3	3	1	3	3	4.01%
Device Ease of Maintenance	3	1/3	1/3	1/3	1/3	3	1	3	3	8.04%
Targeted-ness	1/3	1/7	1/5	1/7	1/3	1	1/3	3	1	2.20%
Cost Effectiveness	1/3	1/7	1/5	1/7	1/3	1	1/3	3	1	3.57%

Table 3-7: Comparison of wireless communication technology for disseminating time-critical early warning (scored)

Output Device	**Wireless Link**	**Coverage**	**Reliability**	**Reachability Indoor**	**Alert Immediacy**	**Device Prevalence**	**Device Portability**	**Device Ease of Maintenance**	**Targeted-ness**	**Cost Effectiveness**	**Score**
		4.7%	**20.3%**	**18.7%**	**24.1%**	**14.4%**	**4.0%**	**8.0%**	**2.2%**	**3.6%**	
Siren	Terrestrial Cellular	3	2	5	6	2	1	1	6	2	**3.54**
	Terrestrial Amateur Radio	1	3	5	6	2	1	1	6	2	**3.65**
	Satellite Amateur Radio	6	6	5	6	2	1	1	6	2	**4.49**
	Satellite L/S-Band	6	6	5	6	2	1	1	6	1	**4.46**
	Satellite VSAT	6	4	5	6	2	1	1	6	1	**4.05**
	Satellite Cellular	6	6	5	6	2	1	1	6	1	**4.46**
TV	Terrestrial TV	2	3	6	5	5	1	5	4	5	**4.46**
	Satellite VSAT	6	4	6	5	4	1	5	4	5	**4.70**
AM/FM Radio	Terrestrial AM/FM Radio	2	3	6	5	4	3	5	4	5	**4.39**
Walkie Talkie (Amateur Radio)	Terrestrial Amateur Radio	1	3	4	4	3	4	5	4	5	**3.63**
	Satellite Amateur Radio	6	6	1	4	3	4	5	4	5	**3.91**
Amateur Radio Station	Terrestrial Amateur Radio	1	3	6	4	2	1	3	4	5	**3.58**
	Satellite Amateur Radio	6	6	6	4	2	1	3	4	5	**4.42**
Cell Phone (SMS)	Terrestrial Cellular	3	2	6	6	6	6	6	6	6	**5.05**
	Satellite Cellular	6	6	1	6	6	6	6	6	6	**5.07**
Website, Social Media, Apps	Terrestrial Cellular	3	2	6	1	5	6	6	1	6	**3.59**
	Satellite VSAT	6	4	6	1	3	6	6	1	6	**3.85**
Satellite Phone	Satellite L/S-Band	6	6	1	4	1	4	5	6	3	**3.60**

Table 3-8: Wireless communication technology for disseminating time-critical early warning (ranked)

Output Device	**Wireless Communication Link**	**Score**
Cell Phone (SMS)	Terrestrial Cellular	5.07
Cell Phone (SMS)	Satellite Cellular	5.05
TV	Satellite VSAT	4.70
Siren	Satellite Amateur Radio	4.49
TV	Terrestrial TV	4.46
Siren	Satellite L/S-Band	4.46
Siren	Satellite Cellular	4.46
Amateur Radio Station	Satellite Amateur Radio	4.42
AM/FM Radio	Terrestrial AM/FM Radio	4.39
Siren	Satellite VSAT	4.05
Walkie Talkie (Amateur Radio)	Satellite Amateur Radio	3.91
Website, Social Media, Apps	Satellite VSAT	3.85
Siren	Terrestrial Amateur Radio	3.65
Amateur Radio Station	Terrestrial Amateur Radio	3.58
Walkie Talkie (Amateur Radio)	Terrestrial Amateur Radio	3.63
Satellite Phone	Satellite L/S-Band	3.60
Website, Social Media, Apps	Terrestrial Cellular	3.59
Siren	Terrestrial Cellular	3.54

Table 3-7 and Table 3-8 show some interesting results. The following paragraphs will discuss the effectivity of each wireless communication technology based on the exercise above and make some recommendations.

3.4.2.1 Siren

Sirens are a very effective way to alert everyone within its vicinity. However, there are a few limitations to the currently deployed sirens. The sirens of InaTEWS currently use satellite VSAT to receive warning messages. In some cases, including during the Palu Tsunami, the standard operating procedure was for a BPBD officer to activate the siren manually after receiving the warning message from BMKG's InaTEWS operations center [45].

As shown in Table 3-7, technically sirens can be activated remotely over different wireless technologies with a simple string of message. A satellite VSAT system for sirens is not ideal because of its directional antenna and its generally higher power to run. Power outage is often inevitable and the backup power would only have so much time to maintain the system's power. Therefore, it would be more reliable to use a wireless communication system that uses an omnidirectional antenna and less power such as satellite L/S-Band like Iridium, Inmarsat, Thuraya, or Globalstar or upcoming technologies such as satellite cellular or satellite amateur radio. Additionally, it's important to regularly maintain the system and reduce any extra potential points of failure like the siren in Palu.

3.4.2.2 TV and AM/FM Radio

Broadcast wireless technologies like TV and AM/FM radio can be very helpful in disseminating early warning because of the prevalence of these devices and their nature of daily usage. Additionally, these devices are able to output much more information than a siren or an SMS message. Satellite TVs might be more likely to receive warnings than terrestrial TVs, due to the extra vulnerability of the nearby TV station tower. However, satellite TVs use directional VSAT antenna which is also prone to earthquakes. Additionally, power backup is also required because TVs are generally not battery operated.

AM/FM radios that are portable or hosted in cars and other vehicles can potentially receive warnings more easily because of their battery operability and antenna's omnidirectionality. However, similar to terrestrial TVs, the radio tower is be a source of vulnerability. Unfortunately, satellite radio services like Sirius XM in the United States do not seem to be common in Indonesia.

3.4.2.3 Amateur Radio Devices

The amateur radio community in Indonesia is well-known for actively helping in difficult times such as natural disasters. Both voice and text (and picture sometimes) can be exchanged over the amateur radio frequencies over terrestrial or satellite repeaters. Walkie talkies have the advantage of being portable and power efficient. Amateur radio stations with antenna mounted on the rooftop have the advantage of being able to receive warnings indoor. Similar to terrestrial TV and AM/FM radio, terrestrial amateur radio repeaters might be prone to earthquakes. But today's satellite technology, e.g. LAPAN-A2, does not cover the country 24/7 and therefore is not suitable for delivering early warnings. However, LAPAN's new satellite constellation project has the potential to do exactly that.

3.4.2.4 Satellite Phone

L-Band satellite services such as from Inmarsat, Iridium, Thuraya, and Globalstar provide voice and text services to their respective proprietary satellite phones. The phones are portable and battery operated, and they can receive messages and calls from anywhere without relying on any terrestrial infrastructure that might be prone to natural disasters. Unfortunately, the price tag is still high, and the use case is not as prevalent as other devices like cell phones or TVs or even amateur radio devices. However, because of the advantage in operability regardless of any natural hazards, it would be a good idea if selected number of local officials can own such a satellite phone.

3.4.2.5 Cell Phone

As shown in Table 3-8, cell phone ranks the highest among all other devices. This is because of its significant prevalence, portability, and ease of maintenance. Additionally, since most people are close to where their cell phones are, the likelihood to notice an alert immediately is higher than one coming out from other devices. However, it also has a source of vulnerability similar to all other terrestrial services, which is the cell tower. Cell towers have to be structurally strong and accompanied with a power backup system.

Satellite GSM based text message technology was recently demonstrated in February 2020. This new technology can be very helpful because unlike L-Band based satellite phones, the satellite can deliver a message directly to standard cell phones. The drawback is similar to L-Band satellite phones, it will not work indoors. However, if satellite GSM service is made available 24/7, it can be a great complement to existing terrestrial cellular networks.

3.4.2.6 Website, Social Media, and Apps

Website, social media, and apps can be accessed from various devices such as home and office computers, laptops, tablets, and cell phones. They are a very good medium for delivering elaborate content to as many people as possible, especially since more and more people are connected to the internet from their cell phones. These media, however, are not ideal for delivering time-critical warning messages. Firstly, not everyone owns or accesses BMKG's app, website, and social media. Secondly, those who own such an app might not activate the push notification. These media require internet to work, therefore they depend on which internet service the users choose. Satellite VSAT based internet might have an advantage in terms of reliability, but power backup must be available.

To summarize, there is no silver bullet when it comes to disseminating time-critical warnings. Every technology has its own benefits and drawbacks. Whenever possible and financially feasible, terrestrial base stations should be made earthquake-proof and provided a power backup system. For cell towers, this has been a regulated requirement since 2009 [4]. Lastly, devices such as sirens should prioritize satellite services that allow omnidirectional antennas, because VSAT antennas are more prone to natural disasters.

3.5 Toward a Sustainable Early Warning System

To be able to use the best technologies that fulfill all the criteria would be a remarkable achievement. However, it is only half of the story. Learning from InaTEWS development and operations over the past 15 years, there are various ongoing challenges in all aspects of the early warning system, but can essentially be categorized into two: (1) awareness/preparedness among the communities at risk on how to respond and what to expect from the early warning system, and (2) sustainable operations, maintenance, and upgrade of the system.

As mentioned in the research publications on GITEWS/InaTEWS, the key challenges behind the lack of awareness/preparedness among the local communities still lie in the lack of national guidance and political will at the local government levels [155]. Capacity building programs have since the beginning been identified to be an important aspect of the GITEWS project [156]. Until the closure of the GITEWS and the subsequent project called PROTECTS (Project for Training, Education and Consulting for Tsunami Early Warning Systems) in 2014, more than 192 training courses have been conducted. This included local disaster mitigation programs such as developing preparedness and strategies at the local administration level in areas at risk. However, according to a report in 2017, only 5 out of 26 districts and provinces at risk have managed to establish solid mechanism and procedures on responding to warnings [27].

A national effort on disaster risk reduction in Indonesia is relatively new, with a disaster management law only introduced in 2007 and the BNPB only formed in 2008. Indonesia also adopts decentralized governance, which means the responsibility for public service at a certain municipal area belongs to the local government. The implication here is that the quality for public service delivery can be different from one city to another, including disaster risk reduction. Not every local government has enough budget and political will to invest in such systems and programs.

When a public warning service at the local level is lacking, many civil society organizations such as the Indonesian Red Cross, the Tsunami Alert Community (KOGAMI), and other local NGOs operate to promote awareness and preparedness at the grassroots level [157]. Although such a strong civic engagement is very helpful, most still opt to educate based on natural warning signs rather than technology-based early warning [155]. The lack of linkage between civic engagement activities and the formal government early warning system is also mentioned in a recent comprehensive study by Sufri et al, who provided a systematic review of community engagement in disaster early warning systems in low and middle income countries including Indonesia [158].

Concurrent to the challenge of awareness and preparedness, there is also the challenge of sustainably operating, maintaining, and upgrading the early warning system. BMKG as the operator of InaTEWS does not currently have enough budget to maintain all instruments annually, not to mention that more and more instruments will have to be installed. Additionally, vandalism is sometimes inevitable. In the case of the early tsunami buoys, for example, they regularly became damaged because they were often used as mooring place for fishing activities and in extreme cases led to a total loss [27]. Such vandalism, however, is a general problem worldwide [159].

In such situation where public service capacity is limited, one idea would be to leverage on volunteers through civic or community engagement with a touch of incentives such as certificates and public recognition or social status.

The activity to engage non-experts in a technical setting is analogous to citizen science. Citizen science programs commonly include a range of activities from collecting data to collaborative science research [160]. Citizen science has turned out to be successful both for the scientists as reflected in the thousands of academic publications and for the participants, as it strengthens the bond between science and society through the ‘democratization’ of science [161] [162] [163].

Applying these concepts to integrate early warning systems in the society might be a good idea, especially when public service capacity is limited like in Indonesia. The kind of activities can range from the deployment, operation, maintenance, to the upgrade of the instruments making up the early warning systems, from the sensors to the output devices such as sirens. To add some control on quality, data security, and sense of ownership, conducting a formal selection process and offering official titles can be considered. The details of how such program should be run is beyond the scope of this thesis, but such a civic engagement program can be very powerful when it is well executed.

To ensure sustainability, transfer of knowledge is also mandatory. Such a civic engagement program could, for example, borrow the concept of open-source community, where people engage in public online forums to exchange information and the active contributors are rewarded with high reputation.

This idea still has to be explored and investigated further, especially because the larger Indonesian community may not be familiar with the concept of citizen science. However, if there is one country that should leverage their society in public services, it ought to be Indonesia as the country ranks the highest among 146 surveyed countries for Civic Engagement Index, according to Gallup World Poll in 2017/2018 on the World's Most Generous Countries [164]. Other countries with comparatively high scores are Australia, New Zealand, United States, Ireland, United Kingdom, Singapore, Kenya, Myanmar, and Bahrain. Additionally, when only 18% people worldwide on average are likely to volunteer their time to an organization, Indonesia ranks the highest with 53%. As a comparison, Australia and New Zealand scores 40% whereas United States and Singapore scores 39%.

There are already some successful examples of civic engagement in the public service in Indonesia. Statistics Indonesia, for example, recruits more than 300 volunteers to help them in conducting the 2020 national census [165]. Civic engagement requiring more specialized technical skills has been promising as well. For example, the collaboration between the Indonesian space agency, LAPAN, and the national amateur radio community, ORARI. Since 2016, radio amateurs throughout Indonesia have been actively involved in using the LAPAN-A2 satellite as a nation-wide amateur radio voice repeater during disasters, including major earthquakes in Lombok and Palu in 2018 and a more recent extreme flood in North Luwu [102] [166].

A civic engagement program in the realms of technical deployment, operations, maintenance, and upgrade of early warning systems has the potential of not only helping the government in sharing the cost, time, and responsibility, but also bridging the technology divide in the society and solidifying their trust in technology-based early warnings. A holistic approach in designing and evaluating sustainable early warning systems can be summarized with the integrated EVDT model as shown in Figure 3-13.

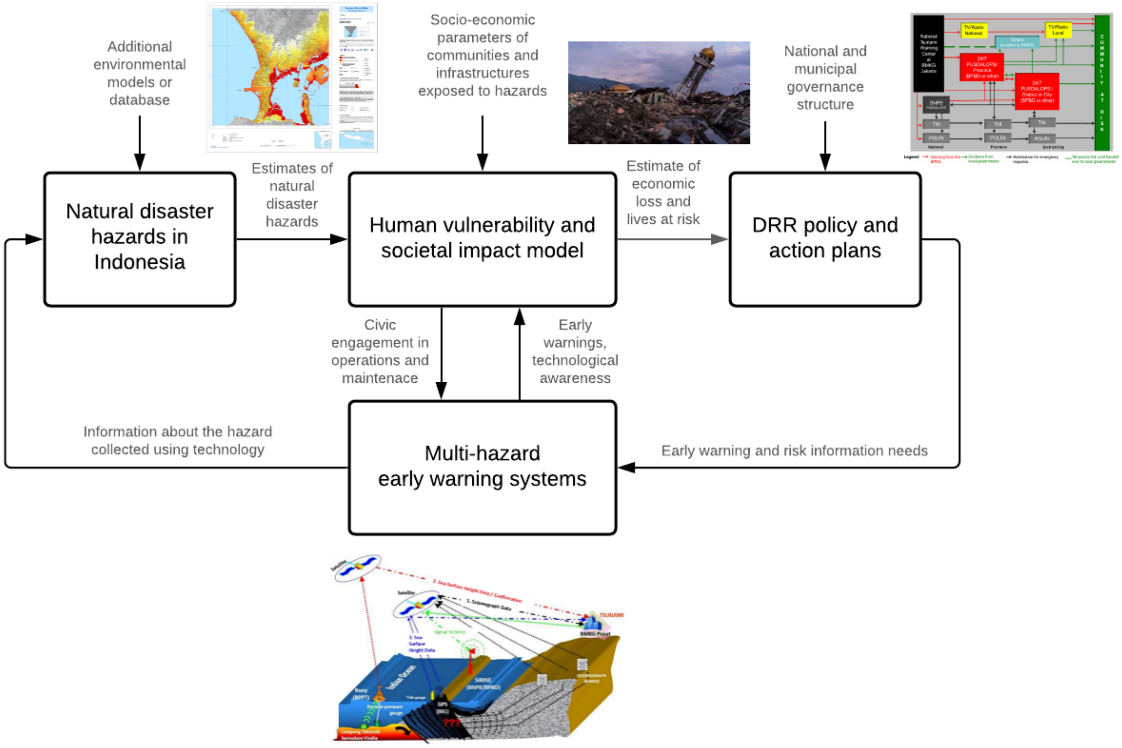


Figure 3-13: EVDT model for early warning systems

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Chapter 4

Conclusion

This chapter summarizes the findings throughout the thesis, proposes some recommendations for the stakeholders of early warning systems in Indonesia and suggests some ideas for future work.

4.1 Conclusion and Recommendation for Stakeholders

The objective of this research is to evaluate the communication architecture of currently deployed early warning systems in Indonesia and propose improvements for better reliability and cost-effectiveness.

Through this research, it is found that development of early warning systems in Indonesia started as early as 2005 after the devastating Indian ocean tsunami. With the help of German researchers and other international collaborators, InaTEWS became one of the best nationwide tsunami early warning systems. Over the past decade, there has also been several significant developments for other natural disasters, including volcanic activities, hydrometeorological disasters and wildfires. These developments are far from sufficient, however, as the country still suffer from major disasters as described in Section 2.1.

Communication technology is the backbone of successful detection and delivery of early warnings. Millions of lives at risk depend on this technology. Whenever it fails, it does not only cause more damages, but also erodes people's trust in technology and public service. For a country like Indonesia that often lacks the budget for high fidelity technologies, cost is an important factor. It is sometimes not enough to argue that investment in early warning systems saves more money in the long run than providing disaster reliefs.

Due to Indonesia's geographical characteristics, satellite communication has been an integral part of the country since the 1970s, and thanks to the development of recent technologies, satellite connectivity of various bandwidths is getting cheaper while still providing connectivity in remote areas. With such a promise, it is expected that in the next several years adoption of satellite connectivity will increase more rapidly. Operators and other stakeholders of early warning systems in Indonesia should take advantage of these recent developments.

The following list summarizes the recommendation for the relevant stakeholders, including the Meteorological, Climatological, and Geophysical Agency (BMKG), the Center for Volcanology and Geological Hazard Mitigation (PVMBG), the Ministry of Environment and Forestry (KLHK), the Peatland Restoration Agency (BRG), the National Disaster Management Agency (BNPB), and the National Institute of Aeronautics and Space (LAPAN):

1. Table 3-5 provides a summary of the recommended wireless communication technology for remotely collecting sensor data. The requirements of the sensors are listed in Table 3-4 and the comparison among the available communication technologies is shown in Table 3-2.
2. Table 3-8 provides a summary of the recommended wireless communication technology for delivering warning information. The technologies are scored based on a comparison matrix that is shown in Table 3-7.
3. As reflected in these tables, analysis results show that satellite communication technology plays a critical role. LAPAN's plan for deploying an equatorial constellation is a strategic step that has the potential to benefit millions of lives. As shown in Table 3-5, LPWAN and L-band or S-band technologies are desirable for most of the sensors. Hence, it is recommended that LAPAN consider these technologies in the design of their satellites. Additionally, these are the technologies that Indonesia's locally owned

satellites are lacking, unlike C-band and Ku-band. Satellite LPWAN is very new and it has only been demonstrated in the past year. Due to the nature of satellite orbits, however, international adoption is expected to grow rapidly. By having LPWAN on its equatorial constellation, LAPAN has the potential to be one of the firsts in the world to provide such connectivity, which can be beneficial for other equatorial countries as well. Satellite communication is also highly recommended for warning information delivery. As shown in Table 3-8, LAPAN's equatorial constellation might want to consider L-band, S-band, amateur radio, and/or the cellular GSM frequency for this purpose. The recently demonstrated satellite GSM is very promising and can be a vital backup in the case of terrestrial cellular network outage. This technology is also very new and was only demonstrated less than a year ago. Adopting this technology on LAPAN's constellation will allow Indonesia to be one of the first countries to benefit from such service with the potential of sharing the service to other equatorial countries.

4. It should be noted that although the analysis provided in this thesis is a good start for selecting the right technology, more detailed analysis for optimum performance and cost is recommended. For upstream, the exact transmit size and interval should be calculated at the hardware level. Some stations might have more than one sensor and so pooling the data into one communication channel might be desirable. Additionally, on-site data compression, whenever possible, can be considered to save bandwidth. A good balance between data clarity and bandwidth usage is worth investigating. Another area requiring further investigation is the spatial distribution of the sensors. A multi-objective optimization at the nationwide level is recommended to balance the sensor density, path diversity, bandwidth usage, cost, and risk profile. There can be a significant performance improvement and cost savings when optimization is done at such a system level. Some other things to consider include the cost of maintenance, the cost of upgrading, and the lifetime of the technology. These considerations might not give an immediate benefit but will be impactful for the long term.

5. Although different agencies might be interested in different natural disaster hazards, the underlying monitoring and communication technology have a lot of similarities. Hence, cross-agency resource optimization is also worth considering. This way, knowledge sharing among the agencies would be enabled. Having a platform where all the agencies can have regular knowledge and technology transfer would be highly valuable.
6. Streamlining the communication chain, whenever possible, is highly recommended. In general, having more parallel channels (path diversity) is better than having more serial connections for the sake of reliability. In the case of InaTEWS' warning chain, for example, having an on-site officer to manually activate the siren creates a point of failure, as evidenced during the Palu Tsunami in 2018.
7. Lastly, it is important to have a periodical evaluation of the technologies that are in place. The chosen technology might not be the best at the first attempt, but with constant evaluation and improvement, the result will be better, especially as innovation keeps pushing the technology envelope. In doing this, relevant agencies can consider involving other parties, such as the universities and local communities. Engaging local communities in the technical deployment, operations, maintenance, and upgrade of early warning systems will help in bridging the technology trust gap in addition to helping the government agencies in sharing the cost, time, and responsibility.

Risk is a factor of hazard, exposure, and vulnerability. At the end of the day, however, technology is only one way to reduce vulnerability. For a country like Indonesia that has a large population and large number of natural disaster hazards, however, it is probably the only option. Having reliable early warning systems will save millions of lives and valuable assets. Such investments will outweigh the cost of disaster reliefs and make Indonesia a more inclusive, safe, resilient, and sustainable country, in line with United Nations' SDG#11.

4.2 Future Work

There are several directions that this thesis can be used as a basis for future research. First of all, a “deep-dive” analysis where a more exact set of data is used is possible as suggested in item 4 of the previous section. In order to do this, field data such as the hardware specifications must be available. Early engagement of stakeholders is recommended, especially within the department of IT, Data, Instrumentation, and Communication Network.

A second possible direction is to focus on new technologies such as satellite-based LPWAN and compression techniques. New compression techniques may be beneficial for making satellite communication more affordable and widely available for everyone. The raw bandwidth requirement for various sensors shown in this thesis can be a start for such research.

As communication technology is getting more and more cost-effective, as evidenced by the rise of LPWAN, so is sensing technology. Because in general having denser network of sensors will provide better results, deploying sensors at a large scale will be possible with low-cost sensors. It would be interesting to explore the possibility to deploy thousands of small and low-cost GNSS buoys, for example, to characterize the sea waves in real time. With low-cost satellite LPWAN as the means of communication, this would be feasible because of economies of scale. Designing such a distributed system will require technical analyses in the field of both communication and instrumentation. This thesis provides initial analysis of the communication aspect for such deployment.

Another way to improve this thesis is the inclusion of other sources of data for early warning systems. As explained in Chapter 1, the scope of this thesis focuses on terrestrially deployed sensors. Airborne and spaceborne remote sensing technologies are getting better and are worth investigating to either complement or even replace terrestrial sensors. Higher data source diversity can provide more validation and hence higher reliability of the system overall. The system architecture framework is applicable for analyzing and evaluating the performance of these technologies as well. Technical requirements such as area and parameters to be monitored should be considered.

Finally, providing an understanding of the natural disaster hazards through monitoring technologies is only partially useful. Such information should be well-integrated with data such as social and economic vulnerability of communities at risk. Together, a holistic and integrated multi-hazard risk assessment will make it easier for policymakers to form better policies. Therefore, a potential research direction is to combine technical analysis provided in this thesis with analysis of the social and economic conditions in Indonesia. Alternative to nation-wide analysis, scoping the research to specific type of natural hazards or specific area would also be useful. As summarized in Table 2-1, some natural hazards are more prominent in certain areas of the country, for example. In this case, choosing the research target based on the historical impact and damage would be interesting.

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