THE CHARACTERISTICS OF AN INTEGRATED FLOOD WARNING AND RESPONSE SYSTEM THAT CAN FACILITATE EVIDENCE-BASED DECISION MAKING: A CASE STUDY IN SRI LANKA

Srimal Samansiri

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Dedication

I dedicate this thesis to those who have lost their lives in disasters. May our work in advancing warning systems contribute to a safer and more resilient world for all…

Declaration

I declare that the research contained in this thesis was solely carried out by me. It has not been previously submitted in this or any other institute for the award of a degree or any other qualification.

Abbreviations

ADPC	Asian Disaster Preparedness Centre
BPM	Business Process Management
BPMN	Business Process Model and Notation
CAP	Common Alert Protocol
CBO	Community Based Organisation
CDR	Call Detail Records
CEA	Central Environment Authority
CEB	Ceylon Electricity Board
CFF	Critical Failure Factors
CRED	Centre for Research on the Epidemiology of Disasters
CREWS	Climate Risk and Early Warning Systems
CRIP	Climate Resilience Improve,emt Program
DDMCU	District Disaster Management Coordinating Unit
DEM	Digital Elevation Model
DEWN	Disaster Early Warning Network
DFD	Dat Flow Diagram
DMC	Disaster Management Centre
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
DSR	Design Science Research
EA	Enterprise Architechture
ECMWF	European Centre for Medium-Range Weather Forecasts
EFAS	European Flood Awareness System
EOC	Emergency Operation Centre
FEWRS	Flood Early Warning and Response System
FFC	Flood Forecasting Centre
GFDRR	Global Facility for Disaster Reduction and Recovery
GIS	Geographic Information System
HTTP	Hypertext Transfer Protocol
IDNDR	International Decade for Natural Disaster Reduction
IFRC	International Federation of Red Cross and Red Crescent Societies
IS	Information Systtems
ISM	Interpretive structural modelling
ML	Machine Learning
NBRO	National Building Research Organisation
NDRSC	National Disaster Relief Services Centre
NEOP	National Emergency Operation Plan
NSDI	National Spatial Data Infrastructure
NWP	Numerical Weather Prediction
OGC	Open Geospatial Consortium
OSM	OpenStreetMap
RS	Remote Sensing
SOA	Service Oriented architecture
TOGAF	The Open Group Architecture Framework

TRMM	Tropical Rainfall Measuring Mission
UK	United Kingdom
USGS	United States Geological Survey
WGS84	World Geodetic System 1984
WMO	World Meteorological Organization
WRF	Weather Research & Forecasting Model

Abstract

Flood is a frequently occurring hazard that imposes adverse effects on a significant number of human lives and causes substantial economic damage worldwide. Flood frequency and impact have increased drastically due to climate change issues and unplanned development in the recent past. It is observed that the number of victims due to floods is rising, hence, flood early warning and response systems (FEWRS) are very crucial in developing risk reduction strategies. Studies show that effective forecasting, warning, and response systems based on accurate real-time intelligence on disasters can reduce up to 35% of the average annual flood damage and by deploying a proper early warning and response system can reduce vulnerability and mortality rates. Even though an effective flood early warning and response system (FEWRS) is considered an essential tool for effective flood risk management and emergency response, no single operational solution that is applicable universally has been developed and implemented. There is a considerable gap in implementing a successful warning and response system due to a lack of policies, sound technological solutions and community engagement.

This research aims to investigate the characteristics of a system architecture that can be used to develop an effective flood warning and response system (FEWRS) which can offer timely intelligence to decision-makers. In addition, the research also aims to investigate additional social, institutional and governance issues that need to be addressed to extract the benefits of such an architecture. The Design Science Research (DSR) approach was used in this research to investigate the problem, capture user requirements, conduct artefact design and validation. Initially, the study conducted a structured literature survey to investigate the intelligence required for flood warning and response processes and the technology solutions that can offer such intelligence. Twenty-seven types of intelligence were identified, together with the technologies that can be used to extract such intelligence. Building on this literature findings, experts from government organisations, civil society organisations and community representatives, who are engaged with the flood warning and response activities in the Sri Lankan context, were interviewed to identify the characteristics of a system architecture for an effective FEWRS. These requirements were captured under multiple views such as process view, data view, technology view, stakeholder view, interface view, and usage scenario view. These views were used to define a modular architecture, loosely coupled with different components to enable an end-to-end, people-centric warning system. Although Sri Lanka was used as the basis for analysing the user requirements, the architecture was then generalised for other similar country contexts.

In addition, the study conducted a structured literature survey to investigate the possible failure factors of FEWRS, which need to be addressed to implement the proposed architecture successfully. The result shows twenty-four critical failure factors (CFF) that impact the success of implementing a successful flood warning and response process. Therefore, the study proposes several recommendations and guidelines for successfully addressing limitations in institutional leadership, multi-agency collaboration, data governance, community engagement and lack of funding to implement the proposed architecture within a multi-agency context.

Keywords: Flood warning and response system, Situational Intelligence, Climate Change, Disaster Risk Reduction, Enterprise Architecture

Chapter 1 Introduction

1.1 Motivation

Floods are a recurrent natural hazard that adversely impacts the human population and cause substantial economic losses globally. Evidently, they constituted 43% of the spectrum of recorded disasters during the period between 1998 and 2017, as reported in the collaborative report from the Centre for Research on the Epidemiology of Disasters (CRED) and the United Nations Office for Disaster Risk Reduction. Floods accounted for an affected population of 2 billion and 142,000 deaths during the above reporting period (Wallemacq et al., 2018). Recently, the frequency of floods and their impact have been increasing drastically due to climate change issues and unplanned urban development (Bronstert, 2003; Knox, 2000).

The EMDAT-derived data further indicates that floods are the most prominent disasters, and their trend has been increasing recently (Figure 1). For example, in 2020/21, floods dominated as the most frequent disaster globally, with 223 occurrences. This is well above the average of 163 annual flood occurrences recorded during 2001-2020. Some of these events are noteworthy for their high mortality and economic losses, as reported in the CRED (CRED, 2022).

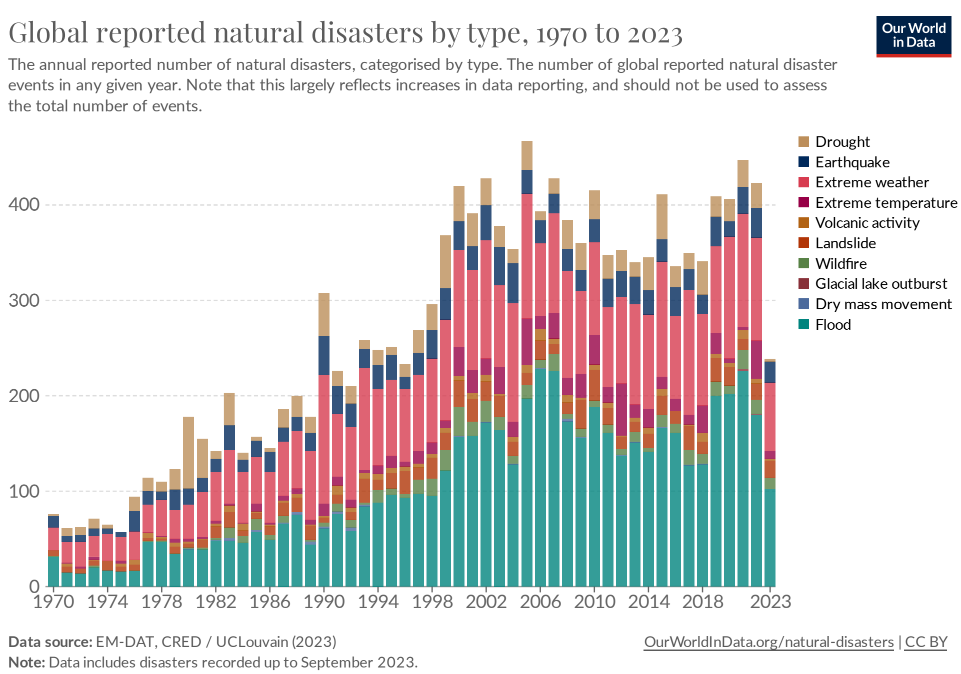


Figure 1: Global reported natural disasters by type from 1970 to 2023. (Source: CRED, 2022)

Further to that, Panwar and Sen (2019) suggested that the economic impact of natural disasters such as floods is more prominent in developing countries. CRED/UNISDR reports that deaths by natural disasters in low-income countries are seven times higher than those in high-income countries (Wallemacq et al., 2018). Moreover, the key drivers behind the increased losses have been identified as population growth and rapid urbanisation (Bouwer, 2011; Hoeppe, 2016).

These losses and casualties can significantly be reduced with the implementation of flood early warning and response systems (FEWRS) in these countries (Hammood et al., 2020). The Sendai Framework for Disaster Risk Reduction (SFDRR) emphasises the need to have sound multi-hazard warning systems and disaster risk information available to the community by the end of 2030. SFDRR promotes member countries' integrated and coordinated approach to "generate, process and disseminate" disaster risk information using state-of-art technologies as a priority action (UNISDR, 2015). According to the UN, an early warning system is defined as "an integrated system of hazard monitoring, forecasting, communication and preparedness activities, systems and processes that enable individuals, communities, government business and others to take timely action to reduce disaster risks in advance of hazardous events" (UNISDR, 2016). Considering increasing damages and losses by natural and man-made disasters, in November 2022, the United Nations Secretary-General formally inaugurated the "Early Warning for All" as a five-year programme to ensure that everyone on earth is protected by early warning and dissemination systems (WMO, 2022). Therefore, the implementation of the Flood Early Warning and Response System (FEWRS) has been identified as an essential strategy to reduce the inreasing trennd of the flood impact.

An end-to-end, people-centred warning system should comprise elements such as (i) risk knowledge, (ii) a monitoring and warning service, (iii) communication and dissemination, and (iv) an emergency response capacity (UN, 2006). These components must be associated with the appropriate legal and policy framework, institutional coordination, appropriate funding and resource allocation, continuous monitoring and feedback mechanisms, and up-to-date tools and technologies (Dutta & Basnayake, 2018). Basher (2006) suggested that political commitments and institutional capacities are important, and public awareness and participation are essential to sustain an early warning system in the long run.

Studies show that an effective forecast and warning system based on accurate real-time intelligence on disasters can reduce up to 35% of the average annual flood damage (Rogers, 2010). Deploying a proper early warning and response system can reduce vulnerability and mortality rates (Seng, 2012). Comfort et al. (2004) also suggested that access to core information can enhance the efficiency and effectiveness of disaster responses and coordination. Keoduangsine and Goodwin (2012) argued that deaths are higher due to the ineffectiveness of warning systems, which can further enhance as a result of bureaucratic water management and digital divide-related issues. In (Prasanna et al., 2013), the authors suggested that information systems play a critical role in decision-making during emergencies. Hammood et al. (2020) argued that a lack of information leads to the unsuccessful implementation of FEWRSs. Information System (IS) quality, information quality, user satisfaction, service quality, and use are considered major success factors in successfully implementing FEWRSs (Hammood et al., 2020).

Information and intelligence are crucial in the disaster preparedness and response phases (UNISDR, 2015). A broad range of technologies are used to capture, process and disseminate intelligence concerning warning and response by integrating multiple, loosely coupled Systems of Systems (SoS). Novel technology and tools such as the Internet of Things (IoT) (Asnaning & Putra, 2018), big data (Yu et al., 2018), and near-real-time satellite data (Ajmar et al., 2016) are used to detect floods. In contrast, integrated information systems (Fang et al., 2015; Turoff et al., 2004), geographic information systems (GIS) (Tomaszewski et al., 2015) and simulation techniques (Eldho et al., 2018) are used to process and generate early warnings. Crowdsource technologies, including social media (Zhang et al., 2019), mobile applications (Bachmann et al., 2015), and volunteer GIS (Castanhari et al., 2016) are examples of community engagement in reporting incidents.

Even though novel technologies are available, numerous challenges and gaps still exist in the flood warning and response process. Countries still lack the availability of appropriate intelligence for evidence-based decision-making. Previous studies have suggested that disaster response will be adversely impacted by both insufficient information sharing and inter-agency coordination (Bharosa & Janssen, 2009; Bharosa et al., 2010; Thompson et al., 2006; Waring et al., 2020). The need for coordination in disaster management is indispensable. Lack of coordination leads to several possible failures, such as false early warnings and evacuations, inappropriate allocation of resources for response, and delayed search and rescue operations, which often result in crisis escalation and higher numbers of casualties. The lack of understanding between Information System Architectures (ISA), emergency responders and coordination authorities leads to issues in warning and response-related information system development and implementation (Prasanna et al., 2017).

Several studies have been conducted to investigate the effectiveness of the FEWRS from warning generation to dissemination. Parker and Fordham (1996) suggest a "stage development model", a maturity model that proposes 14 criteria to assess the effectiveness of the FEWRS. In (Duminda Perera et al., 2020; Perera et al., 2019), the state-of-the-art FEWRS has been evaluated from 53 countries through primary data collection, where numerous challenges and gaps have been identified from the policy, technical, financial and social angles. Hammood et al. (2021), from another research, suggest that the DeLeone and McLean (D&M) model is suitable for assessing the effectiveness of FEWRS. In addition to the above studies, various authors (Nieland & Mushtaq, 2016; Owen & Wendell, 1981; Rana et al., 2020) have also touched on numerous aspects of flood warning and response systems. In (Owen & Wendell, 1981) the authors argue that facts such as comprehensiveness, realism, reliability, accuracy and timeliness play a critical role in making a flood warning system successful. In (Rana et al., 2020), a study from Pakistan, the authors suggest that a lack of resources to keep an Early Warning (EW) system operational, community trust, and guidelines for warning dissemination are critical to making such systems successful.

From the system architecture perspective of the FEWRS, the author finds that limited contributions are available in the plethora of research. Saparamadu (2019) presents a six-layered architecture emphasising big data technology for flood emergency management. The research elaborates on a possible e-government framework using real-time big data to manage future floods in Sri Lanka. Gourbesville et al. (2012) suggested a ubiquitous computing method to act as sensors independently to generate localised warnings to the public. In principle, the system is more distributed and integrated with the multiple IoTs that sense the environment to generate flood warnings. Unlike the conventional centralised approach, the ubiquitous systems are more efficient and user-centric. A different piece of work by Saranya et al. (2014) further emphasised the use of Wireless Sensor Networks (WSN) for improved flood warnings. Further to that, several other research projects evidence improvements in existing flood warning and response systems by introducing systems architectural frameworks (V. V. Krzhizhanovskaya et al., 2011), mobile technology (Omar et al., 2020), System of Systems (Akhtar & Khan, 2019) and service-oriented architecture (Shi et al., 2015). However, Kumar et al. (2020) argue that the a lack of research in this area and further stressed that no single operational solution has been developed and implemented that is applicable universally to cover the whole process of flood warning and response.

The above discussion indicates that some regions of the flood warning and response process have been developed without a holistic view of the entire system. Many research projects have focused on specific areas of interest within the whole process. It was observed that there is a lack of research considering improvements to the entire warning and response process, creating clear research gaps to investigate.

Therefore, there is a need to explore how current approaches for early warning and response to flood disasters can be enhanced by providing accurate and timely information to decision-makers and users through the utilization of emerging novel technologies. This research aims to gather user requirements and develop an architecture for a flood warning and response system, with an in-depth study of the warning and response process. To fulfil the overall objectives, the author suggests Sri Lanka as a case study to explore the current warning and response system and gather user requirements to build the artefact.

Sri Lanka has been selected as the study area primarily due to the increasing trend in past flood events and associated damages and losses. The 'Global Risk Index,' published consecutively in 2016, 2017, and 2018, indicates that the country was globally ranked 4th, 2nd, and 6th, respectively, in terms of disaster impact. In all three instances, 'floods' were identified as the cause of damages and losses. This consistent pattern justifies the selection of the country as a case study for the research. Tables 1, 2 and 3 elaborate on the top-ranking countries in these years, providing adequate justifications for choosing the study area for this research.

Table 1: The top 10 countries of the Global Climate Risk Index 2016

Ranking 2016 (2015)	Country	CRI score	Death toll	Deaths per 100 000 inhabitants	Absolute losses in million US$ (PPP)	Losses per unit GDP in %	Human Development Index 2015[12]
1 (40)	Haiti	2.33	613	5.65	3 332.72	17.224	163
2 (14)	Zimbabwe	7.33	246	1.70	1 205.15	3.721	154
3 (41)	Fiji	10.17	47	5.38	1 076.31	13.144	91
4 (98)	Sri Lanka	11.50	99	0.47	1 623.16	0.621	73
5 (29)	Vietnam	15.33	161	1.17	4 037.70	0.678	115
6 (4)	India	18.33	2 119	0.16	21 482.79	0.247	131
7 (51)	Chinese Taipei	18.50	103	0.44	1 978.55	0.175	Not included
8 (18)	Former Yugoslav Republic of Macedonia	19.00	22	1.06	207.93	0.678	82
9 (37)	Bolivia	19.33	26	0.24	1 051.22	1.334	118
10 (21)	United States	23.17	267	0.08	47 395.51	0.255	10

Table 2: The top 10 countries of the Global Climate Risk Index 2017

Ranking 2018 (2017)	Country	CRI score	Death toll	Deaths per 100 000 inhabitants	Absolute losses (in million US$ PPP)	Losses per unit GDP in %	Human Development Index 2018 Ranking[12]
1 (36)	Japan	5.50	1 282	1.01	35 839.34	0.64	19
2 (20)	Philippines	11.17	455	0.43	4 547.27	0.48	113
3 (40)	Germany	13.83	1 246	1.50	5 038.62	0.12	5
4 (7)	Madagascar	15.83	72	0.27	568.10	1.32	161
5 (14)	India	18.17	2 081	0.16	37 807.82	0.36	130
6 (2)	Sri Lanka	19.00	38	0.18	3 626.72	1.24	76
7 (45)	Kenya	19.67	113	0.24	708.39	0.40	142
8 (87)	Rwanda	21.17	88	0.73	93.21	0.34	158
9 (42)	Canada	21.83	103	0.28	2 282.17	0.12	12
10 (96)	Fiji	22.50	8	0.90	118.61	1.14	92

PPP = Purchasing Power Parities. GDP = Gross Domestic Product.

Table 3: The top 10 countries of the Global Climate Risk Index 2018

Ranking 2017 (2016)	Country	CRI score	Death toll	Deaths per 100 000 inhabitants	Absolute losses (in million US$ PPP)	Losses per unit GDP in %	Human Development Index 2017[10]
1 (105)	Puerto Rico[11]	1.50	2 978	90.242	82 315.240	63.328	-
2 (4)	Sri Lanka	9.00	246	1.147	3 129.351	1.135	76
3 (120)	Dominica	9.33	31	43.662	1 686.894	215.440	103
4 (14)	Nepal	10.50	164	0.559	1 909.982	2.412	149
5 (39)	Peru	10.67	147	0.462	6 240.625	1.450	89
6 (5)	Vietnam	13.50	298	0.318	4 052.312	0.625	116
7 (58)	Madagascar	15.00	89	0.347	693.043	1.739	161
8 (120)	Sierra Leone	15.67	500	6.749	99.102	0.858	184
9 (13)	Bangladesh	16.00	407	0.249	2 826.678	0.410	136
10 (20)	Thailand	16.33	176	0.255	4 371.160	0.354	83

PPP = Purchasing Power Parities. GDP = Gross Domestic Product.

This research examines the flood warning and response mechanism in a country where authorities were studied for meteorological and hydrological warning generation, disaster management agencies, and administrative structures from the national to sub-national levels. A river basin with frequent floods and high impact was selected for studying the local-level early warning and response process. The Kelani River, flowing through the capital city of Colombo, has experienced severe floods and extensive destruction to people, properties, and the economy in recent years. According to the World Bank, over 54,000 families were affected, with over 34,000 houses damaged in the Colombo district. The estimated economic loss was approximately 266 million USD (GoSL, 2016). Therefore, the local-level early warning and response mechanism in the given study area provides adequate conditions for conducting this study.

With this background, the following section discusses the research questions intended to be answered in this research.

1.2 Research Questions

This research aims to address the following research questions:

RQ1: What are the limitations and issues with the current flood warning and response systems?

This research question aims to investigate limitations, gaps, and challenges encountered in flood warning and response systems. It will identify the most critical failure factors of FEWRS and build the relationships between these failure factors. The outcome of this research question will enable the establishment of a baseline of the current FEWRS (objective 1).

RQ2: What intelligence is necessary for making informed decisions during the flood warning and response process, and how can they be captured through advanced technology?

This research question aims to investigate the types of intelligence that are useful in the decision-making process of the flood warning and response phases. Additionally, this research question will explore the state-of-the-art technology used in flood warning and response processes. The answer to this research question will be addressed through a structured literature review. It aims to establish a detailed early warning and response process map and to identify various sources of intelligence necessary at each stage of this process. Furthermore, the research will conduct an in-depth review of the tools and technology that can be used to extract the intelligence required at each phase of the early warning and response process. This research question is linked to objective 2.

RQ3: What are the user requirements and characteristics of a flood early warning and response system that can overcome current limitations?

Both RQ1 and RQ2 will identify the global to-local context problem through the "deductive process" by identifying intelligence and state-of-the-art technology used in flood warning and response systems. Furthermore, the answers to RQ1 and RQ2 will also identify the current issues, gaps and challenges of these systems. Based on these findings, this research question will collect primary data from disaster management experts in Sri Lanka to identify user requirements for FEWRS. This research question is linked to objective 3.

RQ4: What are the system characteristics of a FEWRS that can offer timely intelligence to decision-makers to make informed decisions?

This research question aims to design an architecture for an advanced FEWRS that can overcome the current limitations of FEWRS. This research question will be addressed by analysing the outcome of RQ1, RQ2 and RQ3. The overall architecture will then be evaluated involving domain and ICT experts to ensure the validity of the architecture in a real-world context. This research question is linked to objective 4.

1.3 Aims and objectives

Aim

This research aims to investigate the characteristics and develop a system architecture of a technology platform that offers accurate and timely intelligence for decision-makers in issuing flood warnings and responding. It aims to exploit the power of advanced technologies such as information management systems, remote sensing (sensor networks' satellites), simulation advanced visualisation technologies and mobile communication in designing the overall technology platform.

Objectives

1. To identify current gaps, challenges and limitations of the flood warning and response processes.

2. To review the intelligence required to support the decision-making process during flood warning and response processes and explore technology that can be used to capture such intelligence.

3. To capture user requirements for a flood early warning and response system that can offer timely intelligence for decision-makers to issue flood warnings and respond efficiently and effectively.

4. To define the system architecture that can be used to develop a flood early warning and response system platform that overcomes current limitations and fulfils the user requirements identified in Objective 3.

5. To validate the system architecture of the proposed flood early warning and response system involving experts.

1.4 Structure of the Report

This report currently consists of 09 chapters and other supportive attachments in the annexure. A brief summary of each chapter is discussed below.

Chapter 01: Introduction

The introduction chapter covers the background, the research motive, aims, objectives, and scope of the research.

Chapter 02: Literature Review

This chapter presents the related literature and the concepts used in this research. Preliminary concepts of warning systems, specifically flood warning and response systems and the main characteristics of such systems, are discussed together with state-of-the-art technology and applications. In addition, the theoretical frameworks used to build the system architecture are also discussed, including TOGAF frameworks.

Chapter 03: Research Methodology

This chapter describes the research methods, including the philosophical stance of the research and research approach, research strategy, data collection techniques and method of data analysis. This chapter also briefly describes Design Science Research (DSR), the research approach used in this study. The main phases of DSR, such as explaining problems, defining requirements, designing and developing artefacts, demonstration and evaluation, are briefly discussed. The next few chapters are organised to reflect the above phases of the DSR.

Chapter 04: Failure Factors of Flood Early Warning and Response System (Problem Explicate)

This chapter will present findings of the initial phase of DSR: problem explicate. It will investigate the problem through a structured literature review addressing research question 01. Therefore, this study focused on finding the critical failure factors (CFFs) in flood early warning and response systems through a structured review and discussion with experts.

Chapter 05: Intelligence Required for Flood Early Warning and Response System (Problem Explicate)

This chapter will present findings of the initial phase of DSR: problem explicate addressing research question 2. It will present a wider understanding of information and intelligence required in flood warning and response systems by evaluating research contributions.

Chapter 06: Requirement Capturing and Analysis of the Artefact

This chapter will present the outcome of the interviews that captured the user requirement analysis identified to develop the Information System Architecture of the flood warning and response process. The "as-is" and "to-be" processes of the flood warning and response systems were used as a basis for the requirement-capturing process.

Chapter 07: Development of the Artefact

The proposed conceptual Information System Architecture was discussed from multiple user perspectives using different system views.

Chapter 08: Evaluation of the Artefact

This chapter discusses the evaluation procedure of the proposed artefact and the final outcome of the evaluation results.

Chapter 09: Discussion and Conclusion

This chapter discusses the findings, their relationship with the literature, and whether the objectives have been achieved. The chapter also presents the overall conclusion to this research along with the level of achievement of the aims and objectives of this study. This chapter also includes the contribution to the body of knowledge made by this study, limitations and recommendations for future research in FEWRS.

1.5 Summary

This chapter has discussed the scope of the research. It provides the research motivation, aims, and objectives. It also describes the research questions and the outline of the report. The next chapter will provide the theoretical foundation of this research.

Chapter 2 Literature Survey

2.1 Introduction

The first part of this chapter presents the research and development work related to the Flood Early Warning and Response System (FEWRS). First, it delves into the advanced concepts which are being promoted in developing FEWRS by various international organisations, followed by a discussion on criteria for evaluating the effectiveness of FEWRS. Three FEWRS systems implemented in Australia, Great Britain and Europe are presented as illustrative state-of-the-art examples. The second part of this chapter provides an overview of system architecture frameworks, highlighting the concept of "views" and the “multi-layered” approaches that can be deployed in developing a system architecture for an advanced FEWRS. Finally, it presents the use of Business Process Modelling (BPM) for capturing "as-is" and "to-be" processes for FEWRS.

2.2 Introduction to Early Warning Systems

Various research contributions use numerous nomenclatures for flood warning systems. Three commonly used terms from research contributions and scientific reports are Flood Early Warning Systems (FEWS) (Perera et al., 2019), Flood Forecasting Warning and Response Systems (FFWRS) (Du Plessis, 2002), and Flood Early Warning and Response Systems (FEWRS) (Hammood et al., 2021). The core idea of these terminologies is somewhat similar, even though the abbreviations and terminology are different. In this research, the term “Flood Early Warning and Response Systems” (FEWRS) is used throughout the thesis.

The primary objective of a flood warning system is to minimise loss of life and damage to properties. Human losses and damages to vulnerable assets could be considerably minimised through non-structural measures such as implementing FEWRS (Ahmad, 2003). Smith and Handmaker (1986) argue that the cost of flood early warning is considerably cheaper than other physical flood control measures. However, Kreibich et al. (2021) claim even though flood warning systems reduce human losses, monetary losses will still prevail.

The early warning system is an integral part of a successful risk reduction strategy (Baudoin et al., 2016), representing a set of capacities to generate and disseminate timely and meaningful information to individuals, communities, and organisations to reduce disaster losses (UNISDR, 2016). The global community has identified the importance of early warning systems in disaster risk reduction since the 90s. The International Decade for Natural Disaster Reduction (IDNDR, 1990-1999) has recognised the core concept of early warning, and it was endorsed by the World Conference on Natural Disaster Reduction in 1994 (UN, 2006). Later, the Hyogo Framework for Action 2005 – 2015: Building Nations and Communities' Resilience to Disasters recognised "risk assessment and early warning" as one of the five pillars of disaster reduction (UNISDR, 2005). Sendai Framework for Disaster Risk Reduction (SFDRR 2015 – 2030), the latest global policy framework for disaster risk reduction, adopted at the UN World Conference on DRR held in Sendai, Japan, in March 2015, also identified early warning as one of the key target areas (UNISDR, 2015). Target 7 of the SFDRR emphasises the substantial increase in availability and accessibility to "end-to-end" and "people-centred" multi-hazard early warning systems (UNISDR, 2016). United Nations Office for Disaster Risk Reduction (UNDRR) (formerly known as the United Nations International Strategy for Disaster Reduction - UNISDR) defines Early Warning as *"the provision of timely and effective information, through identified institutions, that allows individuals exposed to hazard to take action to avoid or reduce their risk and prepare for effective response"* (UNISDR, 2016). Based on the definition, the UNDRR has identified effective and end-to-end early warning system may include four key elements as follows: (i) risk knowledge (ii) monitoring, analysis and forecasting of hazards and possible consequences (iii) warning dissemination and communication (iv) Preparedness to respond (Figure 2).

Figure 2: Four elements of early warning systems

Source: (UNISDR, 2006)

Firstly, risk knowledge provides a foundation for any warning system development, which consists of information on underlying hazard types and elements exposed, such as population, infrastructure, environment, and vulnerabilities of a given area of interest. Risk knowledge can be acquired through systematic risk assessment procedures, including hazard modelling, exposure and vulnerability analysis of people, infrastructure, environment and economic activities. Secondly, the monitoring and forecasting stage involves monitoring impending hazards and processing data to formulate forecasts and generate warning information. Sound scientific know-how is necessary to predict and forecast probable events with the operational capability of twenty-four hours a day (UN, 2006). Thirdly, this warning information is disseminated to at-risk communities in a timely manner using various communication dissemination techniques by authorities, from the national to the local level. Finally, communities living in the risk areas respond to possible disasters by evacuating safe locations. The preparedness level of at-risk communities to respond to such warning information is crucially important.

Developing and implementing an effective early warning system is a journey of a multi-stakeholder partnership of institutions and individuals. A successful EW system is a collective effort and coordination of local communities, local authorities, national government and regional/international institutions and bodies (UN, 2006). In addition to that, the private sector also plays an important role in developing EW capabilities in their organisations. The role of the scientific community is imminent in designing and implementing EW systems as they provide technical know-how in these stages. However, the UN Global Survey of Early Warning Systems (2006) argues that EW systems may be unsuccessful if one of the four key elements of the warning system fails (UN, 2006).

Further, the above UN report suggests that the “warning dissemination” and “preparedness to response” stages are more critical as these stages are closely associated with human factors. Human factors play a crucial role in making early warning systems successful (Twigg, 2003). Therefore, policymakers and researchers have identified community participation as a critical factor in a successful EW system; hence, the concept of “people-centred warning systems” has evolved. On the other hand, the multi-stakeholder approach is key to the success of early warning systems. The platform for the Promotion of Early Warning (PPEW) of UNISDR recognised eight actors that are useful in effective EW systems: communities, local government, national government, regional organisations, international organisations, NGOs and the private sector (Basher, 2006).

2.2.1 Key Components of a Flood Early Warning and Response Systems

This section expands on the four key components presented in Figure 1.

2.2.1.1 Risk Knowledge

Risk knowledge is the foundation for any successful early warning and response system. Therefore, it is necessary to understand the terminologies of hazard, exposure, vulnerability and the risk of population and other infrastructure. According to the UNDRR nomenclature, “hazard” is a threatening phenomenon that can cause losses or damages to humans and infrastructure, including livelihood, services, economy, and the environment (UNISDR, 2016). Risk is a product of hazards and vulnerabilities of the exposed elements. Therefore, the acquisition of “hazard”, “elements of exposed”, and their “vulnerabilities” are necessary to understand the flood risk.

Flood hazard zone mapping is a key activity in understanding the flood risk of a given area, which is typically obtained from historical sources (Rilo et al., 2017), hydrological simulation models (Mrnco et al., 2018), remote sensing techniques (Wang & Xie, 2018) or a combination of the above (Duminda Perera et al., 2020). Furthermore, participatory flood hazard and risk mapping techniques are commonly used in community-based disaster risk management at the local level (Kienberger, 2014). Flood hazard maps are integrated with socio-economic information to derive flood risk maps using GIS techniques (Ologunorisa & Abawua, 2005). After evaluating hazard and risk information, authorities, with the participation of the community, will design and implement the warning systems.

2.2.1.2 Monitoring, Warning and Forecasting

The key element for managing floods focuses on real-time forecasting and establishing alert levels. This process is divided into two main sections: Monitoring and Information Processing. Monitoring is essential in accurately predicting and evaluating the flood water level, inundation areas, and depths. Hydrometeorological parameters such as rain precipitation, river water level, river discharge rate, humidity, temperature and solar radiation are typically monitored (Duminda Perera et al., 2020) by relevant authorities and used these data to execute various weather and flood forecasting models. Therefore, a countrywide hydrometeorological observation network (known as hydromet stations) is essential in monitoring the hydrometeorological conditions for effective flood forecasts and warnings (Retamar et al., 2017).

The Information Processing (forecast and warning) section receives this data and uses analysis tools, computer models, and simulators to generate forecasts and warnings. This forecasting process requires advanced technologies like sensors for measuring variables, computational models, simulation software, and advanced visualisation tools for effective interaction with those at risk (Valeria V Krzhizhanovskaya et al., 2011). The following conditions need to be fulfilled to make the forecast successful: (i) the right parameters should be monitored, (ii) there should be a scientific basis for forecasts, (iii) accurate and timely warnings should be generated (UNISDR, 2002; WMO, 2018). During high rainfall events, various runoff and hydraulic models are employed for flood forecasting, relying on real-time measurements of precipitation, water level, and velocity. Based on the outcome of flood forecasting, alerts must be sent promptly, clearly and understandably to everyone (Henonin et al., 2013).

Flood inundation information is also obtained by real-time crowdsourcing techniques such as Twitter responses (Deng et al., 2016) and various other Volunteer GIS techniques (Castanhari et al., 2016). Emergency management authorities typically use inundation maps obtained by near real-time satellites and crowdsourced information to monitor the ongoing situation (Jongman et al., 2015).

2.2.1.3 Communication, Dissemination and Response

The Dissemination-Communication and Response phase plays a pivotal role in the transition from forecast to action (Mayhorn & McLaughlin, 2014). Dissemination leads to the actual sending of warnings, while true communication occurs when the information is not only received but also understood by the recipient (Jacks et al., 2010). Sending alerts to individuals at risk during high-intensity precipitation events is crucial, ensuring that the message is clear, straightforward, and practical. This ensures that responses are appropriate, ultimately safeguarding lives and livelihoods (UNISDR, 2006). Several critical questions must be addressed to ascertain the effectiveness of dissemination and communication systems:

- Does the warning reach the community at risk?
- Does the recipient properly understand the warning message?
- Is the message received clear and usable?

To achieve affirmative answers to these inquiries, alerts must be available in various formats, including text, graphics, color coding, and audio. This diversity facilitates the reception and prompt action on warnings. According to the World Meteorological Organization (WMO), effective alerts should be concise, easily understandable, and address fundamental questions like "What?", "Where?", "When?", "Why?", and "How to respond?" (Jacks et al., 2010). Moreover, they should provide detailed threat information using localised geographic references.

Dissemination of alerts should employ multiple channels to minimise delivery delays to end-users and maximise outreach ((DKKV), 2010). Moreover, ensuring that warnings are delivered by credible, pre-identified, and approved sources is essential. Measures should be implemented to adopt public trust, prompting swift action upon message reception (Cools et al., 2016).

2.3 Evaluation of Flood Early Warning and Response Systems

Evaluation of a flood warning and response system is significantly critical when considering the effectiveness of such a system. A five-stage maturity model is presented in (Parker & Fordham, 1996), which has been developed to evaluate the capabilities of countries' flood early warning and response (FFWRS), using riverine and tidal floods in the Netherlands, United Kingdom, Germany, France, and Portugal as case studies. The study experimented with fourteen criteria to evaluate the maturity level of the FEWRS: stage 1 – basic, stages 2 and 3 – intermediate, and stages 4 and 5 – advanced (Table 4).

The flood forecast philosophy (criteria 1) plays a vital role in development. A country should develop an explicit and coherent philosophy towards FEWRS; the absence of such philosophy is scored 1, and the availability of solid and coherent philosophy will achieve a 4 or 5 score. In countries with a rudimentary level of development, flood warning systems use forecast dominance (criteria 2) and utilise low technology for such systems (criteria 3). Warning coverage for floods in developing and the least development is less than 10 % of the geographical coverage of the country or territory, whereas level 3 or above will have more than 50% of the geographical coverage (criteria 4). The underlying legal framework (criteria 5) used to establish warning systems is also considered to classify the maturity level of the warning systems. Less developed rudimentary flood warning systems use blanket warnings (criteria 6) and crudely disseminate the warning messages (criteria 7). The rest of the criteria identified in the above-mentioned study is equally important and illustrated in Table 4.

Table 4: Staged development model of flood forecasting warning and response systems

TABLE 1
Staged development model of flood forecasting, warning and response systems

Criteria	Development states		
	1	2 and 3	4 and 5
1. Flood warning philosophy	Rudimentary	Intermediate	Advanced
2. Dominance of forecasting vs. warning	Forecast dominant	Equal	Equal and improved accuracy
3. Application of technology to FFWRS	Model with manual	Mixture	Fully automated
4. Geographical coverage	<10%	>10% <50%	>50%
5. Laws relating to FFWRS	No laws/ permissive	Laws	Laws with liability
6. Content of warning messages to public	'Blanket': general location	Mixed: Location/timing	'Target': severity/location & timing
7. Methods of disseminating flood warning	General broadcast	Wardens/agencies/police	Personal phone/fax/ pager'
8. Attitudes to freedom of risk/hazard information	Little, request only	Restricted to general flood plain	Open specific property
9. Public education about warnings	Minimum	Some, e.g. colour codes	Fully informed
10. Knowledge of FFWRS effectiveness	Denial of failure	Recognise limitations	Research tested
11. Dissemination of lessons learned	Little	Partial	Full
12. Performance targets and monitoring	None	Key indicators	Accuracy/timely/ reliability
13. National standards	Parochial	National/regional variations	National/ International
14. Organisational culture	Independent	Agency liaison	Service level agreement with agencies

Source: Parker and Fordham (1996)

Explanations of development stages:
1: Basic - little development
2-3: Improved performance, but some failures apparent
4-5: More advanced performance; failures reduced

2.4 Advanced Flood Warning Systems

Many countries have recognised the importance of flood early warning systems and implemented some aspects of the features discussed in the above sections. This section presents three examples of such systems from Australia, Great Britain and Europe, which can be considered as relatively advanced.

2.4.1 Flood Warning System in Australia

Floods in Australia are influenced by factors like tropical cyclones, which bring heavy rainfall and are responsible for many of the country's record rainfalls. The Australian Bureau of Meteorology plays a vital role in providing effective flood warnings across diverse communities, from major cities to remote areas. The Bureau operates in approximately 150 river basins, using statistical and hydrologic simulation models to predict flood timing and magnitude [37]. Hydrologists utilise spatially semi-distributed rainfall-runoff models and account for factors such as reservoir behaviour. This model employs elevation data to define catchment boundaries and further divides them into 5-25 relatively uniform sub-areas. These subareas, each covering 30-50 km^2, are connected by routing links that represent the river network. The average length of these links is approximately 10 kilometres. The delineation of catchments is performed using a Geographic Information System (GIS) package known as CatchmentSIM (Ryan, 2004).

Australia's low population density, particularly outside major cities, poses unique challenges in flood forecasting and the placement of gauging stations. Australia employs a combination of regional and national forecasting centres to address this. Flood forecasting in Australia involves close collaboration between the Bureau of Meteorology (BoM) and local and state government agencies. The current flood forecasting structure comprises the Head Office in Melbourne and Regional Offices in each state and the Northern Territory. These offices work together to deliver flood warning services through Flood Warning subsections.

According to the BoM, the Australian Flood Warning System consists of the following key components, as shown in Figure 3 below: monitoring and prediction (flood forecast), forecast interpretation, warning construction, communication and dissemination, response, and review.

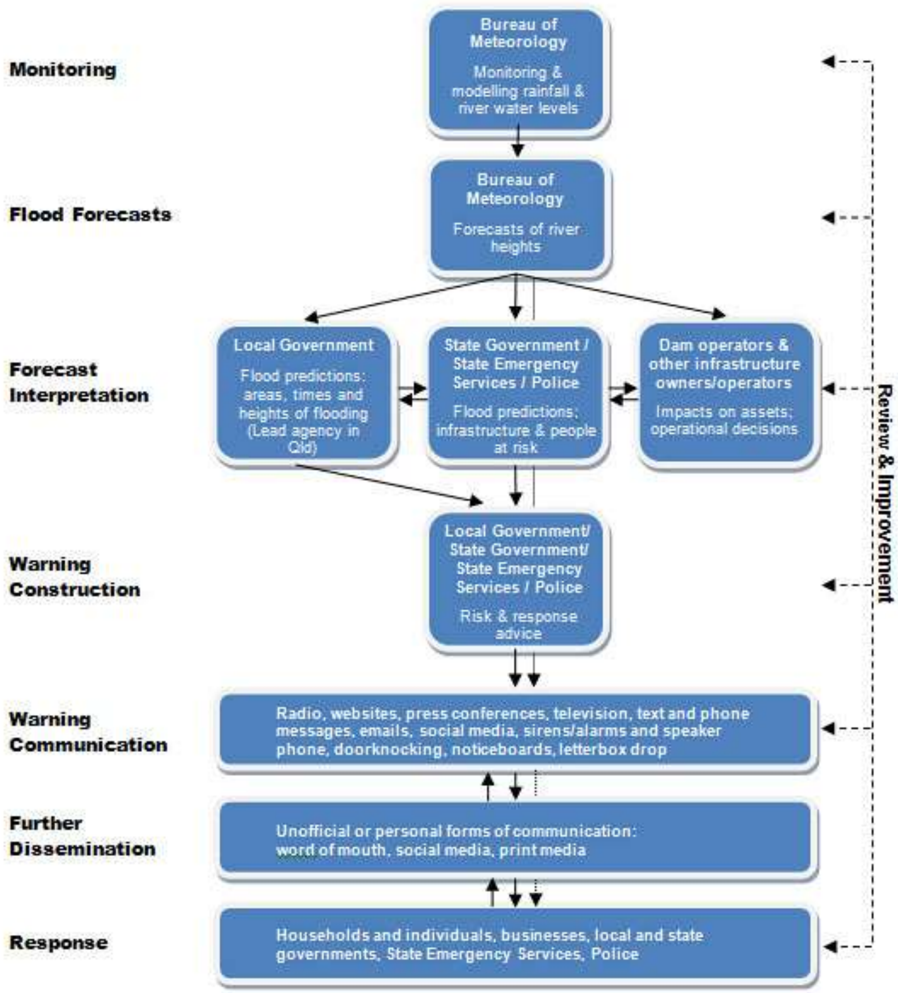


Figure 3: The Overall Flood Forecasting, Warning and Dissemination System in Australia

Source: (Queensland, 2011)

The Bureau of Meteorology (BoM) coordinates the flood warning systems in Australia. The BoM offers forecasts of river water heights at specific locations to relevant authorities and disseminates this information to the public through broadcast media and their website. Local government and State Emergency Services then use BoM's forecasts to predict floods and, generate detailed local information about areas at risk, potential impacts, and disseminate warnings and anticipatory actions for those in vulnerable areas. Additionally, community members often share these warnings through personal or informal networks. Social media platforms like Facebook and Twitter are expected to play an increasingly important role in disseminating flood warnings in the future, although this may also present challenges related to potential misinformation.

Flash floods, which are the leading cause of flooding-related fatalities in Australia, pose significant challenges due to their limited warning time. Although the BoM issues severe weather warnings, including the risk of flash flooding, it generally does not provide specific forecasts and warnings for flash floods, which would include precise details about location and timing. Some local governments, however, have established their own warning systems for such events.

Several operational challenges encountered by BoM in implementing their flood warning system are discussed in (Pagano et al., 2014). These challenges in flood forecasting in Australia are diverse and influenced by the country's unique characteristics. These include understanding specific user needs for effective warnings, adapting to varying population densities which impact service levels, and addressing the difficulty of maintaining skills and stakeholder engagement during long periods between major floods. Complex data management arises from diverse ownership of monitoring networks, resulting in challenges in data collection and transmission. Additionally, the integration of different types of hydrological models poses a challenge, as does translating river level forecasts into actionable flood impact information. Utilising social media and geo-targeted warnings also present opportunities and complexities in communication. Effective collaboration and sustainable funding arrangements, along with a clear dialogue between forecasting agencies and stakeholders, are crucial to establishing precise forecasting objectives. These challenges require tailored approaches and ongoing coordination between government levels and agencies for Australia's successful flood forecasting and warning systems.

The flood warning system in Australia is criticised by various scholars as it does not consider the preparedness and awareness components (Dufty, 2021). In (Molino et al.) the authors have suggested an extended framework to overcome current limitations by including stakeholder and community participation dimensions in the system. The authors argue that "…each of these warning system parts can work well or can work poorly or at worst, not work at all. The overall effectiveness of the warning can only be as strong as the weakest link in the chain and, unlike a real chain, errors or weaknesses can accumulate as they are passed along the chain" (Molino et al.). Researchers proposed an extension to the current flood warning system, as presented in Figure 4.

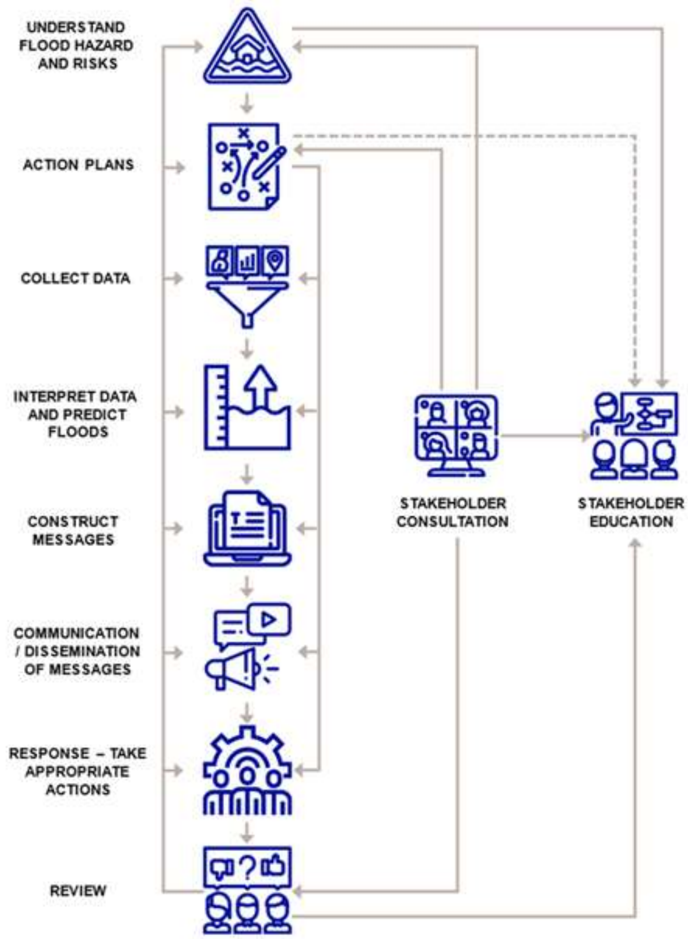


Figure 4: The Proposed Extension of the Flood Warning System

Source: (Molino et al.)

2.4.2 Flood Forecasting and Warning System in Great Britain

Great Britain has made significant progress in flood forecasting capabilities in the last decade. The pivotal moment was the severe flooding in the summer of 2007, which led to organisational changes in flood forecasting. This included closer collaboration between the Environment Agency and the Met Office through dedicated flood forecasting centres aimed at enhancing technical capabilities for flood forecasting (Stephens & Cloke, 2014). It brought about closer collaboration between meteorologists and hydrologists and has become an integral part of flood forecasting (Pitt, 2008). Flood forecasting is now conducted both nationally and locally, with these services working together to provide consistent flood guidance and warnings.

The integration of high-resolution weather prediction models with hydrological and coastal forecasting models has enabled comprehensive flood risk assessments across the country that can offer longer lead times. However, there is an ongoing effort to enhance short-term forecasting through better nowcasting and surface water hazard modelling (Stephens & Cloke, 2014).

The national flood forecasting mechanism is presented in Figure 5.

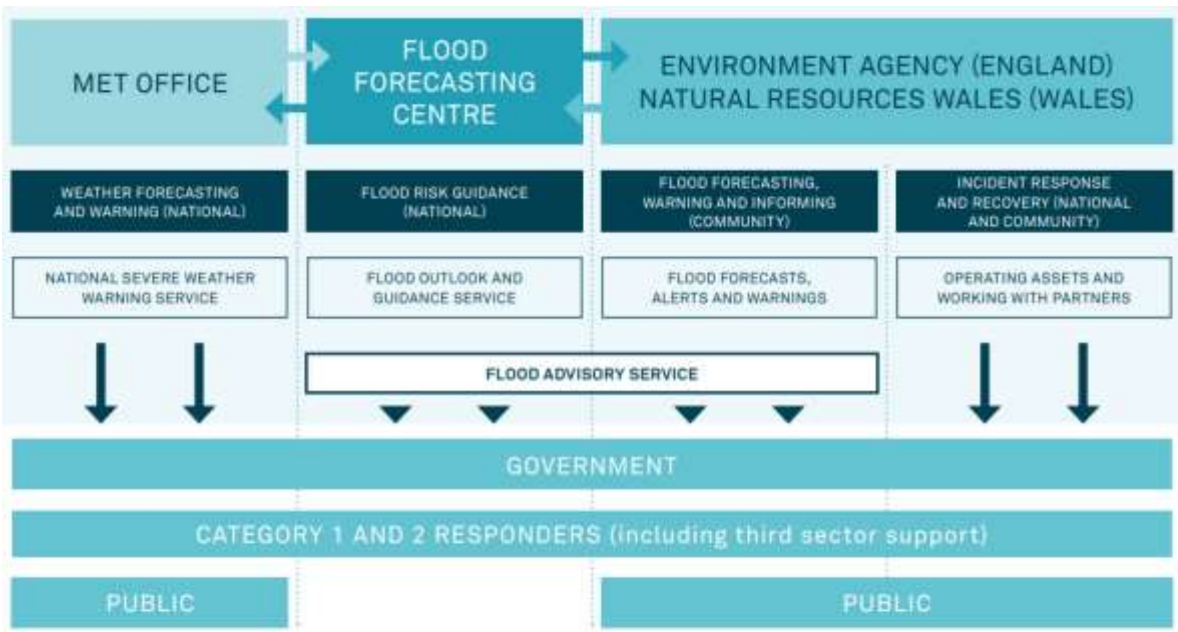


Figure 5: Framework for Flood Forecast and Warning in England and Wales

Source: (FFC, 2021)

Historically, various flood forecasting techniques have been used, including simple triggers, level-to-level correlations, and complex coupled hydrological and hydrodynamic models. These models differ based on the type of flooding (river, surface water, coastal, or groundwater). All flood forecasting models have been integrated into a common platform called Delft-FEWS (NFFS in England and Wales, FEWS Scotland in SEPA). This platform optimises the use of real-time observed and forecast data sets, facilitating comprehensive forecasting.

The Environment Agency adopted the Centre for Ecology and Hydrology's Grid-to-Grid (G2G) model to transform high-resolution numerical weather predictions into accurate flood forecasts.

The G2G model has been configured across England, Wales, and Scotland, operating on a one-kilometre resolution grid with a 15-minute timestep (Kay et al., 2023; Pilling et al., 2016). However, it's not as precise as locally calibrated models, especially in complex river systems. The G2G model relies on various data sources, including observed river level and flow data, observed rainfall data, and forecast data from the Met Office Unified Model. This comprehensive data collection and integration enable better flood forecasting (Speight et al., 2021). To assess potential flood risk across the country, the data is presented as a single threshold exceedance for each grid cell at each time step. It's rendered spatially as a map, providing a visual representation of the flood risk across England and Wales. The Surface Water Hazard Impact Model (SWHIM) is being developed to further enhance surface water flood forecasting, integrating the G2G hydrological model with the vulnerability and exposure data (Pilling et al., 2016).

The Meteorology Office manages severe weather warnings through the National Severe Weather Warning Service (NSWWS), while Floodline, operated by the Environment Agency, SEPA, and Natural Resources Wales, is the primary channel for disseminating warnings of river and coastal flooding (Strong et al., 2015). Coordinated frameworks like the National Flood Emergency Framework for England provide clear guidelines and thresholds for emergency response across agencies.

Recent developments have focused on filling strategic-level gaps in flood forecasting, extending lead times for flood risk warnings, and encompassing various sources of flooding. Emergency responders, categorised as Category 1 and 2 responders as per the Civil Contingencies Act, receive a range of flood forecasting products and guidance. These are generated by the Flood Forecasting Centre (FFC) and the Scottish Flood Forecasting Service (SFFS) for a wide range of recipients, including government bodies, emergency services, and infrastructure operators.

The FFC issues the following key flood forecasting products and services: Flood Guidance Statement (FGS), Three-day Flood Risk Forecast Hydromet Service, UK Coastal Monitoring and Forecasting (UKCMF) Service, Internet-Published Flood Forecasts, Surface Water Flood Forecasts. These products and services represent a significant stride in flood forecasting and warning capabilities, ensuring timely and precise information reaches those who need it most, including emergency responders and the general public. This comprehensive system plays a crucial role in mitigating the effects of flooding on communities and infrastructure.

Figure 6 provides the overall architecture of the flood warning and response system in the UK.

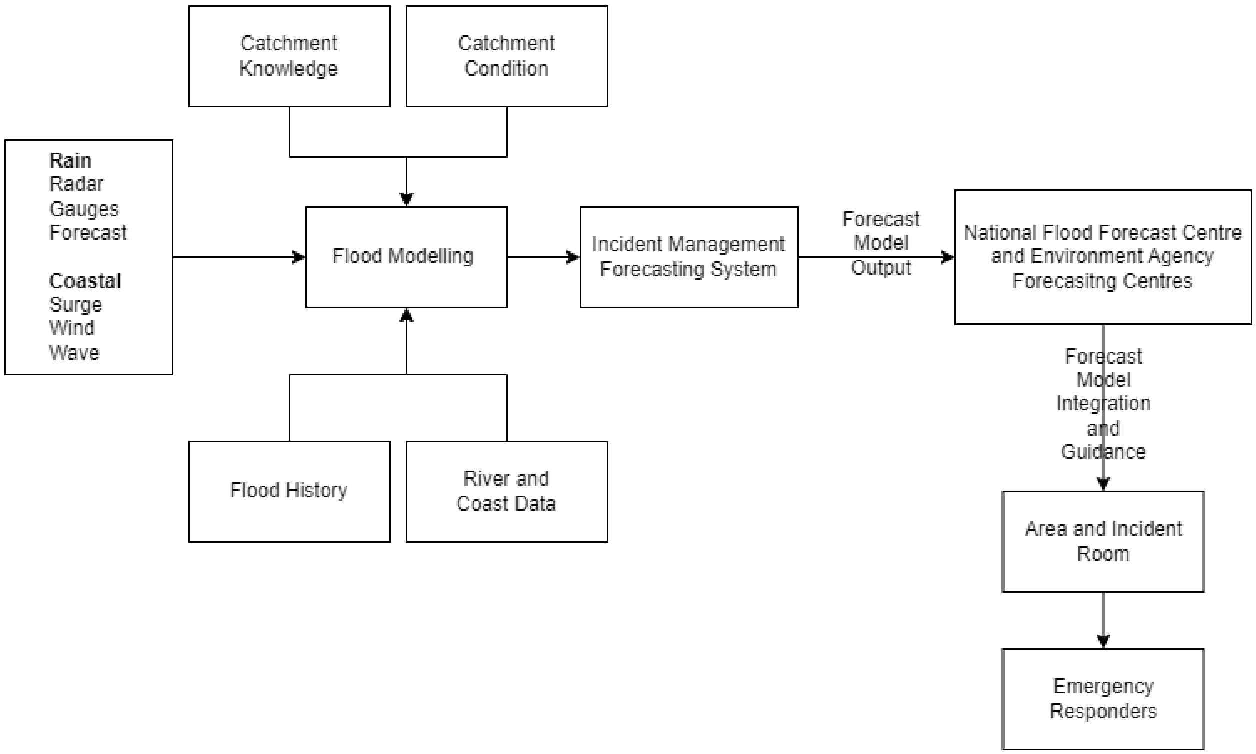


Figure 6: Overall Flood Forecasting and Response Process in England

2.4.3 European Flood Awareness System (EFAS)

European Flood Awareness System (EFAS) is a continental-scale early warning system designed to mitigate the impacts of transnational river flooding in Europe. EFAS aims to provide medium-range streamflow forecasts and early warnings for large river basins, offering pan-European flood hazard maps up to 10 days in advance. The system has evolved from research to operational service, integrating with national and European flood risk management efforts. EFAS is used by over 48 hydrological and civil protection services, and its forecasts are available to relevant authorities (Smith et al., 2016).

EFAS, the European Flood Awareness System, operates by using a hydrological model driven by weather predictions to generate flood forecasts. It relies on observed meteorological data to set initial conditions for the model. The resulting forecasts are made available on a web platform for EFAS partners. The European Commission (EC) manages the system and has been delegated to four specialised centres.

1. Hydrological Data Centre: This consortium collects historical and real-time river discharge and water level data.
2. Meteorological Data Centre: Located at the Joint Research Centre (JRC), it gathers historical and real-time observed meteorological data.
3. Computational Centre: ECMWF compiles numerical weather predictions, generates forecast products and maintains the EFAS Information System web platform.
4. Dissemination Centre: A consortium of institutes that analyse EFAS results daily, assess the situation and share information with EFAS partners and the EC.

EFAS results are disseminated by national hydrometeorological services, ensuring that information is relayed by authorities proficient in flood forecasting and mandated to communicate with civil protection. Communication between centres is facilitated through various standard means, including a dedicated platform for video conferencing, electronic chat, document sharing, and issue tracking. Partner organisations can raise concerns by contacting the centres or by including them on the agenda for the annual meeting.

EFAS (European Flood Awareness System) relies on a network of providers for both hydrological and meteorological data to drive its flood forecasting system. This data from over 800 sites includes real-time and historical observations, crucial for generating accurate flood forecasts. The system also incorporates satellite-derived soil moisture and snow coverage data for visualisation purposes. Additionally, EFAS displays flood alerts issued by national agencies in a standardised format, creating a feedback loop between official warnings and the EFAS system. The data collection centres manage this network, negotiating data agreements and operating 24/7. This robust data acquisition process underpins EFAS's ability to provide accurate flood forecasts (Smith et al., 2016).

The EFAS system employs a combination of meteorological and hydrological models to generate flood forecasts. The meteorological models, including those from ECMWF, German Weather Service, and COSMO, provide the necessary data to drive the hydrological model, LISFLOOD (Thielen et al., 2009). LISFLOOD, a spatially distributed hydrological rainfall-runoff model, calculates water balance at regular intervals for each grid cell. This includes processes like snowmelt, surface runoff, soil infiltration, and more. The model operates on a pan-European scale with a 5 km grid. Various European databases contribute to the spatial data used, including information on soil properties, vegetation, land cover, elevation, and river properties. A comprehensive calibration exercise in 2013 refined parameter values for 693 catchments, resulting in a highly effective model

The EFAS system's forecasting process involves three main steps: collating necessary data, running the LISFLOOD hydrological model, and preparing results for visualisation. The EFAS system produces hydrological forecasts twice a day, with each cycle running four variations of forecasts. Additionally, a water balance module is evaluated, and its results are used to create initial conditions for the subsequent hydrological forecast simulations. The system also includes a mechanism for evaluating and generating flood alerts based on critical thresholds and return periods calculated using observed meteorological data. This helps reduce false alerts and focuses on significant flood events caused by severe precipitation, combined rainfall and snowmelt, or prolonged medium-intensity rainfalls.

EFAS employs two methods for disseminating forecasts to end-users. The first method involves a password-protected web-based interface known as EFAS-IS, accessible only to registered users. EFAS-IS is designed as a Rich Internet Application (RIA) with high interactivity and responsiveness similar to desktop applications. It allows users to control and manage content based on their specific roles, facilitating various workflows in a collaborative environment. This platform enables end-users to contribute, share information, and communicate with EFAS centres. Additionally, public information, such as bimonthly bulletins reviewing recent floods and system updates, is available on the web portal. Under this, two additional services, EFAS SOS (Sensor Observation Service) and EFAS WMS-T (Web Map Service Time), are provided to partner organisations for data download and further analysis. These services adhere to Open Geospatial Consortium (OGC) standards.

The second method involves email alerts sent by the EFAS dissemination centre to corresponding EFAS partners, serving as an initial notification of a potential flood event. These emails serve as a call to attention, with more detailed information available on the EFAS-IS platform. Three types of emails are sent corresponding to different EFAS warnings: EFAS Flood Alert, EFAS Flood Watch, and EFAS Flash Flood Watch. Strict criteria are followed for activating, upgrading, and deactivating these warnings.

The overall process of the EFAS is presented in Figure 7.

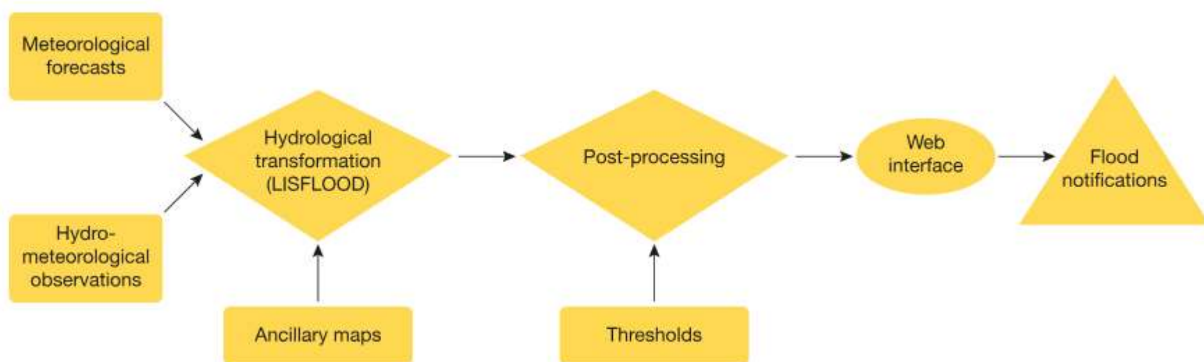


Figure 7: EFAS Configuration

Source: (Mazzetti et al., 2020)

The following section will discuss the fundamental concepts of enterprise architecture, business process management and modelling (BPM) and related topics that were applied in this research to develop the proposed artefact.

2.5 Enterprise Architecture

Enterprise Architecture (EA) is a high-level design of a business, which describes the organisation of the business, its processes and the use of technology. It is a collection of sub-systems that integrate and coordinate with each other to perform organisational tasks. Giachetti (2016) defines that "enterprise architecture describes the structure of an enterprise, its components into sub-systems, the relationship between each component, relationship with the external environment". EA is, therefore, the integration of business processes and information technology within an enterprise (Rouhani et al., 2015). Within this context, an Enterprise Architecture Framework (EAF) is a collection of processes, templates, and tools that can be used to build enterprise architectures. It embodies structure to integrate the enterprise's business and IT entities. (Rouhani et al., 2015). Most of the EA frameworks consist of a hierarchical multilevel system with an aggregation of "layers" and "views" (Schekkerman, 2004).

Layered architecture is a common approach to describe enterprise architecture. In a layered architecture, similar functions and modules are organised into horizontal layers, where each layer performs a specific role within a system (Polovina et al., 2020). Typically, these layers consist of business architecture, process architecture, integration architecture, software architecture and technology architecture (Winter & Fischer, 2006) and are arranged in a multi-layered nature Figure 8.

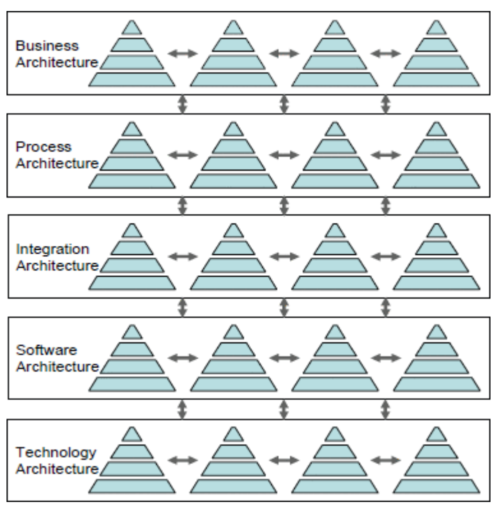


Figure 8: Multi-layered Nature of Enterprise Architecture

Source: (Winter & Fischer, 2006)

Numerous "views" are used to simplify the complexity and understand the system from different perspectives. The main idea behind the view is to focus on a given aspect while restricting attention to the other aspects, and each view needs to be addressed individually. On the other hand, it is impossible to describe a complex system from just one perspective (Clements et al., 2003).

Prior research studies have suggested numerous view models in EA For example, views such as the logical view, process view, development view and scenario view have been presented in the 4+1 view model (Kruchten, 1995). Jaakkola and Thalheim (2011) suggest five standard views for enterprise architecture: (i) information/data view (ii) functional business or domain view (iii) integration or data-flow view (iv) technology view (v) infrastructure view. Even though various authors proposed a fixed set of views for system architecture, Clements et al. (2003) argue that views should not be fixed and should have the flexibility to propose any number of views to describe the nature of the architecture.

Practitioners and academics have proposed several EA development frameworks in the past, and some of the popular frameworks are Zachmans's Framework (ZF), The Open Group Architectural Framework (TOGAF), Open Agile Architecture (OAA).

2.5.1 Zachman's Framework (ZF.)

Zachman's Framework (ZF), which is a well-known enterprise architecture model developed by John A. Zachman and formally published in 1987, offers an ontology or theory of the existence of components for enterprises (Zachman, 2003). The framework consists of a 6 x 6 matrix with interrogative determiners, namely *what, how, when, who, where* and *why*, while rows represent the different stakeholder viewpoints. It distinguishes various stakeholder perspectives of an enterprise and integrates all the stakeholder perspectives to understand an enterprise Table 5.

Table 5: Zachman's framework

	Data (What?)	Function (How?)	Network (Where?)	People (Who?)	Time (When?)	Motivation (Why?)
Scope (Planner's Perspective)	List of business data	List of business functions	List of locations for business operations	List of major organisational units	List of major business events	List of enterprise goals
Enterprise Model (owner's Perspective)	Semantic Data Model	Business Process Model	Business hierarchy	Organisation Chart	Strategic Plan and Timeline	Business Plan

			mapped to location			
System Model (Designer’s Perspective)	Logical ER Model	Activity Level Model	Distributed System Architecture	Job roles and responsibilities	Business Schedule	Business Rules and Policies
Technology Model (Builders Perspective)	Physical ER Model	Data Flow Diagram	Information Technology Architecture	People (Who?)	Control Structure	Reward System and Management Control
Detailed Representation (Subcontractor’s Perspective)	Data Dictionary	Process Specification and Code	Network Infrastructure	People (Who)	Timing and Sequencing Definitions	Supplier Contracts and Performance Criteria

Zachman's framework has been widely used in EA design over the years and is influenced by other EA frameworks developed, including TOGAF.

2.5.2 TOGAF Framework

The Open Group Architectural Framework (TOGAF), developed by The Open Group, is another popular EA framework used in the industry (TheOpenGroup, 2018). It offers a structured methodology to design, plan, implement and manage enterprise architecture. The framework has four architectural views described as follows:

i. Business architecture – This describes the business process that meets the organisational goal.
ii. Application architecture – Describes the individual applications and relationship of each application.
iii. Data architecture – Describes the presence of the data in logical and physical forms and how they are managed.
iv. Technical architecture – Describe the hardware and software infrastructure of the system

TOGAF Architecture Development Methodology (ADM) is the core of TOGAF, comprising a step-by-step process for developing enterprise architectures. It guides architects through various phases, from defining business goals to implementing and managing the architecture. It explains the standard method to derive an enterprise architecture for an organisation or a complex system that addresses business requirements (Blevins et al., 2004). The framework consists of 08 phases of developing EA, shown in Figure 9.

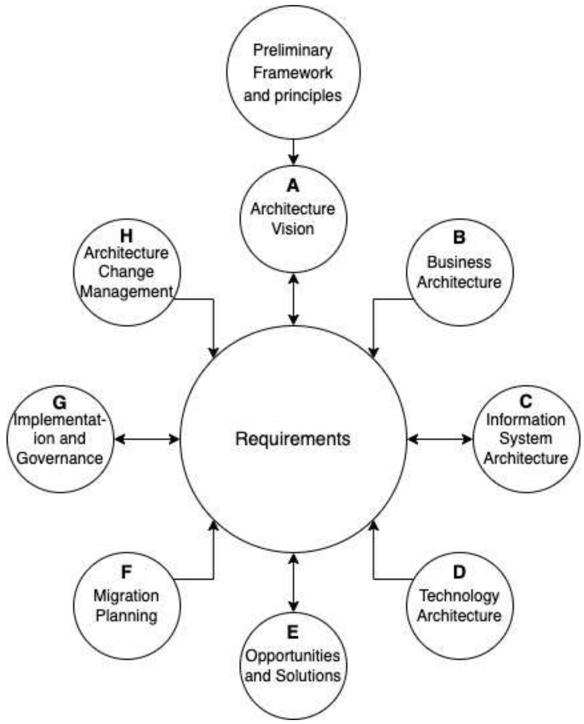


Figure 9: TOGAF Architecture Development Method (ADM)

Source: (TheOpenGroup, 2018).

2.5.3 Views

Typically, complex systems cannot easily comprehend all the aspects from a single and individual perspective. Therefore, the concept of view is to "look" at a complex system from a single perspective. Views allow users to understand a complex problem from multiple angles, enabling the conceptualising of the solution. On the other hand, views would allow users to examine a portion of a complex system. For example, the information view of a system will provide all the functions, technology and management of "information".

The "three schema model" and "4+1 view model" are examples of system view models. The three schema model is one of the first view models, introduced in 1977, consisting of external level, conceptual level and physical level views (Clemons, 1979). The 4+1 view model describes five concurrent views in software architecture: logical view, development view, process view, and physical view and scenarios (Kruchten, 1995).

Zachman's Frameworks and TOGAF Frameworks are popular examples of enterprise architecture views. In Zatchman’s Framework, six views have been identified to answer the problems in enterprise architecture: “what,” “how,” “who,” “where,” “when,” or “why” (Zachman, 2003). Information Framework (IFW) conceptualise three views “Organisational View”, “Business View”, and “Technical View” (Evernden, 1996). The TOGAF framework presents five generic views: Business view, application view, data view and technical view (TheOpenGroup, 2018).

2.5.4 Layers

In system architecture, a "layer" is considered as a logical partition within a software or hardware framework, delineating distinct functionalities or responsibilities. This organisational approach, characterised by a hierarchical arrangement of components, serves to segregate and encapsulate specific concerns, thereby enhancing the system's comprehensibility and maintainability (Bachmann et al., 2000). Each layer is assigned a well-defined set of tasks, contributing to the system's overall functionality through standardised interfaces. This stratified design facilitates the separation of concerns, ensuring that different components are responsible for discrete aspects of the system. Notably, layers engender a level of abstraction, enabling higher layers to interact with lower ones without needing an understanding of their internal complexities (Fowler, 2018). Furthermore, this architectural paradigm affords modularity, as each layer encapsulates its functionality, promoting ease of modification and facilitating change isolation (Gamma et al., 1995). Ultimately, layers in system architecture establish a structured framework that enhances scalability, flexibility, and manageability. Layers in system architecture are like the different parts of a well-organised team, all working together to make sure everything runs smoothly.

Typically EA splits into four standard layers: business, applications, information, and technology (Mignolli et al., 2014) as presented in Table 6:

Table 6: The typical four-layer representation of the system architecture

Layer	Description
Business Layer	This layer focuses on the business processes, functions, and capabilities of an organisation. It defines what the organisation does, how it does it, and why. Spewak and Hill (1993)
Applications Layer	This layer addresses the software applications and systems that support the business processes. It includes applications like Customer Relationship Management (CRM) systems, Enterprise Resource Planning (ERP) systems, and other software used to manage operations. Zachman (1987)
Information Layer	This layer deals with the data and information used by the organisation. It covers databases, data models, data flows, and how information is stored, accessed, and managed. Zachman (1987)
Technology Layer	This layer encompasses the hardware and technology infrastructure that supports the applications and information systems. It includes servers, networks, cloud services, and other technological components. Ross et al. (2006)

Polovina et al. (2020) suggest three layers of business, information and technology. In this three-layer model, the Applications layer is integrated into the Business and Information layers. This approach simplifies the framework while still addressing the essential components necessary for aligning business objectives with technology solutions in EA. The layer configuration, however, is divided into additional sub-layers under each category, as illustrated in Figure 10.

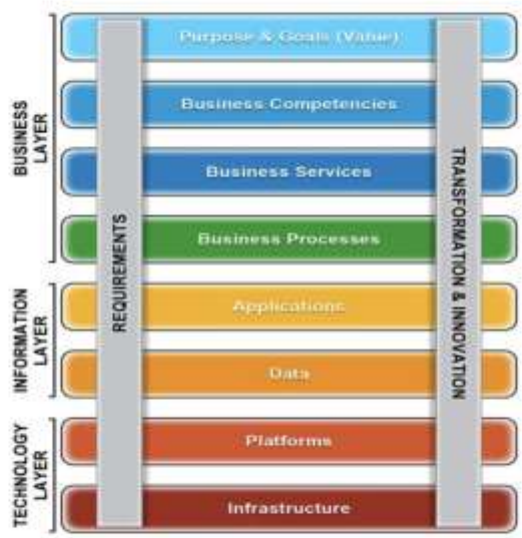


Figure 10: Layers in Enterprise Architecture with Sub-layers

Source: Polovina et al. (2020)

2.6 Business Process Modeling (BPM)

Business process modelling is a fundamental technique in modern enterprise management, providing a visual representation of the operations and activities that drive organisational workflows. It involves systematically analysing, designing, documenting, and improving business processes to achieve operational excellence and meet strategic objectives (Dumas et al., 2018). This approach offers a structured framework for understanding how various processes, subprocesses, activities, tasks, resources, and stakeholders interact within an organisation or a system to deliver products or services.

A key benefit of business process modelling is its ability to capture the processes and enhance their clarity and transparency in complex systems. By utilising graphical representations such as flowcharts, Data Flow Diagrams (DFDs), and Entity-Relationship Diagrams (ERDs), a holistic view of processes enables stakeholders to map various functions and tools. It also provides an opportunity to understand any pre-existing bottlenecks, redundancies, and opportunities for optimisation (Pufahl et al., 2018). Moreover, BPM also serves as a vital communication tool, allowing stakeholders to assess their efforts with overarching business goals and facilitating cross-functional collaboration (Van Der Aalst & Van Hee, 2004).

Furthermore, business process modelling contributes to the implementation of process automation and digital transformation initiatives. Organisations can translate visual models into executable workflows within enterprise software systems using techniques like Business Process Model and Notation (BPMN). It thereby optimises operations and reduces manual intervention by stakeholders and users (Silver & Richard, 2009). This automation fosters greater agility, scalability, and adaptability in response to evolving market dynamics. However, the business process modelling process requires a balance between abstraction and granularity. Balancing detail in business process models is critical. Excessively detailed models may lead to analysis unresponsive, while too abstract models will not serve the expected objective (Lankhorst, 2013). Therefore, organisations must employ modelling techniques that align with their specific needs and objectives.

In conclusion, business process modelling stands as a foundation in modern organisational management, offering a structured approach to analyse, design and optimise workflows. By leveraging visual representations and automation techniques, the expected outcome of complex systems can be enhanced efficiency, innovation, and dynamic demands of the business landscape. The Flood Early Warning and Response System (FEWRS), consisting of multiple systems distributed among various stakeholders, presents an excellent opportunity for analysis using Business Process Management (BPM) concepts.

2.6.1 Data Flow Diagrams

The Data Flow Diagram (DFD) is a graphical representation that illustrates how data moves between various elements of a process, such as data storage, internal processing and external entities of a typical business process (Kettinger et al., 1997). It facilitates documentation by emphasising data flow into, within, and out of the system boundaries, similar to flowcharts. However, DFDs differ in that they specifically focus on data rather than activities and controls. While DFDs are widely adopted for data modelling and are the standard notation for traditional systems analysis and design (Yourdon, 1989), they do have certain limitations. Firstly, they predominantly address data and lack modelling constructs for representing workflow, individuals, events, and other elements of business processes. Secondly, they do not provide information on decisions and event sequences, such as temporal or precedence relationships. Lastly, DFDs lack defined start and end points or execution paths, rendering them static representations that don't readily lend themselves to analysis or decision-making. To address these limitations, data flow diagramming is sometimes supplemented with structured textual descriptions of procedures, known as process specifications (Yourdon, 1989).

2.6.2 Entity-relationship (ER) diagrams

The entity-relationship (ER) diagrams are commonly utilised for visual representation of processes and data modelling. They are network models that illustrate the organisation of stored data within a system (Yourdon, 1989). ER diagrams concentrate on representing the data and their connections independently from any processing that might occur on that data. This separation between data and operations is crucial for complex data and their intricate relationships. Additionally, ER diagrams offer an advantage to system analysts by emphasising relationships between data stores in the Data Flow Diagram (DFD) that would otherwise only be apparent in textual process specifications.

However, when it comes to business process modelling, ER diagrams share similar limitations with DFDs. They primarily emphasise data and their relationships, lacking constructs for modelling other process elements. Moreover, these diagrams do not offer information about the functions associated with creating or using data, unlike DFDs. Ultimately, Entity Relationship diagrams are entirely a symbolic representation and do not offer any time-related information for analysis or measurement.

2.6.3 As-Is Process and To-Be Process

Central to BPM, "As-Is Process" and "To-Be Process," serve as essential stages in the process improvement cycle (Dumas et al., 2018). The "As-Is Process" represents the current state of an organisation's business processes. It involves detailed documentation and analysis of existing workflows, activities, roles, and interactions within the organisation (Pufahl et al., 2018). This step provides an existing view of the process that is being executed. It allows a clear understanding of the current process's strengths, weaknesses, bottlenecks, and inefficiencies. The As-Is analysis typically includes process flowcharts, data flow diagrams, and other modelling techniques to represent the current state visually. This documentation is crucial for identifying areas that require improvement and for providing a baseline against which future changes can be measured (Van Der Aalst & Van Hee, 2004).

On the other hand, the "To-Be Process" envisages the desired future state of a business process. It involves the "redesign" and "reengineering" of processes, procedures and workflows to achieve improved efficiency, effectiveness, and alignment with the desired level of objectives (Pufahl et al., 2018). The To-Be process incorporates best practices, industry standards, novel technology and innovative solutions to address the identified shortcomings of the As-Is process.

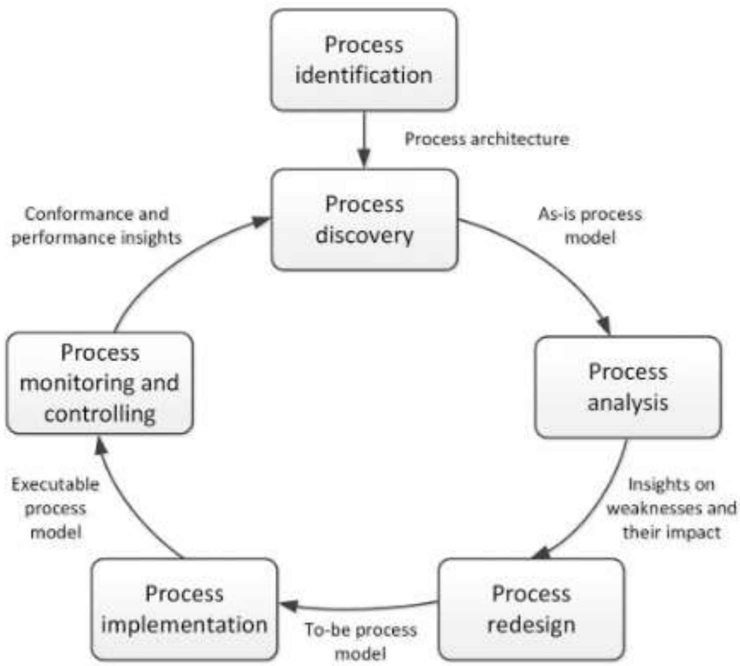


Figure 11: The Lifecycle of Business Processes Modelling Reflects As-Is and To-Be Processes

Source: Dumas et al. (2018)

The To-Be process modelling utilises various techniques, such as the Business Process Model and Notation (BPMN), to create a graphical representation of the redesigned workflows. Figure 11 presents the role of As-is and To-be process models within the Business Process Management lifecycle.

2.7 Summary

This chapter discusses the related works relevant to the FEWRS. It examined the generic components of an early warning system, particularly flood warnings, followed by comprehensive criteria for evaluating various perspectives of FEWRS. This review identified the four key stages that should be considered in developing a FEWRS, namely : (i) risk knowledge (ii) detection, monitoring, analysis and forecasting of hazards and possible consequences, (iii) warning dissemination and communication (iv) Preparedness to respond.

Three advanced FEWRS from Australia, Great Britain and Europe were presented to illustrate the current state-of-the-art flood warning systems. The assessment of these three systems illustrated how countries are promoting collaboration between meteorologists and hydrologists to strengthen accuracy in flood prediction as well as collaboration between national and local agencies to produce localised flood warnings. However, it was apparent that there is less emphasis on local risk assessment in order to create impact-based early warnings. The overall effectiveness of the warning can only be as strong as the weakest link in the chain, and errors or weaknesses can accumulate and be passed along the chain to produce inaccurate warnings. The Australian Flood Warning System highlighted the need for community participation in operationalising the flood warning systems.

The latter part of the chapter covers enterprise architecture concepts, the introduction of Enterprise Architecture frameworks, view models, and layered architectural approaches. The views and layered architectures presented were chosen as the approach for presenting the complex underlying architecture of the proposed FEWRS in this research. The Business Process Management (BPM) discussed in this chapter presents a sound methodology for capturing the current As-is and To-be processes of FEWRS in Sri Lanka,

The next chapter covers literature reviews that were conducted to capture the critical failure factors of the current FEWRSs.

Chapter 3 Methodology

3.1 Introduction

Research is a creative and systematic process that generates new knowledge (OECD, 2015), while research methodology is a step-by-step procedure and guidance used for the researcher to achieve research objectives. Somekh and Lewin (2011) argued that methodology is "the collection of methods or rules by which a particular piece of research is undertaken" while Mackenzie and Knipe (2006) suggested that "methodology is the overall approach to research linked to the paradigm or theoretical framework while the method refers to systematic modes, procedures or tools used for collection and analysis of data". The generation of new knowledge needs to follow a systematic sequence and order to achieve the expected results (Collins & Hussey, 2003). Therefore, a researcher needs to follow a specific method of inquiry to solve a research problem. Therefore, a methodology is a unique approach driven by the research scope, aims and objectives, and the researcher.

There are several research methodological frameworks that researchers have introduced; the "Nested model" (Kagioglou, 1998) and the "Research Onion" (Saunders et al., 2012) are two popular models amongst them, containing a layered approach. The nested model consists of 3 layers (Figure 12), from the outer perimeter to the inner core, which can be identified as research philosophy, research approach, and research techniques. In contrast, the research onion (Figure 13) follows the same steps with more information compared to the nested model. The research onion can be considered as an extension of the nested model.

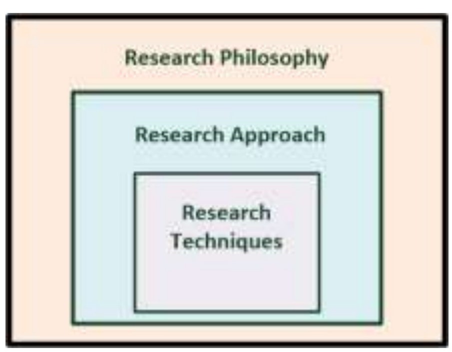


Figure 12: The nested model of research

Source: (Kagioglou, 1998)

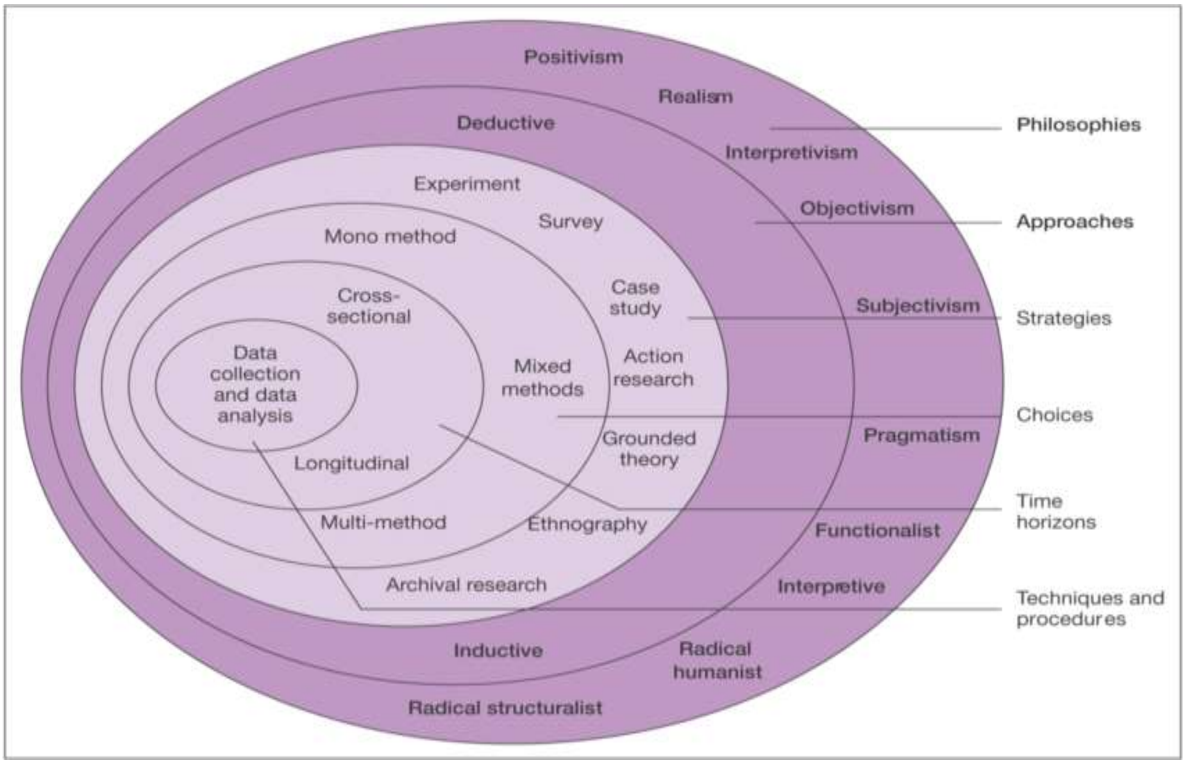


Figure 13: The Research Onion by Saunders

Source: (Saunders et al., 2012)

This study uses Design Science as the research methodology, as this research aims to design an artefact. Simon (1996) argued that design science is a science of artificial knowledge in designing human-made objects or phenomena. On the other hand, natural science is a body of knowledge of objects or phenomena in the natural world. Design Science Research (DSR) is mainly employed in information systems, engineering, architecture and healthcare research.

Understanding the philosophical stance is very important in designing a research methodology. This chapter discusses the philosophical stance of design science research, the design science process model, and the data collection techniques employed in this research.

3.2 Philosophical Instances of DSR

Understanding the philosophical stance of research is essential at the design stage of research. It clarifies the nature of the research, its design perspectives, and the position of the researcher.

According to Saunders et al. (2007), the term "research philosophy" is known as "the development of knowledge and the nature of that knowledge". The research philosophy that a researcher adopts encompasses crucial assumptions regarding their fundamental outlook on the world (Saunders et al., 2007). These underlying beliefs form the basis for selecting the research approach and the methodologies that accompany it (Saunders et al., 2007). Such assumptions construct the foundations for the researcher to choose an appropriate research approach and the methods selected as a part of the approach (Saunders et al., 2007). While practical considerations may occasionally influence a researcher's choice of philosophical assumptions, the most influential factor is the researcher's specific perspective on how knowledge is related to its development process (Saunders et al., 2007).

Smith et al. (2008) categorised the two primary philosophical traditions as 'positivism' and 'interpretivism'. Positivism holds that the social world exists externally and advocates for objective measurement methods rather than subjective inference through sensation, reflection, or intuition. In contrast, the interpretivism paradigm suggests that reality is not objective or external but is socially constructed and given meaning by people (Smith et al., 2008).

Based on this discussion, derived from Saunders et al. (2012), Table 7 establishes the relationship between positivism, interpretivism and Design Science.

Table 7: Philosophical assumption of three research perspectives

	Research Perspective		
Basic Belief	**Positivist**	**Interpretive**	**DSR**
Ontology	A single reality, knowable, probabilistic	Multiple realities, socially constructed	Multiple, contextually situated alternative world states. Socio-technologically enabled
Epistemology	Objective: dispassionate, detached observer of truth	Subjective (i.e. values and knowledge emerge from the	Knowing through making: objectively constrained construction within a context iterative

		researcher-participant interaction)	circumscription reveals meaning
Axiology: What is value	Truth: universal and beautiful; prediction	Understanding: situated and description	Control; creation; progress (i.e. improvement); understanding

Positivism, as outlined by Saunders et al. (2012), is a research paradigm that emphasises empirical observation and measurement. It relies on large sample sizes and controlled, artificial settings to conduct experiments or gather data. Positivist research is primarily concerned with hypothesis testing, aiming to establish causal relationships and generalise conclusions. This approach produces precise and objective quantitative data subject to rigorous statistical analysis. While positivism excels in producing results with high reliability due to its standardised methodologies, it tends to be criticised for potential shortcomings in terms of validity.

In contrast, interpretivism represents a research paradigm that acknowledges the subjective nature of reality. Saunders et al. (2012) argued that interpretivism promotes smaller sample sizes, conducts research in natural settings, and allows a deeper understanding of the complexities of human behaviour and social phenomena. Even though positivism focuses on hypothesis testing, interpretivism greatly emphasises theory generation. This leads to collecting more subjective, qualitative data through various methods, including interviews, observations, and content analysis. However, according to Saunders et al. (2012), interpretive research may demonstrate "less reliability" than positivism. On the other hand, interpretivism research often demonstrates higher "validity" as it captures the deep and rich human experiences.

As presented in Table 7, three major attributes are used to describe the research philosophical stances of Ontology, Epistemology and Axiology. The attribute "Ontology" answers the question of "what it is" whereas "Epistemology" determines "how we know that?". The Axiology determines the judgement about "Values". The following sections will further elaborate on these fundamental concepts and will connect with the current research. Table 7 describes how the researcher sees the world through ontological, epistemological and axiological assumptions.

3.2.1 Ontological Assumptions

Ontology refers to the foundational philosophical assumptions that researchers hold about the nature of reality. According to scholars like Creswell (2007) and Smith et al. (2008), it sets the stage for how researchers perceive the world. Two different ontology extremes exist: subjectivism and objectivism (Saunders & Lewis, 2012), which are also referred to as realism and idealism, where realism (Johnson & Duberley, 2000) describes a physical phenomenon or object, while idealism (Saunders et al., 2007) is known as knowledge or product in mind (Wong & Heng, 2012). The objective stance asserts that the external world has a fixed nature and structure, termed 'realism' by some authors (Johnson & Duberley, 2000), or 'objectivism' by others (Saunders et al., 2007). Conversely, the subjective stance suggests that the external world lacks a predefined nature, being understood in various ways by individuals; this is referred to as 'subjectivism' by Saunders et al. (2007) and 'idealism' by (Gummesson, 2000).

As column three of Table 7 indicates, this research employs qualitative and quantitative data to develop the artefact under design science. The development of the artefact will use various quantitative data sources, such as social behaviour, society's requirements, and authorities' requirements, through different qualitative data collection processes and methods. On the other hand, this research design will have multiple data sources and observations of nature and natural processes. Disaster risk management has two major components: the environmental process and the response of individuals, society and authorities. In such a scenario, this research is a mixture of realism and idealism; the philosophical stance is more biased towards 'pragmatism' as it will be asserted to orient with actions (Kelemen & Rumens, 2008). In pragmatism, research is associated with the problem and aims to offer a practical solution to future practice (Saunders et al., 2016).

3.2.2 Epistemological Assumptions

The epistemological stance of a researcher plays a significant contribution in guiding their choice of research methods, according to Smith et al. (2008). Therefore, a clear understanding of the epistemological framework underlying a research study is paramount. In this context, epistemology consists of two main philosophical traditions: "Positivism" and "Interpretivism". Positivism advocates for the use of objective measures to uncover general laws and cause-and-effect relationships. In contrast, interpretivism suggests employing subjective measures to understand human actions and perceptions. Therefore, Epistemology establishes the relationship between the researcher as an individual and the research objectives.

In positivist research, the epistemological assumption involves employing objective measures to uncover cause-and-effect relationships through rational means, believing that reality can be objectively studied. In contrast, interpretive research relies on subjective methods to probe into how individuals perceive and understand the world. This perspective establishes that reality can be assessed through interpretive methods by examining the perceptions of individuals (Collins & Hussey, 2003; Smith et al., 2008).

For interpretive studies, the epistemological assumption leads researchers to close engagement with participants, particularly in qualitative research. This approach aims to establish a deep understanding of their perspectives and experiences (Creswell, 2007).

In design science research, epistemology is known as "knowing through making" (Vaishnavi & Kuechler, 2015), establishing the relationship between the researcher and the research objectives. Therefore, this research employs mostly subjective measurements to conceptualise, build, and operationalise an information system that links a flood forecast, warning and response system through an iterative process using the DSR method.

3.2.3 Axiological Assumptions

According to Saunders et al. (2007), axiology pertains to the nature of values the researcher incorporates in the study; in principle, it addresses the function and influence of values within the research endeavour. In other words, it deals with the role of values in research. The researcher, as an individual, has a personal opinion that will be associated with the outcome of the study. On the other hand, axiology will also explain how to deal with the values of research participants (Saunders et al., 2016).

From the positivist angle, the researcher does not add value to the knowledge accumulation process and is called "axiologically value-free". The positivist believes that the objects and phenomena

they are investigating are unchanged by their research action and are static. Therefore, Crotty (1998) suggested that positivism is neutral and detached from the outcome of the research.
On the other hand, in interpretivism, the researcher adds his own values to the data and research findings and axiologically becomes an integral part of the research (Smith et al., 2008), which is also called "Value-laden". The value-laden research is influenced by human beliefs and knowledge.

This research designs a system for natural phenomena and actions. It will collect data from natural processes and human actions; hence, it uses value-free and value-laden perspectives. Furthermore, the researcher will also add value to the data collection process and the development of the artefact. This research will actively engage the community and other stakeholders in deciding the proposed flood warning and response process. Moreover, the system will also have active engagement and the embedded beliefs of the researcher.

Considering all these aspects, the author would prefer to position this research toward pragmatism. This study aligns with interpretivism because it focuses on understanding people's actions and their beliefs. However, the research also touches on positivism as it relates to a natural process. This places the research towards the interpretive side of the spectrum regarding how knowledge is approached. Lastly, the study falls on the value-laden side of the spectrum because it aims to influence participant behaviour by developing the FEWRS, including the researcher's choices.

3.3 Research Approach – Design Science Research

This section presents the detailed design, approach and data collection methods proposed to achieve the objectives of the research.
According to Yin (2009), three primary research types exist: explanatory, descriptive, and exploratory. These can be identified as action research, archival research, experiments, grounded theory, ethnography surveys and case studies. The selection of a suitable research approach is essential for successful research (Robson, 2002a). Considering the objective of this study, the researcher has evaluated the suitability of these existing strategies. This research is positioned primarily in the Information System (IS) domain, blending software engineering, operation

science, information sciences, and social science. It can be argued that none of the above strategies fit this study's objective. The overarching aim of this research is to identify information system characteristics that can help make timely decisions in flood warning and response stages. In this case, the author had two choices: either to employ Action Research (AR) or Design Science Research (DSR) to achieve research objectives. The DSR resembles AR as both strategies solve real-world problems along with the actions that might improve them. In AR, stakeholders actively participate in the research process (Järvinen, 2007) with the facilitation of the researcher. However, the DSR differs from AR as in DSR, the researcher primarily aims to solve complex problems by taking the initiative in the research process as both a researcher and observer, working closely with the stakeholder (Brendel et al., 2018). Therefore, Considering the nature of this research and its relation to identifying characteristics of an IS, a design science research approach was chosen to utilise in this research. Design science is a research approach that enables the design, development and validation of an artefact which can improve organisational processes to overcome a current problem. Understanding an existing system and its limitations could help solve the current issue by designing a novel artefact (Davis & Olson, 1984). According to Hevner et al. (2008), DSR typically consists of the following stages: (i) explicate the problem, (ii) define the requirement, (iii) system design and development, and (iv) demonstration and evaluation of the artefact.

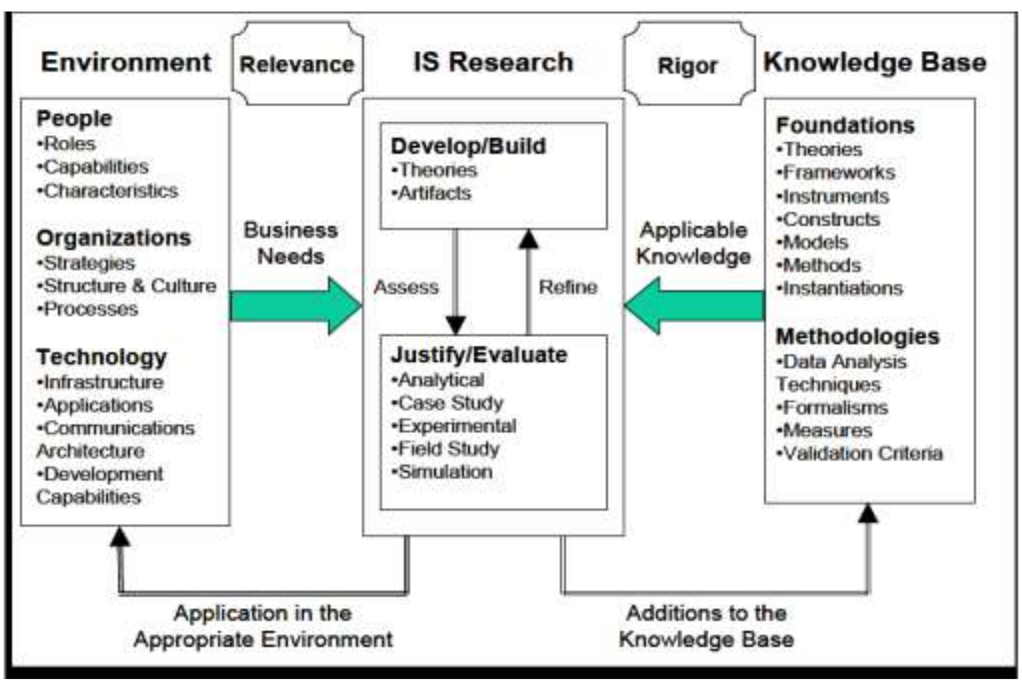


Figure 14: Information Systems' Research Framework of Design Science (Havner et al. 2004)

Figure 14 outlines the three main components of IS research. Firstly, the "environment" section defines the issue at hand and the existing elements involved, which encompass people (their roles, capabilities, and characteristics), organisations (including strategies, structure, culture, and current business processes), and existing technology (covering infrastructure, applications, communication architectures, and development capabilities). Together, these elements identify the business need or problem, as outlined by Simon (1996).

Next, the "knowledge base" provides various resources for conducting IS research. It includes foundations and methodologies. Foundations incorporate theories, frameworks, instruments, constructs, models, methods, and instantiations used in the research development phase. Procedures involve data analysis techniques, formalisms, measures, and guidelines for validation criteria used in the evaluation phase. A robust design is achieved by applying these established foundations and methodologies.

Lastly, the environment and knowledgebase collaborate to produce the research, which involves the development of artefacts. These artefacts are subject to further refinement and improvement, which can be accomplished through methods such as case studies, experiments, and field testing.

In line with the DSR approach, Figure 15 summarises the proposed research approach of this research. A systematised literature review has been conducted to achieve objectives 1 & 2 to identify the gaps, challenges, and limitations of the current flood warning and response processes and mechanisms, and to identify the intelligence required in the flood warning and response process.

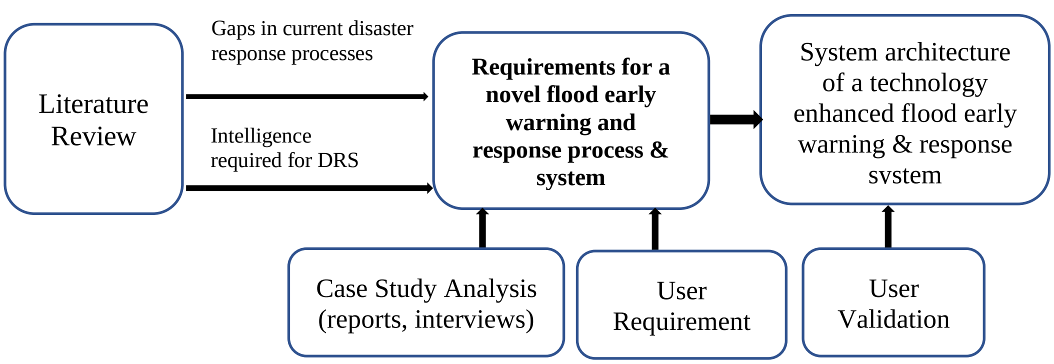


Figure 15: Overall Research Design

The researcher has proposed Sri Lanka as a case study to develop an artefact by collecting user requirements, developing a system architecture for FEWRS, and evaluating them. The selection of the country was justified based on the recent increasing trend in flood events and per capita economic damage and loss. According to the “Global Risk Index” published in 2016, 2017, and 2018, the country was ranked 4th, 2nd, and 6th respectively. All three events were floods triggered by monsoon rainfall on the western slope of Sri Lanka.

The Disaster Management Act, introduced in May 2005, lays the legal foundation and proposes an institutional structure and coordination mechanism from the national to the local level. The National Council for Disaster Management, headed by the HE President, and its implementation arm, the Disaster Management Centre (DMC), oversee overall coordination with the government, non-government organizations, and the private sector. In the case of floods, the Meteorology Department and Irrigation Department play a critical role in early warning generation, while the DMC and sub-national administrative structures provide supporting response coordination and implementation. Therefore, a detailed investigation of these institutions for the flood warning and response process was suggested in the primary data collection.

For this purpose, interviews ~~and brainstorming sessions~~ were conducted to validate the literature survey findings, capture the user requirements, and evaluate the artefact. Participants were selected based on their involvement in the flood warning and response process. Key organizations such as the Meteorology Department, Irrigation Department, Disaster Management Centre, District Secretariats, and Divisional Secretariats were chosen, and representatives from each of these organizations were identified. In addition, subject experts and practitioners were also selected to strengthen the overall outcome of the primary data collection. Furthermore, community representatives were included in the data collection process to gather user requirements from the victims' perspectives.

Thirteen participants were finally selected in the qualitative data collection processes. User requirements were captured through "User Stories", a software and product development technique. User stories allow system designers to capture the user requirements of a complex system from the perspective of the system user and end-users. The flood warning and response system is a multi-agency collaborative system that involves numerous organisations and individuals, including the end-user community.

The overall research strategy is summarised in
Table 8, which illustrates the relationship between the research question, objectives, and data collection methods. The design science approach suggested by Johannesson and Perjons (2014) is used in this research. The design process contains five main components of design science research implementation: explicate the problem, define the requirement, system design and development, and demonstrate and evaluate the artefact.

Table 8: Proposed Research Design

DSRM Phase	Research Objectives	Research Question	Data Collection Method
Explicate Problem	1. To identify current gaps, challenges and limitations of the flood warning and response processes.	RQ1: What are the limitations and issues of the current flood warning and response systems?	Systematic review Interview industrial practitioners, secondary source data collection Strategy: grounded theory / narrative inquiry method: interviews
	2. To review the intelligence required to support the decision-making process during flood warning and response processes and explore technology that can be used to capture such intelligence.	RQ2: What intelligence is necessary for making informed decisions during the flood warning and response process, and how can they be captured through advanced technology?	

Define Requirement	3. To capture user requirements for a flood early warning and response system that can offer timely intelligence for decision-makers to issue flood warnings and respond efficiently and effectively.	RQ3: What are the user requirements and characteristics of a flood early warning and response system that can overcome current limitations?	User stories/interviews
System Design and Development	4. To define the system architecture that can be used to develop a flood early warning and response system platform that overcomes current limitations and fulfils user requirements identified in Objective 3.	RQ4: What are the system characteristics of a FEWRS that can offer timely intelligence to decision-makers to make informed decisions?	Standard system development method – (Layered Architecture / TOGAF / Micro Service Architecture)
Demonstrate and Evaluate the Artefact	5. To validate the system architecture of the proposed flood early warning and response system involving experts.		Interviews

The following section further examines these steps in detail.

3.3.1 Explicate the Problem

The problem was identified and justified in this phase, and its importance and underlying causes were investigated. This phase is connected with answering research questions RQ1 and RQ2, where it investigates challenges, gaps, and issues related to the flood warning and response process (RQ1). Additionally, it explores the intelligence used for making informed decisions during the flood warning and response process and how they can be captured through advanced technology (RQ2). In order to address these research questions, a comprehensive literature survey was proposed. The author employed the 'systematized literature survey' method (Grant & Booth, 2009) to extract relevant studies and accumulate knowledge through search, appraisal, synthesis, and analysis (SALSA). A systematized review is a condensed version of the 'systematic review,' typically conducted in postgraduate research projects. Systematized literature reviews were employed in research for their structured and unbiased approach to retrieving and synthesizing relevant information on a specific topic. They are crucial in identifying research problems, informing decision-making, and promoting transparency and reproducibility. Systematized reviews are efficient in terms of time and resource utilization, contributing to the advancement of knowledge and guiding future research efforts.

The two systematised literature reviews conducted in this step are also linked with objectives 1 and 2.

3.3.2 Define Requirements

In this phase, user requirements were collected through structured interviews, and the results were analysed systematically to identify the features of the proposed artefact.

A series of interviews with the stakeholder agencies, experts, and community were conducted. Notably, user stories from each nodal agency and selected community representatives were collected to define the characteristics of the proposed artefact. The result of this phase is the Tentative Design of the proposed artefact. This phase is connected to objective 3.

3.3.3 System Design and Development

Further development of the tentative design took place in this phase. Since the proposed artefact is an information system that improves flood warning and response systems, traditional waterfall system development methods, information engineering, or agile development methods were considered. Agile methods mainly employed iterative development approaches, and there were practical limitations in applying the above technique. Given the nature of this research towards system architectural framework development, the author selected using a combination of conventional 'Waterfall' and 'Information Engineering' methods. In line with overall information system development, the TOGAF framework, a successful enterprise architecture framework used in modern information system development, was employed to develop the system architecture with multiple views from the users' perspectives. Popular architectural views, such as the information, stakeholder, process, etc., were used. Out of these views, the 'process view' was deemed critical, and the researcher paid the highest attention to developing it. The 'as-is' and 'to-be' scenarios were captured to understand the current and proposed process workflows. Business Process Modeling and Notation (BPMN), an approach to optimizing and managing business processes within an organization, was employed to derive the 'process view' of the current and anticipated Flood Early Warning and Response System (FEWRS). BPMN is a key component in Business Process Management (BPM) as it provides a standardized graphical notation for representing the steps in a business process. Based on the process view, other subsequent views of the proposed system architecture of the FEWRS were derived and discussed in Chapter 6.

This phase relates to the objective 4 of this research.

3.3.4 Demonstrate and Evaluate the Artefact

The final phase of this project is to demonstrate and evaluate the system. The system design was presented to various experts to assess the overall effectiveness of the system. In the second phase of the data collection, which focused on evaluating the prototype, a scenario was presented to the participants. A questionnaire survey was administered to gather individual opinions from the participants. The questionnaire incorporated close-ended rating scale questions. This exercise was followed by personal discussions.

To enable this, an evaluation strategy was deployed. Several key aspects were taken into account during the formulation of the evaluation strategy, encompassing (i) the scope of assessment, (ii) the selection of assessment criteria, (iii) the establishment of the assessment context, and (iv) the identification of suitable assessment techniques.

The "scope of assessment" pertains directly to the flood warning and response system itself, conceptualised as an artefact aimed at enhancing the existing mechanisms governing flood warnings and responses, as elaborated upon in Chapter 7. This delineation governs the subsequent evaluation process.

In DSR, the “assessment criteria” refers to the standards and measures that are used to evaluate the artefact for its quality, effectiveness, and usability. The criteria used to evaluate this research are identified as (i) goal/efficacy, (ii) environment (encompassing people, organisations, and technology), and (iii) activity/performance derived from a previous study that suggests a set of common criteria for DSR evaluation (Prat et al., 2014).

In terms of the "assessment context," the assessment was conducted remotely using Microsoft Teams and Mural Collaborative. A hypothetical flooding scenario similar to a major flood event that occurred in the Kelani River basin in 2016 was identified as the potential incident to review the usability of the proposed artefact. The Kelani River flood in 2016 was a significant event, with a 50-year return period, and caused considerable socio-economic and infrastructure damage in the Colombo District, Sri Lanka (Alahacoon et al., 2016). Four experts from disaster management, who were involved in the user requirement phase, and three experts from the IT sector were involved in the evaluation process.

A visual representation of the evaluation methodology is graphically represented in Figure 16, encapsulating the comprehensive approach undertaken to evaluate the flood warning and response system prototype.

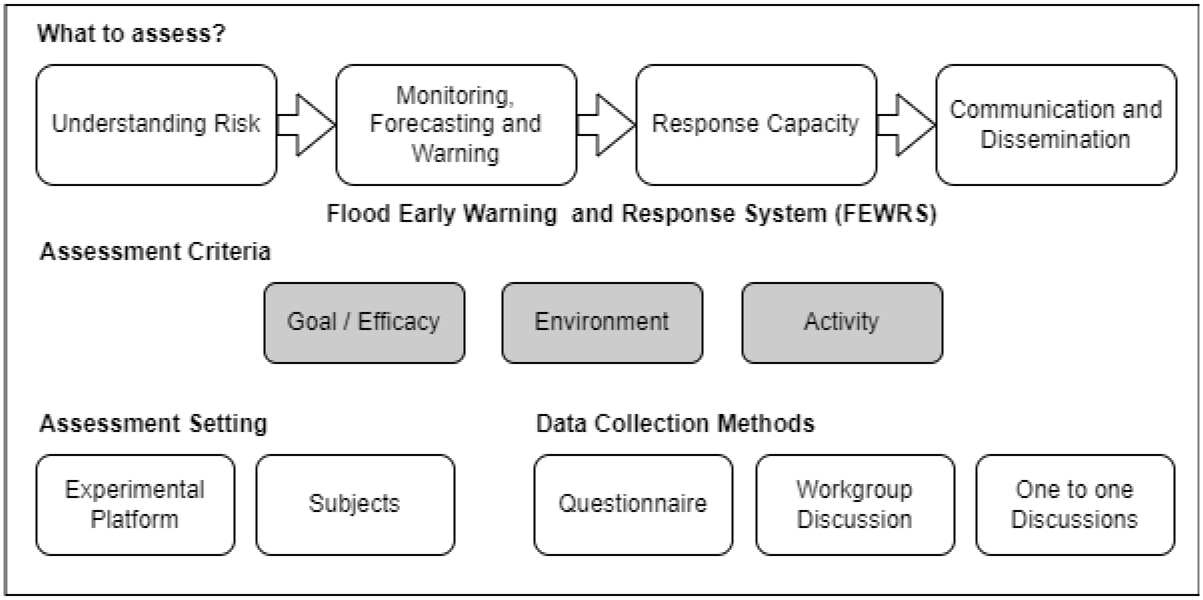


Figure 16: The overview of the evaluation methodology used to assess FEWRS

The overarching objective of this evaluation is to rigorously assess the efficacy of the flood warning and response system prototype architecture, with a specific focus on its potential to facilitate a comprehensive decision-making process spanning from higher-level strategic considerations to a granular operational level. The multi-dimensional evaluation process encompasses diverse perspectives, evaluating the proficiency of the architectural framework's presentation, its usability attributes, its sustainability considerations and offering recommendations for enhancing productivity. The approach presented in (Prat et al., 2014), which offers a comprehensive framework with twenty distinct evaluation criteria, was used to conduct the system evaluation. These criteria provide a foundation for conducting a comprehensive assessment of the overall system architecture and are aimed at assessing perspectives such as (i) goal, (ii) environment, and (iv) activity. The following framework Table 9 was used to formulate questions in each phase of the flood warning and response system.

Table 9: The framework used to design the questions in the evaluation

Dimensions	**Generic questions**	**Information sought via the questions (for each phase of FEWRS)**
Goal / Efficacy	Does the overall architecture meet the goals of each phase of FEWRS ?	

Environment (Consistency with organisation)	Does the architecture fulfil the organisational needs for each phase of FEWRS?	(i) Understanding risk (ii) Monitoring, forecasting and warning (iii) Communication and dissemination (iv) Response Capacity
Environment (Consistency with people)	Does the proposed architecture meet the user's needs in each phase of FEWRS?	
Environment (Consistency with technology)	Does the presented architecture deploy state-of-the-art technological tools in each component of the FEWRS?	
Activity	Does the proposed architecture increase the accuracy, efficiency, and performance of each stage of FEWRS?	

3.4 Research Techniques

This section discusses the research techniques used in this study. Research techniques are divided into two subdivisions: data collection and data analysis. In section 3.4.1, data collection techniques are explained, while section 3.4.4 explains the data analysis techniques.

3.4.1 Data Collection Techniques

According to Yin (2009), six significant data collection sources have been suggested, illustrated in Table 10. These include interviews, observations, questionnaire surveys, document reviews etc.

Table 10: Data Collection Techniques (Source: Yin, 2009)

Sources of Evidence	Strengths	Weaknesses
Documentation	-Stable: can be reviewed repeatedly -Unobstructed: not created as a result of the case study -Exact: contains exact names, references and details	- Retrievability can be low - Biased selectivity if the collection is incomplete - Reporting bias: reflects bias of the author - Access: may be deliberately blocked
Archival Records	-Same as above	-Same as above

	- Precise and quantitative	-Accessibility may be limited for privacy reasons
Interviews	-Targeted: focus directly on the case studies -Insightful: provides perceived causal inferences	-Bias due to poorly constructed questions -Response bias -Inaccuracies: Interviewees say what they think the interviewer wants to hear
Direct observation	-Reality: covers the event in real time -Contextual: covers the context of an event	-Time-consuming - Selectivity: poor unless broad coverage -Reflectivity: events may be processed differently
Participation	-Same as for direct observation -Insightful into interpersonal behaviour and motives	-Same as for direct observation -Bias due to investigator's manipulation of events
Physical Artifacts	-Insightful into cultural features Insightful in technical operations	-Selectivity -Availability

As explained by Yin (2009), interviews allow direct access to people's views, allow for deep investigation of the situation, and deal with human concerns. Jones (1985) and Punch (2005) suggested that interviews will give an insightful understanding of a situation. They stressed that "to truly understand how others perceive reality, it's crucial to ask them... and to do so in a way that allows them to express themselves in their own terms". On the other hand, a questionnaire survey involves large samples of data gathering, which needs a broader sample size (Saunders et al., 2007).

This study used multiple data collection techniques in different phases from the same sample of data sources. The structured literature survey captured the current issues, gaps, and challenges of flood warning and response systems. Interviews were conducted to capture the user requirements for the characteristics of the proposed artefact. Participants involved in flood warning, coordination, and response process and nationally identified experts, practitioners, and community leaders were interviewed. After the conceptual framework for the system was developed, follow-up data collection was conducted to validate and evaluate the proposed artefact. A combination of different data collection techniques was used in this study to reduce the weaknesses of each individual technique and to improve the validity and reliability of the research outcome. Yin (2009) also suggested using more than one data collection technique to improve the quality of the research outcome.

3.4.2 Interviews

Interviews are a vital data collection technique widely used in research approaches. According to Yin (2009), interviews play a crucial role in gathering data and information. Swartz et al. (1998) highlighted that interviews are prominent in qualitative data collection. Collins and Hussey (2003) defined interviews as a method where selected participants are asked questions to understand their thoughts, actions, or feelings. Interviews are beneficial when deeply probing an individual's beliefs, values, experiences, and knowledge (Smith et al., 2008). In research, three common types of interviews are employed: structured, semi-structured, and open-ended (unstructured), as outlined by Smith et al. (2008) and Punch (2005).

As described by Easterby-Smith et al. (2012), structured interviews involve a predetermined set of questions the researcher asks consistently of all respondents. On the other hand, open-ended (unstructured) interviews allow interviewees to freely express themselves without interference from the researcher (Smith et al., 2008). Robson (2002b) depicted semi-structured interviews as a combination of structured and unstructured formats. While the questions are predetermined, the sequence and duration can be adjusted within each topic during the interview. Additionally, both semi-structured and open-ended interviews yield richer data as respondents tend to provide more detailed information and insights in their responses, as noted by Smith et al. (2008).

Semi-structured interviews offer a level of adaptability crucial for specific types of studies (Jankowicz, 2005). They allow researchers the freedom to modify questions during the interview process, even incorporating additional ones if necessary if they are beneficial for the research. Moreover, as highlighted by Saunders et al. (2012), semi-structured interviews in qualitative research serve not only to reveal the 'what' and 'how', but also to investigate the 'why' of a given context. This is especially valuable in qualitative aspects, such as verbal expressions, interpersonal connections, behavioural patterns, and individual experiences. This approach facilitates a deeper understanding and interpretation of the complexities involved in qualitative data.

Semi-structured interviews ensure a balance between depth and flexibility in gathering participants' perceptions. This level of organisation was crucial in this study to align captured data closely with the flood warning and response process. The questions were structured around the four stages of the flood warning and response process. This approach aimed to gather comprehensive and closely aligned data with each stage. Consequently, semi-structured interviews proved to be a fitting research method for understanding the specific features desired by stakeholders.

Before arranging interviews with the senior officers of the authorities, domain experts and users, a pre-test was undertaken. As Saunders et al. (2012) described, a pre-test is a small-scale examination of test questionnaires, interview checklists, or observation schedules. Its purpose is to reduce respondents' likelihood of having difficulty in answering questions and to minimise data-recording issues. Additionally, it allows for an initial assessment of the questions' validity and the reliability of the collected data. Conducting a pilot study serves several purposes, including validating interview questions, enhancing their effectiveness, and evaluating the overall research method, as noted by Yusof and Aspinwall (1999).

Finally, an interview guideline was established. A concise introduction about the research aims, and interview purpose was provided to each participant. This step was crucial to ensure successful data collection. Participants were briefed on the study's objectives, the interview's purpose, and the benefits to their organisation. This approach aimed to motivate participants and prompt, clear thinking about current and proposed processes of FEWRS and requirements in this context.

3.4.3 Sampling

Sampling was necessary for this research since gathering data from the entire population was not feasible. In research terms, the population refers to the entirety of the people or phenomena being studied (Somekh & Lewin, 2005), while sampling involves the selection of specific cases from this broader population (Wood & Bloor, 2006). Tashakkori and Teddlie (2003) provided a definition of sampling as the "process of choosing units such as events, people, groups, settings, or artefacts in a manner that optimises the researcher's capacity to address the research questions".

Sampling techniques fall into two categories: probability sampling and non-probability sampling (Easterby-Smith et al., 2012; Saunders et al., 2012). Probability sampling is often used in quantitative research to ensure a representative sample is chosen from the population being studied. This enables researchers to generalise from the sample to the larger population it represents. On the other hand, qualitative researchers typically select non-probability sampling, which does not necessitate the selection of a large sample or using random sampling procedures (Easterby-Smith et al., 2012).

Saunders et al. (2009) highlighted five types of non-probability sampling: quota sampling, snowball sampling, convenience sampling, purposive sampling, and self-selection sampling. Denscombe (2017) defined purposive sampling as selecting subjects based on specific characteristics, the researcher's understanding of the population, and the study's purpose. For this research, subjects needed specialised expertise in the investigated field. The choice of purposive sampling significantly impacts upon data quality; therefore, it is crucial to ensure the reliability and competence of the informants. Bernard (2017) emphasised that the researcher identifies what needs to be understood and seeks out individuals who can provide valuable information based on their knowledge or experience.

Therefore, this research adopted purposive sampling techniques to collect the required data at each phase. In the first phase of the data collection, to capture requirement, the researcher identified a list of responders based on their responsibilities within the flood warning and response process and their expertise and experience in disaster risk management. Thirteen participants for the data collection were selected to fulfil the needs of the investigation. A list of the participants is listed in Table 11.

Table 11: List of the participants to be interviewed for the semi-structured interviews

Organisation	**Job Function**	**Level**
Organisations responsible for FEWRS (9 members)		
Irrigation Department	Senior Engineer (Hydrology)	National
Disaster Management Centre	Additional Director General	
	Director Mitigation, Research and Development	
	Deputy Director Early Warning	
	Assistant Director Preparedness	
District Administration	Assistant Director Disaster Management	Sub National
Divisional Secretary	Divisional Secretariat	Local Level
GN Officer	Village Officer	Local Level
Community member	Village Disaster Management Committee	Local Level
Experts in DRM (4 members)		
World Bank	Senior DRM Specialist	National
Learn Asia Foundation	Chairman	National
World Food Programme	VAM Specialist	National
Janathakshan	Consultant	National / Local

In the second phase of data collection, seven participants has been selected. Four experts from disaster management, who were involved in the user requirement phase, and three experts from the IT sector were involved in the evaluation process. Table 12 lists the subjects who participated in the evaluation process.

Table 12: The list of panellists who took part in the evaluation process

Code Name	**Job Position**	**Organisation**
E1	Senior Meteorologist / Director	Meteorology Department
E2	Senior Hydrologist / Director	Irrigation Department
E3	Member of Middle Management	Disaster Management Centre
E4	Disaster Risk Management Expert	World Bank
E5	IT Consultant	Information Communication Technology Agency (former)
E6	Retired IT Secretary	Ministry of Information Technology
E7	System Architect / CTO	A Private IT Firm and former CTO of ICTA

The overall system architecture, comprising the four core stages of the early warning and response process, was presented to the experts through Microsoft Teams. The presentation focused on the conceptual processes, data flows, and stakeholder arrangement to ensure that the user thoroughly understood the proposed architectural framework. The researcher used MS Teams and Mural as the medium for capturing the feedback from the experts.

The evaluation approach employed individual responses to gather user feedback using a pre-shared questionnaire. Three group meetings were conducted to evaluate the artefact with the following combinations: a representative from the Irrigation Department (E1) and the Meteorology Department (E2) in the first meeting; DMC (E3) and the World Bank representative (E4) in the second meeting, and three IT experts (E5, E6 and E7) in the last meeting, as there were difficulties in bringing all the members together in one meeting due to their busy schedules. The process began with the researcher giving a brief presentation that covered the rationale, the research problem, the key findings, and a demonstration of the proposed artefact that consisted of four co-processes and overall architectural views. Individual interviews were then administered to reveal/suggest observations for further improvement. The results were subsequently discussed with the researcher to reach a consensus and to formulate the overall conclusions and suggestions.

Additionally, before the meetings commenced, participants were provided with consent forms outlining their right to withdraw from the evaluation process at any point. They were also informed of their freedom to express any opinions or comments during the evaluation. Voice and video recordings were used to capture the user responses. These recordings were later reviewed to extract valuable discussions.

Individual questionnaires offered participants the opportunity to express their personal opinions. It contained a mix of open-ended and close-ended questions, with choices ranging from "agreement" to "disagreement" for multiple-choice queries. The multiple-choice questions enabled participants to address specific aspects of the evaluation. Moreover, besides the concise questions, responders were also encouraged to provide additional comments and cross-check their viewpoints with various facets of the prototype.

This combination of concise questions and qualitative discussions allowed for an extensive evaluation of the entire architecture. This dual-method approach was aimed at achieving broad coverage and depth in the evaluation process. Participants offered insights on the proposed architecture during the discussions and feedback sessions. This method facilitated participants in expressing their independent feedback in an open manner.

3.4.4 Data Analysis Techniques

The nature of this research is to develop an artefact that is designed based on the users' participation. Therefore, a vital step of this research is to capture the user requirements of the proposed artefact. Capturing of characteristics involves qualitative data produced from the semi-structured interviews. Therefore, the data analysis technique is equally essential to translate the numerous user views into user requirements. According to Yin (2009), data analysis is "examining, categorising, tabulating, testing or otherwise recombining evidence to draw empirically-based conclusions". Six different data analysis methods are suggested: content analysis, grounded analysis, disclosure analysis, narrative analysis, conversation analysis and argument analysis (Smith et al., 2008).

Braun and Clarke propose six steps of iterative thematic analysis (Clarke & Braun, 2013) as follows:

Step 1: Become familiar with the data,

Step 2: Generate initial codes,

Step 3: Search for themes,

Step 4: Review themes,

Step 5: Define and name themes,

Step 6: Produce reports

Researchers are responsible for selecting the most appropriate analysis technique to achieve the research objectives. This study utilised qualitative data to gather user requirements to design and evaluate the artefact. Furthermore, the grounded theory approach was unsuitable for achieving interview data collection objectives. In this context, the researcher has decided not to forego the content analysis of the interview data. Instead, thematic analysis was employed to scrutinise the data, enabling the identification of key themes derived from the interview script. These themes were then systematically aligned with user requirements and evaluation feedback, providing an insightful approach to the analysis.

In this study, the author employed numerous flowcharts to illustrate processes and data flow diagrams, effectively capturing various aspects of the processes and data/information flows. These charts were meticulously constructed from both primary and secondary data sources. Throughout the user requirement analysis, both the 'As-is' scenario and 'To-be' scenario were captured to construct the proposed 'process view.' Subsequently, the 'data flow' diagrams were further derived from the process view.

The 'As-is' scenario was built upon secondary documents that defined processes and procedures, providing insights into the current flood warning and response scenario. Conversely, the 'To-be' scenario relied solely on responses captured during the initial phase of the interviews. The interview outcomes were transcribed, answers were grouped based on similarity, and then generalized to form unique 'user requirements.' These requirements were methodically documented in tables for systematic analysis and reference.

For instance, the user requirement *"multiple gauge networks should be integrated into a single platform"* articulates the need for integrating standalone gauge networks into a unified platform. Another response highlighted that *"the data acquired by these sensors should be available to the public to view"* indicating that the public should be able to visualize the data acquired. Consequently, these two requirements were transformed to generate Data Flow Diagrams, as presented in Figure 17. This process was iteratively repeated throughout the requirement analysis and design phase.

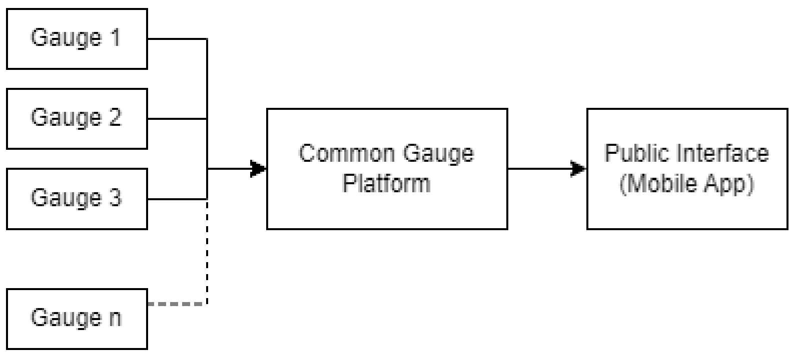


Figure 17: The process of building a flow diagram from the responses

3.4.5 Ethical Considerations

The researcher has thoroughly addressed ethical considerations throughout the course of this research. The invitation letter explicitly stated that the provided data would be kept confidential, would not be shared with third parties, and anonymity would be ensured. Additionally, as mentioned earlier, participants received a thorough explanation of the research and gave their informed consent willingly. In the prototype evaluation phase, participants were allowed to express their opinions in a group discussion or through a written questionnaire. This latter approach allowed them to convey their thoughts without feeling obligated to deliver in front of colleagues or partners if they preferred not to.

3.5 Summary

This chapter has outlined the nature of the research from interpretivism, idealism, and the researcher's role in the research study. Furthermore, this chapter also delivered the basic research principles from Saunders's "research onion" and discussed the design science research approach.

Due to the nature of the information system, the researcher has proposed the DSR approach for this study. Finally, the data collection and data analysis techniques were presented. The next chapter will discuss the first phase of the DSR research: explicate the problem.

Chapter 4 Failure Factors of Flood Early Warning and Response System

4.1 Introduction

Flood incidents in the recent past have proved that both developing and developed nations are equally facing unexpected damages and losses due to the inadequacy of the linkage between the warning providers and responders. Flood events in Germany in June 2021 (Paye & Forestier, 2021; Thieken et al., 2022), Pakistan in 2022 (Bhutta et al., 2022; Wyns, 2022), and New York in 2021 (Hanchey et al., 2021; Kozlov, 2021) are some examples of the numerous failures of early warning systems in the recent past. Such situations call for researchers to investigate the connectivity between the failures of FEWRS and their root causes.

Parker and Fordham (1996) have studied several flood warning systems in the European Union, with reference to key river basins in the United Kingdom, Germany, France, Portugal and The Netherlands, and have suggested 14 criteria to evaluate the effectiveness of FEWRS and proposed a "staged development model" with five stages of development from rudimentary (level 1) to advanced (level 5). The criteria highlighted in their study include the philosophy used for flood warning, the tools and technologies utilised, the geographical coverage of the warning, dissemination methods, legal support, governance approach, and public awareness. For example, countries with rudimentary warning systems have blanket warnings, while targeted warning systems are typically implemented in countries with advanced warning systems. However, the above study does not reveal the critical failures of the FEWRS.

In (Duminda Perera et al., 2020; Perera et al., 2019), the state-of-the-art FEWRS has been evaluated from 53 countries through primary data collection. This research has identified numerous challenges encountered by FEWRS; these can be broadly classified into four categories: technical, institutional, financial, and social. Some of the technical challenges identified in this research are the lack of availability and accessibility of data, the lack of technical expertise in flood forecasting, and inadequate hydrological coverage. Furthermore, financial commitment to maintaining existing systems, modernisation, and the recruiting and training of staff with knowledge of state-of-the-art technologies have also been identified as challenges hindering the effectiveness of FEWRS. Lack of coordination among the institutes that are involved in warning generation and early responder agencies is highlighted as one of the key institutional challenges. Most importantly, social challenges are critical and such systems have no value unless they provide timely and effective warning and the community at risk acts appropriately (Dutta & Basnayake, 2018).

In Hammood et al. (2020), the authors have put forward the 16 most influential factors from 66 factors that affect the success of FEWRS by reviewing 40 papers, namely: system quality, information quality, user satisfaction, service quality, use, perceived usefulness, intention to use, net benefits, perceived ease of use, compatibility, user experience, relative advantage, complexity, perceived risks, educational quality, and confirmation. The same authors (Hammood et al., 2021), from separate research, suggest that the DeLeone and McLean (D&M) model is suitable for assessing the effectiveness of FEWRS. The research findings from Hammood et al. (2021) suggest broader influential factors for "information systems", but not specifically for flood warning systems and, therefore, do not offer a clear understanding of the failure factors of FEWRS. In addition to the above studies, various authors (Nieland & Mushtaq, 2016; Owen & Wendell, 1981; Rana et al., 2020) have also touched on numerous aspects of flood warning and response systems. In (Owen & Wendell, 1981) the authors argue that facts such as comprehensiveness, realism, reliability, accuracy and timeliness play a critical role in making a flood warning system successful. In (Rana et al., 2020), a study from Pakistan, the authors suggest that a lack of resources to keep an Early Warning (EW) system operational, community trust, and guidelines for warning dissemination are critical to making such systems successful.

The aforementioned studies have identified certain elements in the failures of flood warning and response systems. However, up until the present time, there is no comprehensive literature survey which has been conducted to investigate the failures of flood warning systems and their root causes. This chapter presents the outcome of a structured review conducted to identify common gaps, barriers, and challenges that impact the effectiveness of FEWRS. This literature survey addresses Objective 1 of this research.

4.2 Identification of the Critical Failure Factors

The key objective of this particular study was to identify the critical failure factors (CFFs) affecting FEWRS, through a structured literature survey, and to build the inter-relationships within these factors using Interpretive Structural Modelling (ISM). The key question intended to answer through this literature survey was: "What are the gaps, barriers and challenges that impact the effectiveness of Flood Early Warning and Response Systems?". The methodology used in conducting the structured survey and Interpretive Structural Modelling is illustrated in Figure 18.

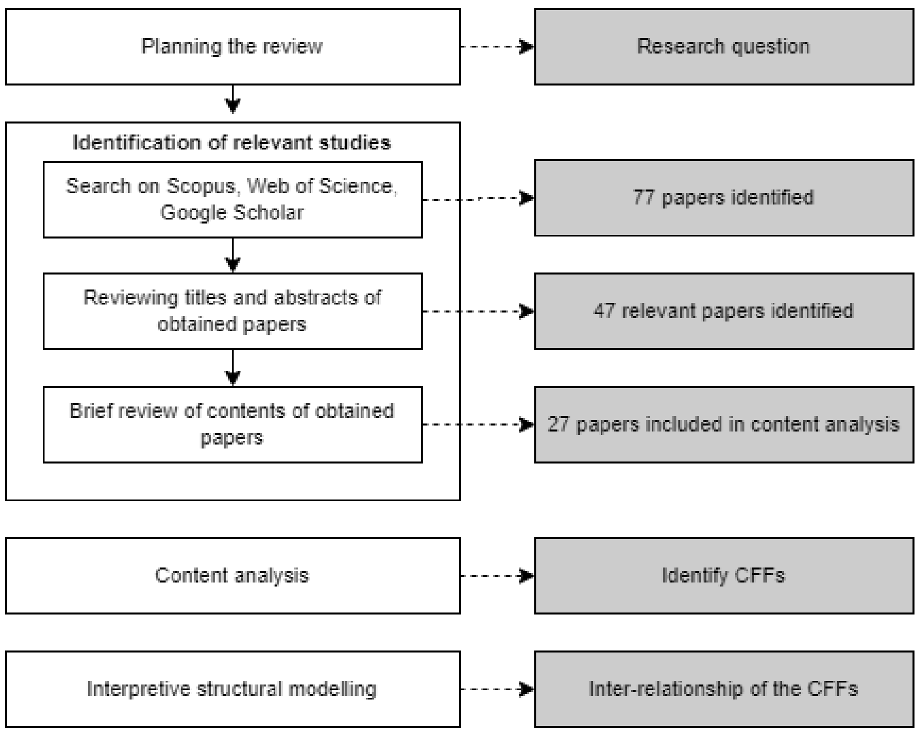


Figure 18: Overview of the search strategy used to extract research contributions on barriers and challenges of FEWRS

The review methodology developed by Webster and Watson (2002) was used to identify the published key research contributions. The keywords "gaps", “barriers”, challenges”, “limitation” and “issues” were used to define the scope of the search and the keywords “flood early warning” “flood response”, “flood forecasting”, “FFWRS” (flood forecasting and warning systems), “FEWRS” (Flood early warning and response systems), “flood response*” were used to define the context of flood warning and response. The generic string used for the search was:

(“gaps” OR “barriers” OR “challenges” OR “issues” OR “limitation”

OR “effectiveness”) AND (“flood warning” OR “flood early warning” OR “Flood EW” OR “flood response” OR “flood forecasting” OR “FFWRS” OR “FEWRS” OR “flood response*”).

This generic string was used to search for relevant research articles in the Scopus, Web of Science and Google Scholar databases. A title search was employed to extract the most pertinent papers and to limit the number of results to a manageable level. The search was limited to journal articles, conference papers, and book chapters published from 1970 onwards, which were written in English. The initial search found 77 research articles from all three databases. After the removal of duplication and subsequent title and abstract screening, the total number of selected papers was reduced to 47. After reviewing the full text of these publications, twenty-seven (27) research articles, which provided clear evidence of barriers, challenges and issues related to operationalising FEWRS, were selected for the final review. In terms of the year of publication, most of the articles were found in the period between 2015 and 2021. All 27 papers were examined, analysed and synthesised to extract the critical failure factors of FEWRS.

4.2.1 Interpretive Structural Modelling (ISM)

Interpretive Structural Modelling (ISM), a well-established methodology, was conducted to build the relationship (Attri et al., 2013) between the failure factors identified in this review. ISM has been extensively used by researchers to understand the inter-relationships of various elements. A review study by (Kumar & Goel, 2022) shows exponential growth in similar studies and that over 200 research articles incorporating ISM have been published annually since 2018. Some of the popular studies are in the fields of information systems (Kanungo & Bhatnagar, 2002), green supply chain management (Diabat & Govindan, 2011), health care (Kumar, 2018) and solid waste management (Tsai et al., 2020). Therefore, identifying the interrelationship and inter-dependencies of CFFs is helpful in collectively understanding the complexity of a particular problem from a broader scale. It also provides an understanding of the most influential factors that cause a problem.

The structured self-interaction matrix (SSIM) was initially developed using pairwise comparisons of each variable to generate a reachability matrix (RM). The pairwise comparison was performed via consultation with five experts (two from academia, two from the United Nations, and one from the World Bank). The majority vote for each pair was considered to construct the reachability matrix (RM). Following these steps, the transitivity of these reachability matrices was checked, and a final reachability matrix was derived. Finally, level portioning was applied to obtain the final matrix model. The details of the ISM process are further elaborated upon in the next section.

4.2.2 Analysis of Critical Failure Factors

The structured literature survey revealed 24 critical failure factors that constrain the effective implementation of FEWRS. Based on the nature of their origin, these factors are demarcated into three categories: (i) factors which belong to authorities who generate forecasts and operate the warning systems (generation end) (ii) factors that belong to the warning receivers/users (receiver end) and, finally, (iii) factors associated with enabling tools and technology. Therefore, based on the above classification, the CFFs are broadly categorised into (i) institutional (ii) social and (iii) technical. Furthermore, these factors have also been mapped with the phases of the flood early warning and response process, which further shows their relationship with the warning stage (Table 13).

Table 13: The key barriers and challenges in Flood Early Warning and Response Systems

Critical Failure Factors	**The stages of the FEWR process**				**Sources**
	Risk Knowledge	**Monitoring and Warning Service**	**Communication and Dissemination**	**Emergency Response**	
Institutional					

Weak institutional governance, coordination and custodianship	x	x	x	x	(Almoradie et al., 2020; Kumar et al., 2020; Moisès & Kunguma, 2023; Duminda Perera et al., 2020; Perera et al., 2019; Rana et al., 2020; Yeo & Comfort, 2017)
Lack of funding to operationalise, modernise, and maintain FEWRS	x	x	x	x	(Aguirre et al., 2018; Almoradie et al., 2020; Basha & Rus, 2007; Moisès & Kunguma, 2023; D. Perera et al., 2020; Duminda Perera et al., 2020; Perera et al., 2019)
Data sharing and data governance issues	x	x	x	x	(Almoradie et al., 2020; Basha & Rus, 2007; Moisès & Kunguma, 2023; Northfield et al., 2021; Duminda Perera et al., 2020; Perera et al., 2019)
Lack of skilled human resources for data analysis, modelling and forecasting	x	x			(Moisès & Kunguma, 2023; Duminda Perera et al., 2020; Perera et al., 2019)
Lack of political will and institutional leadership	x	x	x	x	(Moisès & Kunguma, 2023; D. Perera et al., 2020; Duminda Perera et al., 2020)
Inadequate local-level preparedness for response				x	(Dutta & Basnayake, 2018; D. Perera et al., 2020; Duminda Perera et al., 2020)
Lack of knowledge and awareness of key stakeholders	x	x	x	x	(Almoradie et al., 2020; D. Perera et al., 2020)
Lack of access to warnings and less warning coverage				x	(Owen & Wendell, 1981; Parker et al., 2009; Duminda Perera et al., 2020)
Issues with physical protection of sensors/IoT installed		x			(Aguirre et al., 2018; Basha & Rus, 2007)
Lack of inclusion of community and vulnerable groups in planning and decision making	x	x	x	x	(D. Perera et al., 2020)
Technical					
Lack of understanding of the risk and	x	x	x	x	(Almoradie et al., 2020; Drobot & Parker, 2007; Dutta & Basnayake, 2018; Moisès & Kunguma, 2023;

unavailability of risk information/maps					Northfield et al., 2021; Rana et al., 2020)
Data/information errors	x	x			(Aguirre et al., 2018; Hossain, 2006; Kumar et al., 2020; Moisès & Kunguma, 2023; Parker & Priest, 2012; Duminda Perera et al., 2020; Perera et al., 2019)
Issues with flood forecast modelling accuracies and techniques		x			(Basha & Rus, 2007; Khatibi et al., 2003; Duminda Perera et al., 2020; Perera et al., 2019; Rana et al., 2020)
Inadequate flood warning lead time and inefficiencies in warning generation and dissemination	x	x	x	x	(Cawood et al., 2018; Drobot & Parker, 2007; Khatibi et al., 2003; McEwen et al., 2002; Nieland & Mushtaq, 2016; Northfield et al., 2021; Parker et al., 2009)
Issues with communication and dissemination systems		x	x		(Almoradie et al., 2020; Basha & Rus, 2007; Dutta & Basnayake, 2018; Moisès & Kunguma, 2023; Parker et al., 2009; Duminda Perera et al., 2020; Perera et al., 2019)
Unavailability of SoPs (standard operating procedures), systems and plans for better warning and response		x	x	x	(Dutta & Basnayake, 2018; Moisès & Kunguma, 2023; Northfield et al., 2021; Perera et al., 2019)
Lack of appropriateness, completeness and understanding of warning messages and dissemination in-efficiencies			x		(Basha & Rus, 2007; Cawood et al., 2018; Dutta & Basnayake, 2018; Moisès & Kunguma, 2023; Northfield et al., 2021; Owen & Wendell, 1981; Parker et al., 2009; Duminda Perera et al., 2020; Rana et al., 2020)
Limited computing capacity		x			(Almoradie et al., 2020; Basha & Rus, 2007; Moisès & Kunguma, 2023)
Social					
Lack of public awareness or ability to understand the warning				x	(Basha & Rus, 2007; Drobot & Parker, 2007; Dutta & Basnayake, 2018; Kreibich et al., 2016; Kumar et al., 2020; Moisès & Kunguma, 2023; Northfield et al., 2021; Pandey & Basnet, 2023; Parker et al., 2009;

					Duminda Perera et al., 2020; Perera et al., 2019; Rana et al., 2020)
Lack of trust and credibility in the warning system			x	x	(Aguirre et al., 2018; Dutta & Basnayake, 2018; Parker et al., 2005; D. Perera et al., 2020; Rana et al., 2020)
Lack of public interest and culture of neglect				x	(Kreibich et al., 2016; Owen & Wendell, 1981; D. Perera et al., 2020; Duminda Perera et al., 2020; Rana et al., 2020)
Lack of community understanding of risk				x	(Basha & Rus, 2007; Drobot & Parker, 2007; Dutta & Basnayake, 2018; Duminda Perera et al., 2020)
Lack or neglect of community participation				x	(Dutta & Basnayake, 2018; D. Perera et al., 2020; Duminda Perera et al., 2020; Rana et al., 2020)
Lack of community capacities in the reception of warning			x	x	(Parker et al., 2009; Duminda Perera et al., 2020)

4.2.3 Institutional factors

The CFFs of institutional and governance origin which adversely affect the FEWRS are discussed in this section. According to Table 13, 10 of the 24 CFFs identified in this review are categorised under the institutional category, which plays a vital role in implementing FEWRS. Among these factors, weak institutional governance, coordination and custodianships (Almoradie et al., 2020; Kumar et al., 2020; Moisès & Kunguma, 2023; Duminda Perera et al., 2020; Perera et al., 2019; Rana et al., 2020; Yeo & Comfort, 2017); a lack of political will and institutional leadership (D. Perera et al., 2020; Duminda Perera et al., 2020); deficiency of funding to operationalise, modernise, and maintain FEWRS and obtain qualified human resources (Aguirre et al., 2018; Almoradie et al., 2020; Basha & Rus, 2007; Moisès & Kunguma, 2023; D. Perera et al., 2020; Duminda Perera et al., 2020; Perera et al., 2019); a lack of knowledge and awareness of key stakeholders (Almoradie et al., 2020; D. Perera et al., 2020), and data sharing and data governance issues (Almoradie et al., 2020; Moisès & Kunguma, 2023; Perera et al., 2019) are highlighted in the literature. Most of these factors affect all four stages of the flood warning and response process, as shown in Table 13.

Researchers have asserted that poor inter-agency coordination and communication (Almoradie et al., 2020; Duminda Perera et al., 2020; Perera et al., 2019; Rana et al., 2020; Yeo & Comfort, 2017) and weak governance in the implementation of systems (Kumar et al., 2020; Moisès & Kunguma, 2023) primarily affect the effectiveness of FEWRS. For example, poor coordination between flood management authorities and urban planning organisations (Almoradie et al., 2020) and between technical institutes that generate warnings and municipal authorities (Perera et al., 2019) are highlighted by several researchers. Findings from the review in (D. Perera et al., 2020) indicate that a weak relationship between warning producers and consumers affects warning dissemination and follow-up response activities. In (Rana et al., 2020), an example from Pakistan showed that no custodian was available for flood warnings at the local level. The research mentioned above supports the argument that inter-organisational coordination, communication and governance are among the most critical factors which affect the proper functioning of FEWRS.

Similarly, a lack of political will and organisational leadership, and political/leadership commitment are also crucial factors that adversely affect all four stages of the flood warning and response process (D. Perera et al., 2020; Duminda Perera et al., 2020). Du Plessis (2002) argues that the proper function of FEWRS may fail due to a lack of institutional leadership and commitment.

The deficiency of funds for establishing and maintaining FEWRS is another critical challenge faced mainly by developing nations, as indicated in many studies (Aguirre et al., 2018; Almoradie et al., 2020; Basha & Rus, 2007; Moisès & Kunguma, 2023; D. Perera et al., 2020; Duminda Perera et al., 2020; Perera et al., 2019). These include establishing and maintaining hydrometeorological observation networks (rain and river gauge stations), data assimilation systems, computer processing capacity, etc. (Moisès & Kunguma, 2023; Perera et al., 2019). Limited funding for maintaining systems may lead to the discontinuation of system operations (Moisès & Kunguma, 2023). Almordie et al. (Almoradie et al., 2020) emphasise that data collection from gauge stations usually stops due to a lack of maintenance of such systems after the termination of foreign-funded projects.

A lack of qualified and experienced human resources capable of flood forecasting, modelling and risk analysis is experienced by most developing countries (Moisès & Kunguma, 2023; Duminda Perera et al., 2020; Perera et al., 2019). A lack of adequate funds and a lack of the acquisition of experts and their capacity building is a significant challenge to the proper functioning of FEWRS.

Availability and accessibility to data and information are reported by many researchers (Aguirre et al., 2018; Almoradie et al., 2020; Basha & Rus, 2007; Moisès & Kunguma, 2023; Northfield et al., 2021; Duminda Perera et al., 2020; Perera et al., 2019). The lack of current and archived data for risk analysis, forecasting and early warning generation seriously affects the warning and response processes (Moisès & Kunguma, 2023). A deficiency in the appropriate funding to modernise hydrometeorological observation networks (Perera et al., 2019) and preserve maintenance (Almoradie et al., 2020) are the main root cause of the unavailability of data on most river basins in developing countries. The absence of data governing mechanisms also leads to inefficiencies in sharing data in implementing FEWRS (Almoradie et al., 2020). In (Aguirre et al., 2018; Basha & Rus, 2007; Moisès & Kunguma, 2023; Duminda Perera et al., 2020), researchers have emphasised that a lack of policies and institutional interventions also prevents the availability of historical hydrologic time series data which will affect the understanding of risk, risk modelling and model calibration.

The physical protection of hydrometeorological observation networks and other facilities at remote locations also affects the proper implementation of FEWRS. In (Aguirre et al., 2018), researchers report that weathering, equipment decay, neglect, infrastructure collapse, robbery and vandalism are reported as specific factors that affect implementation and utilisation. In (Basha & Rus, 2007), the authors state that the physical security of sensor networks is challenging as sensor instruments were vandalised in most cases. In some instances, components of gauge stations may short circuit and telemetry systems could fail due to the submerging of these stations by high floods (Heritage et al., 2001).

Lack of access to warnings due to poor broadcast and mobile service coverage (from the recipient's perspective) is identified in many studies. Remote locations with limited broadcast services and mobile signals lead to accessibility issues (Parker et al., 2009). Inefficiencies in warning dissemination and a lack of coverage lead to delays or not receiving the warning at all by certain local communities (Parker et al., 2009). Owen and Wendell (1981) confirm these findings and suggest that a flood warning received too late has little or no value.

At a local level, the lack of inclusion of communities and vulnerable groups in response planning and decision-making, inadequate local-level preparedness for response, and the lack of knowledge and awareness of key stakeholders and communities are the other main factors that affect the effectiveness of flood warnings. Perera et al. (Duminda Perera et al., 2020) highlight that the lack of participation by the community in response planning would inevitably mean a poor adoption of a response plan for localised needs. Excluding minority groups without respecting Gender Equality and Social Inclusion (GESI) in preparedness activities will decrease their interest, resulting in a lack of ownership, leading to less participation in the response (D. Perera et al., 2020).

Inadequate local-level preparedness for a response is also key to the failure of FEWRS. The absence of evacuation locations and routes (Dutta & Basnayake, 2018), limited and irregular drills and simulations (Dutta & Basnayake, 2018; Duminda Perera et al., 2020), the absence of local level emergency operation centres (Dutta & Basnayake, 2018), a lack of sufficient resources for response (Duminda Perera et al., 2020), and the nonexistence of tailor-made contingency plans (Duminda Perera et al., 2020) are considered as some of the root causes for the failure of FEWRS.

It is evident that the factors of poor risk knowledge and the awareness of the participating community and stakeholder agencies also critically affect the success of the FEWRS (Moisès & Kunguma, 2023). Research studies state that a poor understanding of risk reduction practices (D. Perera et al., 2020) and the lack of knowledge on flood preparedness among stakeholder agencies (Almoradie et al., 2020) are prominent. Even though DRR policies are available, they are not well executed at the grassroots level (D. Perera et al., 2020). As a result, when a community receives a warning, many of them fail to understand the warning context (D. Perera et al., 2020).

4.2.4 Technical Factors

The CFFs which have more technical origins are classified in this section. The study identified eight key technical barriers that adversely affect the implementation of FEWRS.

As per the UNDRR framework, risk understanding provides one of the four pillars of the flood warning and response system. From the technical point of view, poor risk understanding is a challenge in implementing FEWRS (Almoradie et al., 2020; Drobot & Parker, 2007; Dutta & Basnayake, 2018; Northfield et al., 2021; Rana et al., 2020). The lack of flood (hazard) maps (Almoradie et al., 2020; Northfield et al., 2021), the unavailability of evacuation maps (Dutta & Basnayake, 2018), the lack of risk maps (Almoradie et al., 2020; Dutta & Basnayake, 2018; Rana et al., 2020), inaccuracies in hazard and vulnerability models (Drobot & Parker, 2007), and the lack of understanding of the cascading effect (Almoradie et al., 2020) are the key causal factors in relation to the appreciation of the level of risk in a local context. Even when hazard and risk assessments have been conducted, their coverage is often only limited to certain districts (Almoradie et al., 2020). On the other hand, a finer resolution of hazard and risk assessment is frequently not achievable due to limited computing capacity and the scarcity of data (Almoradie et al., 2020).

Data unavailability and poor data quality due to technical issues have been highlighted by several researchers (Aguirre et al., 2018; Hossain, 2006; Kumar et al., 2020; Parker & Priest, 2012; Duminda Perera et al., 2020; Perera et al., 2019). One of the most highlighted issues is obtaining good-quality terrain data which is essential for hydrological modelling (Duminda Perera et al., 2020). In (Aguirre et al., 2018), the authors report on the limitation in acquiring accurate digital elevation data (DEM) from aerial photography and LiDAR surveys due to the dense forest canopy. Land use, population distribution and soil moisture data are either not available or not updated regularly (Aguirre et al., 2018; Perera et al., 2019). Manual data collection and manual data transfer is a key technical challenge that substantially reduces flood warning and response efficiencies in most developing countries (Duminda Perera et al., 2020). The lack of continuous measurement of rainfall (Hossain, 2006; Kumar et al., 2020), river flow (Hossain, 2006), and measurement accuracies (Parker & Priest, 2012) are also key factors that substantially reduce the quality of flood forecast, warning and response systems. In (Parker & Priest, 2012), the authors also indicate that gauge data is sometimes not available due to the interruption of data acquisition and transmission due to flood impacts. In (Di Baldassarre & Claps, 2011), the authors report that the rating curves for computing discharge as a function of river levels are less reliable during floods.

In flood forecasting, a long lead time is essential to reduce flood risk as it provides adequate time for flood warning and emergency response. Many studies have reported a short lead time (the time delay between a flood warning and flood onset) as a key challenge in FEWRS (Cawood et al., 2018; Drobot & Parker, 2007; Khatibi et al., 2003; McEwen et al., 2002; Nieland & Mushtaq, 2016; Northfield et al., 2021; Parker et al., 2005; Parker et al., 2009). Parker et al. (Parker et al., 2009) suggest that an improved lead time can lower the death rate and property damage (Parker et al., 2009). In (Nieland & Mushtaq, 2016), a study from Toowoomba, Queensland, Australia, suggests that a lead time of two and a quarter hours would be sufficient for the local community to relocate to safe places. According to a research study in Britain (Parker et al., 2005), whether two and a quarter hours of lead time is sufficient in a flash flood situation is doubtful and therefore, further research is recommended. Drobot and Parker (2007) indicate that lead time in flood warnings is always less than 24 hours or even less in a flash flooding context. However, they observe that weather, radar and quantitative rainfall measurement could improve the lead time. In [29], the authors also argue that a combination of automated gauge stations, meteorological forecasting and flood forecasting will potentially improve the lead time. Cawood et al. (Cawood et al., 2018) argue that the lead time and the time to reach the peak were used for flood forecasting several decades ago, and nowadays, these are often considered insufficient. Instead, the authors suggest that such flood forecasts could incorporate potential damage information for the community to understand the flood impact easily (Cawood et al., 2018).

Numerical models play a significant role in successful FEWRS as such models are used to forecast the amount of rainfall, water flow and flood arrival time (Rana et al., 2020). Early warning systems can be much more effective if these models can credibly simulate the water flows. In most developing countries, model outputs are not accurate enough to provide reliable forecasts due to a lack of good-quality hydrological data (Perera et al., 2019). The increased complexities of 2D/3D models that require high-quality elevation data, expert knowledge, and computational capacity are some of the challenges (Duminda Perera et al., 2020). The lack of suitable model input data (Duminda Perera et al., 2020) and computational capacities (Basha & Rus, 2007) are significant problems in developing countries.

Many researchers have observed the inadequacy of data communication among gauge stations to nodal agencies, inter-agency communication and early warning communication from authorities to the community level (Almoradie et al., 2020; Basha & Rus, 2007; Dutta & Basnayake, 2018; Moisès & Kunguma, 2023; Parker et al., 2009; Duminda Perera et al., 2020; Perera et al., 2019). Dutta and Basnayake (2018), point out that a critical gap exists in early warning message dissemination, especially from the national to the local level and the last mile connectivity, from a study of early warning systems in South East Asia. A global survey of 53 countries shows that 50% of responding countries have deficient technology with regard to gauges and data-transferring instruments (Perera et al., 2019). Meanwhile, a lack of standards in terminology, protocols and dissemination standards affects the quality of the warning message (Duminda Perera et al., 2020).

Irregularities in the geographical coverage of a warning system also affect the uniformity of the warning dissemination in the last mile (Parker et al., 2009).

A lack of completeness, appropriateness and understanding of a warning message at the local level affects the effectiveness of FEWRS. A clear gap has been observed between a warning message that is disseminated and the level of understanding of such a warning (Moisès & Kunguma, 2023). In (Basha & Rus, 2007), Basha and Rus (2007) propose that warning messages be disseminated in an understandable form. Misinformation and a lack of clarity (Parker et al., 2009), erroneous warning messages (Owen & Wendell, 1981), credibility and impact of delivery (Owen & Wendell, 1981), and appropriateness of the message (Northfield et al., 2021) are some of the key issues identified by various researchers. Message dissemination inefficiencies (Northfield et al., 2021; Owen & Wendell, 1981) and inadequate warning coverage of at-risk communities (Northfield et al., 2021) are other issues highlighted in the literature. In (Basha & Rus, 2007) Basha and Rus (2007) propose that a proper warning should have (i) an understanding of the effect of the event (ii) a timeline of the progression, and (iii) an understanding of the uncertainties involved.

A lack of controls and regulatory mechanisms such as standard operating procedures (SoP), systems, processes and plans for better implementation of FEWRS is another dimension that needs to be addressed (Dutta & Basnayake, 2018; Moisès & Kunguma, 2023; Northfield et al., 2021; Perera et al., 2019). Dutta and Basnayake (2018) show some examples of a lack of response, incident command, decision-making, and communication plans (Dutta & Basnayake, 2018). Furthermore, they also observe that the unavailability of early warning standard operating procedures (SoPs) and a lack of technical guidelines on early warning processes such as formulation, validation, confirmation and withdrawal also adversely affect the proper function of FEWRS.

4.2.5 Social Factors

In this review, 6 out of 24 barriers have been identified as social factors. A lack of public awareness of understanding the warning information is the most highlighted barrier cited by many researchers (Basha & Rus, 2007; Drobot & Parker, 2007; Dutta & Basnayake, 2018; Kreibich et al., 2016; Kumar et al., 2020; Moisès & Kunguma, 2023; Northfield et al., 2021; Parker et al., 2009; Duminda Perera et al., 2020; Perera et al., 2019; Rana et al., 2020). The absence of knowledge and awareness of understanding the warning message (Dutta & Basnayake, 2018; Northfield et al., 2021; Duminda Perera et al., 2020) and the lack of community understanding on how to respond to the warnings (Kreibich et al., 2016; Kumar et al., 2020; Parker et al., 2009; Perera et al., 2019) and minimising the impact (Parker et al., 2005) have been highlighted by several researchers. Rana et al. (Rana et al., 2020) argue that technical jargon and the complexities of official warning messages may inhibit a better understanding of warning messages. Irregular drills and preparedness practices (Duminda Perera et al., 2020), and a poor literacy rate (Basha & Rus, 2007) are also other reasons for less community awareness concerning warning messages.

Community trust and credibility in warning systems has been identified as a factor by several researchers (Aguirre et al., 2018; Dutta & Basnayake, 2018; Moisès & Kunguma, 2023; Parker et al., 2005; D. Perera et al., 2020; Rana et al., 2020). The trustworthiness of a warning system and its messages have been emphasised in (Dutta & Basnayake, 2018; Rana et al., 2020). For example, false positive and false negative warnings will adversely affect public trust in such systems (Aguirre et al., 2018). This will finally lead to a lack of confidence in the authorities associated with the warning generation and emergency response (D. Perera et al., 2020).

Poor public interest and a culture of neglect can reduce the effectiveness of the FEWRS, as indicated in studies (Kreibich et al., 2016; Owen & Wendell, 1981; D. Perera et al., 2020; Duminda Perera et al., 2020; Rana et al., 2020). Due to this reason, a lack of community response to warning messages is indicated in the study (Owen & Wendell, 1981). Perera et al. (D. Perera et al., 2020) advise that certain communities do not respond to warnings due to a "culture of neglect" which could be caused by poor public awareness and issues with the trustworthiness of warnings.

Incorrect risk perception and poor knowledge of potential and impending disasters adversely affect community interest in warning and response systems (Dutta & Basnayake, 2018; Duminda Perera et al., 2020). Providing adequate knowledge and awareness of a potential flood inundation, a timeline of the progression of the event and possible damage using historical flood events' data are proposed by (Basha & Rus, 2007) to overcome this issue.

Finally, poor community participation in the flood warning and response process was identified by many researchers (Dutta & Basnayake, 2018; D. Perera et al., 2020; Duminda Perera et al., 2020; Rana et al., 2020). Community participation in order to incorporate their feedback in the early warning designing or redesigning process is essential to operationalise a more efficient system (Rana et al., 2020). In (D. Perera et al., 2020), the authors identify failures in using participatory approaches involving communities and in addressing their concerns through warning mechanisms. Inadequate gender-based participation and the exclusion of minority groups are also observed in all stages of FEWRS (D. Perera et al., 2020).

The lack of community capacity to receive warning messages is comparatively challenging in the implementation of FEWRS (Parker et al., 2009; Duminda Perera et al., 2020). Most vulnerable groups have limited access to television, radio and mobile phones, and hence, these groups may not receive the warning message efficiently (Duminda Perera et al., 2020).

Inefficiencies in warning dissemination and the lack of access to warning amenities are other key issues affecting local preparedness (Owen & Wendell, 1981; Parker et al., 2009) (D. Perera et al., 2020). In (D. Perera et al., 2020), a survey by Perera et al. (2020) suggests that warnings do not reach all vulnerable groups due to the lack of access to amenities to receive such warning messages.

4.2.6 Structured Self-Interaction Matrix (SSIM)

In this step, a pairwise comparison was conducted in consultation with five experts to establish the SSIM matrix. The SSIM matrix was developed with the twenty-four (24) variables placed in both rows and columns, enabling pairwise comparisons.

The contextual relationship was established using a pairwise comparison of each variable based on expert opinion on “one factor influencing another factor”. Four symbols were used to denote the inter-relationship of each variable (i-row and j-column), where the symbol “V” is used if factor ‘i’ influences factor ‘j’; “A” is used if factor ‘j’ influences factor ‘i’; “X” is used if factors ‘i’ and ‘j’ influence each other and “O” is presented if there is no relationship. Table 14 illustrates the representation of the SSIM matrix of this study.

Table 14: Structural self-interaction matrix of CFFs of FEWRS

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1		V	V	V	A	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
2			O	V	A	V	V	V	V	O	V	V	V	V	V	V	O	V	V	V	O	V	V	O
3				O	A	V	V	O	O	O	V	V	V	V	O	O	O	O	O	V	O	O	V	O
4					A	V	V	O	O	O	V	V	V	V	O	O	O	O	O	V	O	V	V	O
5						V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
6							A	A	A	A	A	A	A	A	A	A	O	O	A	O	A	A	A	A
7								O	O	O	A	O	O	O	O	A	O	O	O	V	O	O	O	V
8									O	A	O	O	O	O	A	A	O	O	O	V	O	O	V	O
9										A	O	O	V	O	O	A	O	O	O	O	O	O	O	O
10											V	O	O	O	O	A	V	O	V	V	V	V	V	V
11												O	V	O	O	O	O	A	O	V	O	V	V	V
12													V	V	O	O	O	O	O	V	O	O	O	O
13														V	O	O	O	A	O	V	O	O	O	O
14															A	A	O	A	O	V	O	O	O	O
15																A	O	O	O	V	V	O	O	O
16																	V	O	V	V	V	V	V	V
17																		O	V	V	V	O	V	O
18																			O	V	O	O	O	O
19																				V	A	A	A	O
20																					O	O	O	O
21																						V	V	V
22																							V	V
23																								V
24																								

1	Weak institutional governance, coordination and custodianship
2	Lack of funding to operationalise, modernise, and maintain FEWRS
3	Data sharing and data governance issues
4	Lack of skilled human resources for data analysis, modelling and forecasting
5	Lack of political will and institutional leadership
6	Inadequate local-level preparedness for response
7	Lack of knowledge and awareness of key stakeholders
8	Lack of access to warnings and less warning coverage
9	Issues with physical protection of sensors / IoT installed
10	Lack of inclusion of community and vulnerable groups in planning and decision making
11	Lack of understanding of the risk and unavailability of risk information/maps
12	Data/information errors
13	Issues with flood forecast modelling accuracies and techniques
14	Inadequate flood warning lead time and inefficiencies in warning generation and dissemination
15	Issues with communication and dissemination systems
16	Unavailability SoPs, systems and plans for better warning and response
17	Lack of appropriateness, completeness and understanding of warning message and dissemination in-efficiencies
18	Limited computing capacity
19	Lack of public awareness or ability to understand the warning
20	Lack of trust and credibility in the warning system
21	Lack of public interest and culture of neglect
22	Lack of community understanding of risk
23	Lack or neglect of community participation
24	Lack of community capacities in the reception of warnings

4.2.7 Reachability Matrix

In this step, both the reachability matrix and the final reachability matrix were established. In order to develop an initial reachability matrix from ISM where if the i,j entry in SSIM is "V", then an entry in the reachability matrix becomes '1'. If the 'i''j' entry in SSIM is 'A', then the entry in the reachability matrix becomes '0'. If the 'i','j' entry in the matrix is 'X', then the entry in the reachability matrix is '1'. If the 'i','j' entry in SSIM is 'O', then the entry in the reachability matrix becomes '0'. The initial reachability matrix is further examined to identify transitivity links. For example, if factor 'i' relates with factor 'j' and factor 'j' relates with factor 'k', then factor 'i' relates with 'k'. Based on this logic, the initial reachability matrix has been modified, and the final reachability matrix was achieved. The final reachability matrix is shown in Table 15.

Table 15: Final reachability matrix with driving and dependence power

Variables	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	Driving Power
1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
2	0	1	0	1	0	1	1	1	1	1*	1	1	1	1	1	1	1*	1	1	1	1*	1	1	1*	21
3	0	0	1	0	0	1	1	0	0	0	1	1	1	1	0	0	0	0	1*	1	0	1*	1	1*	12
4	0	0	0	1	0	1	1	0	0	0	1	1	1	1	0	0	0	0	1*	1	0	1	1	1*	12
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
7	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	4
8	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1*	1	0	0	1	1*	6
9	0	0	0	0	0	1	0	0	1	0	0	0	1	1*	0	0	0	0	0	1*	0	0	0	0	5
10	0	0	0	0	0	1	1*	1	1	1	1	0	1*	1*	0	0	1	0	1	1	1	1	1	1	15
11	0	0	0	0	0	1	1	0	0	0	1	0	1	1*	0	0	0	0	1*	1	0	1	1	1	10
12	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	5
13	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	4
14	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	3
15	0	0	0	0	0	1	0	1	0	0	0	0	0	1	1	0	0	0	1*	1	1	1*	1*	1*	10
16	0	0	0	0	0	1	1	1	1	1	1*	0	1*	1	1	1	1	0	1	1	1	1	1	1	17
17	0	0	0	0	0	1*	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1*	1	1*	8
18	0	0	0	0	0	1*	1*	0	0	0	1	0	1	1	0	0	0	1	1*	1	0	1*	1*	1*	11
19	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	3
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
21	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1*	1	1	1	1	7
22	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1*	0	1	1	1	6
23	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1*	0	0	1	1	5
24	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
Dependence Power	2	3	3	4	1	23	10	7	6	5	9	6	12	14	5	4	6	4	16	22	8	13	15	17	

(1* indicates the transitivity links)

4.2.8 Level Partitioning

Level partitioning was developed to establish the hierarchical relationship between variables. The reachability and antecedent set for each factor were obtained from the final reachability matrix. The factor itself and the factors that are being influenced by the factor are known as the reachability factor, whereas the factor itself and the factors that are influencing the factor are known as the antecedent set. The intersection of the reachability set and the antecedent set is derived for all the factors. The factors for which the reachability set and intersection set are the same, those factors were assigned as level 1. Once the first level of the hierarchy was achieved, the factors with level 1 were removed from the process, and the procedure is repeated until a level for each factor was determined. The results of this process are summarised in Table 16.

Table 16: Levels of the variables identified from the level partitioning process

Elements	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24	1, 5	1	10
2	2, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24	1, 2, 5	2	9
3	3, 6, 7, 11, 12, 13, 14, 19, 20, 22, 23, 24	1, 3, 5	3	6
4	4, 6, 7, 11, 12, 13, 14, 19, 20, 22, 23, 24	1, 2, 4, 5	4	6
5	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24	5	5	11
6	6	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 21, 22, 23, 24	6	1
7	6, 7, 20, 24	1, 2, 3, 4, 5, 7, 10, 11, 16, 18	7	3
8	6, 8, 19, 20, 23, 24	1, 2, 5, 8, 10, 15, 16	8	4
9	6, 9, 13, 14, 20	1, 2, 5, 9, 10, 16	9	4
10	6, 7, 8, 9, 10, 11, 13, 14, 17, 19, 20, 21, 22, 23, 24	1, 2, 5, 10, 16	10	7
11	6, 7, 11, 13, 14, 19, 20, 22, 23, 24	1, 2, 3, 4, 5, 10, 11, 16, 18	11	5
12	6, 12, 13, 14, 20	1, 2, 3, 4, 5, 12	12	4
13	6, 13, 14, 20	1, 2, 3, 4, 5, 9, 10, 11, 12, 13, 16, 18	13	3
14	6, 14, 20	1, 2, 3, 4, 5, 9, 10, 11, 12, 13, 14, 15, 16, 18	14	2
15	6, 8, 14, 15, 19, 20, 21, 22, 23, 24	1, 2, 5, 15, 16	15	6
16	6, 7, 8, 9, 10, 11, 13, 14, 15, 16, 17, 19, 20, 21, 22, 23, 24	1, 2, 5, 16	16	8
17	6, 17, 19, 20, 21, 22, 23, 24	1, 2, 5, 10, 16, 17	17	6
18	6, 7, 11, 13, 14, 18, 19, 20, 22, 23, 24	1, 2, 5, 18	18	6
19	6, 19, 20	1, 2, 3, 4, 5, 8, 10, 11, 15, 16, 17, 18, 19, 21, 22, 23	19	2
20	20	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23	20	1
21	6, 19, 20, 21, 22, 23, 24	1, 2, 5, 10, 15, 16, 17, 21	21	5
22	6, 19, 20, 22, 23, 24	1, 2, 3, 4, 5, 10, 11, 15, 16, 17, 18, 21, 22	22	4
23	6, 19, 20, 23, 24	1, 2, 3, 4, 5, 8, 10, 11, 15, 16, 17, 18, 21, 22, 23	23	3
24	6, 24	1, 2, 3, 4, 5, 7, 8, 10, 11, 15, 16, 17, 18, 21, 22, 23, 24	24	2

The above-mentioned process produces the inter-relationships among variables with the hierarchical arrangements as presented in Figure 19.

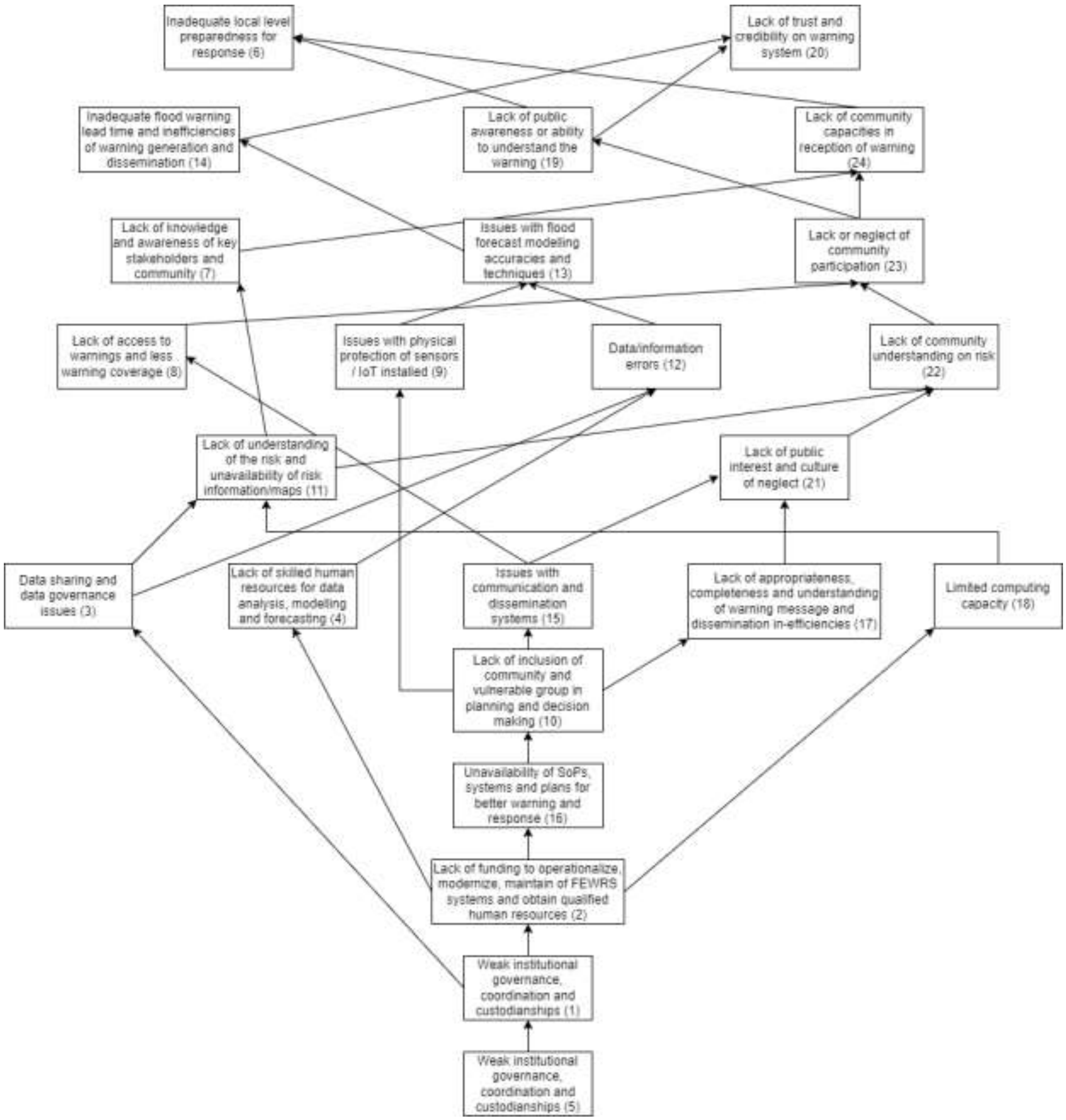


Figure 19: The ISM model showing the inter-relationship of the critical failure factors of FEWRS

4.2.9 Conical Matrix

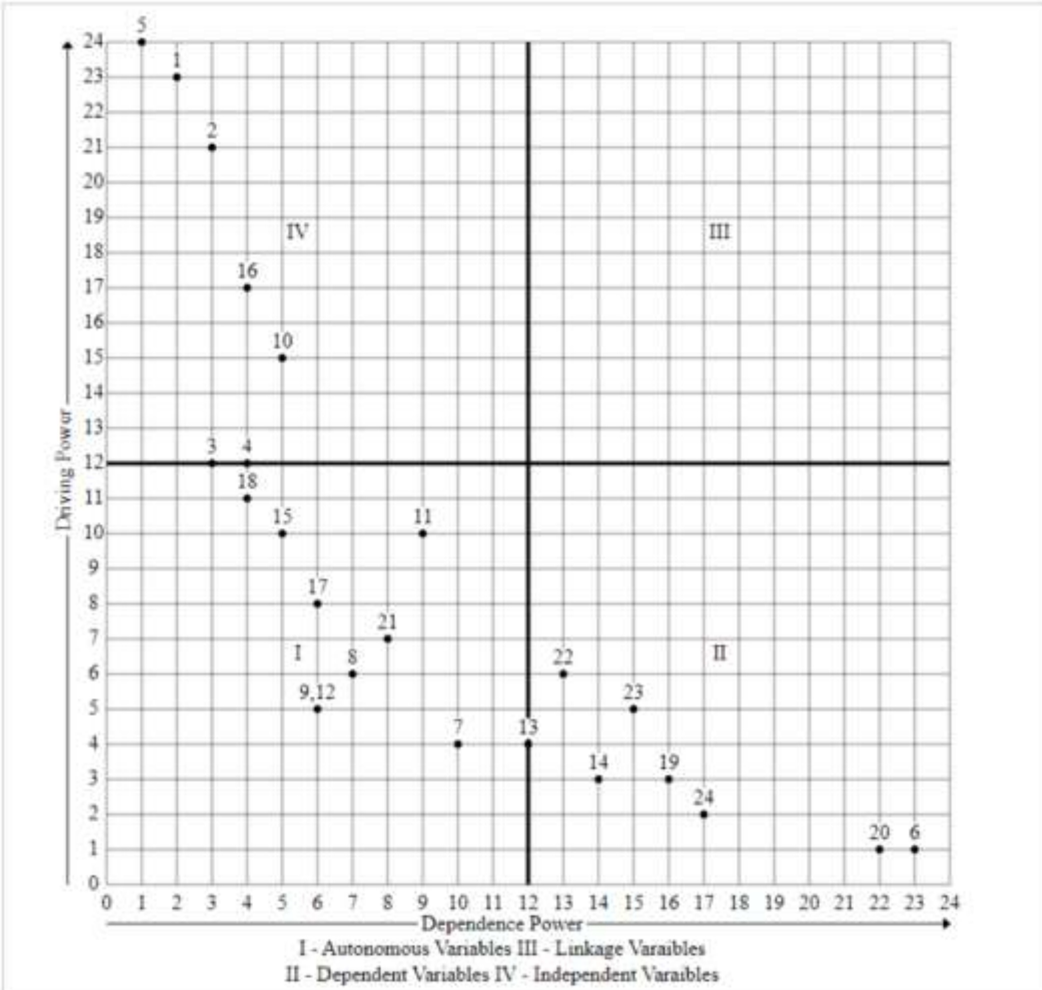
A conical matrix is developed by ordering factors with the highest driving power and dependency power in a matrix (Table 17). The driving power is calculated by adding the numbers in the row, while dependency power is calculated similarly for the column values. The driving and dependency power ranks are calculated from high to low according to their values in the rows and columns in the matrix, respectively.

Table 17: The Conical Matrix

Variables	6	20	14	19	24	7	13	23	8	9	12	22	11	21	3	4	15	17	18	10	16	2	1	5	Driving Power	Level
6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
20	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
14	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2
19	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2
24	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
7	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3
13	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3
23	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3
8	1	1	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	4
9	1	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	4
12	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	5	4
22	1	1	0	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	6	4
11	1	1	1	1	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	10	5
21	1	1	0	1	1	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	7	5
3	1	1	1	1	1	1	1	1	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	12	6
4	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	12	6
15	1	1	1	1	1	0	0	1	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	10	6
17	1	1	0	1	1	0	0	1	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	8	6
18	1	1	1	1	1	1	1	1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	11	6
10	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	1	0	1	0	0	0	0	15	7
16	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0	1	1	0	0	0	17	8
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	21	9
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	23	10
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24	11
Dependence Power	23	22	14	16	17	10	12	15	7	6	6	13	9	8	3	4	5	6	4	5	4	3	2	1		

4.2.10 MICMAC Analysis

The purpose of the MICMAC analysis was to classify four groups of factors based on their driving and dependency powers (Attri et al., 2013). Therefore, it was used to represent the factors in a two-dimensional cartesian graph based on their driving and dependence powers derived from the conical form of the reachability matrix. For example, the driving and dependency power of factor 6 are 1 and 23, respectively; hence, the position of factor 6 in the di-graph is represented as coordinates (1,23) (Figure 20). The cartesian graph is further divided into 4 clusters based on their driving and dependency power, i.e. autonomous factors, linkage factors, and dependent and independent factors.



1	Weak institutional governance, coordination and custodianship
2	Lack of funding to operationalise, modernise, and maintain FEWRS
3	Data sharing and data governance issues
4	Lack of skilled human resources for data analysis, modelling and forecasting
5	Lack of political will and institutional leadership
6	Inadequate local-level preparedness for response
7	Lack of knowledge and awareness of key stakeholders
8	Lack of access to warnings and less warning coverage
9	Issues with physical protection of sensors / IoT installed
10	Lack of inclusion of community and vulnerable groups in planning and decision making
11	Lack of understanding of the risk and unavailability of risk information/maps
12	Data/information errors
13	Issues with flood forecast modelling accuracies and techniques
14	Inadequate flood warning lead time and inefficiencies in warning generation and dissemination
15	Issues with communication and dissemination systems
16	Unavailability SoPs, systems and plans for better warning and response
17	Lack of appropriateness, completeness and understanding of warning message and dissemination in-efficiencies
18	Limited computing capacity
19	Lack of public awareness or ability to understand the warning
20	Lack of trust and credibility in the warning system
21	Lack of public interest and culture of neglect
22	Lack of community understanding of risk
23	Lack or neglect of community participation
24	Lack of community capacities in the reception of warnings

Figure 20: Results of the MICMAC Analysis

The "Independent factors" have strong driving power with weak dependence power, while the "dependent factors" have strong dependence power with weak driving power. On the other hand, the "autonomous factors" demonstrate weak driving and dependence power, and the "linkage factors" have strong driving power as well as dependence power.

4.2.11 Critical Failure Factor Analysis

FEWRS is an integral part of the flood risk reduction strategy, which the Sendai Framework for Disaster Risk Reduction (SFDRR) also recognises as a high priority. Recent trend analysis shows that climate change-induced flood incidents are gradually increasing, and both developed and developing nations feel its impact. For example, the German flood event in 2021 demonstrates that failure to respond to warning systems can lead to a tragic situation. Transforming the current warning mechanisms into a people-centric, inclusive and efficient design trusted by users is still challenging. Thus, it is necessary to determine the factors that negatively affect warning and response mechanisms in order to address them.

Previous research shows that warning systems are, generally, a system of systems (Arru et al., 2020; Horita et al., 2019), operated in a multi-stakeholder environment, with the active involvement of authorised warning senders and receivers. Such warning systems are also backed by numerous tools and technologies to improve the efficiencies of the entire process (Samansiri et al., 2022). However, it has been recognised that there is a considerable gap between 'warning senders' and 'warning receivers' and inefficient use of tools and technologies. Hence, in this study, the authors have attempted to identify the most critical factors that affect the implementation of FEWRS.

The structured review identified 24 critical failure factors that adversely influence FEWRS. They were classified into three categories based on the nature of the problem: institutional (10 factors), technical (8 factors) and social (6 factors). The ISM modelling process identified the inter-dependencies among the identified CFFs and produced a 'hierarchical structure' (Figure 19) based on expert opinion. Furthermore, the MICMAC analysis grouped these factors into four categories according to the 'driving and dependence power' (see Figure 20). The independent cluster in Figure 20 shows the factors with high driving power and less dependence power. This is the most crucial cluster, as these factors considerably influence the failure of FEWRS. It can be observed that five factors (#1, #2, #5, #16, #10) are dominant in this cluster with considerable driving power. Three out of these dominant factors are related to governance, leadership, financial and coordination aspects and are: "weak institutional governance, coordination and custodianships" (#1), "lack of funding to operationalise, modernise and maintain FEWRS (#2), "lack of political will and institutional leadership (#5). In addition, two other factors that impact upon the failure of FEWRS with considerable driving power are the "Unavailability of SoPs, systems and plans for better warning and response" (#16) and a "lack of inclusion of community and vulnerable groups in planning and decision making" (#10). The MICMAC analysis also reveals that two additional factors, namely 'data sharing and data governance' (#3) and 'lack of skilled human resources for data analysis, modelling and forecasting (#4)' are also marginally associated with the independent cluster. Therefore, the availability of data and data sharing mechanisms and the availability of skilled human resources are essential to implement successful FEWRS. These factors, with their strong driving power, form the base level of the ISM hierarchy.

In contrast, the autonomous cluster (Figure 20) contains failure factors with weak driving power and weak dependency power. In general, these factors provide less influence on other factors as well as have a lower chance of being influenced by other factors. Six out of ten factors in this cluster are considered failure factors with a technical origin, and most of the others are related to institutional capacity.

Active engagement in the community plays a key role in making early warning systems successful (Sufri et al., 2020). Therefore, the role of the authorities from the perspective of early warning system governance, coordination and resource allocation is important, and the role of community engagement is vital to make early warning systems successful. Social factors such as lack of public awareness or ability to understand the warning (#19), lack of trust and credibility in the warning system (#20), lack of community understanding of risk (#22), lack or neglect of community participation (#23), lack of community capacities in the reception of warnings (24) drives the failure of FEWRS when viewed from the community aspect. All these "social" factors are classified in the dependant cluster which has a high dependence and low driving power. The results show that none of the CFFs has been categorised under the linkage cluster, as no CFFs have high driving and dependence power.

Based on the MICMAC and ISM hierarchical model, the authors have identified the seven most crucial factors that are mainly responsible for the failure of the FEWRS, and these are summarised in Table 18.

Table 18: The most critical factors that lead to the failure of FEWRS

No.	Critical Failure Factor	Relationship of CFF with the stages of the EW System
(#5)	Lack of political will and institutional leadership	All four stages
(#1)	Weak institutional governance, coordination and custodianship	All four stages
(#2)	Lack of funding to operationalise, modernise and maintain FEWRS	All four stages
(#16)	Unavailability of SoPs, systems and plans for better warning and response	Communication and dissemination stage, emergency response stage.

(#3)	Data sharing and data governance	Risk knowledge stage and monitoring and warning services stage
(#4)	Lack of skilled human resources for data analysis, modelling and forecasting	Risk knowledge stage, and monitoring and warning services stage
(#10)	Lack of inclusion of community and vulnerable groups in planning and decision-making	Emergency response stage.

The first three CFFs in Table 18 impact all the phases of FEWRS and require political and institutional leadership, multi-stakeholder coordination and funding to design and implement an effective FEWRS. The unavailability of standard operating procedures (SoP), response plans, and dissemination systems critically impact the flood warning system's communication and dissemination phase and the emergency response capacity phase. In addition, the availability of data and skilled human resources are mostly required in understanding risks and monitoring and warning services stages. In some instances, even if data are available, most warning systems can fail due to a lack of data governance for effective data sharing. A lack of human resources to undertake data analysis to develop hazard and risk maps, warnings, and forecasting services also plays a major role in the failure of FEWRS. Lastly, community engagement in planning and decision-making is necessary to design people-centric warning systems. The elimination of these independent critical failure factors will solve most issues in FEWRS.

Several international initiatives have directed the national governments to implement proper early warning and response mechanisms by providing policy guidance, technical support and funding support. One of the key priorities of the SFDRR for the member states was to enhance the EW and dissemination systems. Target G of the SFDRR recommends "substantially increasing the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030" (UNISDR, 2015). In November 2022, "Early Warning for All", a five-year programme (2022-2027) was initiated by the United Nations to accelerate the objectives defined by Target G of the SFDRR by providing three-tier technical, financial and political level support to the countries which have not been covered by proper early warning systems (UNDRR & WMO, 2022). An advisory panel consisting of representatives from UN agencies, multilateral development banks, humanitarian agencies, civil society, insurance and IT companies has been formed to support this initiative.

Furthermore, National Determined Contributions (NDCs) under the Paris Agreement also encourage countries to strengthen EW systems as an integral part of their effort to address climate risk. In addition, the Climate Risk and Early Warning Systems Initiative (CREWS) is another partnership of UNDRR, WMO (World Meteorological Organisation) and the World Bank, which provides financial and technical assistance to the least developed countries (LDCs) and Small Island Developing States (SIDS) to establish EW services with other international partner agencies such as the International Federation of Red Cross and Red Crescent Societies (IFRC) (IFRC, 2022). It is hoped that these global initiatives will play a significant role in addressing the most critical failure factors identified in this study and will create a substantial impact.

4.3 Conclusion

Due to proliferating climate change actions, flood events have increased recently in developed and developing nations, with huge recorded losses in lives, infrastructure, and economy. To reduce the adverse effects of such events, as a non-structural measure, early warning and response systems are used in countries and regions. The importance of such early warning and response systems at regional and national levels is emphasised in several global policies and strategies. However, recent flood incidents have caused significant losses of human lives due to failures in current flood warning and response mechanisms, and therefore, studying the effectiveness of such systems is vital.

Several studies have focused on exploring the effectiveness of early warning and response systems with limited scopes. Therefore, this study focused on finding the critical failure factors (CFFs) in flood early warning and response systems through a structured review and discussion with experts. This study resulted in identifying 24 CFFs that affect the effectiveness of FEWRS. These 24 critical failure factors were broadly classified into institutional, social, and technical categories. The ISM and the MICMAC analysis conducted in this research showed that addressing the following seven key CFFs, which have high driving power, can lead to more effective and efficient FEWRS: (1) a lack of political will and institutional leadership; (2) weak institutional governance, coordination, and custodianship; (3) a lack of funding to operationalise, modernize, and maintain

FEWRS; (4) unavailability of SoPs, systems, and plans for better warning and response; (5) data sharing and data governance; (6) a lack of skilled human resources for data analysis, modelling, and forecasting; and (7) a lack of inclusion of community and vulnerable groups in planning and decision-making. These results reveal that government policies and institutional leadership are critical in establishing successful warning and response systems. Addressing the institutional capacity for data governance and data analysis and implementing sound SoPs for warning and response can make significant improvements to current FEWRS. Furthermore, as evident in the research, it is important to include the community as a key stakeholder in overcoming the failures of FEWRS.

In addition to the above key CFFs with high driving power, the research shows that there are many technical factors, which were classified as autonomous factors, that need addressing since they still show a relatively high level of driving power. Therefore, attention should be given to addressing the technical challenges, such as limited computing capacity, technical issues with communication and dissemination systems, warning coverage, issues with IoT sensors, erroneous data, and the unavailability of risk information.

The research shows that most social factors relating to the community come under the dependent cluster (Figure 20) and need to be addressed through government policies or institutional leadership to build up community capacity and engagement. Most of the CFFs identified under the dependent cluster can be addressed by giving attention to the CFF factor (#10) identified in the independent cluster, which is the "inclusion of community and vulnerable groups in planning and decision-making". By addressing this CFF, other identified social CFFs can be resolved, such as a lack of public awareness or ability to understand the warning, a lack of trust and credibility in the warning system, a lack of community understanding of risk, a lack of neglect of community participation, and lack of community capacities in the reception of warnings.

This research has provided a comprehensive analysis of the CFFs that lead to the failure of FEWRS. It is hoped that initiatives such as the "Early Warning for All", announced by the United Nations, will overcome many of these failure factors and assist in improving and operationalising FEWRS at the regional and country level.

4.4 Summary

This chapter provides insightful information on the current barriers and challenges of the Flood Early Warning and Response System and addresses Objective 1 of this research. The next chapter will focus on the types of intelligence that are necessary for developing an advanced Flood Early Warning and Response System.

Chapter 5 Intelligence Required for Flood Early Warning and Response System

5.1 Introduction

Flood is a frequently occurring hazard that imposes adverse effects on a significant number of human lives and causes substantial economic damage worldwide. Many researchers (Hammood et al., 2020; Pappenberger et al., 2015) have asserted that losses and causalities can significantly be reduced by implementing an effective Flood Early Warning and Response System (FEWRS). In this regard, the Sendai Framework for Disaster Risk Reduction (SFDRR) emphasises the need for the availability of multi-hazard warning systems and disaster risk information to the community by the end of 2030 (UNISDR, 2015). SFDRR promotes the necessity for having an integrated and coordinated approach to "generate, process and disseminate" disaster risk information using state-of-art technologies as a priority action in the member countries (Zhou et al., 2018).

A study conducted by Rogers (2010) reports that an effective forecast and warning system based on accurate real-time information on disasters can reduce the average annual flood damage by up to 35%. Furthermore, Seng (2012) asserts that such a system can reduce vulnerability and mortality rates. The reasons for the existence of ineffective early warning systems that cause higher death rates are considered to be due to bureaucratic water management and digital divide-related issues (Keoduangsine & Goodwin, 2012), resulting in the lack of timely information for issuing warnings (Hammood et al., 2020). Therefore, the availability of an information system (IS) that can offer accurate and timely data with high service quality and user satisfaction has been recognised as one of the key success factors for implementing efficient FEWRSs (Hammood et al., 2020). Such information systems for flood warning and response systems should offer hazard detection, forecasting, warning and response (Parker & Fordham, 1996). The study of global early warning systems within developed and developing countries (Duminda Perera et al., 2020; Perera et al., 2019) has found that the availability of such technology platforms is an important factor in influencing the effectiveness of early warning systems, in addition to policy and institutional and societal factors.

Situational intelligence is crucial for making sound decisions, especially in a crisis situation to react quickly and efficiently (Dent, 2013). In simple terms, situational intelligence is an ability to anticipate and react in a given situation (AlertMedia, 2022). Schilling argues that situational intelligence is a process that offers insight into a situation by processing and visualising multi-sourced data to make an appropriate decision on a specific situation (Schilling, 2012). The concept of situational intelligence has been used in numerous applications, including military (Gruszczak, 2018; Winkler et al., 1996), power and energy (Bedi et al., 2016; Bedi et al., 2018), petroleum (Shokooh & Nordvik, 2019), aviation (Li & Kamal, 2011) and disaster response (Appling et al., 2014; Gruszczak, 2016). In a crisis scenario, authorities need credible information to understand the ground reality. For example, in fluvial flooding, rainfall, river water level, and the number of persons impacted are typical intelligence that is required by authorities for making better decisions when issuing early warnings and responding to disasters.

The role of technology is important in acquiring intelligence in a crisis situation. In the quest for intelligence for FEWRSs, a broad range of technologies such as Internet of Things (IoT) (Asnaning & Putra, 2018), big data (Yu et al., 2018) and near real-time satellite data (Ajmar et al., 2016) is used to capture critical information such as rainfall, rising river levels and floor rates to detect flood threats. Furthermore, integrated information systems (Fang et al., 2015; Turoff et al., 2004), geographic information systems (GIS) (Tomaszewski et al., 2015), and simulation techniques (Eldho et al., 2018), are being used to process such information and to generate early warnings. Increasingly, crowdsource technologies based on social media (Zhang et al., 2019), mobile apps (Bachmann et al., 2015), and Volunteer GIS (Castanhari et al., 2016) are being used for engaging communities in reporting incidents during the response phase. However, in order to exploit the potential of such technology, it is important to establish a clear understanding of the "intelligence" required and the appropriate "technologies" that can be used to generate such intelligence for developing early warning and response systems.

Therefore, this study presents a full range of intelligence needed for flood warning and response phases as well as the technologies that can be used to provide such intelligence, captured through a structured review of academic papers published between 2015 and 2020. The finding of this review is then synthesised to produce a conceptual architecture which illustrates how the identified intelligence and advanced technology can be deployed to help the decision-makers make evidence-based decisions for early warnings and response during a flood event. The outcome of this study addresses the Objective 2 of this research.

5.2 Structured Review Methodology

The research question established in this review is "What are the types and sources of intelligence required for effective early warning and response for flood events ?". The methodology established by Webster and Watson (2002) was followed to identify and analyse the relevant literature for this review. A set of keywords was defined to search for relevant research articles, and an inclusion/exclusion criterion was used to determine relevant and quality papers. A search criterion was established to filter relevant articles by conducting a "title" search using a combination of keywords. The keywords "floods', "response" and "warning" were used in the search since the context of this study is "floods" within the scope of disaster management phases of "response" or "warning". Furthermore, the keywords "information" and "intelligence" were included to limit the articles that are written in the specific area of interest in this review. These keywords were combined to create the generic search string "flood" AND ("warning" OR "response") AND ("information" OR "intelligence").

The keyword combination was used on Scopus, Web of Science, Wiley, and Gale databases, which resulted in the retrieval of 150 records. These databases allowed literature searches within a broad range of high-ranked journals and conference proceedings. Furthermore, snowball sampling was conducted, which resulted in adding 16 more articles to the investigation. The overall search was limited to articles published from 2015 onwards and written in English.

Following the above step, the title and abstract of all the papers were thoroughly examined to remove duplicates and to remove articles that are not suitable for the final analysis. This step resulted in 65 articles. In the next step, the contents of the articles were analysed to identify the relevant papers. After studying the full texts, only the articles, written on flood warning and response systems and processes, and those which describe the use of information and intelligence in the warning and response process, were considered in this study. The papers that discussed flood hazard and risk assessments, flood preparedness, flood management, health and other emergencies were excluded. Only the articles which focused on the intelligence for detecting, monitoring and evaluating the flood hazards during the warning to response stage were selected for the final analysis. This resulted in fifty-four articles (54) for the content analysis (see

Figure 21). These fifty-four research articles were analysed and synthesised to extract the state-of-art knowledge on intelligence used in flood warning and response stages and the tools and techniques used to derive such intelligence.

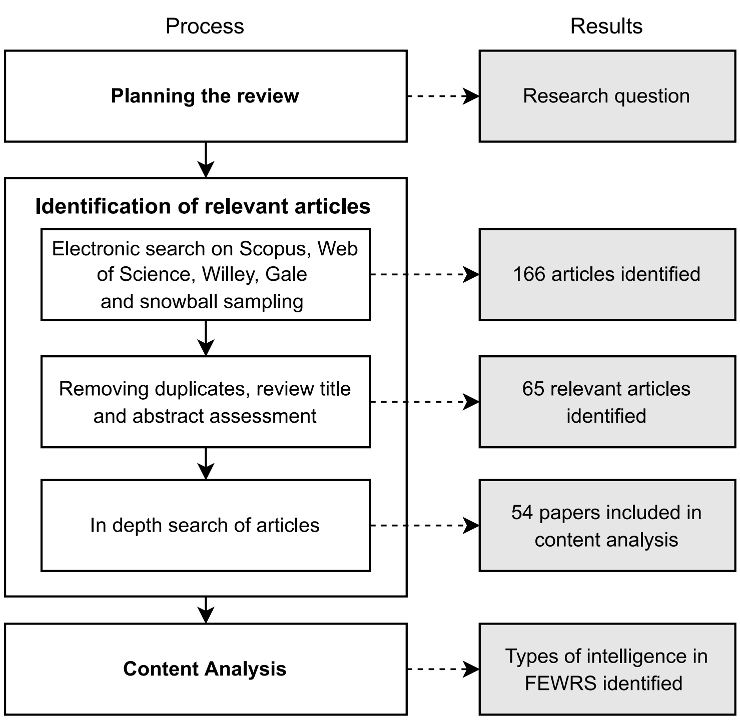


Figure 21: The workflow of the reviewing process

The scope of this review concurs with the flood risk management framework adopted by Adelekan (2016). According to Adelekan, planning for flood warning, evacuation, and relief are considered sub-activities in the preparedness phase, whereas emergency rescue, humanitarian assistance and reconstruction are considered sub-activities of the response phase. Following this framework, the intelligence related to potential and historical flood inundation, damages and losses was considered as part of the preparedness phase. Similarly, the intelligence associated with the actual flood levels, damages and losses was considered as part of the response phase (see Figure 22).

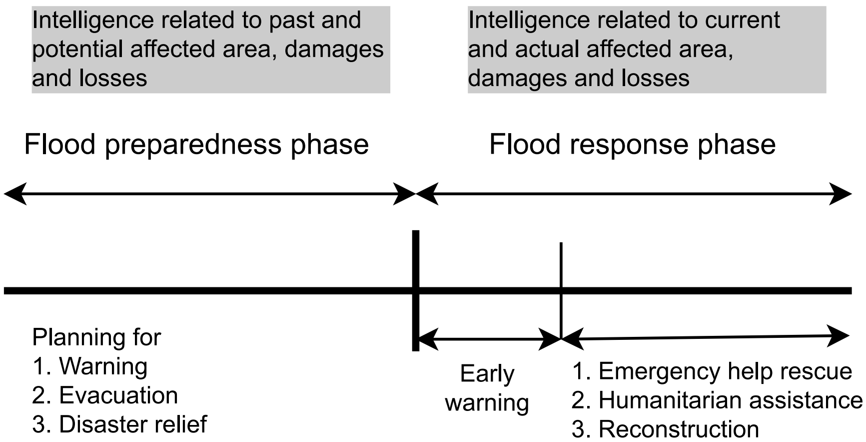


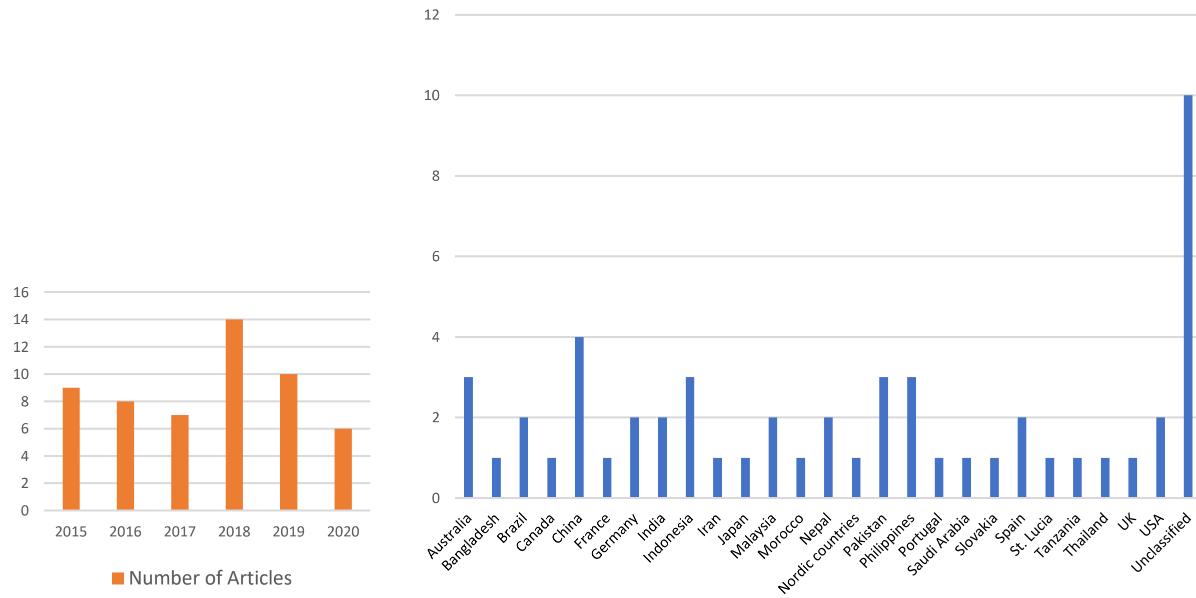
Figure 22: Scope of the intelligence used in the review (adapted from Adelekan (2016))

Fundamental stages of early warning systems such as risk knowledge capture, monitoring and warning, dissemination and communication of warning, and preparedness to response defined by UNDRR (UN, 2006) have been used to structure the review findings. The outcome of this review is then used to establish a relationship between the flooding process, situational intelligence required at various stages, and methods (technologies) that can be used to derive intelligence to support strategic decisions at each stage of the flood warning and response.

5.3 Results

5.3.1 Research landscape of the contributions

Figure 23(a) shows the spread of publications used in this review between 2015 and 2020. Figure 23(b) shows where the study had taken place, distributed across 26 countries. The main contributors were China (3 articles), Philippines (3 articles), Pakistan (3 articles) and USA (5 articles). However, ten contributions were either review papers or were not classified under a particular country.



(a) (b)

Figure 23: Distribution of articles (a) based on the year of publication and (b) based on the country of case studies.

5.3.2 Intelligence used for flood warning and response phases

The types of intelligence that were identified as necessary for issuing flood warnings and responses from the review can be categorised as follows: intelligence on flood hazards; intelligence related to the population at risk; intelligence on impacted infrastructure; intelligence on resources and capacities required during the response phase. Table 19 below summarises the type of intelligence under each category with their attributes, purpose/use, and citations.

Table 19: Type of intelligence used in flood warning and response process

Category	Intelligence	Purpose / Use	Reference
Intelligence on flood hazards	Rainfall values real-time	Flood forecasting in real-time	(Caseri et al., 2016; Kim et al., 2018; Panganiban & Cruz, 2017; Rilo et al., 2017; Wang & Xie, 2018; Zhang et al., 2019) (Caseri et al., 2016; Jean-Francois & Srikantha, 2018; Satria et al., 2020)
	Rainfall values - historical	Predict a possible flood scenario from past flood incidents for a given rainfall.	(Archer & Fowler, 2018)
	Rainfall duration	Quantify the rainfall and forecast the floods	(Munir et al., 2019; Panganiban & Cruz, 2017)
	River Flow/ water flow rate (total volume passed in a given location)	Forecast floods	(Archer & Fowler, 2018), (Trizio et al., 2020)
	River or flood water level, measured	Assess whether the river is about to be flooded or has flooded and issue warnings accordingly	(Abana et al., 2019; Asnaning & Putra, 2018; Bachmann et al., 2015; Castanhari et al., 2016; Katu et al., 2017; Satria et al., 2020; Satria et al., 2019; Trizio et al., 2020; Zhang et al., 2018)
	River or flood water level, observed		(Castanhari et al., 2016; Henriksen et al., 2018; Zhang et al., 2019)
	River or flood water level, forecasted		(H. Badrzadeh et al., 2015; Fang et al., 2015; Faruq et al., 2020; Fotovatikhah et al., 2018; Horita et al., 2015; René et al., 2018)
	Flood inundation extent	Establish a spatial representation of floods to understand the impacted area	(Ajmar et al., 2016; Ali et al., 2019; Brouwer et al., 2017; Chen et al., 2015; Chokmani et al., 2019; Deng et al., 2016; Eldho et al., 2018; Henriksen et al., 2018; Hung et al., 2016; Jongman et al., 2015; Khantong & Ahmad, 2020; Liu et al., 2015; Mrnco et al., 2018; Munir et al., 2019; Qadir et al., 2016; Saad et al., 2019; Shi et al., 2020; Tomaszewski et al., 2015; Velev &

			Zlateva, 2016; Wang & Xie, 2018; Yu et al., 2018; Zhang et al., 2019)
	Flood inundation depth	Identify the hazard/risk level for the community and infrastructure	(Brouwer et al., 2017; Castanhari et al., 2016; Chokmani et al., 2019; Rilo et al., 2017; Zhang et al., 2019)
	Flood intensity flood frequency/flood magnitude/ return period	Predict the hazard levels and use them to evaluate possible damage to the community, infrastructure and natural environment.	(Ali et al., 2019; Castanhari et al., 2016; Zhou et al., 2017) (Deng et al., 2016; Eldho et al., 2018; Liu et al., 2015; Munir et al., 2019; Tabyaoui et al., 2019; Vitoriano et al., 2015; Zhou et al., 2017)
	Historical flood events & water level	Understand inundation levels and impact caused by past flood events and extrapolate this knowledge to an emerging flood situation.	(Henriksen et al., 2018; Rajesh & Rajendran, 2019; Zhang et al., 2018)
	Flood propagation time/lead time,	Calculate lead time (travel time) of floods to plan early warnings, evacuation and response. eg. upstream to downstream) or flood arrival time based on predicted or actual rainfall	(Fotovatikhah et al., 2018; Jongman et al., 2015; Khantong & Ahmad, 2020; Liu et al., 2015; Mrnco et al., 2018; René et al., 2018; Shi et al., 2020; Tekeli & Fouli, 2017; Wang & Xie, 2018; Zhou et al., 2017)
	Soil moisture level	Determine the level of water infiltration and flood forecasting	(Kim et al., 2018; Satria et al., 2020)
Intelligence related to the population at risk	Mobility of crowd	Monitor movements of people during a disaster	(Qadir et al., 2016; Yu et al., 2018)
	Potentially affected population	Plan for better response, evacuation, relief distribution and family reunification	(Bachmann et al., 2015; Deng et al., 2016; Qadir et al., 2016; Tzavella et al., 2018; Vitoriano et al., 2015; Yu et al., 2018)
	Population density/demography and distribution	Useful for response planning and relief operations	(Fang et al., 2015; Saad et al., 2019; Velev & Zlateva, 2016)

	Basic needs (Food, water etc.)	Acquisition and managing basic needs during the response period	(Deng et al., 2016)
	Evacuation (estimated and actual)	Evacuation planning and relief management	(Eldho et al., 2018; Hung et al., 2016)
	Affected population	Plan rescue operation and provide emergency treatments	(Bachmann et al., 2015; Deng et al., 2016; Eivazy & Malek, 2019; Qadir et al., 2016; Ragini et al., 2018)
Intelligence related to infrastructure at risk	Potential impact on infrastructure	Develop response plan in preparedness phase to ensure efficient and effective response	(Ali et al., 2019; Chokmani et al., 2019; Fang et al., 2015; Gebremedhin et al., 2020; Neubert et al., 2016)
	Potential impact on roads	Make necessary re-routing of traffic as well as identify routes and transport methods to reach	(Gebremedhin et al., 2020; Hung et al., 2016; Tzavella et al., 2018; Vitoriano et al., 2015)
	Actual impact infrastructure	Conduct actual damage assessment during and after the disaster to support ongoing response as well as future risk management and response planning	(Bica et al., 2017; Jongman et al., 2015; Nguyen et al., 2017; Rilo et al., 2017)
	Actual impact roads		(Chen et al., 2015; Deng et al., 2016; Hung et al., 2016; Yu et al., 2018)
Intelligence on Resources and Capacities required during the response phase	Resources (helipads, evacuation centres, medical services etc)	Plan and co-coordinate response	(Saad et al., 2019; Vitoriano et al., 2015)
	Active NGOs and other voluntary organisation	Advance response planning	(Saad et al., 2019; Vitoriano et al., 2015)
	Food and Supply Information	Understand help available for humanitarian support during response.	(Saad et al., 2019)
	Service range (coverage) of responders (fire brigade, military, other emergency services)	Plan and coordinate response.	(Tzavella et al., 2018)

5.3.3 Intelligence on Flood Hazards

The inter-relationship between the stages of the flooding process, numerous intelligence captured to detect and monitor each stage, and tools and techniques that are being used to capture intelligence are discussed in this section.

5.3.4 Rainfall

Rainfall data at various point locations are typically captured through rain gauges (Caseri et al., 2016; Kim et al., 2018; Panganiban & Cruz, 2017; Rilo et al., 2017; Turoff et al., 2004; Wang & Xie, 2018; Zhang et al., 2019), and its spatial variability is captured through Doppler and satellite radar systems (Caseri et al., 2016; Jean-Francois & Srikantha, 2018). Such live rainfall data, as well as historical rainfall data, are used as input to the hydrological models for flood forecasting (Archer & Fowler, 2018). However, in cases where rain gauge data is not available, satellite observation is used to monitor and predict floods (Moazami et al., 2013). In some cases, the analysis of past flood events and their magnitude has been used as the basis for preparing and responding to emerging flood events (Caseri et al., 2016; Jean-Francois & Srikantha, 2018). The study reported in (Kim et al., 2018), shows how the analysis of 35 years of soil moisture, data derived from the satellite, integrated with gridded rainfall and elevation can be used for flood forecasting (Kim et al., 2018).

5.3.5 River Water Level

Measuring the river water level could be classified into three categories based on the method employed: measured water level (by IoT) (Abana et al., 2019; Asnaning & Putra, 2018; Bachmann et al., 2015; Castanhari et al., 2016; Katu et al., 2017; Satria et al., 2019; Zhang et al., 2018), observed water level (by the public) (Castanhari et al., 2016; Henriksen et al., 2018; Zhang et al., 2019), and forecasted water level through simulations (H. Badrzadeh et al., 2015; Fang et al., 2015; Fotovatikhah et al., 2018; Horita et al., 2015; René et al., 2018). Many modern early warning systems have employed IoT devices such as automated river gauges to continuously measure real-time river water levels with greater accuracy (Abana et al., 2019; Asnaning & Putra, 2018; Bachmann et al., 2015; Castanhari et al., 2016; Katu et al., 2017; Satria et al., 2019; Zhang et al., 2018). On the other hand, active and passive social media systems and crowdsourcing platforms are also being used to report water levels observed by the community as text and photographs with time and location data (Castanhari et al., 2016; Henriksen et al., 2018; Zhang et al., 2019). The crowdsourcing methods are beneficial for areas that do not have expensive sensor-based water level monitoring systems (Castanhari et al., 2016; Henriksen et al., 2018). The integration of these two approaches (IoT and crowdsourcing) can complement each other and enhance the confidence level of the water level measurements during disaster situations (Castanhari et al., 2016).

In order to gain further lead time for issuing an early warning for evacuation, predictive models such as hydrological models and rainfall-runoff inundation models (H. Badrzadeh et al., 2015; Fang et al., 2015; Fotovatikhah et al., 2018; Horita et al., 2015; René et al., 2018) are being used to forecast water levels at a given point. The accuracy of these models can be enhanced by providing continuous real-time data gathered through both IoT and crowdsourcing (Abana et al., 2019; Asnaning & Putra, 2018; Bachmann et al., 2015; Castanhari et al., 2016; Katu et al., 2017; Satria et al., 2019; Zhang et al., 2018).

5.3.6 River Water Flow

River water flow is a key parameter used in hydrology that measures the amount of water passing through a specific point in time. The flow rates are typically measured by gauge stations and are used in hydrology models (Archer & Fowler, 2018) for predicting potential floods (Trizio et al., 2020).

5.3.7 Flood Inundation

Flood inundation extent and inundation depth are two vital intelligence used in flood warning and response systems. At present, near real-time satellite data is being used to collect such intelligence during and post-event scenarios (Ajmar et al., 2016; Chokmani et al., 2019; Henriksen et al., 2018; Jongman et al., 2015; Qadir et al., 2016; Tomaszewski et al., 2015; Wang & Xie, 2018; Yu et al., 2018). Radar data analysis (Ajmar et al., 2016) tends to be the most popular method in flood inundation mapping during the rainy season as it has the capability to penetrate clouds. In addition to the satellite, airborne sensors attached to UAVs, that can supplement or even replace traditional satellite remote sensing systems can detect spatial coverage of flood disasters (Tomaszewski et al., 2015).

Passive crowdsourcing media such as Twitter, Facebook (Zhang et al., 2019) and active crowdsourcing platforms such as Ushahidi (Hung et al., 2016) have become popular in collecting information on flood inundation and damages (Deng et al., 2016). Citizen's observation of the flood events in the form of photographs uploaded via social media and crowdsourcing applications have shown their value for decision-making in the disaster response phase (Henriksen et al., 2018). In Brouwer et al. (Brouwer et al., 2017), both probabilistic and deterministic approaches have been used to transform the Twitter response to flood extent. The review articles by Tomaszewski et al. (Tomaszewski et al., 2015) and Yu et al. (Yu et al., 2018) elaborate on how the combination of satellite and crowdsource information can be used to determine the flood extent in near real-time (Tomaszewski et al., 2015; Yu et al., 2018). Two case studies from the Philippines and Pakistan, reported in Jongman (Jongman et al., 2015), show how the combination of multiple sources, such as near real-time satellite data and Twitter response collected from the community, were utilised for monitoring the flood extent. These case studies have demonstrated how the integration of traditional remote sensing data with real-time social media data could increase the situational awareness of the flood hazard context in the form of location, time, cause and impact, hence improving the efficiency and speed of the response action.

Many are using numerical models and GIS-based inundation mapping to determine the possible inundation zones, which allows advanced planning for the disaster response (Archer & Fowler, 2018; Eldho et al., 2018; Jean-Francois & Srikantha, 2018; Tabyaoui et al., 2019; Turoff et al., 2004). Such intelligence for response planning by disaster agencies offers sufficient time to mobilise their teams to respond efficiently and warn citizens well in advance.

Along with the inundation extent, flood depth can also be predicted before and after a flood (Brouwer et al., 2017; Castanhari et al., 2016; Chokmani et al., 2019; Rilo et al., 2017; Zhang et al., 2019) to estimate the impact on the people and properties by relevant authorities (Castanhari et al., 2016; Pistrika et al., 2014). Flood depth is typically calculated using hydrological models (Castanhari et al., 2016), but recently, social media systems such as Twitter have been used to collect the flood inundation depth (Zhang et al., 2019).

5.3.8 Flood Arrival Time

Flood arrival time (lag time) is known as the time difference between rainfall time centroid and peak discharge (Sharp, 2003; Zhou et al., 2017). Early prediction of the arrival time of floods at a given point is used for issuing flood early warnings to the community (Fotovatikhah et al., 2018;

Jongman et al., 2015; Khantong & Ahmad, 2020; Liu et al., 2015; Mrnco et al., 2018; Shi et al., 2020; Tekeli & Fouli, 2017; Wang & Xie, 2018).

Traditionally, this is measured by hydrological modelling techniques such as rainfall-runoff inundation modelling in combination with Geographic Information System (GIS) and Remote Sensing (RS) (Mrnco et al., 2018; Wang & Xie, 2018). Recently, researchers have used intelligence from multiple sources to improve the accuracy of predicting flood arrival time and eliminating false flood warnings. For example, Jongman et al. (Jongman et al., 2015) present an approach that combines passive radar satellite response on soil moisture (AMSR) and social media to improve accuracy in flood prediction. Similarly, Tekeli and Fouli (2017) present an approach that combines AMSR satellite data with Tropical Rainfall Measuring Mission (TRMM) satellite data to improve accuracy. In (Zhou et al., 2017), the authors present the analysis of historical river gauge data and satellite data (radar) of various return periods to ascertain the lag time over a given river basin in the Charlotte Metropolitan region in the USA.

Flood arrival time is also being estimated by employing various Artificial Intelligence (AI) techniques since conventional methods are unable to capture nonlinearity and non-stationarity related to hydrological applications (Fotovatikhah et al., 2018). Fuzzy sets and neural networks are two other popular Computational Intelligence (CI) techniques that are commonly used in the hydrology field (Fotovatikhah et al., 2018). Recent research based on the Wavelet Transform Neuro-Fuzzy (WT-NF) technique has shown promise in forecasting floods with an increased lead time (Fotovatikhah et al., 2018). Some researchers have explored how the accuracy of the CI techniques can be enhanced by using hybrid methods that combine different CI methods for improving the accuracy and lead time of flood forecasting (Fotovatikhah et al., 2018; Mosavi et al., 2018). For example, (Chau et al., 2005) combines neural networks with Generic Algorithms, and (Honey Badrzadeh et al., 2015) combines neural networks with Wavelet to increase flood forecast accuracy.

Other developments in this area are the use of Service-Oriented Architectures (SoA) (Liu et al., 2015), linked with ontological frameworks (Khantong & Ahmad, 2020), for capturing and processing data from a variety of sources (IoT sensors, social media, crowdsourcing, satellites) to support the prediction of flood arrival times using aforementioned techniques.

5.3.9 Flood Frequency and Return Period

Flood frequencies and return periods are two interrelated factors essential in understanding and preparing for possible situations since they indicate the magnitude of an emerging event (Ali et al., 2019; Castanhari et al., 2016; Deng et al., 2016; Eldho et al., 2018; Liu et al., 2015; Tabyaoui et al., 2019; Vitoriano et al., 2015; Zhou et al., 2017). Flood frequency analysis is a statistical technique used by hydrologists to estimate the flood return period or exceedance probability by measuring peak discharge values over a period of time. Flood frequency analysis provides decision-makers to pursue a broader understanding of the hydrological behaviours of a given river from the perspective of the flood response (Zhou et al., 2017). Higher peak discharge and runoff rates increase the flood frequency, hence increasing the severity of floods. Therefore, it is necessary to understand the flood hazard level at different flow conditions so that proper evacuation planning could be arranged in advance (Eldho et al., 2018). In addition to the frequency calculation, historical flood events are useful for validating various models, developing risk and damage functions and preparing for future events (Henriksen et al., 2018; Rajesh & Rajendran, 2019; Zhang et al., 2018).

5.3.10 Intelligence Related to Exposed Population

The intelligence required to understand and estimate the exposed population and the underpinning technology that can be used to acquire such intelligence during flood hazards are discussed in this section.

5.3.11 Population Densities, Distribution, and Demography

Spatial distribution and population density is a primary data set required to identify and estimate an exposed population for a given hazard (Fang et al., 2015; Saad et al., 2019; Tenerelli et al., 2015; Velev & Zlateva, 2016). Population data are usually obtained from the national census, available in spatially aggregated forms up to local administrative boundaries, which are too coarser for disaster impact analysis. Hence, land use maps (Tenerelli et al., 2015) and satellite-derived settlement data (Bagan & Yamagata, 2015) are being used to derive population density maps at finer scales. In addition to that, global data sources such as Landscan data also provide population grids at various grid sizes (Bhaduri et al., 2007).

5.3.12 Potentially Affected Population

The potentially affected population by the flood is the most important intelligence required by authorities to make decisions during the early warning and response stages (Bachmann et al., 2015; Deng et al., 2016; Qadir et al., 2016; Tzavella et al., 2018; Vitoriano et al., 2015; Yu et al., 2018). Furthermore, an estimation of the affected population is essential to plan for relief assistance and post-disaster impact assessments (Deng et al., 2016; Vitoriano et al., 2015). Data from various sources, such as government authorities and municipalities, are typically combined with open-source spatial data to estimate the exposed population in the GIS domain (Tzavella et al., 2018). Tzavella et al. (Tzavella et al., 2018) report how Volunteered Geographic Information (VGI) has successfully been used in an extreme flood event in Cologne, Germany, to improve the efficiency of flood response with the decreased response time.

Numerous models and approaches have been used to evaluate the potential effect of floods on people. For example, the Disaster Diagnostic and Evaluation System (SEDD) offers a fuzzy rule-based classification system that can be used to assess the possible consequences on people just after a disaster (Vitoriano et al., 2015). It uses the Emergency Events Database (EM-DAT) as the primary source of population data, together with sources such as the Human Development Index (HDI), published by UNDP, to calculate the vulnerabilities. Deng et al. (Deng et al., 2016) propose a social media-based model to estimate the impact of a disaster on the community, which has been tested for typhoon Haiyan. In contrast, Ushahidi collects the actual affected population during the Haiti earthquake (Qadir et al., 2016) using crowdsourcing.

5.3.13 Mobility of Crowd

The intelligence with respect to the locations and mobility of the crowd is critically important in the emergency response phase, which provides response authorities to target the people who need immediate rescue and medical assistance. Call Detail Records (CDR), referred to as digital trails of modern mobile device users, can be used to monitor population movement and displacement and for disaster response planning (Qadir et al., 2016) since it offers a detailed record of mobile phone location and call logs generated by mobile companies in real-time. The successful use of CDR techniques is reported in (Yu et al., 2018) during the Haiti earthquake. Even though CDR is a useful technology for understanding population dynamics, it is still not widely used due to privacy issues and a lack of supportive legal frameworks (Qadir et al., 2016).

5.3.14 Evacuation

People who need evacuation or have already been evacuated are another critical intelligence useful in the response phase. The number of people who require evacuation is typically estimated and identified during the preparedness planning process for various flood simulation scenarios for multiple return periods (Eldho et al., 2018). However, a more accurate picture of the evacuated people can be captured through social media platforms, active and passive crowdsourcing and geo-referenced VGI techniques during a disaster (Qadir et al., 2016).

5.3.15 Affected Population

Intelligence on affected people such as those who are trapped, injured, and victims who need immediate rescue is critical during emergency response. Furthermore, they require a mechanism to connect with response teams and inform their situation to their families and friends who are concerned about their safety and well-being.

Crowdsource applications (Qadir et al., 2016), social media microblogs (Deng et al., 2016; Ragini et al., 2018), and mobile CDR (Qadir et al., 2016) are potential tools and technologies used to gather the status and needs of the affected people in real-time. As successfully demonstrated during Typhoon Haiyan, semantic analysis of the microblog posted through social media can help authorities to understand the concerns of affected people at different stages of the disaster and respond better (Deng et al., 2016). Ushahidi is another popular crowdsource application that has been successfully used to collect, visualise, and map data gathered from affected communities (Qadir et al., 2016).

Eivazy and Malek (2019) illustrate an example of how agent-based solutions, integrated with crowdsource services, were used during the Aquala flood disaster in Iran in 2019 to help victims obtain emergency support from rescuers. In this example, individuals injured in a critical situation are reported through crowdsource systems, and an agent-based information system attempts to ensure the victims' safety by connecting them with the rescuers (Eivazy & Malek, 2019). The increasing trend in providing safety checks through social media systems such as Facebook to inform friends and family during a disaster is now common and reported in (Qadir et al., 2016). Bachmann et al. (Bachmann et al., 2015) present a mobile app that can be used to reunify families affected by disasters.

5.3.16 Essential Needs

During the response phase, government authorities are also responsible for supplying essential needs such as food and water required by the displaced population. The intelligence regarding essential needs is typically collected from microblogs such as Twitter (Deng et al., 2016; Ragini et al., 2018), social media and crowdsource systems (Yu et al., 2018). Deng et al. (Deng et al., 2016) report that during Typhoon Haiyan, a community in Hainan, China, used social media techniques (“Sina Weibo”, a Chinese microblog similar to Twitter) and semantic analysis to inform the needs of the affected people to the relevant authorities.

5.4 Intelligence Related to Affected Infrastructure

5.4.1 Potential Impact on the Infrastructure

The potential impact of floods on infrastructures, buildings (Ali et al., 2019; Chokmani et al., 2019; Gebremedhin et al., 2020; Neubert et al., 2016) and roads (Gebremedhin et al., 2020; Hung et al., 2016; Tzavella et al., 2018; Vitoriano et al., 2015) are essential intelligence required for disaster preparedness and response. The geo-referenced data of buildings, critical infrastructure, and road networks obtained from administrative sources and VGI techniques, including OpenStreetMap, integrated with the flood inundations maps, can be used to obtain the infrastructure exposed to the floods (Fang et al., 2015; Gebremedhin et al., 2020).

Potential damages to residential buildings and other infrastructures are typically carried out with simulation techniques for multiple return periods with different exceedance probabilities of floods (Ali et al., 2019; Chokmani et al., 2019; Neubert et al., 2016). Vulnerability curves that represent damage functions of the building for different levels of floods are used to assess the possible damage to the buildings and to propose hard and soft mitigation solutions (Ali et al., 2019). The monetary value of the damages is then aggregated at different scales, from an individual building to administrative boundaries to catchment areas (Neubert et al., 2016). In addition, early identification of road inundation possibilities allows authorities to explore different re-routing options during a disaster (Tzavella et al., 2018).

5.4.2 Affected Infrastructure

The intelligence regarding the actual impact on infrastructure, both during and after a disaster situation, is essential in managing disaster situations. The use of near-real-time satellite data and social media responses (Tweets) for calculating such intelligence is reported in (Jongman et al., 2015). Similarly, the use of geo-tagged images of damaged buildings to conduct damage assessment is reported by Bica et al. (Bica et al., 2017) and Nguyen et al. (Nguyen et al., 2017). Based on a study conducted in Nepal by Bica et al. (Bica et al., 2017), a positive correlation has been observed between actual ground damage and the damage assessment results conducted using the geo-tagged Twitter responses of the earthquakes that occurred in April and May 2015.

Analysis of historical damage data in multiple flood events provides a comprehensive view of past flood damages. In (Rilo et al., 2017), the authors present a comprehensive database that captures actual damage to housing, infrastructure, and the economy for various historical flood events that can be used for future mitigation and response planning processes.

Intelligence regarding the inundated road network is necessary during the emergency response phase to plan and re-route rescue services as well as establish regular transportation. Road inundation during the flood is acquired mainly by social media, crowdsourcing, near real-time satellites and UAV (Chen et al., 2015; Deng et al., 2016; Hung et al., 2016; Yu et al., 2018).

5.5 Intelligence on Resources and Capacities

5.5.1 Resources and Capacities

Intelligence on available resources and capacities are required in order to respond to disasters (Saad et al., 2019; Vitoriano et al., 2015), such as available response organisations and volunteers (Saad et al., 2019), health services (Saameli et al., 2016) and food and supply information (Saad et al., 2019). Saad et al. (Saad et al., 2019) present a successful implementation of an Integrated Flood Disaster Management system in the District of Kemaman in Malaysia, that is comprised of a database with critical resources and capacities required during the flood response. In their system, intelligence such as details of evacuation centres, data on non-governmental Organisations (NGO) and other volunteer organisations and data on helipad locations have been identified as capacities necessary during the responses in order to manage logistics to transport foods and essential needs and efficient response management (Saad et al., 2019). The locations of these facilities are typically organised and stored in GIS databases.

The locations of health facilities and travel time to such facilities are considered useful intelligence in the emergency response phase to manage flood-affected victims (Saameli et al., 2016). OpenStreetMap (OSM) derived global health facility data with their locations and other attributes are made available via www.healthsites.io. In (Weiss et al., 2020), access to healthcare facilities has been analysed and presented in global maps to visualise travel time by foot and motorised transport.

Tzavella et al. (Tzavella et al., 2018) calculate the service range of the first responders such as the fire brigade, through network analysis, taking into account the road network, points of resources and floods in Cologne, Germany.

5.6 Discussion

The critical analysis of the literature shows that the situational intelligence obtained for flood warning and responses are associated with rainfall, river flow, inundation, impact on people, properties, and response capacities. It was observed that numerous tools and technologies are used to derive intelligence that transforms into decisions. The relationship between the flooding process, intelligence required, tools and technology to derive such intelligence can be presented as a conceptual system architecture for making informed decisions for early warnings and response. This conceptual architecture can be presented in four key segments for ease of understanding, as discussed below.

5.6.1 Conceptual Model of Flooding Process and Warning Generation

According to the literature, it was observed that numerous technological approaches such as IoT (Abana et al., 2019; Asnaning & Putra, 2018; Bachmann et al., 2015; Castanhari et al., 2016; Katu et al., 2017; Satria et al., 2019; Zhang et al., 2018), crowdsourcing (Brouwer et al., 2017; Castanhari et al., 2016; Zhang et al., 2019), satellites (Ajmar et al., 2016; Chokmani et al., 2019; Jongman et al., 2015; Tarrant et al., 2018; Tekeli & Fouli, 2017; Wang & Xie, 2018) and numerical modelling (Eldho et al., 2018; Fotovatikhah et al., 2018; Neubert et al., 2016; René et al., 2018) are used to extract intelligence in relation to flooding at various stages, such as rainfall, river flow propagation, and inundation as indicated in Figure 24.

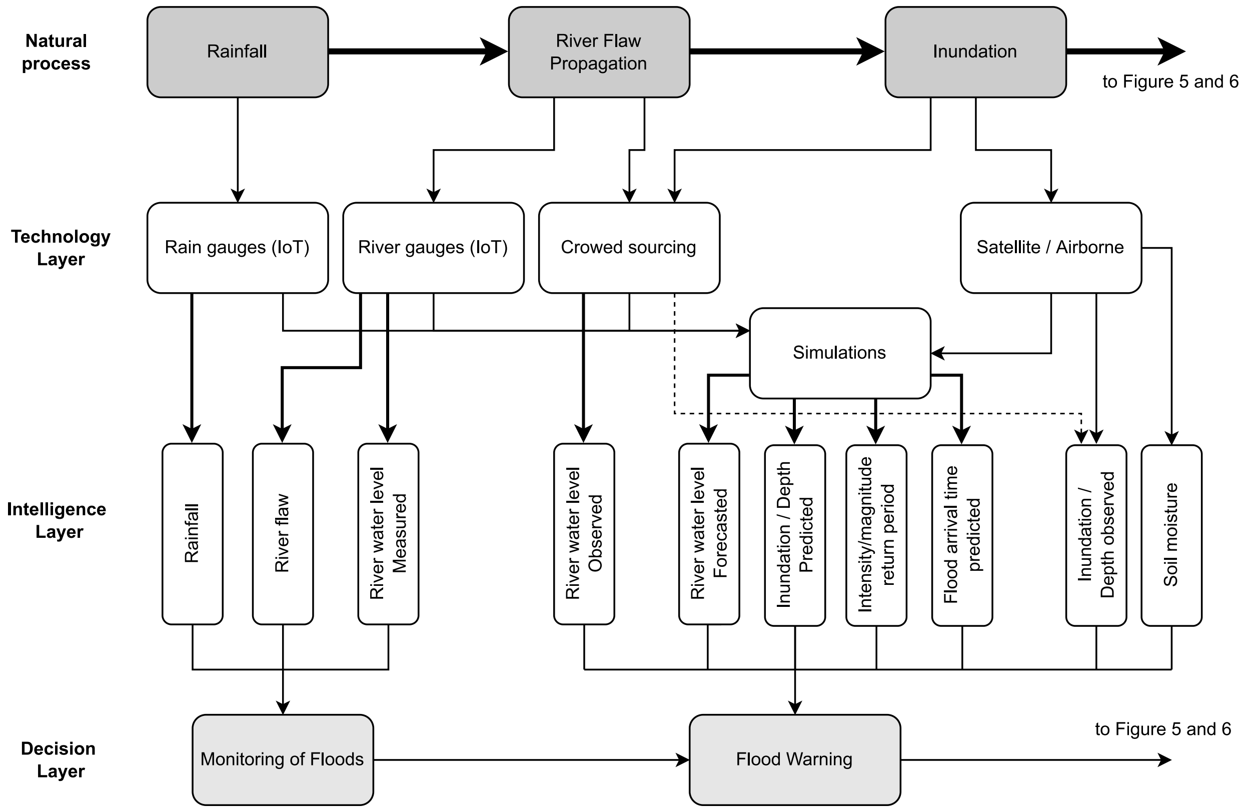


Figure 24: Intelligence required for monitoring the emerging flood situation

According to the literature, it was observed that numerous technological approaches such as IoT (Abana et al., 2019; Asnaning & Putra, 2018; Bachmann et al., 2015; Castanhari et al., 2016; Katu et al., 2017; Satria et al., 2019; Zhang et al., 2018), crowdsourcing (Brouwer et al., 2017; Castanhari et al., 2016; Zhang et al., 2019), satellites (Ajmar et al., 2016; Chokmani et al., 2019; Jongman et al., 2015; Tarrant et al., 2018; Tekeli & Fouli, 2017; Wang & Xie, 2018) and numerical modelling (Eldho et al., 2018; Fotovatikhah et al., 2018; Neubert et al., 2016; René et al., 2018) are used to extract intelligence in relation to flooding at various stages, such as rainfall, river flow propagation, and inundation as indicated in Figure 24.

The intelligence extracted from these technologies includes rainfall, river level (measured, observed, and forecasted), both inundation depth and extent (measured, observed, and forecasted), flood frequency, return period, intensity, flood arrival time, and soil moisture.

Figure 24 captures the use of technological approaches for extracting intelligence to respond to various activities by disaster management personnel during a flood disaster scenario. The overall conceptual architecture presented in Figure 24 integrates four layers: process layer, technology layer, intelligence layer, and activity/decision layer. The process layer represents how the flooding process evolves, starting from the rainfall and river flow to inundation. The technology layer can then be built using the technological solutions identified in this survey to monitor the evolving flooding situation and extract and pass the relevant information to the intelligence layer. The information captured in the intelligence layer can then be used by the disaster management authorities to monitor the evolving flood situation over time and generate flood early warnings in advance, as illustrated in the decision layer. The conceptual architecture presented in Figure 24 can be implemented using the state-of-the-art technology presented in the previous sections to extract the relevant intelligence, allowing decision-makers to ensure public safety before, during and after the floods.

However, it should be noted that there are many barriers to implementing such systems (Kumar et al., 2020; Opolot, 2013; Perera et al., 2019). Some barriers and challenges include (i) inadequate coverage of IoT sensors due to capital and maintenance costs and unavailability of internet connections (Perera et al., 2019), (ii) lack of accurate flood simulation models running on high-performance computers to provide near real-time response (Kumar et al., 2020), (iii) limitation of acquisition and limited coverage of near-real-time satellite images (Opolot, 2013). Although many developing countries have access to the International Charter for Space and Major Disasters, Copernicus System, and Sentinel Asia System, the average time for satellite activation for receiving the first image reception is three to four days (Allenbach et al., 2005). As a result, many disaster management agencies in developing countries resort to historical inundation information to estimate the possible inundation zones during flooding incidents. In this context, crowdsourcing techniques are more efficient than satellite observation, even with the limitation of their effectiveness and accuracy (Panteras & Cervone, 2018).

5.6.2 Conceptual Model of Flooding Impact on People

When a population is exposed to floods, intelligence such as movements of people, their vulnerabilities, numbers, and location of people trapped or injured, people evacuated and their basic needs are required by authorities and response teams. These are acquired during different phases of the disaster event (before, during and after) using simulations, crowdsource techniques, voluntary GIS activities, social media, carrier detail records (CDR) and remote sensing.

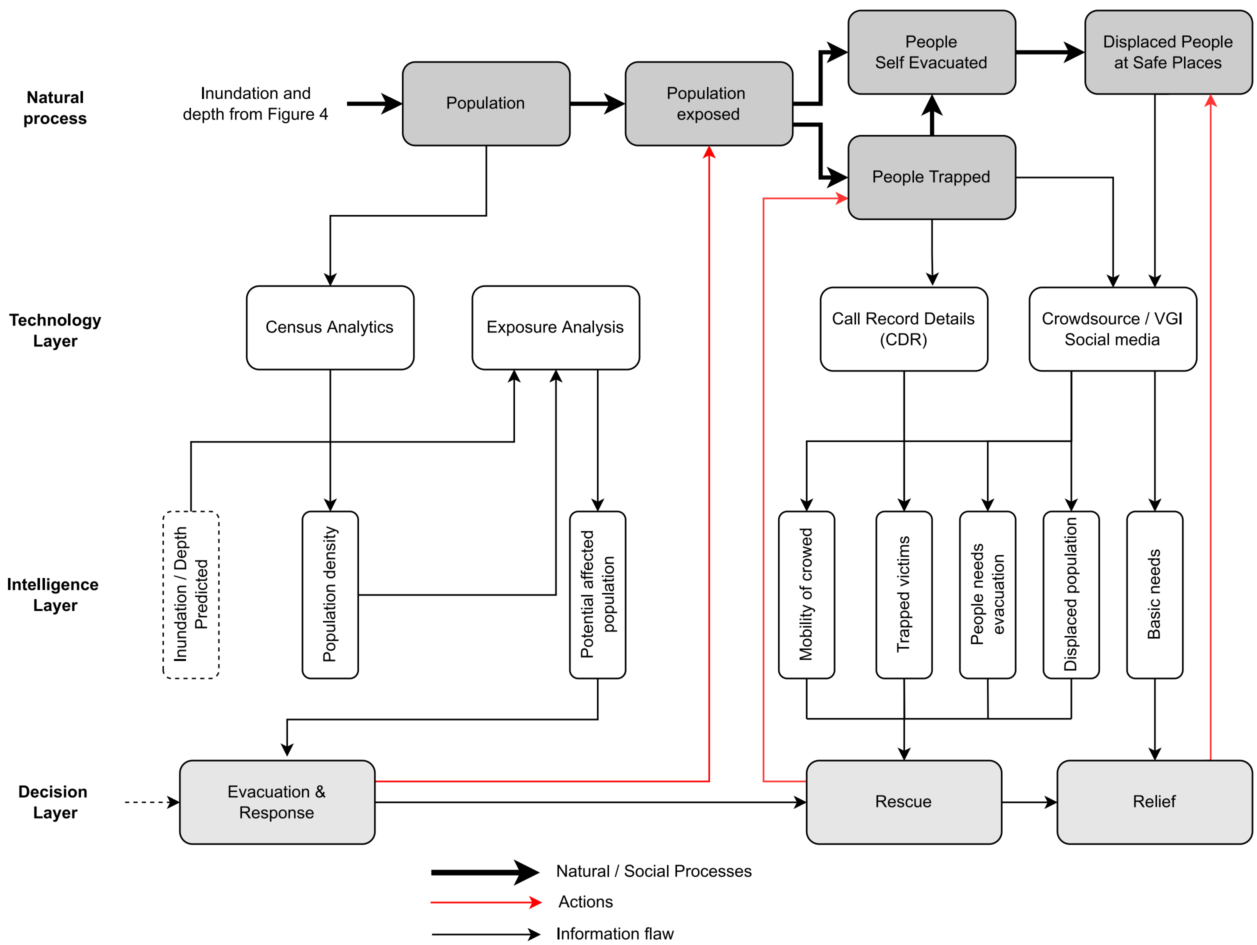


Figure 25: Intelligence required for issuing early warnings, rescue and relief operations

Figure 25 illustrates the relationship between the impact of flood inundation on the people and the technologies that can be used to derive intelligence for supporting evacuation and rescue operations. As shown in Figure 25, as the inundation is impacting the population, people will begin to self-evacuate themselves, sometimes with support from government agencies and NGOs for evacuating vulnerable people who have mobility and health conditions. Following the same layered approach used in Figure 24, Figure 25 shows how various technology solutions identified in this survey can be used to extract intelligence required for issuing early warnings and conducting intelligence-driven rescue and relief operations as the inundation is impacting the people, as shown in the process layer.

The flood inundation results, derived by simulations and satellites, overlayed with census data have the potential for providing intelligence on potentially affected people and those who are at risk. Such information can be used to disseminate targeted warning messages to the people at risk before the floods, hence saving lives. As the flood begins to impact people, technologies such as CDR, crowdsource, and social media techniques can be utilised to gain intelligence on the affected people on the ground, in near-real-time, to coordinate evacuation and rescue operations.

However, access to up-to-date population data is problematic since the population distribution and demography are obtained mainly from the national census, where most countries typically release such data sets in 10-year intervals. As a result, the population growth in the in-between years is not captured by these censuses. Furthermore, the national census registers do not usually capture the population dynamics at workplaces, schools, hospitals, hospices and other public localities. Hence, census data alone will not provide actual ground situations to estimate the potentially affected population during a flooding situation. Hence, there is a need for the local actors to maintain a more comprehensive database of their local population in order to better respond to disasters.

On the other hand, the accuracy of the predicted inundation scenario plays a vital role in determining the affected population. Therefore, simulation models used during disaster situations should be calibrated and validated well in advance to ensure the accuracy of their outputs.

Even though social media and crowdsourcing techniques exist, these systems are not standardised and well recognised in disaster response plans at a local level (Harrison & Johnson, 2019). Furthermore, at present, community participation is not actively encouraged to get the maximum benefit of these techniques. Although CDR technology has the potential to offer active mobile SIM card locations and the movement of people at risk during a disaster (Qadir et al., 2016), such information is typically not available due to privacy issues. The exploitation of these possibilities would require disaster management agencies to work closely with the mobile service providers and integrate them with their current disaster response processes while providing a legal framework for accessing such private data for emergency purposes.

5.6.3 Conceptual Model of Flood Impact on Infrastructure

Intelligence on physical properties such as housing, utilities, other infrastructure and road networks that could be affected by the flood is required by authorities for optimum risk management planning and response. These intelligence needs can be classified into two categories: (i) pre-disaster intelligence on infrastructure that can potentially be affected, and (ii) intelligence on actually affected infrastructure during and post-disaster phases.

Figure 26 presents a layered approach that represents the relationship between the impact of flood inundation on infrastructure and the potential technology that can be used to derive intelligence to support decisions. As in the previous sections, the layered architecture is represented through the activity layer, technology layer, intelligence layer and decision layer. The infrastructure that can potentially be impacted by floods is usually identified through exposure analysis using the infrastructure data collected from various government agencies and estimated inundation. This intelligence can be used for advanced evacuation planning, safeguarding household items and livestock, building mitigation plans and business continuation plans for infrastructure (utility, public services, government buildings and economic centres).

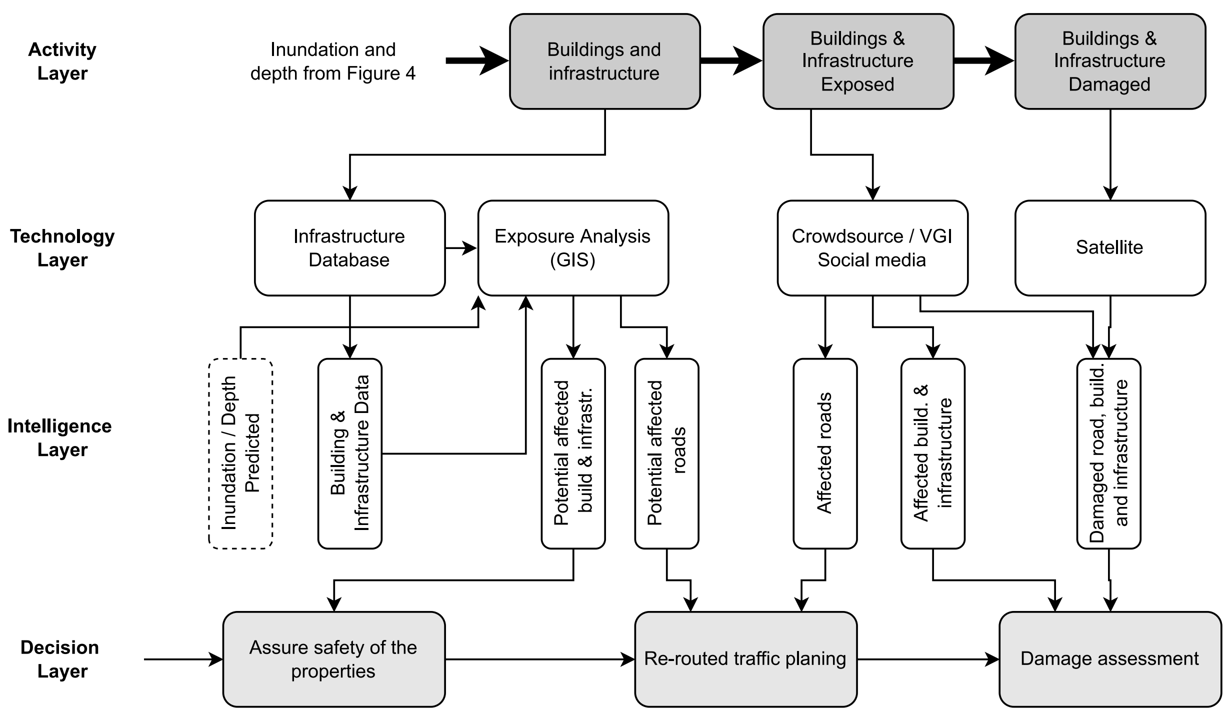


Figure 26: Intelligence required for identifying affected infrastructure

Although the above flood preparedness plans allow authorities to identify potential risks to infrastructure and implement mitigation measures using existing data, sources such as social media, crowdsourcing technology and satellite imageries are important to establish the actual situation on the ground during a disaster. However, the use of satellite images for the response is still challenging as the acquisition and derivation of intelligence from such sources requires considerable time (Zhang & Kerle, 2008).

5.6.4 Conceptual Model of Response Capabilities

Intelligence on resources and capacities required for a successful response is necessary for the authorities to make timely coordination with relevant parties. For example, situational intelligence on safe centre locations, their capacities, evacuation routes, transport facilities and locations of affected people is essential for effective evacuation planning. Novel process models could optimise mass-scale evacuation planning by coordinating resources with affected communities efficiently (Yazdani et al., 2020). Furthermore, authorities also require information on surge capacities for food, medical assistance, transportation and availability of volunteers for better coordination of evacuation. Hospital evacuation needs extra attention as patients are one of the most vulnerable groups during flood emergencies. State-of-the-art hospital evacuation models can be used as potential solutions to safeguard patients' safety during floods (Yazdani et al., 2022).

Figure 27 illustrates the layered approach where intelligence on capacities and resources can be obtained through numerous resource management databases and systems to assist in the decision-making process. More specifically, during a flood emergency, authorities need to locate the nearest evacuation centres and health facilities with appropriate capacities that match the requirement to relocate displaced or treat injured persons. Typically, local flood preparedness plans identify such facilities and hosting capacities well in advance. In addition to that, volunteers, volunteer agencies, and other resources such as transport, heavy machines and tools are required to respond on demand.

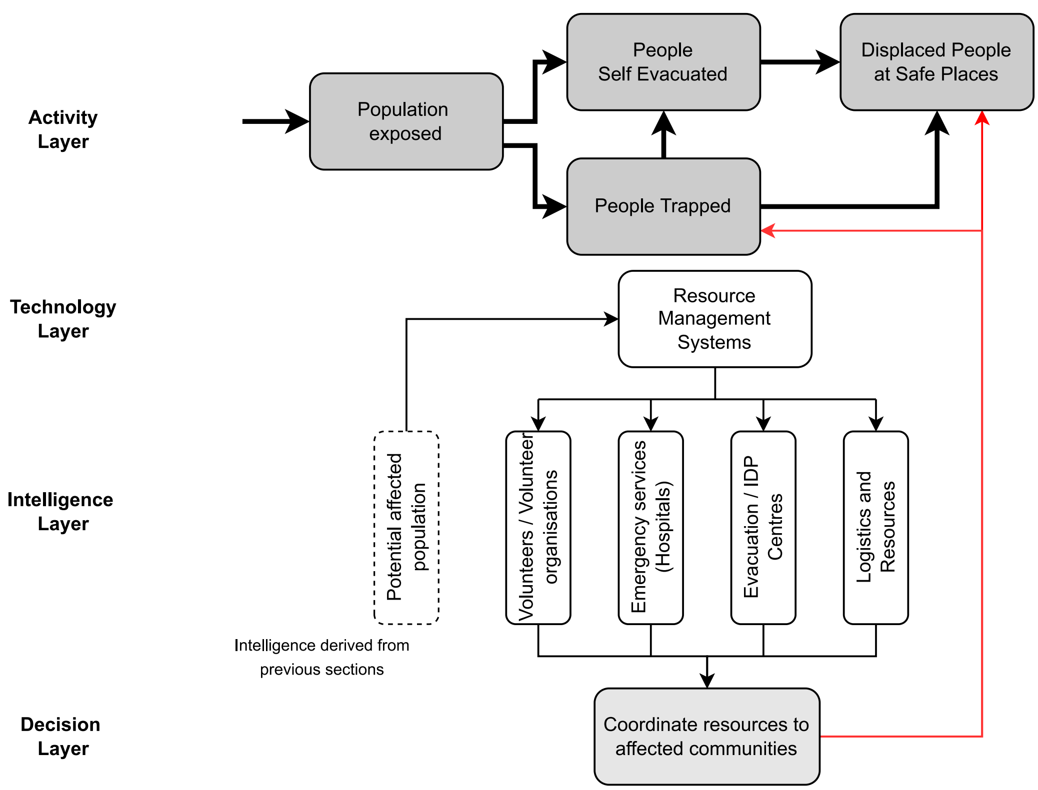


Figure 27: Intelligence required for capacities and resources in response

5.7 Conclusion

The review of literature presented in this chapter identified twenty-eight types of intelligence necessary during various stages of the FEWRS (pre-flood, during the flood and post-flood) to issue flood warnings in advance and to respond efficiently to safeguard people and properties. Over 54 published articles from several bodies of knowledge, including information systems, disaster risk management, and hydrometeorology, have been examined to establish a relationship between the flooding phenomena, intelligence required for evidence-based decision-making, and sources of technology that can be used to extract such intelligence.

The pre-condition for extracting critical intelligence during a flood situation is the availability of exposure and vulnerability data of people and infrastructure of the flood-prone area under consideration. As the flood situation begins to develop, real-time information regarding the flood hazard can be captured using numerous techniques and tools: citizens as sensors, satellite remote sensing technology, IoT devices and mobiles. Information from citizens can be captured through social media and crowdsourcing techniques. These raw data can then be used by GIS, artificial intelligence (AI) or hydro-dynamic modelling to extract critical intelligence such as the dynamic characteristics of the hazard **(**rainfall, river water level/flaw, flood arrival time), population and infrastructure exposed or at risk, and capacities required during response as presented in Table 19.

The conceptual architecture presented in this paper offers a foundation guidance for deploying various advanced technology approaches for deriving the necessary intelligence required by disaster management agencies as the floods begin to spread and impact the community and the environment. The architectural diagrams presented from Figure 4 to Figure 7 illustrate how the required intelligence during the flood cycle needs to be managed in order to inform, evacuate, rescue and offer relief to citizens and safeguard the properties in a timely manner.

Moving forward, the layered approach presented in this paper offers a foundation for developing a technology platform that disaster management agencies can use to issue early warnings with sufficient time for people to evacuate, better respond during floods and efficiently manage relief operations. Furthermore, the conceptual system architecture presents a range of technical solutions that can be adopted by the decision-makers based on the availability of the technology and offers a pathway to increase the accuracy and efficiency in receiving the necessary intelligence as the resources become available. It shows how information from sensors, databases, big data systems, GIS, hydrological simulations and satellite remote sensing can be combined to offer a rich set of information for decision-making and interventions by various agencies. Integration of these technologies has the potential to increase the effectiveness, efficiencies, and accuracy of the overall approach to flood monitoring and early warning and evacuation.

The proposed integration will overcome the limitations of the present early warning and response systems, such as unavailability of information and intelligence (Hammood et al., 2020); insufficient information sharing (Bharosa & Janssen, 2009; Bharosa et al., 2010; Thompson et al., 2006; Waring et al., 2020); lack of coordination among agencies (Almoradie et al., 2020; D. Perera et al., 2020); false early warnings (Aguirre et al., 2018); lack of allocations of resources for response (D. Perera et al., 2020); delayed response (Chua et al., 2007), which often result in crisis escalation and higher numbers of causalities.

5.8 Summary

This chapter provides a wider understanding of information and intelligence required in flood warning and response systems by evaluating 54 research contributions. The structured literature survey identified twenty-eight types of intelligence necessary during various stages of the flooding to issue flood warnings. Conceptual four-layer frameworks for the flooding process were defined. The next chapter will build on these findings and present a conceptual architecture of an advanced FEWRS.

Chapter 6 User Requirement Analysis

6.1 Introduction

This chapter presents the user requirement gathering and analysis used to design the proposed flood warning and response system under the DSR approach. As stated in the previous chapter, fifteen responders were interviewed to capture the characteristics of each stage of the flood warning and response process. The chapter has been divided into key sections which describe the questionnaire design, the methods of data collection, the data analysis, and the results' discussion.

6.2 Interview Questions' Design

The overall interview questions were designed based on the four stages of the early warning process defined by the UNDRR: (i) risk knowledge (ii) monitoring and warning service (iii) dissemination and communication, and (iv) response capability. The questionnaire was designed to capture responses through semi-structured interviews. The framework of the flood warning system suggested by the UNDRR, with the key stages illustrated in Figure 28, was incorporated into the interview questions' design.

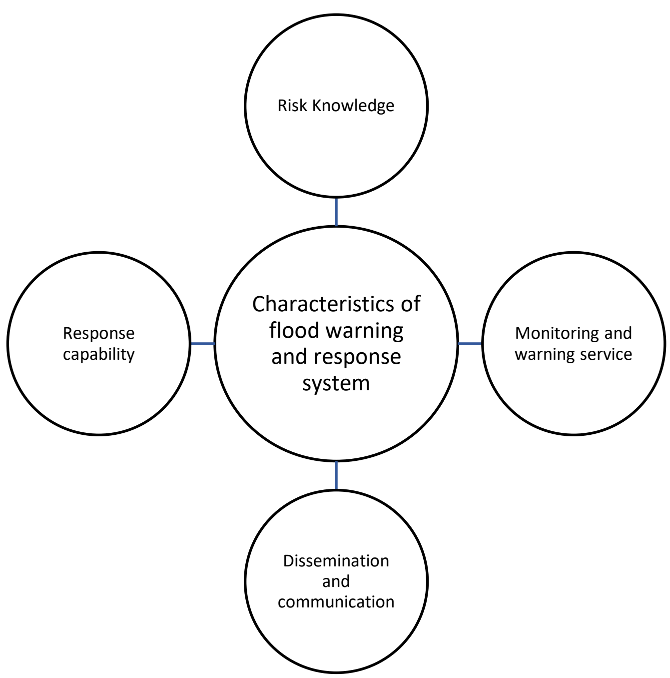


Figure 28: Four stages of the warning systems used in the questionnaire design

The questions designed for the interviews consist of two sections, the first section captures gaps and challenges in the current flood warning and response process, and the second section focuses on capturing user requirements. The questions for the second part were designed for each stage of the early warning systems.

One of the outcomes of the structured literature survey conducted in this study was the identification of the critical failure factors that affect the successful implementation of flood warning and response systems. This finding was used to formulate the interview questions in the first section. Twenty-four critical failure factors have been included in this section to be verified with the users to obtain the overall situation in the study area.

The second part of the questions was designed to explore the current status of the flood warning and response process ("as is" condition) in Sri Lanka and to capture the characteristics of the proposed flood warning and response system ("to be" condition), following the stages depicted in Figure 28. In the risk knowledge stage, questions were aimed at understanding modes of acquisition and the visualisation of flood risk knowledge. The objective of this section was to understand the sources of flood risk data and information, the nature of data representation, acquisition frequency etc. The next section was then designed to understand the "as is" and "to-be" processes of the monitoring and warning service, where the responders were asked about the sub-processes of gauge data acquisition, flood forecasting and warning generation, and impact-based forecasting. The third set of questions was then focused on the warning dissemination and communication process. These interview questions were designed to capture the current warning dissemination and communication process and user requirements for the proposed system. Finally, the last stage of the warning system covered the response capacity where the responders were asked to capture the following sub-processes: sources, tools and techniques to monitor the actual impact on the ground; rescue and medical services; local level capacities to respond to emergencies; and relief mechanisms for the internally displaced persons (IDPs). Each question in the second section was designed to scrutinise numerous dimensions such as process, data, tools and technology, stakeholders and systems, in order to understand the context in detail.

6.3 Method Used to Collect Data

Thirteen responders were employed in this research (Table 20). The purposive sampling technique was used to select suitable responders from the organisations involved in the flood warning and response process. Experts from the Meteorology and Irrigation Departments were interviewed since these two organisations are involved in flood risk assessment, forecasting and warning services. Experts from the Disaster Management Centre (DMC) were chosen as subjects since DMC is recognised as the overall coordination body for warning dissemination and emergency response coordination at the national level. District and Divisional Secretariats were also included since they are the local administrative bodies that coordinate the response partners while working under the overall coordination of the DMC. At the local level, government representatives at the village level (Grama Niladhari Officers) and community responders were also interviewed to capture the user requirements from the grassroots level. Furthermore, leading disaster risk management experts were interviewed to capture their views to understand the current and proposed flood warning and response processes. As listed in Table 20, within the data collection, several published and unpublished documents that provide legal, policy, institutional and operational aspects were also used to derive the current flood warning and response system process and associated background information. All the interviews were conducted via Microsoft Teams, and answers were recorded in Microsoft Teams.

Table 20: A list of experts who participated in the interviews

Code Name	Job Position	Organisation
G1	Senior Meteorologist / Director	Meteorology Department
G2	Senior Hydrologist / Director	Irrigation Department
G3	Member of Higher Management	Disaster Management Centre
G4	Member of Higher Management	Disaster Management Centre
G5	Member of Middle Management	Disaster Management Centre
G6	Member of Middle Management	District Secretariat
G7	Grama Niladhari Officer	Divisonal Secretariat
E1	Disaster Risk Management Expert	Former DMC Officer

E2	Disaster Risk Management Expert	World Bank
E3	Disaster Risk Management Expert	Learn Asia (NGO)
E4	Disaster Risk Management Expert	World Food Program, United Nations
E5	Disaster Risk Management Expert	Janathakdhan (NGO)
C1	Community Representative	Community

Table 21: Documents Associated with the Data Collection

Code Name	Source Document
D1	Disaster Management Act
D2	National Disaster Management Plan
D3	National Emergency Operation Plan 2014 – 2018
D4	Standard Operating Procedures (ADPC-2020)

6.4 Process of Data Collection

The selected responders were contacted via email and initial invitations were sent, followed by a telephone discussion to agree the interviews. During the verbal conversation, they were briefed on the research and the interview process. Subsequently, a formal invitation was sent explaining the research objectives and the interview process, along with the interview guidelines and other supporting documents. During the online interviews, participants were given a clear explanation of the purpose of the research context of the study, before initiating the semi-structured interviews. Semi-structured interviews were used since this method provides greater flexibility to discuss wider areas of the specific subject concerned in the research and explore deeper insights into the topic (Easterby-Smith et al. 2008).

The interviews were digitally recorded with the permission of the interviewee. The length of each interview was circa 90 – 120 minutes. Interviews were recorded and transcribed by the researcher for further analysis.

The key expected outcomes of the interviews were:

1. To develop an "as is" flood warning and response process in Sri Lanka concerning a given sample river basin (in this research the Kelani river basin was used as a sample study area to collect the primary data).
2. To understand current gaps and challenges inherent in the flood warning and response process.
3. To define the characteristics of a desirable flood warning and response system that overcomes current limitations.

6.5 Risk Knowledge Stage

Risk knowledge is the baseline for a typical early warning and response system, according to the EW (Early Warning) framework proposed by the UNDRR. The first outcome of the Sendai Framework (2015-2030) also stresses the need for adequate risk knowledge for disaster risk reduction and response mechanisms. Therefore, designing and deploying a warning system requires that sufficient risk knowledge is held by the partner agencies involved in disaster risk reduction and response activities. SFDRR additionally recommends that general risk understanding by the public is also essential.

The overall objective of the questions in this section was to capture the current process used to acquire and visualise flood risk knowledge, to understand the associated gaps and challenges faced in acquiring such information and to obtain proposals to overcome current issues.

6.5.1 Current Process of Acquisition and Visualisation of Flood Risk Knowledge

The Irrigation Department (ID) is the authorised organisation for flood control, responsible for flood forecasting and issuing flood early warnings in Sri Lanka. They have prepared historical flood inundation maps based on past river flooding. According to the past experiences of the Irrigation Department, approximately 25 out of 103 river basins have been identified as vulnerable to frequent floodings with considerable losses and damage (G2). However, according to the National Hazard Profile, published by the Disaster Management Centre in 2012, ID has prepared these historical flood inundation maps based on field surveys for six river basins: Kelani, Kalu, Walawe, Gin, Nilwala and Attanagalu Oya. Even though the department was established in the 19th century, it still does not possess a proper mechanism to prepare flood hazard and risk knowledge in the form of maps (G2). E4 also confirmed this point raised by G2, saying that "the flood risk information generation process is not a systematic approach". Respondent E4 elaborated upon this fact saying that "the current practice generates risk in an ad-hoc manner".

Nevertheless, ID has established observation stations for the systematic collection of hydrological data for many decades. Several initiatives established by different organisations for generating risk knowledge are discussed below.

Phase one of the World Bank-funded Climate Resilience Improvement Project (CRIP) prepared flood hazard maps using probabilistic flood modelling for ten highly vulnerable river basins during 2014 – 2021. The project delivered risk models and information on potential damages of floods using a probabilistic approach to hazard modeling and risk analysis. However, interviewee E2 argued that both the "Irrigation Department and CRIP project does not focus much on risk analysis". "The Irrigation Department in Sri Lanka does not have risk-related knowledge as they are more focused on hazards. Even in the CRIP project, the risk is not given much priority as they have only collected risk data using a 1km grid" (E2).

Secondly, in collaboration with Sentinel Asia and the International Charter: Space and Major Disasters, the Disaster Management Centre has acquired satellite imageries for past flood events and derived historical flood maps for the period of 2008 – 2019. Furthermore, a mechanism has been established with the international partners to collect, process and prepare flood inundation maps on a case-by-case basis (G4). The existing building, road and other exposure data acquired from the Survey Department and other data providers (including open sources such as OpenStreetMap (OSM)) have been used to combine with flood inundation maps to generate flood exposure maps. DMC hosts such information in its official web portal (www.dmc.gov.lk) and in the risk information platform (www.riskinfo.lk). The responder E2 stated that DMC has a limited capacity to focus on vulnerability and risk data generation and suggested that organisations like the World Bank should improve the risk analysis technical capacity of DMC (E2).

Thirdly, Desinventar (www.desinventar.lk) is a database that has hosted losses and damage data since 1975. It mainly consists of statistics on affected persons (deaths, injuries), housing damage, and damage to agriculture. Since the data is reported at the Divisional Secretariat level, these damage and loss data are considerably coarser in resolution. The data is collected from daily situation reports published by DMC and updated weekly on the portal (G4, G5).

Moreover, the World Bank has provided technical assistance for the DMC in preparing past flood maps for the period 2003 to 2014 (the "Wessa" Project) by analysing historical satellite imagery. The World Bank also has supported the DMC in preparing exposure maps for a few river basins (Attanagalu oya, Kalu and Gin) in Sri Lanka to detect buildings vulnerable to flood impact (E2).

At present, various government organisations are involved in generating useful exposure data to analyse the elements exposed to various hazards. For example, the Survey Department is the primary data provider of topographic, land use, and elevation maps at different scales, in paper and digital form, along with boundary demarcation information and the setting up of mapping standards. The Census and Statistics Department also collect spatial data on the population, housing and socio-economic data from the Grama Niladari Divisions. Different sectoral lead agencies, such as health, transport and tourism, also collect other essential exposure data useful for disaster risk management (E4).

Increasing the availability and accessibility of spatially referenced data is one of the priorities of the government that came into their agenda in 2014. As a result, the setting up of a "National Spatial Data Infrastructure (NSDI)" was initiated by the Government of Sri Lanka (GoSL); a series of policy and technology interventions that brought spatial data into a single platform that enables authorised users to explore, consume and share spatial data among peer government agencies. One of the critical use cases of the NSDI was to bring together various data from providers who own and generate hazard, exposure and risk data into a single window, enabling easy access to these data for exposure and risk analysis (E2 and G4).

Based on the findings from the interviews, Table 22 provides the key data sources useful for flood risk knowledge.

Table 22: Commonly available data sources for flood hazard, risk and exposure analysis

Available key data sources	Source of Agency	Year Prepared	Description
National Hazard Profile – Flood Hazard (www.dmc.gov.lk/hazard)	Irrigation Department and Disaster Management Centre	2012	Kelani, Kalu, Nilwala, Gin and Attanagalu Oya River basins
National Risk Information Portal www.riskinfo.lk	Disaster Management Centre	2012	Various hazard, exposure and boundary data are available from the national to the local level.
National Spatial Data Infrastructure	Information Communication and Technology Agency	2017	Various hazard, exposure and boundary data from national to local level
Desinventar www.desinventar.lk	Disaster Management Centre	2008-2012	Disaster events, including floods, with information on damages and some losses, are inventoried from 1974 to date.

In addition to the above, government organisations and universities have generated data sets for various purposes. Moreover, the Irrigation and Meteorological Departments have their own data archives for rainfall, river flow, river water level, and other weather and climatic parameters.

However, even though some data sources and initiatives are available for flood hazard, exposure, and risk, it has been observed that flood hazard and risk knowledge is only partially available for the early warning and response process. The data is collected mainly on an ad-hoc basis from various sources and initiatives. No standard operating procedure is agreed upon and implemented by the Irrigation Department, Disaster Management Centre, Meteorology Department, and other data providers for collection, processing, and consumption. Even though a policy for data sharing through the National Spatial Data Infrastructure is available, such mechanisms are not correctly functioning. Information obtained from the interviews suggests that poor supply chain management practice has been observed concerning generating and updating flood risk knowledge. Therefore, there is a lack of policies and inter-agency collaboration for data acquisition, processing, updating and sharing of flood risk management and the early warning process. An interviewee also confirmed that no formal mechanism is available to collect, process and host exposure data at the national level (E2). The Desinventar, which maintains the multi-hazard damage and loss data system, is the only system that demonstrates a proper supply chain management mechanism established to collect data, then to update and visualise.

6.6 User Requirements for Flood Risk Knowledge Acquisitions and Visualisation

The prevailing approach to acquiring and visualising risk knowledge was discussed in the preceding section. This section delves into the outcomes from the obtained primary data, providing an analysis of how the acquisition and visualisation of risk knowledge can be enhanced from the user's perspective.

Interviewee G4 emphasised that risk knowledge encompasses a broad concept which requires an understanding of a specific context and the meaningful integration of processed observational data with other information sources. However, the current process of generating risk knowledge lacks a systematic approach to generating such knowledge (E4). This interviewee suggested that "risk information generation should follow a highly systematic approach, encompassing data collection, processing, and visualisation”.

Flood risk knowledge is derived from the amalgamation of diverse data sources and formats, including rainfall, river flow, census, residential information, etc. The resulting risk knowledge can be manifested either as monetary values, quantitative data or qualitative data which can aid decision-making in risk mitigation and response. Interviewee G4 further asserted that comprehensive risk knowledge, tailored to a specific context, plays a crucial role in designing an early warning system.

At the local level, two types of user groups consume risk knowledge: long-term residents or "inheritance" and short-term residents or "aliens" (G7, C1). Those who live permanently (inherent) in a local environment have prior experience with local risk knowledge, while the other category, "aliens", who are temporary travellers, are unfamiliar with the given area. Both G7 and C1 expressed that the community who has lived in a given area for several decades comprehend local risk knowledge. This local community knows of the monsoon period with its heavy flooding, and they have prior knowledge of the maximum flood level that has occurred over the past several decades. This community also knows the maximum flooding zones; hence, they have an understanding of the safer routes and safer locations to evacuate to during the floods. However, G7 and C1 suggested that a community that has moved in the recent past ('aliens') does not have adequate ground knowledge of a given area. Risk knowledge presented from a system will be able to confirm the current knowledge of existing residents and will provide awareness to new residents (C1, G7)

Interviewee G4 proposed that an effective early warning system should primarily focus on residential areas and offer customised warnings to individual community members. The prioritisation of a warning system should be based on social, economic and geographical considerations. Based on theoretical understanding, the prioritisation of warning systems in a specific area hinges on the presence of hazards, their occurrence frequency, the potential extent of damage, and the subsequent evaluation of the population at risk [1]. The design of warning types and methods should be tailored according to the socio-economic and geographical characteristics of the exposed community [1]. Hence, E2 proposed that authorities must continually evaluate underlying risks and refine their warning strategies.

The data collection process can be optimised by implementing a streamlined approach that delineates specific responsibilities among the relevant authorities (G4). It is imperative to prioritise data standardisation as a fundamental aspect of effective data management and sharing, enabling seamless integration and utilisation (E4). The authorities entrusted with urban planning (encompassing the construction of buildings and other infrastructure) should be offered the capability to update the local exposure data. Respondent E4 suggested that building plans should be provisionally updated in a central database during the planning process and should be confirmed once the construction is completed. One of the anomalies in the planning process in Sri Lanka is that, according to current laws, regulations and practices, no government agency is responsible for building construction in rural areas. For example, the Pradeshiya Sabhas (PS) do not have control over building construction in their control areas (E2) which makes it difficult to maintain an updated record of buildings. One of the potential solutions to this situation is to assign the responsibility to the Grama Niladharai, the local-level government officer responsible for the central government, to monitor new building construction and occupancy through the Interior Ministry and the Divisional Secretariat (E2).

Although there is much emphasis placed on producing impact-based forecasting and warning, these demand more granular level information such as on population, residential buildings, critical infrastructure, annual event calendars, information on disabled people, and other vulnerabilities in a given local context (E2). Furthermore, the systematic collection of pertinent information, including building materials and occupancy statistics for temporary and permanent inhabitants, needs to be frequently gathered. Such a comprehensive dataset also has the potential for contributing to post-disaster response strategies and relief initiatives and to facilitate the streamlining of the processing of insurance claims (E4). Therefore, a national policy framework for the agencies with mandates should be established for risk data collection, processing and sharing risk data (E2). Furthermore, data collection efforts at the local level by the Divisional Secretariat should be better utilised (as they usually publish resource profiles at the Divisional Secretariat level) (E2).

With regard to the Irrigation Department, they should have a regular process to derive flood information and generate flood maps for each incident. Remote Sensing is an effective tool for acquiring post-flood events' information which could be used as a source of risk knowledge (E2). Even though the Irrigation Department has not addressed the presence of risk knowledge, the level of flood inundations have been categorised by introducing various thresholds to define the intensity levels of alerts, namely as minor, major, dangerous and critical (G2). At present, discharge during flood events is not captured and therefore, mechanisms should be introduced to record flood discharge (G2) to understand their impact. G2 further mentioned that "We should have pre-defined information for possible flood scenarios available in the system for a given river basin. For each flood level (minor/major), floods' demarcation should be available listing the households and other infrastructure that are going to be submerged. If we can identify these vulnerable people, we can send evacuation orders to remove communities which are at high risk from floods, with the assistance of the authorities. Therefore, information on residential areas which are in the high flooding zones should be regularly updated. We have to identify individual houses, and persons who are in flood-risk areas should get a warning well in advance. At the moment, we are giving only a general warning, and it is not targeted at a specific risk community".

G4 suggests that the risk visualisation could be in any format, such as maps, pictures, text or maps. The visualisation style should depend on the user preferences and literacy level. The visualisation should be very simple, showing exposed objects, their vulnerability, and potential damage. According to E2, it is essential to visualise the following objects: (i) areas in danger from flood risks (ii) road segments that are going to submerge (affecting railways and buses, and private drivers), (iii) disabilities of people living in the risk areas, (iv) areas where the response teams to be deployed (v) potential social and economic impact. However, C1 emphasised the need to ensure the quality of the shared information. The need to deliver relevant information to the public through a popular mobile app that already has a high reach out to the public was emphasised by both G3 and C1.

Table 23 summarises the requirements captured from the above inputs for creating comprehensive risk knowledge.

Table 23: Summary of User Requirements Which Should be Captured for Risk Knowledge Acquisition and Visualisation

User Requirement	Interviewee
Meaningful integration of risk data.	G4
Risk generation should be a systematic approach encompassing data collection, processing, and visualisation.	E4
Comprehensive risk knowledge should be maintained for flood EW systems.	E4
Risk knowledge should be customised to cater for the needs of the user.	C1
Customised targeted warnings should be produced.	G2/G4
Authorities should have updated risk data and information to create more effective warning systems.	E2
A streamlined approach that delineates specific responsibilities among the relevant authorities should be maintained.	G4
Data standardisation is important for the better sharing of data, enabling seamless integration and easy utilisation.	E4
A centrally managed spatial database should be maintained, including newly erected buildings and associated infrastructure.	E4
The monitoring of new building construction should be vested in a GN Officer at the local level.	E4
For impact-based forecasting and warning, more granular level information should be collected such as on population, residential buildings, critical infrastructure, annual event calendars, information on disabled people, and other vulnerabilities.	E2
Systematic collection and regular updates of information on buildings and occupancy statistics are necessary for evacuation and insurance purposes.	E4/G2
A national policy framework for agencies with mandates should be implemented for risk data collection, processing and the sharing of risk data.	E2
Remote sensing should be used for acquiring information on post-flood events as a source of risk knowledge.	E2
ID should have a mechanism to record flood discharge during floods.	G2

Risk visualisation should use any practical formats, such as maps, pictures, text or maps.	G4
The following information should be collected for visualisation: (i) areas at danger from flood risks (ii) road segments that are going to submerge (affecting railways and buses, and private drivers), (iii) people with disabilities, (iv) areas need response teams are deployed (v) potential social and economic impact.	E2
Risk information could be delivered through a mobile app.	G3
A popular news app with a high reach out to the public could be used to push the notification of risk information/warnings.	C1

6.7 Current Process of Monitoring, Forecasting, and Warning

An accurate weather forecast is essential to make flood forecasting credible and, therefore, the role of the Meteorology Department is critical in the flood forecasting process. Established in 1948, the Meteorological Department is one of the oldest departments in the country. The Meteorology Department is the authorised agency responsible for weather forecasting, seasonal weather prediction, and meteorological data collection and warehousing. The Department of Meteorology (DoM) in Sri Lanka plays a crucial role in receiving international meteorological data through the Global Telecommunication System (GTS). They obtain satellite weather images from various sources such as INSAT, Meteosat, and Korean satellites via the internet. The department has 38 automated weather stations and 23 weather stations that collect rainfall manually and then transmit that data over the telephone system. Another 170 manual rain gauge stations are also available that send data in a delayed mode.

The DoM runs Weather Research and Forecasting (WRF) models and generates forecasts based on Numerical Weather Prediction models. DoM has recently subscribed to a numerical weather model from the European Centre for Medium-Range Weather Forecast (ECMWF), which provides outputs in a 9-km grid size. Regarding cyclone warnings, the DoM relies on its own warning services and the advisory bulletins issued by the Regional Specialised Meteorological Centre

(RSMC) in the India Meteorological Department (IMD) in New Delhi. DoM also utilise the Joint Typhoon Warning Center (JTWC) website for weather updates.

Although the dissemination of severe weather warning messages to end users is primarily handled by the Disaster Management Centre (DMC) of Sri Lanka, DoM also conducts media briefings on weather events and warnings. A flow diagram illustrating the Early Warning System (EWS) for weather hazards affecting Sri Lanka is provided in Figure 29.

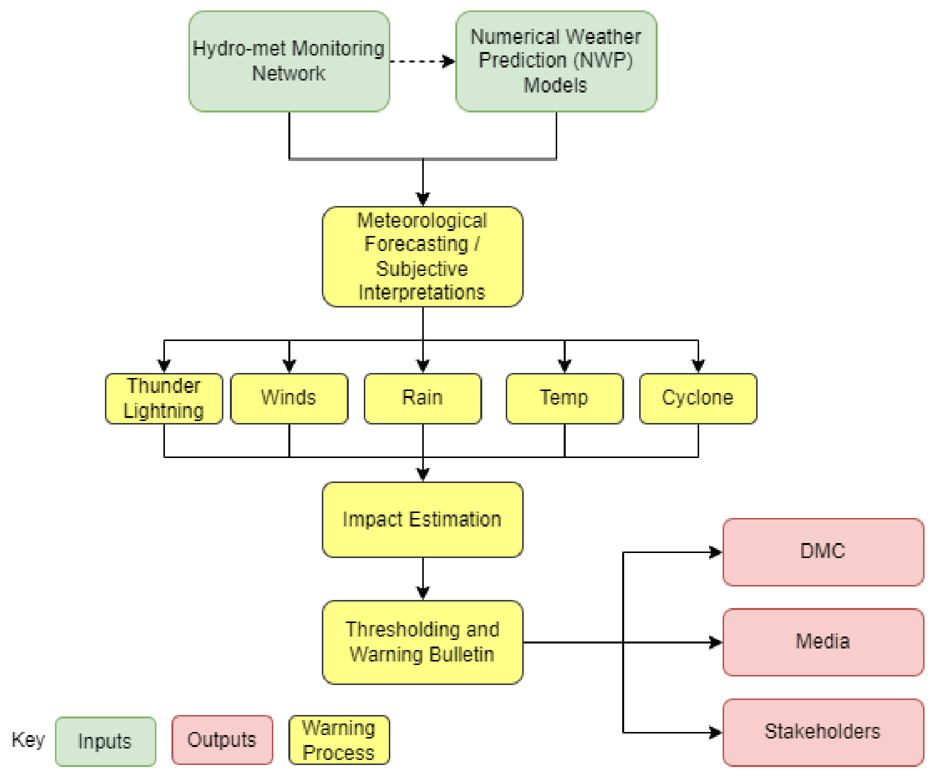


Figure 29: Meteorological Forecasting Process

The Irrigation Department (ID) is mandated to use the weather forecasts issued by the DoM and initiate flood monitoring, forecasting and issue flood early warnings. The Flood Protection Ordinance No. 24 of 1924 sets the initial basis for the ID to flood controls in the country. The Disaster Management Plan (2013-2017) and the National Emergency Operation Plan (NEOP) have recognised the role of ID as the authorised agency for flood forecasting and issuing flood warnings for riverine floods.

Approximately 22 rivers in Sri Lanka are prone to frequent flooding, and the potential hazard area covers almost two-thirds of the country. Despite these flood risks, the flood mitigation investment in Sri Lanka is minimal compared to many other countries. Therefore, the systematic monitoring of river basins is critical in addressing flood risk. With this in mind, the Irrigation Department originally established 35 manual river gauge stations across the main river basins in the country. Hourly water levels are manually transferred to the department over the telephone. In order to enhance the capacity of ID to monitor flood risks, a Hydrometeorological Information System (HMIS) with 106 automated river gauge stations was established in 2013 by the World Bank, and funded under the Dam Safety and Water Resource Planning Project (DSWRP). These automated gauge stations are capable of transmitting information on water levels at 10-minute intervals. However, G2 mentioned that manual gauge stations are more reliable than automated stations. These gauge stations are manned by ID permanent employees during flood times. The department currently has 41 manual gauge stations to monitor river water levels. The data gathered from the manual gauge stations are transferred to the Hydrology Unit of the Irrigation Department over the telephone. The water level of the major reservoirs managed by the department is also reported to the hydrology division. The current data transfer mechanism is illustrated in Figure 30(b).

The Irrigation Department has classified floods into several threat levels based on statistical data analysis and inundation levels. These are alert, minor floods, major floods, dangerous floods, and critical floods. Flood levels at alert and minor floods are not considered harmful to human life, and evacuation orders are issued only for major floods and for the levels above. The Flood Monitoring Committee is the internal body consisting of the Directors of hydrology, asset management, water management and flood studies, drainage, and disaster management, headed by one of the additional Director Generals. The committee reports to the Director General of ID and functions around the clock during emergencies.

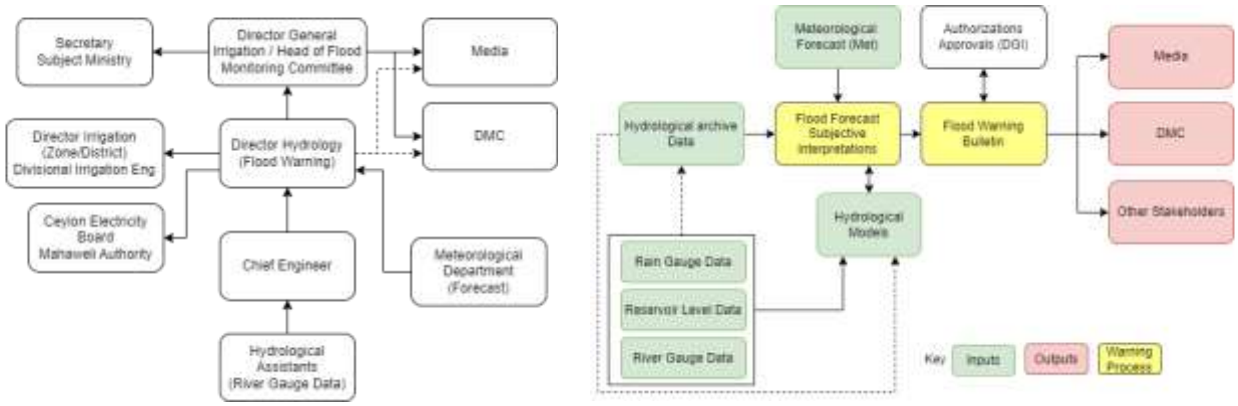
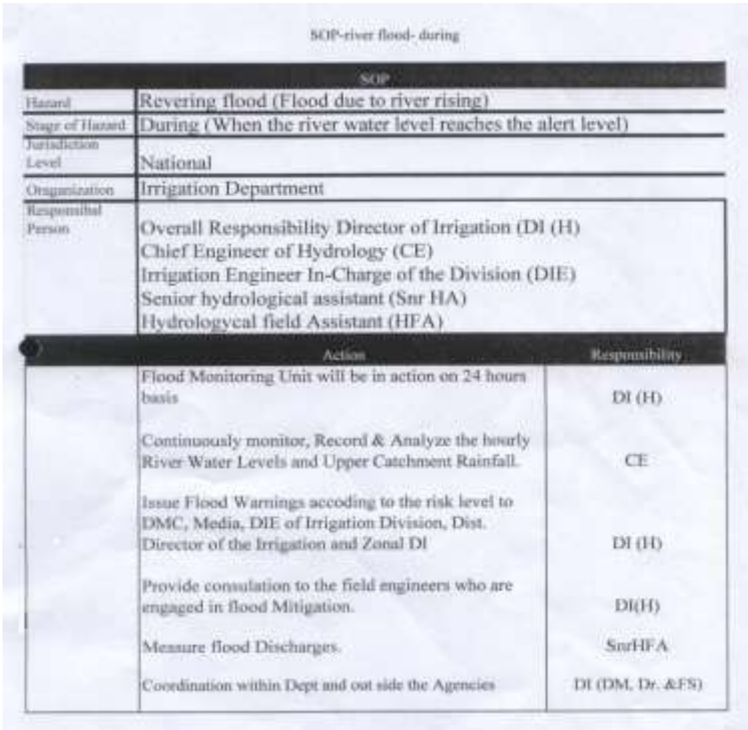


Figure 30: Flood warning process of the Irrigation Department (a) left-hand side presumably stakeholder view (b) right-hand side presumably Data Flow View

The river gauge data is collected through both manual and automated processes. In the case of manual gauge stations, hydrological assistants record and submit the values to the hydrological branch of ID via telephones. In the meantime, the data from automated gauges update the HMIS system at the central level. The Director of Hydrology is technically responsible for monitoring and generating flood forecasts, which use hydrological analysis of past events while taking into account current rainfall, river flow, and the weather forecasts issued by the Meteorology Department. The forecasting process also involves the tacit knowledge of the officers based on their prior experiences to generate the forecast. The outcome is validated with hydrological models whenever necessary for further confirmation. The expected flood levels are then classified based on threshold levels, and flood warnings are issued (Figure 30b) to the internal (Directors of Irrigation at zonal, district, and divisional levels) and external (DMC, Media, CEB and Mahaweli etc.) stakeholders (Figure 30a). However, the Director General decides with respect to the warning decisions for major floods and above, in the consultation of the Director of Hydrology. The flood warning process is documented as a Standard Operating Procedure (SoP) within the Irrigation Department to standardise the warning process (Figure 31).

The flood warning advisory message is shared with the DMC for further response actions and to the media for public dissemination. DMC's role is to coordinate with the other response agencies at the national and local levels to provide the necessary responses and ensure the safety of the public and properties.



SOP-river flood- during

SOP	
Hazard	Revering flood (Flood due to river rising)
Stage of Hazard	During (When the river water level reaches the alert level)
Jurisdiction Level	National
Organization	Irrigation Department
Responsibal Person	Overall Responsibility Director of Irrigation (DI (H) Chief Engineer of Hydrology (CE) Irrigation Engineer In-Charge of the Division (DIE) Senior hydrological assistant (Snr HA) Hydrologycal field Assistant (HFA)

Action	Responsibility
Flood Monitoring Unit will be in action on 24 hours basis	DI (H)
Continuously monitor, Record & Analyze the hourly River Water Levels and Upper Catchment Rainfall.	CE
Issue Flood Warnings accoding to the risk level to DMC, Media, DIE of Irrigation Division, Dist. Director of the Irrigation and Zonal DI	DI (H)
Provide consulation to the field engineers who are engaged in flood Mitigation.	DI(H)
Measure flood Discharges.	SnrHFA
Coordination within Dept and out side the Agencies	DI (DM, Dr. &FS)

Figure 31: Standard Operating Procedure (SoP) of the Flood Forecast and Warning Process of the Irrigation Department

6.8 User Requirement for Proposed Monitoring, Forecasting, and Warning (To Be Scenario)

The preceding section discusses the user requirements which should be collected to streamline monitoring, forecasting and warning. It discusses monitoring and data acquisition, a forecast system and a warning mechanism.

As specified in the previous section, numerous hydrometeorological observation stations are placed across the country to monitor rainfall, river flow and other climatic parameters by multiple authorities. Even though the country is covered by rain and river gauges, these are inadequate to monitor the current situations and, therefore, the density and coverage of the rain gauge and river gauge stations should be increased (G1, G2, G3 and E4). "At the moment, different agencies own automated gauge stations. For example, the Meteorology Department, NBRO and Irrigation

Department manage three rain gauge networks available through three different platforms. I suggest integrating these three into a single platform will allow user agencies to observe and consume the data easily" (G1). E4 also supported the above argument and proposed the installation of more robust sensors that have the ability to communicate in low-bandwidth environments. Furthermore, E4 also proposed that these sensors should not be interrupted by power issues.

E2 proposed a joint forecasting and warning platform in which all the rain, river and other environmental monitoring sensors and gauge stations are integrated. "It should not necessarily be at the WMO (World Metereorological Organisation) standards for all these sensor and gauge stations and but it should be reasonable enough to detect and monitor environmental changes" (E2). The proposed sensor platform could be open, collaborative, and continuously updated to improve the monitoring and warning process substantially (C1 and E2). The data acquired by these sensors should be available for the public to view and thus be aware of the ongoing situation through online systems, and these data should be standardised for common use (G4). A facility should be available for citizens to view and monitor real-time gauge information in pre-defined areas or based on current location or a current driving route (C1). C1 further elaborated "Let's say if I am driving with the assistance of Google navigation, I should be able to see observation data along my route".

The forecasted and actual sensor values could be visualised in the same platform so that the user can compare the predicted values versus the actual values (E4). These gauge data could be shared among the numerous government stakeholders for emergency use, and limited accessibility should be available for public use. National agencies would be able to see the countrywide data, while provincial, district, and local agencies could observe the data visualisation within their own administrative boundaries. A Mobile App could be utilised to create a public interface to visualise the data and the last saved data could be retrieved in the absence of the internet at certain locations (E4).

The maintenance and archiving of these data sets are essential for climatic analysis, and therefore, a custodian for these data sets should be established. Monitoring should also be enhanced with near real-time satellite observations that can detect rainfall (G1). Crowdsourcing is another alternative option whereby the public can collect and report rain and river flow observations through a mobile app for the areas where the sensor network is unavailable (G1, G2). C1 also suggested that public engagement is essential to increase awareness. Interviewee C1 further stated that the "public tends to share data rather than consume. We can use their interest to share data to keep the system more interactive and live. These users can also be ranked based on their active engagement". On the other hand, E4 argued that a crowdsourced system via public engagement can only be used to verify the ground observations.

E2 stressed that effective early warning is not possible with only real-time monitoring. E2 further elaborated upon this point by saying that "three things are necessary for effective flood forecast and warnings: firstly, medium range flood forecasting is necessary to predict the situations, that is not necessarily to be used for warning, but is useful for planning ahead and alerting the agencies on possible upcoming situations accomplished by using numerical weather models; secondly utilising now-casting which can generate warnings just before heavy rain occurs. Radar systems are a type of now-casting that can deliver quantitative forecasts. Lastly, monitoring devices such as rain and river gauges should be used to monitor the situation as the event is unfolding. Therefore, we have to develop a robust flood forecasting and warning system based on medium-range forecasting, now-casting, and real-time observations". On the other hand, human resources should be enhanced to understand and implement the latest weather models. Implementation and scaling down of these models need adequate processing power in order to execute these models. This weather model output should be shared among the general public in pixel-based maps instead of the traditional forecasts which are generalised to provincial boundaries.

A robust forecast and warning mechanism is necessary to warn of potential floods in major river basins, 48 hours prior to an event (E4). Limited area numerical models with high-resolution outputs are necessary to improve weather forecasting. However, limited computing capacity is a critical challenge for localising global models at finer resolutions with higher accuracies. Dynamic flood models are necessary to improve the current flood forecasting mechanism to achieve 48 hours prior warnings (G1, E4). The integration of hydro-dynamic models with high-resolution weather forecasting models, radar systems, sensors, and gauge observation could make real-time flood forecasting more dynamic (G2). Inter-agency collaboration is essential to minimise the complexity of the warning process. The key agencies such as the Meteorology Department, the Irrigation Department and the Disaster Management Centre should closely collaborate, regardless of the physical and soft barriers of these organisations. Future flood forecasting and warning processes should operate as a single entity that enables data collection, processing, and decision-making in a centrally managed virtual environment (G1, E2, E4). Moreover, G2 also encouraged the use of community-based warnings, based on the localised sensors, which could be complementary to the official warning process.

Integration of dynamic data (hazard data) and static data (mostly exposure data) can generate potential impact data prior to a flood event enabling impact-based warnings (G4). Based on the impact level, these warnings could be classified into threat levels easily understood by the public (G3). Table 24 summarises the requirements captured from the above inputs for monitoring, forecasting and warnings.

Table 24: Summarised User Requirements Captured for the Monitoring, Forecasting and Warning Stages of a Flood Warning and Response System

User Requirement	**Interviewee**
The density and coverage of the rain gauge and river gauge stations should be increased.	G1, G2, G3 and E4
Multiple gauge networks should be integrated into a single platform.	G1, E2
More robust sensors should be installed that have the ability to communicate in low-bandwidth environments.	E4
A sensor platform should be open and shared to improve the monitoring and warning process.	C1, E2
The data acquired by these sensors should be available to the public to view.	G4
Citizens should be able to view real-time gauge information in pre-defined areas, based on current location and the current driving route.	C1
Forecasted parameters and observed sensor values should be visualised in the same window for easy comparison.	E4
It should be possible to filter data according to geographical boundaries.	E4

Mobile Apps should be introduced as a public interface for warning and response systems.	E4
Options should be available to visualise the last saved data when a device is offline.	E4
Near real-time satellite data should be available to complement rainfall monitoring.	G1
Crowdsourcing should be exploited to collect rainfall and river flow observations.	G1, G2
Citizens can be ranked based on their active engagement.	E2
Medium range flood **forecasts** should be available to predict hazard situations.	E2
Radar systems should be deployed to offer now-casting rainfall information.	E2
Initial flood warnings should reach the responders and community, at least 48 hours prior to the event.	E4
Dynamic flood models integrated with meteorological models, radars, and sensors should be explored to improve the current flood forecasting mechanisms.	G1, E4, E2
Flood warnings should visualised in pixel-based maps	E2
The flood forecasting and warning process should be a single entity that enables data collection, processing, and decision-making in a centrally managed virtual environment. A joint forecasting and warning system involving DoM, DMC, ID is proposed	G1, E2, E4
Community-based warnings, based on the localised sensors, should complement the official warning process.	G2
Integration of dynamic data (hazard data) and static data (mostly exposure data) should be used to generate potential impact data prior to a flood event.	G4

6.9 Current Process of Warning Dissemination (As is Scenario)

The Disaster Management Centre is the authorised agency legally mandated for early warning dissemination. The National Emergency Operation Plan (NEOP) and Standard Operating Procedures (SoPs) define each level's warning dissemination processes, channels, and responsible agencies (D2,D3,D4).

It is important to ensure warning messages on impending disaster situations are disseminated on time to the exposed population and businesses, including respective government agencies. Multiple sources of warning services have been established to meet this objective. For example, the public is informed by state and private media in the form of television and radio. Mobile service providers also play a crucial role in delivering warning messages through their networks. A Dialog Emergency Warning Network (DEWN) system covers a wider range of communities through its Mobile App and cell broadcast service. Furthermore, various media agencies also operationalise their SMS subscription services to inform the public. In the case of critical situations, mostly at night time, Police and Military establishments are given authority to reach the vulnerable communities.

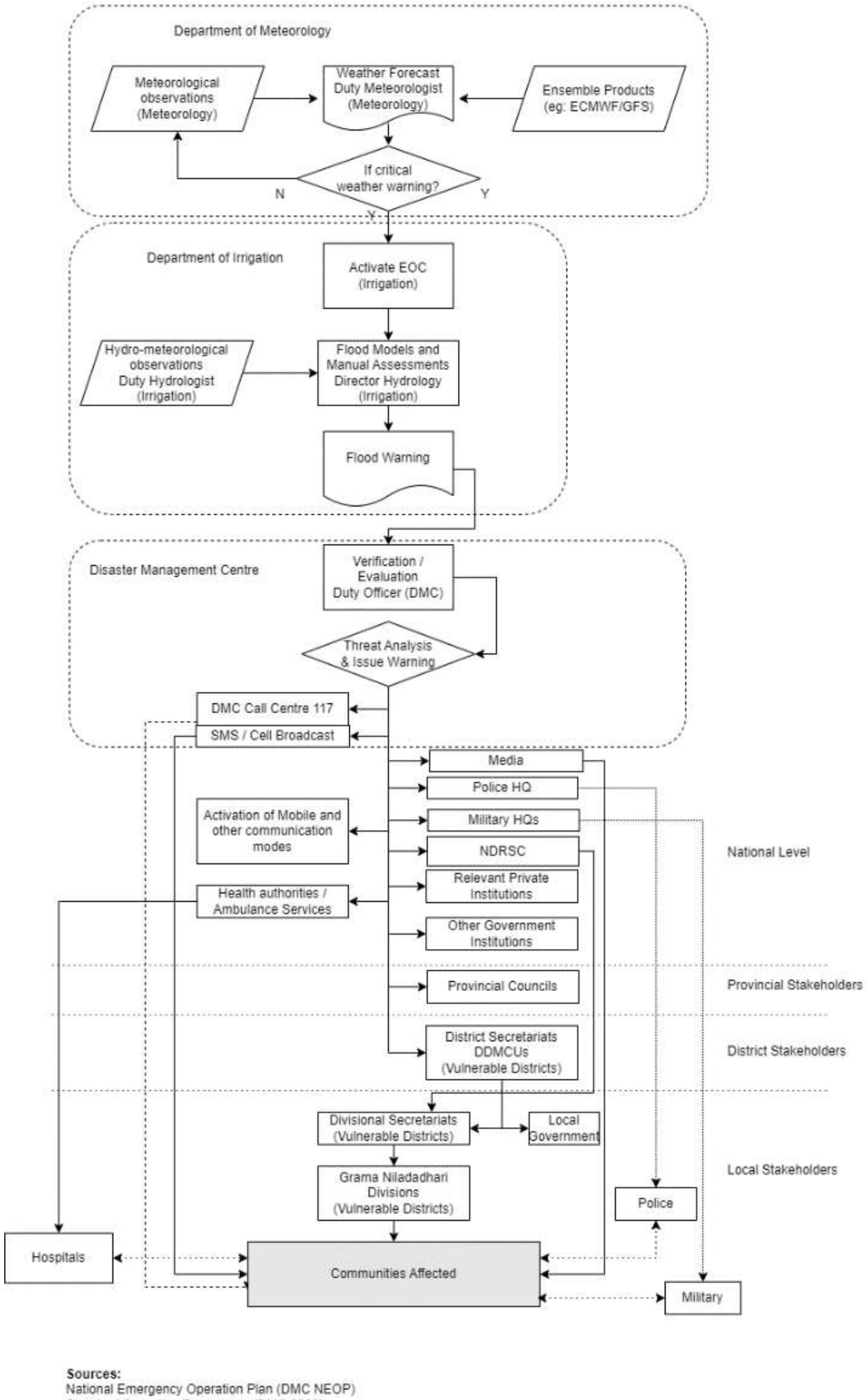


Figure 32: Multi-hazard Early Warning Dissemination System in Sri Lanka
(Source: Disaster Management Centre)

Once the warning message is received from a technical agency, in this case, the Irrigation Department, the Emergency Operation Centre of the DMC, which is manned 24hrs x 7 days, receives the warning and takes necessary actions to disseminate the message at various horizontal and vertical levels (Figure 32).

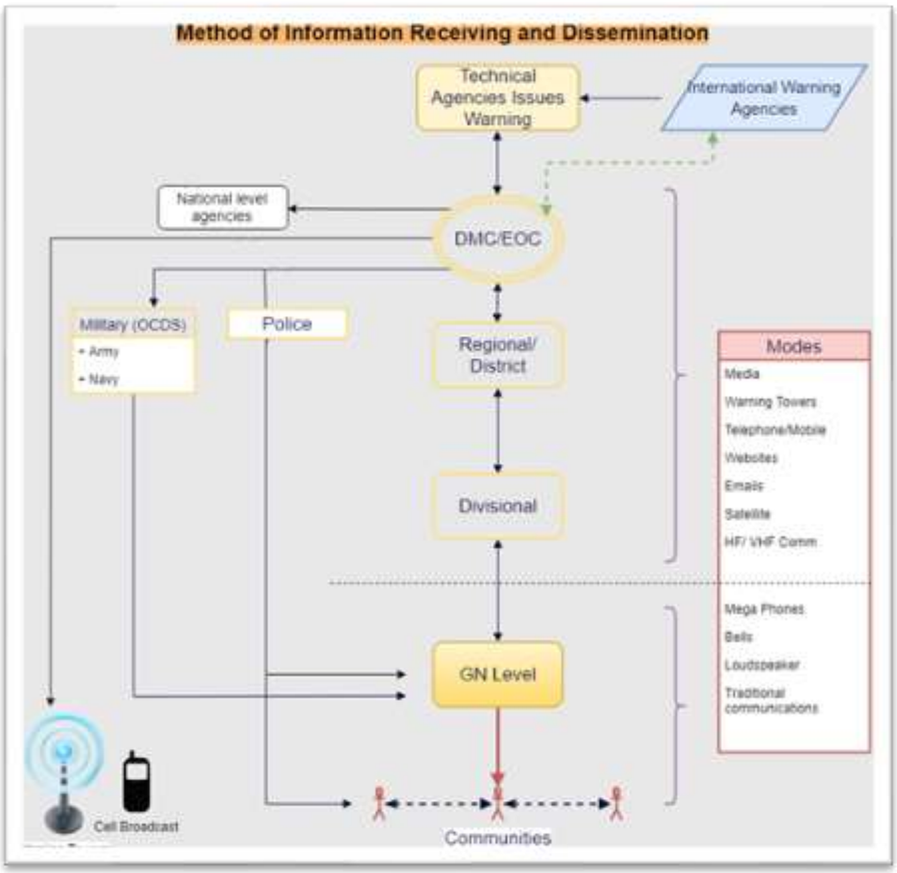


Figure 33: Methods of information receiving and dissemination during an emergency

Within the established communication mediums to reach the vulnerable communities, the EOC notifies at-risk communities (Figure 33) through the District and Divisional Secretaries and the Grama Niladharis to make the public aware of the impending situation in three phases: (1) Alert: Informing the public of the impending hazardous situation in order to take precautionary measures; (2) Warning: To take appropriate measures to save lives and safeguard properties; (3) Evacuation: Through the district authorities, the EOC disseminates messages to the public to vacate their homes to go to secure areas, identified during the preparedness planning process. Furthermore, the media communicates early warning messages, received from technical agencies and the DMC, to the general public. The DMC has dedicated military communication links with tri-service military operation rooms and camps scattered nationwide. This facility effectively disseminates Early Warning Messages to vulnerable communities and coordinates the troops on response missions. In the cases where there is an absence of communication networks, and during the night time, police and military forces disseminate the messages by loudspeakers and door-to-door in the case of critical scenarios (D3, D4).

6.10 User Requirements for Warning Dissemination (To Be Scenario)

The objective of effective warning dissemination is not to leave behind anyone and ensure exposed people are brought out of danger (C1). The warning dissemination should be a redundant process with existing multiple channels, which will avoid the interruption of dissemination in the case of the failure of one channel (E1). The approach to warning dissemination should be standardised in order to keep uniformity throughout the country (E4). A single body should disseminate the initial warning message to avoid confusion among the public and other users (E1). "I suggest a national unified warning dissemination system is necessary to avoid much of the confusion and duplications" (E1). E4 expressed that warning messages should not pass through intermediates and emphasised the necessity for direct dissemination to the users. E4 also suggested that targeted warnings to a community, who are directly exposed to flood inundation, are possible by detecting their mobiles' locations. C1 suggested that a user's live location would enable authorities to track them and issue a warning if they are likely to be exposed to threats.

A common mobile application that indicates potential flood inundation alongside exposure data would be useful to push warning messages (E4). Users' residential locations would be useful during the registration process for these apps (C1).

The complexity of warning messages should be based on the user's level of understanding (C1). C1 further elaborated upon this point by saying that the "first category is technical people; they can understand potential impact by reading raw values such as rainfall, water level, and model results. They should be fed with more primary-level raw data/information for them to further add value and generate forecasts and warnings. However, the second category are those who are only able to understand the processes of technical data in a more meaningful layman's language. The third category is those who do not understand any such warning information at all. They should be somewhat forcefully informed of the incoming threat by overriding their current actions. For example, if a child is playing a computer game, the screen may overlay the warning message constantly". G4 and C1 suggested that warning messages should be customised based on the recipient's nature, interest and level of understanding. "Warning messages should be customised differently for government users, for private sector users and for the general public" (G4).

Warning messages should have a feedback loop to ensure that the individuals in danger receive the warning (C1). C1 also suggested that other existing mobile applications, such as news and media, e-commerce, and banking applications, should be enabled to receive warning dissemination messages (C1). In this context, public-private partnerships are necessary to get telecommunication and media agencies to play an active role in the warning dissemination process (G4).

Table 25 summarises the user requirements captured through the interviews for enhancing warning generation and dissemination.

Table 25: Summarised User Requirements Captured for Warning Dissemination and Communications of the Flood Warning and Response System

User Requirement	Interviewee
Warning dissemination should employ multiple channels.	E1
Warning dissemination should be standardised in order to keep uniformity throughout the country.	E4
A single body should disseminate the initial warning message to avoid confusion among the public and other users.	E1
Warning messages should not pass through intermediates, and there is a need for direct dissemination to users.	E4
Targeted warnings should be issued to users who are directly exposed to potential flood inundations.	E4

The tracking of the live locations of people should be possible to enable authorities to track vulnerable populations to issue warnings.	C1
A common mobile application should be made available that visualises potential flood inundation with the exposure data.	E4
It is important to capture users' residential locations.	C1
Warning messages should be customised based on the recipient.	G4, C1
Warning messages should have a feedback loop to ensure that the individuals in danger have received the warning.	C1
Existing mobile applications used for news, media, e-commerce, and banking should be able to disseminate warning messages.	C1
Public-private partnerships are necessary to enable the participation of telecommunication and media agencies in the warning dissemination process.	G4

6.11 Current Process of Response Capacity (As is Scenario)

The response capacity is the final stage of an early warning system. Providing efficient and effective responses to safeguard life and properties is the overarching objective of this phase. Disseminating warning messages to the last mile is necessary as a pre-requisite for this stage. Even if all three previous stages are successful, any failure of this stage will completely collapse the objective of the warning system.

Responder G5 suggested that the critical objectives of the response capacity phase of the warning system can be identified as follows: (i) activate search and rescue (SAR) teams, (ii) make sure of the emergency medical and health conditions of the victims and affected communities (iii) safety centre management and welfare of the Internally Displaced Persons (IDPs) (iv) coordinate humanitarian support services and volunteers.

The military services are deployed nationwide to deliver search and rescue services during emergencies (see Figure 34). The Search and Rescue (SAR) teams are coordinated through the Office of the Chief of Defence Staff (OCDS), the military entity that coordinates tri-forces. Approximately 45 SAR teams are deployed to rescue victims from floods and other disasters.

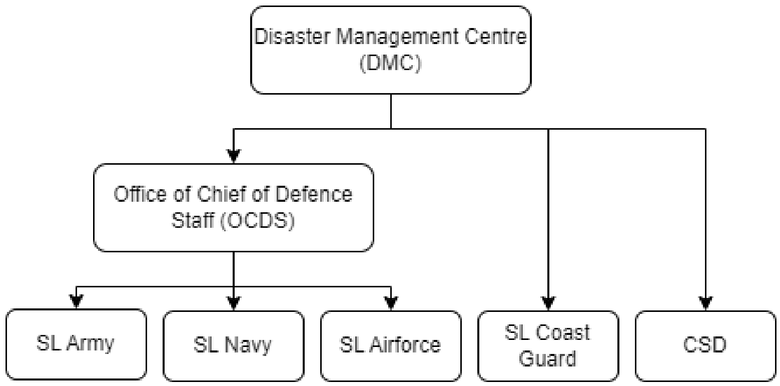


Figure 34: Emergency response coordination with the military forces

The Ministry of Health is responsible for the medical and health aspects of the victims who are affected by disasters. The disaster management unit of the Ministry of Health develops response plans and coordinates response efforts through national, provincial and local health establishments. In the event of a disaster, there may be injuries and casualties due to evacuation, thus needing immediate attention for the affected people before professional medical facilities are available. Such first aid services are provided by trained volunteers or volunteer agencies such as Red Cross, St. John's Ambulance Service or certified first aiders who are eligible to provide such services. The Department of Health, medical teams under the Military, Police and Fire Brigades, and Regional/District/Divisional authorities are responsible for providing medical assistance, including first aid for affected people during a disaster. These services are further assisted by the Sri Lanka Red Cross Society, St. John's Ambulance, and emergency ambulance services based on resource availability.

The divisional authorities manage the safety centres with the support of the National Disaster Relief Services Centre (NDRSC) based on the contingency plans for relief management. Cooked meals and relief materials are provided to the displaced population who are relocated to the designated safe locations. The relief process is coordinated by the relief officer placed in the Divisional Secretariat with overall coordination by the District Disaster Management Coordinating Unit (DDMCU).

Coordinating and managing the humanitarian sector, including the volunteers, is necessary for a successful emergency response. The United Nations (UN) is one of the main actors that has a significant role during a major disaster, with special pre-determined arrangements to support the Government of Sri Lanka. The UN Resident Coordinator is the key official to respond to a disaster upon the request of the government. They conduct coordination procedures among the humanitarian partners in times of disaster. In addition, the UN may activate a cluster system depending on the scale of the disaster with the agreement of the Sri Lankan Government. Simultaneously, many international agencies may trigger their networks to assist the Government of Sri Lanka in managing a large-scale disaster. International agencies and NGOs such as the Red Cross Movement, OXFAM, and Save the Children in Sri Lanka are key humanitarian organisations that activate their assisting mechanisms in response to an international appeal made by the government.

Furthermore, volunteers and resources are registered across the country to provide various volunteer services such as medical, health, and engineering-related activities during emergencies. DMC maintains the Sri Lanka Disaster Response Network (SLDRN), a database hosting the key contacts of volunteers and resources necessary during emergencies.

The National Emergency Operation Plan (NEOP) specifies the responsible organisations that operate at the national, provincial and local levels during emergencies. The list of the agencies and their responsibilities are given in Table 26.

Table 26: Organisations and their responsibilities during the emergencies

Actions	**Responsible Stakeholder Agencies**
General coordination of all activities	• Administrative heads of Provincial, Local Authority, District, Divisional, GN levels • DMC at the National level

Actions	**Responsible Stakeholder Agencies**
Search & Rescue Safety and Security	• Tri -forces, Police and Civil Defence • Fire Service Departments of Local Authorities • Community Volunteer Teams • Fire Service Departments etc. • Non-Government Organisations (NGOs) and International NGOs
Restoration of communication facilities	• Telecom and other telecommunication agencies
Restoration of the power supply	• Ceylon Electricity Board (CEB)
Emergency clearing of roads, repairs and identification of alternative roads, etc.	• Road Development Authority (RDA), Provincial Road Development Authority (PRDA), Local Authorities
Restoration of water supply and distribution systems, Sanitation facilities	• National Water Supply and Drainage Board (NWS and DB) • Local Authorities
Assisting in maintaining law and order;	• Armed Forces, Police, Para-military forces
Temporary shelters, animal shelters, and other welfare facilities	• Armed Services, Police, Para-military forces, Fire Service Departments, NGOs & Community Based Organisations (CBOs), Communities • National Disaster Relief Services Department (NDRSC) • NWS and DB, CEB
First aid, medical aid, disposal of dead bodies, health and sanitation	• Central and Provincial Ministries of Health; Govt. & Private Hospitals; Sri Lanka Red Cross / NGOs, Fire Service Departments; Communities
Relief activities, cooked food, dry rations, etc.	• NDRSC, NGOs, INGOs, CBOs, Communities, etc., Dept. of Social Services if applicable
Rapid needs' assessments	• NDRSC with the support of District authorities and DMC

Actions	**Responsible Stakeholder Agencies**
Disposal of lethal, toxic and adverse chemicals, etc.	• Central Environment Authority (CEA), Police, Military, Atomic Energy Authority (AEA), Fire Service Departments, and other relevant agencies
Provision of International Assistance Relief items International Search Rescue teams	• Ministry of Disaster Management • NDRSC, with the assistance of Airport & Aviation Services, Customs Dept., Dept. of Immigration & Emigration, Ministry of Health, Foreign Affairs, Defense, • Director General DMC

The emergency operation mechanism consists of inter-connected processes between multiple agencies governed by the National Council for Disaster Management as the policy-making body. The Ministry of Disaster Management acts as the central agency for coordination between the Ministerial levels, whilst the DMC implements the overall emergency coordination in collaboration with related agencies from the national to the local level. Figure 35 illustrates the institutional mechanism during an emergency or disaster; this iterates the public administrative mechanism that acts as the backbone of the entire operation with close coordination by the Disaster Management Centre.

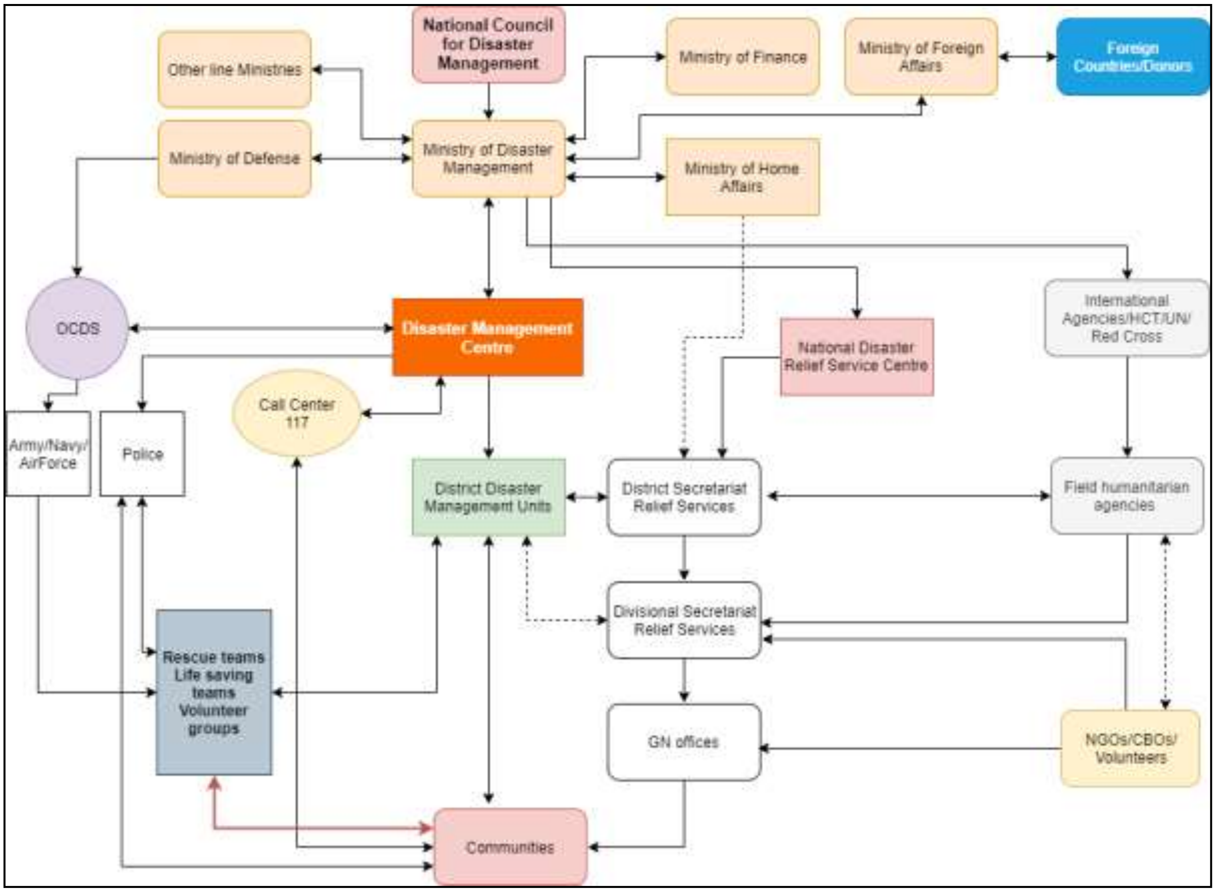


Figure 35: The overall emergency operation mechanism in Sri Lanka

6.12 User Requirements for Response Capacity

The response capacity is the final stage of the warning and response system. This section consists of gathering the user requirements for obtaining actual flood impact, managing capacities, medical response, and relief management.

The actual impacts could be monitored and reported through official and volunteer channels (C1). E2 and E4 suggested that crowdsourced applications would be most useful in capturing the real impact on the ground after a flood event. The crowdsourced interface could display the anticipatory damage versus actual damage for the users to compare pre- and post-scenarios which could be used as a guide to collect field data (G6, G7,E4). This crowdsource information would be tentative and could be published immediately; the authorities may release official reports after validation of the information (E4 and C1). Additionally, satellite and airborne data could provide comprehensive post-event damage reports. Hydrological models with actual gauge data can re-construct the actual flood inundation, allowing authorities to easily estimate the damage from the exposure data (G4). Subsequently, the actual damage information could be used for damage claim purposes (C1).

Once the warning message is issued, some affected people may be evacuated from the site. However, there may be victims who remain in the affected areas where the assistance of rescue teams is necessary (C1). Ambulance and air rescue could be arranged in such a scenario (C1). C1 further elaborated, "Sri Lanka has only 119 to request emergency aid. We need to integrate the emergency rescue management component through a mobile application".

Effective utilisation of resources during the response is essential. Resources are wasted in most of the responses. "Responses are very attractive and are mostly politically motivated, which we have to avoid" (G4). The resources' requirement can be classified as "what", "how", "where" and "when" according to C1. "We have to identify "what" resources are needed, "where" they are located, "when" these resources are required and "how" to utilise them. A mechanism should be available to answer these four questions in relation to the resources" (C1) . The "Sri Lanka Disaster Resources Network" was an approach to coordinate and host the information into a single database, developed with the support from UNDP. However, according to E2, this system is not used by the authorities (E2). Therefore, E2 suggested that a similar system should be established to manage resources.

A centralised relief system is necessary to identify appropriate beneficiaries based on actual impact. This will avoid the current practice of politically motivated selection mechanisms influenced by politicians. E4 suggested that a system similar to SAP would be ideal to cater for this requirement, and E2 emphasised the importance of following international standards for this process. However, G4 and G6 suggested that there is no requirement for an Internally Displaced Persons (IDPs) system in Sri Lanka as the floods last for only a few days, and the victims can cope with such a situation through the assistance of family and friends.

A reduction in the number of victims is a sustainable solution for relief management. Suppose a family is affected by floods on an annual basis. In that case, the authorities should use this information to avoid the impact of the floods by applying DRR measures such as re-location. Therefore, there is a need to identify and establish a database of frequently impacted people who need relief support. The development of a system which can help the authorities to evacuate these families well in advance can avoid last-moment rescue missions and reduce the cost of emergency re-location. (C1).

Table 27 summarises the requirements captured during the interviews for enhancing response capacity.

Table 27: Summary of the User Requirements Captured for the Response Capacity of Flood Warning and Response Systems

User Requirement	**Interviewee**
The actual impact should be monitored and reported through official and volunteer channels.	C1
Crowdsourced applications should be developed to capture the actual impact on the ground after a flood event.	E2, E4
The crowdsourced interface should display the anticipatory damage versus the actual damage for the users to compare pre and post-scenarios.	E4
Hydrological models with actual gauge data should re-construct the actual flood inundation so that authorities can easily estimate the damage.	G4
Citizens should be able to request ambulance and other rescue services through a mobile application.	C1
The actual damage information should be available to be used for damage claim purposes.	C1
The Sri Lanka Disaster Resources Network (SLDRN) should be implemented electronically to coordinate the resources.	E2
A centralised relief system is necessary to identify the appropriate beneficiaries based on actual impact.	E4

There should be a system that can identify and host a database of potentially impacted people who need frequent relief support.	C1

6.13 Chapter Summary

This chapter presented the outcomes of the semi-structured interviews that were conducted, involving experts from key disaster management organisations and individuals representing the community. The face-to-face interviews were recorded, transcribed, analysed and consolidated to identify the current warning process ("as is process"), and the challenges, gaps and issues, as well as identifying a broad range of user requirements that can be used to develop an advanced early warning system to overcome the limitations of the current early warning and response system in Sri Lanka. The next chapter utilises these requirements as a basis for designing a comprehensive early warning and response system.

Chapter 7 Design System Architecture for Flood Waring and Response System

7.1 Introduction

This chapter describes the design of an integrated flood warning and response system that enables the timely decision-making of authorities to ensure the safety of people, properties and businesses. Designing such a system should consider numerous options that satisfy the requirements of beneficiaries and stakeholders. However, such requirements need to be gathered, giving due consideration to the flood warning and response process in detail. A typical flood warning and response system consists of four significant stages: risk identification, data capturing and forecasting, warning dissemination, and response capability. Each stage consists of numerous sub-systems such as data collection, data processing, data warehousing, communication, workflow management, community feedback, etc. Therefore, such a system requires an enterprise architecture design approach to fulfil user requirements and meet the system's complexity. The following chapter provides a step-by-step approach for a system architecture design based on multiple views and a multi-layered approach derived from the primary and secondary data collections.

7.2 Conceptual Architecture Design

Based on the theoretical approach of the system architectural frameworks, system views and layered concepts, the conceptual architecture of the FEWRS is discussed in this section. Since the proposed system is complex and consists of several independent and loosely coupled systems of systems (SoS), a view approach is used to capture numerous attributes from different perspectives. The conceptual design of the system architecture for the flood warning and response system is based on the following views: the process view that captures the flood warning and response process; the stakeholder view that captures the roles and responsibilities of each stakeholder; the scenario view that considers each possible scenario that can happen in the flood warning and response process; the information view that captures the data and information required for the entire flood warning and response process; the interface view that provides user interaction in each module; a technology view which captures the technology used, and the system view that captures the system components of the FEWRS (Figure 36). These views reflect the enterprise architecture of the proposed flood warning and response system. Details on these views are discussed in the subsequent sections below.

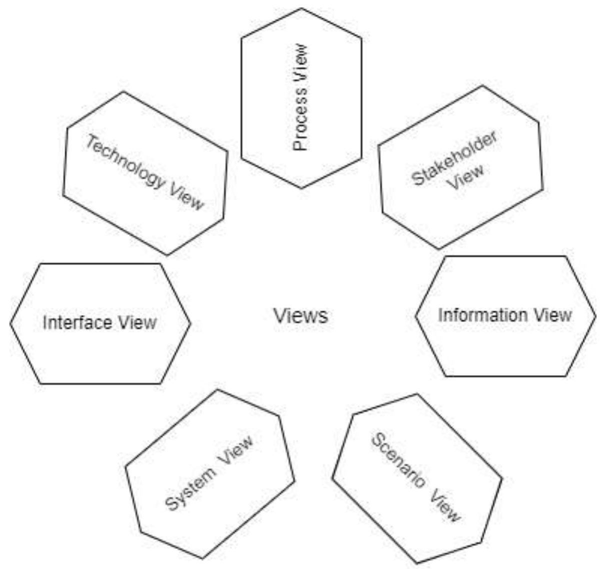


Figure 36: Proposed conceptual views of the system

7.2.1 Process View

The process view describes the process of the end-to-end flood early warning and response system. The process view has been designed with a “to-be” process model in order to overcome the limitations of the current “as-is” process model.

According to the UNDRR terminology (UN, 2006; UNDRR & WMO, 2022), the EW process is broadly categorised into four stages: risk knowledge, monitoring and warning service, dissemination and communication, and response capability, whereby key processes have been identified and related to these stages. The structured review, as discussed in Chapter 4, provided an overview of the “flooding process”, a combination of a series of natural phenomena of rainfall, increased river water flow, and inundation due to excessive water discharge (Figure 37). This process also comprises a series of activities: observation of rainfall and river flow, forecasting river water level and inundation, impact assessment, warning generation, dissemination of warning messages to stakeholders and response actions to safeguard people and properties. The process diagram, derived from the literature review, as illustrated in Figure 37, was used as a basis to construct the process view of the proposed design. The warning process was further localised with the Sri Lankan flood early warning and response context by accumulating primary and secondary data sources.

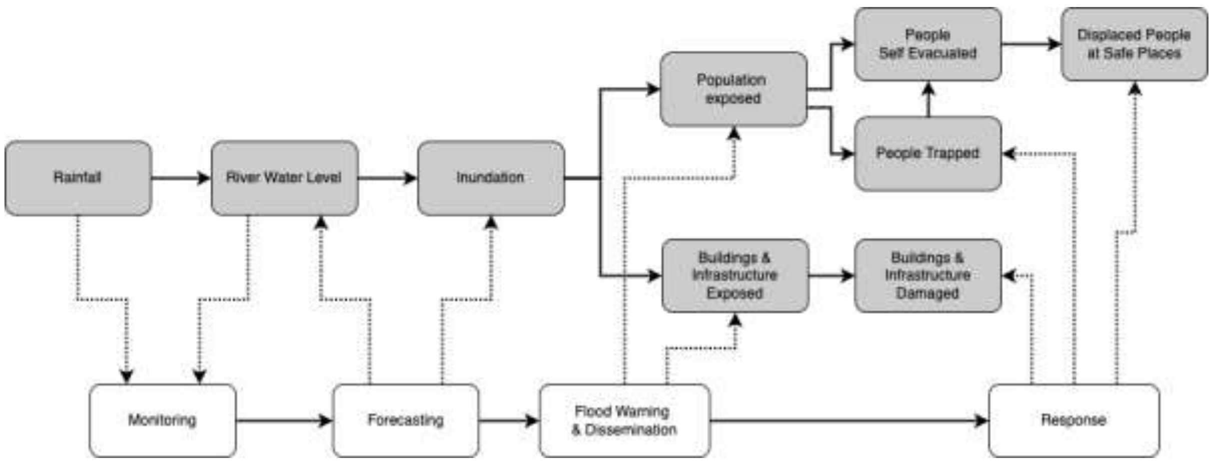


Figure 37: Process view of the Flood Early Warning and Response according to the literature review

Figure 38 illustrates a summarised version of the "as is process model" of the end-to-end flood warning and response process in Sri Lanka that has been captured from primary and secondary data sources. The "as-is" process model provides a current view of the early warning and response process (Lodhi et al., 2010), which is essential to building a "to-be" process (Okrent & Vokurka, 2004).

According to the "as-is" process, as illustrated in Figure 37, a typical warning is triggered by a short-range weather prediction, typically three days before, issued by the national meteorological agency, the Meteorological Department. The Meteorology Department produces weather forecasts from meteorological observation and with the assistance of numerical weather predictions. The Meteorology Department currently employs the European Centre for Medium-Range Weather Forecast (ECMWF), a popular Numerical Weather Prediction (NWP) model, for weather forecasting. With the initial alert from the Meteorological Department, depending on the scale of the potential events, the national hydrological agency (Department of Irrigation) decides whether to activate the emergency operation centre. Depending on the severity of the event, the Irrigation Department continuously monitors the rain and river gauge levels of the targeted river basins to detect abnormal increments in the precipitation and river water levels. Most river gauges in the country are manually operated, whereby river water levels are observed and the information sent to the head office via electronic means. Automated gauge stations are installed in several locations to receive live data digitally, which complements the manual gauge observation and reporting process.

The forecasting process involves a critical analysis of several parameters, including weather forecasts, current and past river and rain gauge data, hydrographs, boundary conditions, and past inundation information. Frequency analysis and hydrological simulations are used to understand the possible future scenarios. The combination of these parameters, together with the tacit knowledge of the hydrologist, is combined to generate flood forecasts and issue warnings over targeted river basins. The warning message is then delivered to the Disaster Management Centre (DMC), the national disaster management authority, for further evaluation and to take necessary action. During this process, the content of the message is further evaluated on its threat level based on the potential impact of the event, and formal warnings are disseminated to the respective district/divisional secretaries, relevant ministries, departments, response agencies, and the community. Depending on the intensity and arrival time of the floods, the warning message is colour-coded with yellow, amber and red levels with instructions.

DMC uses pre-formulated preparedness plans at national, district and local levels to ensure proper coordination and functionality of the response mechanisms at each level. Numerous stakeholders, including government, non-government, private sector and the local community, are identified and assigned clear duties and responsibilities prior to the event. Each stakeholder is given clear roles and responsibilities to perform pre-identified duties before, during and after emergencies, and these plans are updated and tested periodically.

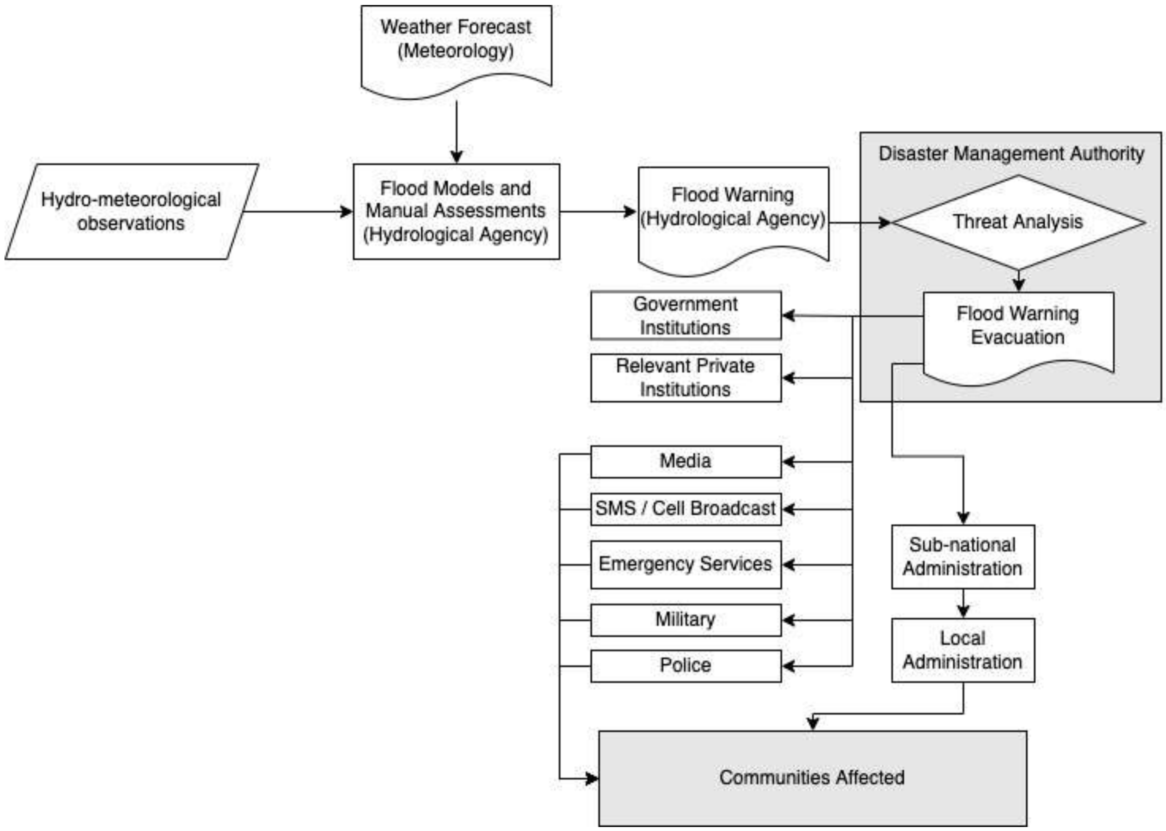


Figure 38: The detailed end-to-end flood warning and response process in Sri Lanka

The "as is" warning process presents the key tasks of the current flood warning and response process that is distributed among numerous stakeholder organisations and is executed as stand-alone processes as follows: meteorological monitoring and forecasting by the Department of Meteorology; flood monitoring, warning and forecasting by the Irrigation Department; warning dissemination and response coordination by the Disaster Management Centre, and response activities by health authorities, the military, police, and provincial, district and divisional level administrative authorities. It can also be observed that each organisation has its own methods, procedures and practices. However, poor inter-organisational collaboration, inefficient workflows, and poor data/information sharing challenge the warning and response process. Therefore, the researcher has observed that the current inefficient processes adversely influence the warning process, resulting in many significant delays. For example, some agencies only share printed data, and the recipient again digitises the data for analysis and value addition. Inter-agency data and information sharing are primarily based on non-digital means such as faxes and emails with attachments that are non-machine readable and need extra human interactions to process such information. Most of the approval procedures involve conventional paper-based letters. Therefore, the workflow consists of inefficient and ineffective agency-specific information capturing, processing and data-sharing standards.

On the other hand, communities receive generalised weather and flood forecast advisories targeting broad geographic areas with poor temporal information. Due to the inaccurate temporal and spatial probabilities disseminated through bulletins, the users cannot accurately determine the geographic regions at risk and flood arrival times (FAT).

The user interviews suggested "to-be" processes to overcome many of these issues concerning the flood warning and response process. The following suggestions have been proposed in building the "to-be" process by the interviewees as presented in Chapter 6:

1. The individual processes performed by each organisation should be properly coordinated and coupled to act as a unified single process among multiple agencies while removing duplications.
2. The relevant data should be collected and consumed across the warning and response process by all the agencies. This data should be updated regularly to build confidence in data accuracy.
3. An interoperability framework should be established to integrate data and process workflows among multiple agencies.

The "to-be" process has been designed to incorporate these suggestions and to overcome the inefficiencies in the "as-is" process. The "to-be" process has been divided into four key processes reflecting the principle of an early warning system defined by UNISDR: (i) risk identification (ii) monitoring, forecasting and warning (iii) warning dissemination and communication, and (iv) response capacities. Figure 39 to Figure 42 below present these four core processes and discuss them in detail. These process diagrams follow the standard format of presenting business processes using context diagrams.

Core Process 01 – Flood Risk Knowledge Generation and Visualisation

The purpose of this core process, "flood hazard and risk knowledge generation and visualisation" is to collect, analyse, store, retrieve and visualise the hazard, exposure and risk information of a given river basin. Here, four sub-processes can be introduced to achieve the key objectives of the core process (Figure 39). Acquisition of hazard data, acquisition of exposure data, exposure and risk analysis, and visualisation of the processed information is proposed to be implemented in these sub-processes, as presented in the Figure.

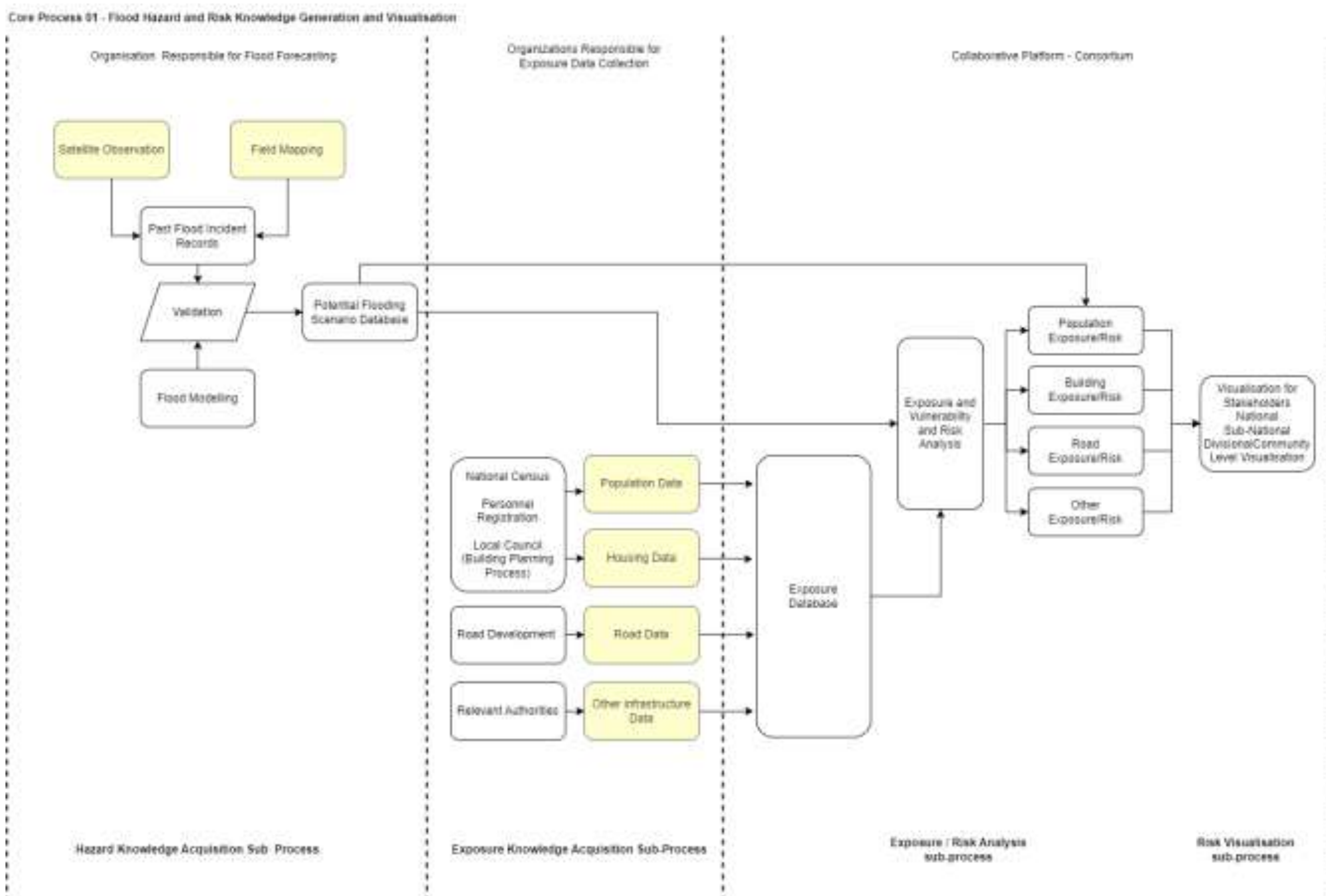


Figure 39: Flood hazard and risk knowledge generation and visualisation co-process

1. Hazard knowledge acquisition sub-process

   The Irrigation Department (ID) is responsible for the collection of past flood occurrence data through field surveys and remote sensing sources such as satellites and airborne mappings. In addition, ID also generates probabilistic flood hazard maps by numerical modelling using hydrodynamic models. The historical flood occurrence data collected from the field is utilised to validate and calibrate the outputs of numerical models. The empirical data suggests that a "potential flooding scenario database" is a useful module that captures possible flooding scenarios modelled and validated for risk understanding and forecasting purposes.

2. Exposure knowledge acquisition sub-process

   Exposure data is obtained from numerous sources. Population information comes from the Census and Statistics Department, road data from the Road Development Authority, and other exposure data such as land use and agriculture are obtained from the respective authorities. Building data is typically obtained from the Survey Department. It is proposed to set up a unique addressing system to identify residential, private and public properties.

3. Exposure risk/analysis sub-process

   In this sub-process, population, building, land use, utility and other exposure elements are overlaid with the flood hazard to identify the elements exposed by floods. The risk analysis will facilitate identifying potential damage to the exposed elements. According to the primary data, a few experts suggested including a " exposure database" that hosts all the exposure data for risk analysis. The need for a national policy framework for the agencies with mandates to collect, process and share these exposure data, and data standardisation for seamless integration, was identified during the primary data collection in order to facilitate the above database.

4. Risk visualisation sub-process

   This sub-process allows decision-makers to query, visualise, and generate reports of the potential flood zone and the exposed elements through pre-determined boundaries. The boundaries are either administrative, river basin or user-defined geographical areas. The users suggest these visualisations should be in the form of maps, pictures or be text-based and should visualise hazards, exposed elements, areas or people that need an urgent response.

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Core Process 02 – Monitoring Forecasting and Warning

The whole idea of the core process 02 is to generate flood forecasts and issue impact-based flood warnings from weather forecasts and hydrological modelling. The core process, therefore, consists of 3 sub-processes, as illustrated in Figure 40:

1. Hydro-meteorological sub-process

   In this sub-process, automated gauge stations collect and transmit rainfall, river flow and river water level data to the weather and flood forecasting sub-processes (sub-processes 2 and 3 indicated below). In the areas where there is an absence of automated gauge stations, alternative methods are proposed to obtain data from crowdsourcing and satellite remote sensing methods. The crowdsourced gauging network can be considered as a collection of low-cost automatic gauges operated by a group of volunteers, based on pre-defined guiding principles. The relevant authorities will define the standards of the sensor stations offered by the volunteers to provide trustworthy data. The data collected in this process will be available through "the national hydro-meteorological platform", a standard open data platform to host different types of hydro-meteorological gauge data as suggested during the user requirement phase.

2. Weather forecast and warning sub-process

   This sub-process delivers medium and short-range weather forecasts and now-casts, as suggested in the primary data collection, and it notifies of bad weather conditions by sending yellow, amber and red alerts. The Meteorological Department is responsible for this sub-process, and key recipients would be the Irrigation Department, the Disaster Management Centre, other stakeholder organisations, the media and the general public.

3. Flood forecasting and warning sub-process

This sub-process delivers up to 7-day flood forecasting and impact-based warnings. It directly depends on the two sub-processes of "meteorological monitoring" and "weather forecast and warning" as mentioned above. An upcoming bad weather condition may trigger this process and issue a provisional flood forecast for up to 7 days and a more realistic 3-day flood forecast using numerical flood modelling techniques. It can also deliver now-casting from real-time radar observations, as suggested in the primary data collection. The process consumes gauge data and meteorological ensemble data generated by two other sub-processes. The output flood forecast is then transformed into an impact-based warning through impact analysis.

An impact-based forecast is a type of weather or disaster forecast that focuses on communicating the potential impacts of a weather event or natural disaster rather than just providing a warning in scientific terms. The purpose is to convey the possible consequences in the form of potential damage to life or properties. This approach is often used to improve public understanding and response to weather-related hazards and is suggested and advocated for by various meteorological and emergency management agencies worldwide. The user requirement suggested that the "national exposure database" be used to transform flood warnings into more meaningful impact warnings.

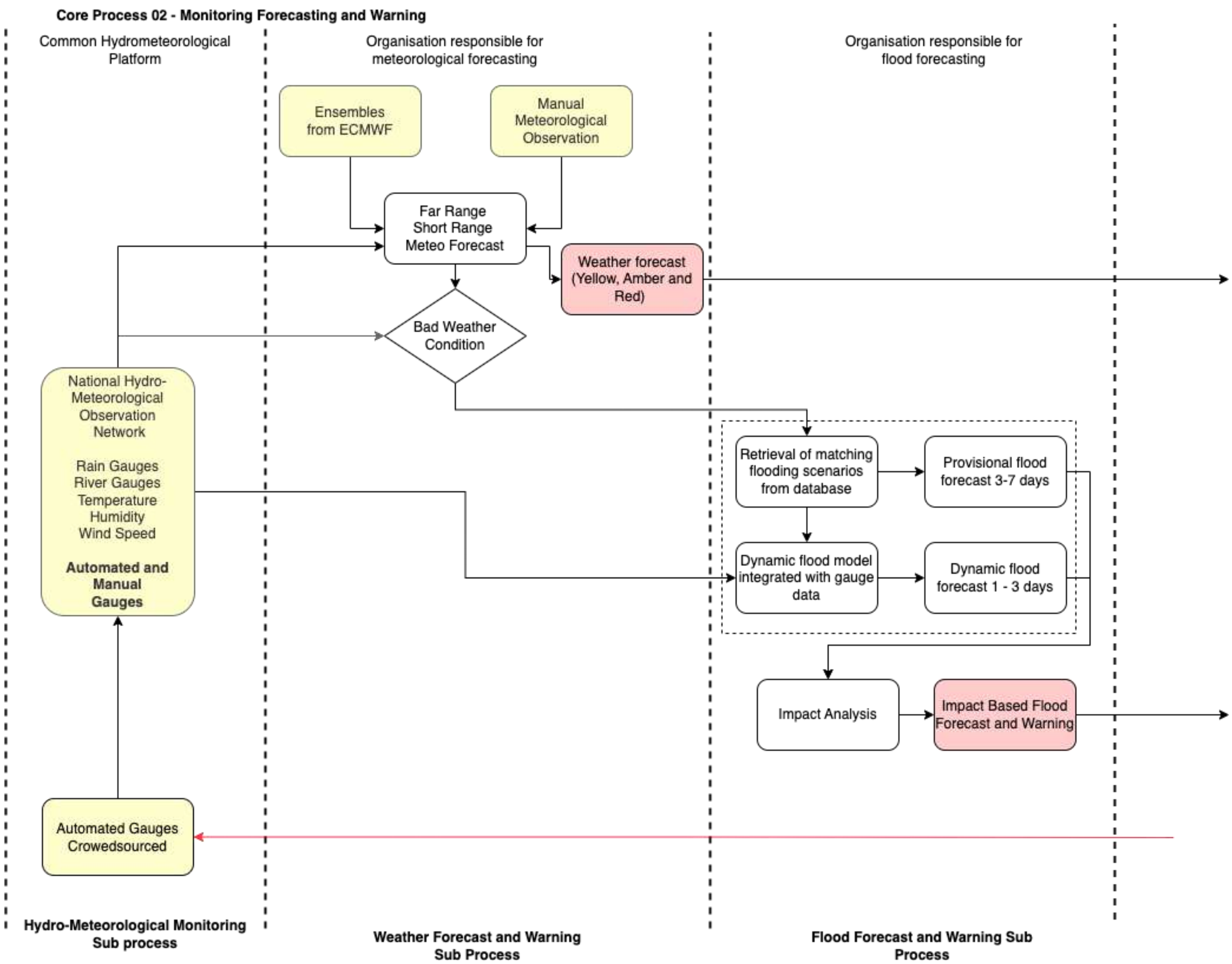


Figure 40: Monitoring forecasting and warning core process

Core Process 03 – Communication and Dissemination

The third core process in the early warning and response system, "communication and dissemination," facilitates the dissemination of the warning message to multiple parties, from various stakeholders, media agencies and the general public. This process is divided into two sub-processes: "warning encoding" and "warning broadcasting" (Figure 41). The "warning encoding" sub-process is a primary role of the Disaster Management Centre which ensures the message formats and dissemination process adhere to the Common Alert Protocol (CAP), a standard dissemination technique used in emergencies. The warning message will then be transformed and customised to the end user's requirements and socio-economical conditions.

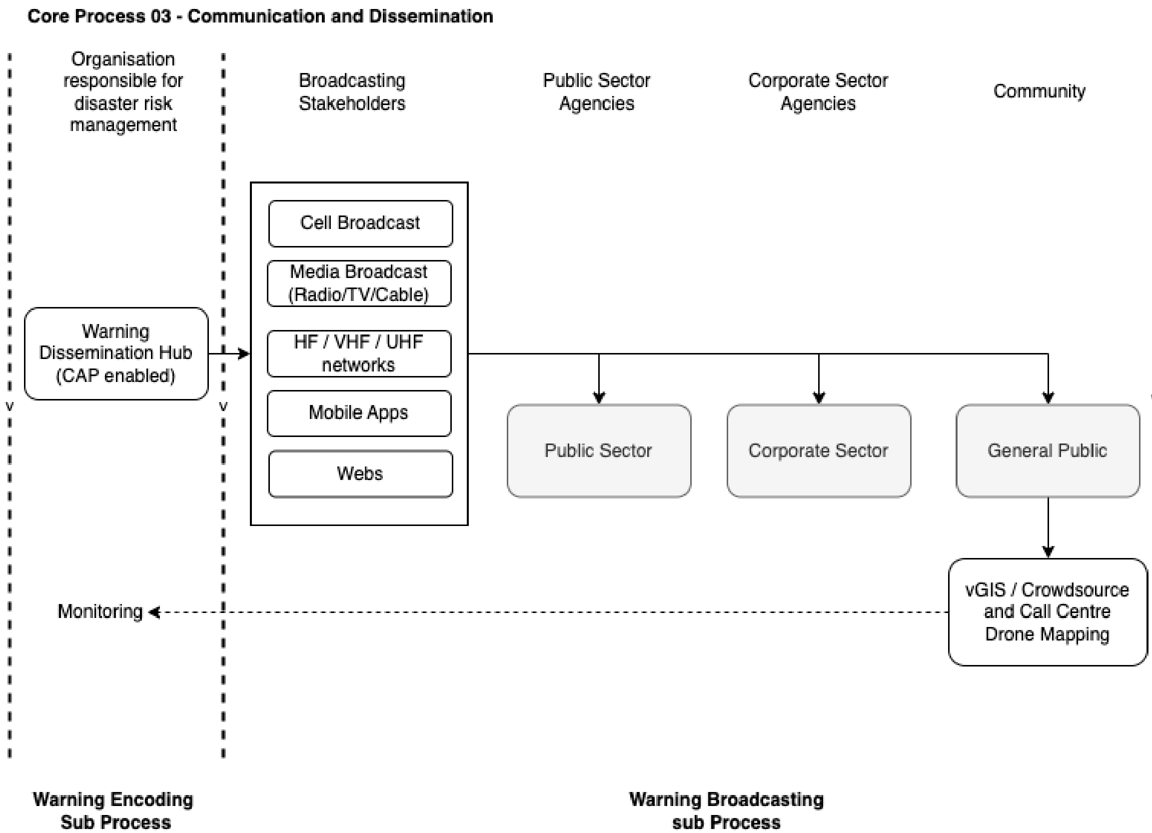


Figure 41: Warning dissemination and communication core-process

The "warning broadcasting" sub-process involves multiple stakeholders in disseminating the warning message. Public and private broadcasting agencies typically disseminate the message to the grassroots level using popular media forms such as TV and radio. Telecommunication Service Providers (TSP) companies also facilitate the dissemination of the message via cell broadcast and SMS services. DMC will establish dedicated communication links with key strategic response partners such as the police, the military and ambulance services. These links could be via Very High Frequency (VHF), microwave radio and general telephone links. Additionally, DMC also sends the warning message to other public sector organisations (tourism, transport, utility) and private sector organisations (hotels, business entities etc.). The government should facilitate a feedback mechanism to capture information from the public during disaster situations through crowdsource techniques. The crowdsource apps and social media responses from multiple partners could be captured and processed to analyse situational intelligence from the public. Many participants in the primary data collection suggested the need for a mobile application.

Core Process 04 – Response Capacities

The core process, "Response Capacities," is the final stage of the flood warning and response process, and it facilitates the coordination of response activities from the national to the local level.   The process consists of four sub-processes, as illustrated in (**Error! Reference source not found.**.

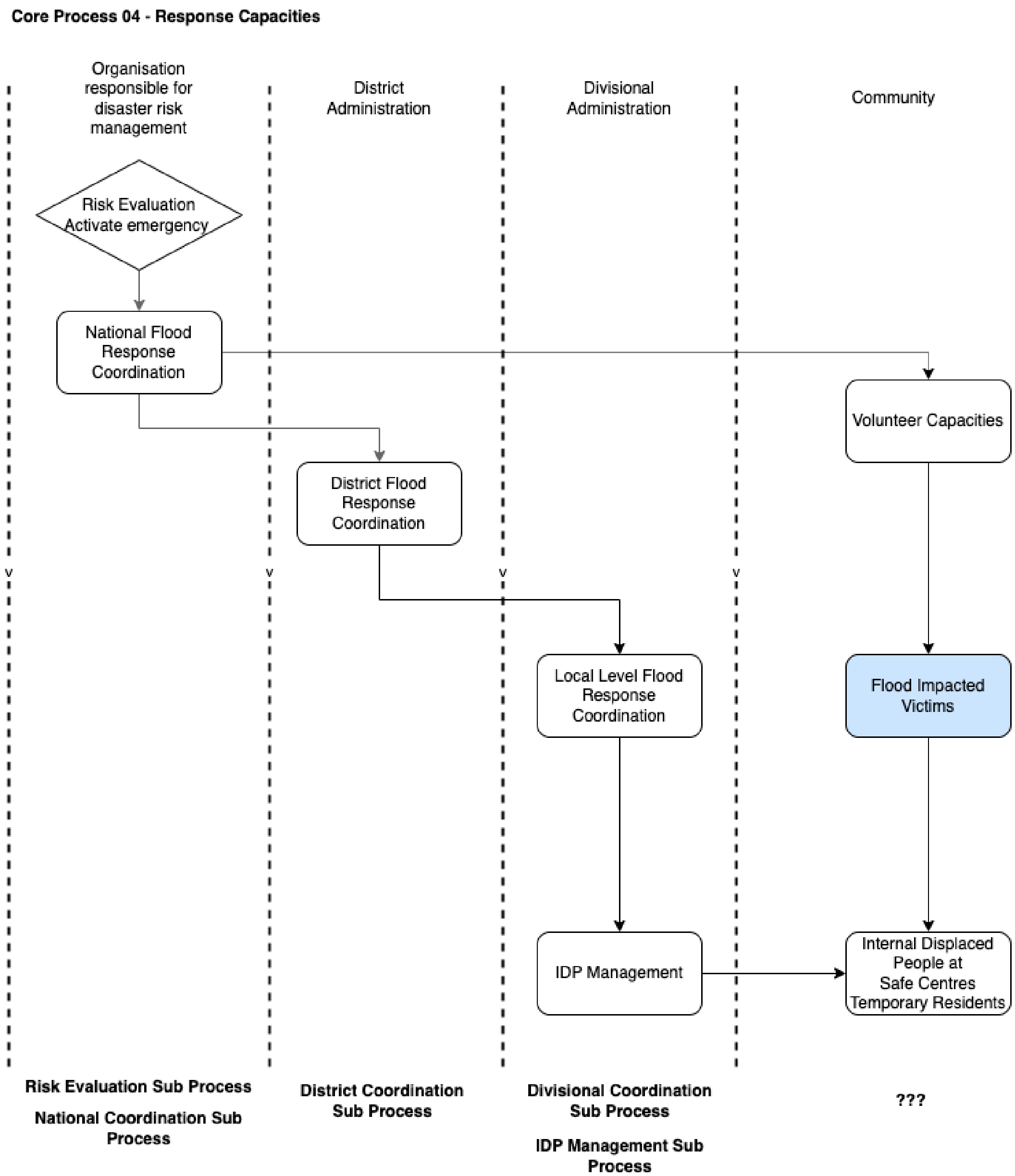


Figure 42: Response capacities' core-process

As the national coordination body for disaster management, the DMC evaluates the possible risk level and activates an emergency state in a given geographical zone or in the entire country. It will activate respective district and divisional coordination mechanisms for emergency response services which have been defined in the emergency response plans. Further, DMC also activates other national response arms such as the police, the military, ambulance and medical services through their institutions. At the local level, the affected communities are relocated to safe centres for a short period where their relief, safety and healthcare can be managed. Individual volunteers are placed to support ongoing rescue, medical and relief operations. The entire process consists of multi-party engagement from the national, district, divisional and local levels. The response is a series of multiple systems that need further study to visualise the processes in detail. Therefore, in this study, these processes are kept at the abstract level to limit their complexities.

7.2.2 Stakeholder View

The stakeholder view describes the types of stakeholders and their roles and responsibilities involved in each stage of the FEWRS. The flood early warning and response is a process with multi-stakeholder partnership; typically, such responsibilities are shared among multiple institutions. Therefore, inter-institutional coordination, collaboration, and communication are essential in the flood warning and response process, including in the monitoring, forecasting, warning and response stages.

Typically, the responsibilities for monitoring, forecasting, and warning generations are vested in hydro-meteorological institutions, while disaster management authorities are vested with warning dissemination and response coordination. Further, the response is again via multi-agency collaboration, where numerous organisations are responsible for certain activities. For example, rescue operations are led by fire agencies and the military, while the police ensure the civil protection of the affected area and the affected people. Moreover, health services provide emergency medical services for severely affected people and manage dead bodies. Local authorities and administrative bodies are responsible for all kinds of civil services for the affected population during disastrous situations.

Table 28 below describes the roles and responsibilities of each organisation based on the flood warning and response process defined in the Disaster Management Act, the National Disaster

Management Plan, and the National Emergency Operation Plan and data collected from the primary data collection.

Table 28: A summary of stakeholder responsibilities within the FEWRS

Role	**Institution**	**Responsibility**
Monitoring	Irrigation Department	Measure hydro-climatic parameters
Flood Forecasting	Irrigation Department	Flood forecasting
Flood Warning	Irrigation Department	Issue early warnings
Warning Dissemination	Disaster Management Centre	Warning dissemination/coordination national-level stakeholders, media and public
	District Secretariats	Warning dissemination at the district level
	Media	Warning dissemination among the public
	Police Department	Warning dissemination among the public
Response	Disaster Management Centre	Response Coordination at the national level
	District Secretariats	Response Coordination at the district level
	Disaster Relief Services Centre	Provide relief support
	Police Department	Rescue and relief
	Health Department	Emergency medical assistance (Varvasovszky & Brugha, 2000)
	Military	Rescue and relief

The influence-interest matrix (Varvasovszky & Brugha, 2000) is a popular tool used in stakeholder analysis (Figure 43) in which stakeholders are classified based on their relative importance and influence in a two-dimensional cartesian matrix. The flood warning and response process consists of numerous stakeholders; therefore, such an analysis provides insight into their engagement. Stakeholders are classified based on their location in the matrix. Key players are the stakeholders with high interest and high influence who actively engage in the flood warning and response process. The secondary data collection suggests that most stakeholders fall into this category.

The primary data suggests that local authorities and the private sector are two key groups classified into the “monitor” category as they indicate less influence and less interest. The potentially affected community is a key stakeholder classified into the “inform stakeholders” with less influential power but high interest. In general, the key users of the warning and response systems come under this category, including the media and telecommunication providers.

The final category is those who are in high influential power with less interest, also called “satisfy stakeholders”. None of the stakeholders have fallen into this group.

Even though the influence-interest matrix is a useful tool, it is important to note that the interest and influence of stakeholders may change over time. Therefore, the impact of such changes should be considered in developing flood warning and response systems.

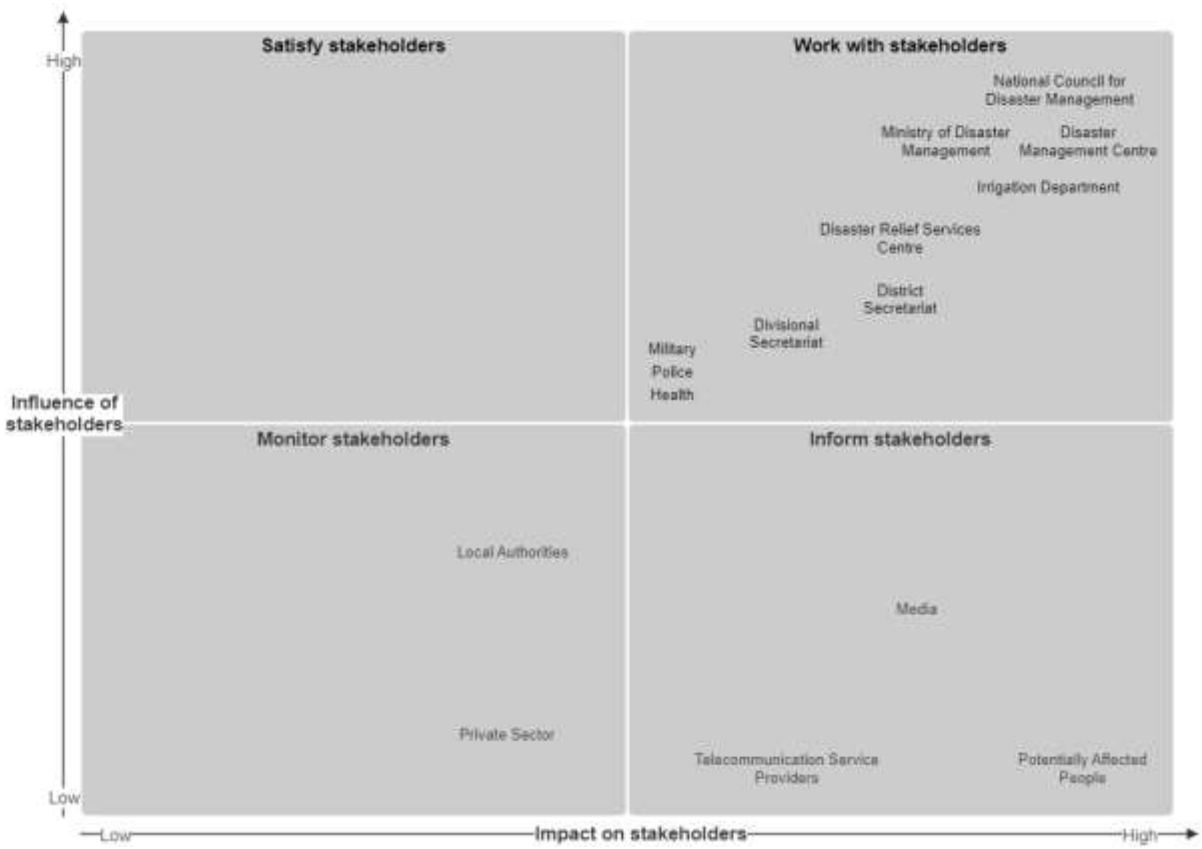


Figure 43: Stakeholder analysis of the participating organisations and other stakeholders in FEWRS

7.2.3 Scenario View

The scenario view captures the numerous scenarios used in the FEWRS. It has a close link with the process view, as each type of scenario is a unique sub-process. The scenario is governed by the magnitude of the floods, which positively correlates with the severity of the impact on people and properties. According to the United States Geological Survey (USGS) two critical factors affect flooding: rainfall intensity and rainfall duration. Intended rainfall in a short period of time can cause a significant flood. This research does not consider other sources of flash floods, such as dam breaches and coastal floods. Hydrologists typically measure water level, discharge and velocity as key parameters to calculate the severity of the floods. Evaluation of these parameters and upstream rainfall levels reveals forthcoming floodwater levels in the downstream area.

Hydrologists usually classify the severity of floods based on the flood height of a given location. Flood hazard assessment is typically carried out by using analysis of the exceedance probability of potential floods (Grünthal et al., 2006). Typically, the flood magnitude is inversely related to the frequency. Therefore, the objective of the flood frequency analysis is to correlate the magnitude of extreme flood events to their frequencies using probability distributions (Westen & Montoya, 2011). Typically, flood magnitude is indicated by the flood water level. For example, in the Sri Lankan context, flood magnitude is classified based on the water levels for each gauge station as follows: minor, major, dangerous, and critical (Table 29). Each magnitude level refers to different scenarios, as the potential impact on people, houses, roads, utilities, and other infrastructures could be different. An increment in magnitude level could increase the flood inundation area; hence, the exposure of people and properties could increase gradually.

Table 29: Classification of flood magnitude level based on water level, Nagalagam Street Station, Kelani River Basin

Water Level (in feet)	**Nature of Floods**
5 – 7	Minor
7 – 9	Major
9 – 12	Dangerous

12 and above	Critical

Therefore, each magnitude level creates different scenarios that need different levels of response approaches (Figure 44). Each scenario constitutes the following attributes which are governed by the flood frequency and magnitude: inundation area, affected elements such as people, houses, roads, infrastructure etc. In this context, the level of the response, such as warning type, stakeholder participation, response strategies, response capacities, and response time, could be different for each scenario. Therefore, the scenario view provides a key role in defining the system architecture.

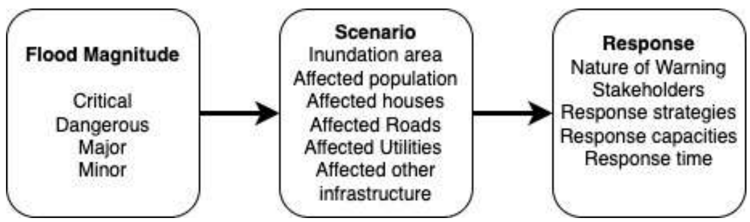


Figure 44: The scenario view provides information on the potential impact on people and infrastructure

7.2.4 Information View

The data, information and intelligence are from multi-source and in multi-form; these are managed in a collaborative process to achieve the system objectives. The information view provides a definition of the data, information and intelligence captured, processed, and consumed in the FEWRS. The data and information view is arguably the most comprehensive view in the enterprise architecture. According to the DIKIW framework (Liew, 2013), raw data is captured and transformed into multiple stages of information, knowledge, intelligence and wisdom by adding value in each stage. The raw data is processed and transformed into information and situational intelligence that is useful for understanding the disaster situation and assisting in the decision-making process.

The data and information used in the flood warning and response process can be generally classified into two principal groups: (i) static data (ii) dynamic data.

Static Data and Information

Static data is relatively unchanged for a period of time and is useful for the decision-making process in the flood warning and response phase. This information provides potential flood inundation zones, past records of inundations, and the risk to the people and other infrastructure. The main categories of static data used in flood warning and response systems are hazard information (historical and simulated), exposure data, risk information, administrative boundaries, response capacities and facilities, as listed below:

1. **Hazard Information:** This category includes historical flood inundation data and numerical model results for various return periods. Historical data provides insights into past flood events, including their proximity to specific areas and the height of inundation. Numerical flood models offer simulations of potential future flood scenarios. Both types of data are unchanging over time and are essential for understanding the potential impacts of floods.

2. **Exposure Data:** Exposure data encompasses information related to both living (people) and non-living (assets, infrastructure) entities that may be affected by a disaster. This data includes details on population, housing, utilities, infrastructure, points of interest, and land use. It helps assess the risk and potential impact of floods and other disasters on a specific area.

3. **Risk Information:** This category includes risk indexes, potential damage to people, houses, and infrastructure, as well as historical damage information. Such data is invaluable for response planning and determining the areas and assets at the highest risk during a flood event.

4. **Administrative Boundaries:** Administrative boundaries remain fixed over time and are essential for organising and managing disaster response efforts. They help aggregate situational intelligence into specific administrative zones, enabling better coordination and governance during a crisis.

5. **Other Data on Response Capacities:** This includes information on evacuation locations, evacuation routes, and various other capacities that are relatively static. These details aid in

improving response coordination and ensuring that resources are allocated effectively during flood emergencies.

Dynamic Data and Information

Dynamic data capture rapid changes in the environment; this information is processed and integrated with other data sources to allow for the making of situational decisions. Most of the hydro-meteorologic data, captured by IoTs and manual methods, are the main source of the dynamic data used in FEWRS. Such data include rainfall data, river flow data, and river water levels captured by hydrologists to forecast floods. Flood inundations, captured by airborne and satellite sensors, are also used to determine how the floods spread over time and space during an event. Social media and crowdsourcing platforms are other alternative methods used to report incidents on a near real real-time basis by the citizens. In addition, call detail records (CDR), a technique to identify unknown mobile users by triangulating mobile towers, is used to track affected people in a disaster situation.

As discussed in Chapter 4, combining numerous dynamic and static data with numerical modelling, AI techniques, and geospatial analysis can generate a predictive forecast. Table 30 provides the data used in each stage of a typical FEWRS.

Table 30: Relationship of the data sets with the stages of the EW process

Stage of EW	Data / Information / Intelligence	Nature of Data Source
Risk knowledge	Historical flood inundation Flood hazard (modelled output) Population densities Building data Road data Utility data Land use data Flood risk (potential damage) Archived hydro-climatic data	Static sources

Monitoring Forecasting and Warning	Current rainfall Current river flow Current river water level Meteorological ensembles Crowdsource data on water level and inundation	Dynamic sources
Warning Dissemination	Potentially impacted upon residents Potentially impacted upon business entities Vehicles Potentially impacted upon critical lifelines and utilities such as healthcare services, schools, roads, energy and other infrastructure	Dynamic and static sources
Response	CDR Data Crowdsource data upon the impact Camp location Response stakeholders	Dynamic and static sources

A riverine flood is triggered by excessive rainfall accumulation that causes water to flow over riverbanks and submerge downstream areas. Such floods will encounter the built environment, affecting people, properties, various infrastructures and services. As indicated in Figure 37, numerous tools and technology could capture each stage of the flooding process by sensors picking up various data and transforming it into valuable information and situational intelligence that is useful in decision-making.

7.2.5 Technology View

The technology view consolidates all the tools and technology used in the proposed enterprise architecture. The tools and technology used in the proposed system can be classified into three main categories i.e., (i) data capturing (ii) data analysis, and (iii) dissemination, which are employed in all four phases of the FEWRS. Table 31 provides a general overview of the tools and technologies that are required to build the enterprise architecture of the FEWRS.

Table 31: List of tools and technologies required to build FEWRS

Tools and Technology	Purpose	Phase
IoT	Measure rainfall, water levels and other hydro-meteorological variables	Monitoring
Crowdsource & Social Media	Incident reporting (flood) Model validation	Monitoring Response
Satellite / Airborne Sensors	Flood inundation mapping	Response
GIS Analysis	Exposure analysis	Forecast and Warning
Hydrological Simulations	Flood forecasting	Forecast and Warning
Call Detail Records	Identify affected people	Response
Information Systems	Camp management Resource management	Response
Cell broadcast / mobile Apps	Dissemination	Dissemination

Internet of Things (IoT) – The role of sensors is to monitor the hydro-meteorological parameters continuously and facilitate the detection of floods. IoT captures rainfall, river flow, river water level, and other hydro-meteorological parameters via installations in remote locations and transmits the readings in real-time to the observation centres.

Crowdsource / Social Media – Crowdsourcing is a community engagement technique used by the community to report incidents in real time. Crowdsource systems are designed to capture pre-determined textual information, images and positional information to report incidents. Various open-source and proprietary crowdsource platforms are available for disaster reporting and crisis mapping. Furthermore, social media platforms such as Twitter and Facebook are two other popular platforms used to report incidents.

Crowdsourcing is proposed to capture flood inundation and water heights and assist post-flood impact assessments in the FEWRS system.

Satellite / Airborne Sensing – Remote sensing systems are able to capture information from wider areas with multiple return periods during flood inundations. Airborne platforms provide higher flexibility with less area coverage, whereas satellite platforms can cover wider coverage with optical and radar sensing technologies. The proposed Enterprise Architecture (EA) of FEWRS should acquire real-time to near real-time imageries to monitor and map the flood inundation and, thus, map the impact area.

Hydrological Simulations – Numerous hydrological simulation techniques are used for flood forecasting. Various open-source and proprietary software systems can simulate floods in 1-D and 2-D forms. Machine learning (ML) techniques have shown remarkable potential in flood forecasting in recent years. Therefore, a 3D hydrological simulation service that utilises AI / ML techniques is suggested in the proposed system.

Call Detail Records (CDR) – CDR contains information such as call/message delivery time and utilises an associated mobile tower, which allows mobile providers to determine the approximate locations of the mobile user. This technology is useful in a time of disaster to determine the movement of the exposed population at a low cost. Therefore, the proposed system will have a facility to receive and analyse CDR data to identify population dynamics.

Information Systems – Various information management and database systems are used to collect, process and assist in making decisions in an emergency response. For example, camp management systems assist in managing displaced people, whereas resource management systems host and manage the human and physical resources required in an emergency response.

Cell Broadcast / Mobile Apps – In an emergency warning, cell broadcast is used to disseminate messages to the users in a particular area of interest. The proposed system should employ a cell broadcast facility to disseminate messages to the public.

7.2.6 User Interface View

The users of FEWRS consist of multiple stakeholders with numerous roles. Therefore, the user interface should be designed based on the roles and responsibilities of the users (individuals and institutions) involved in the FEWRS. Each interface view will be unique to the user roles and their level of engagement. For example, organisations that generate early warnings will be authorised to engage in the functionalities of hazard monitoring, simulation and warning generation, whereas disaster management institutions will be allowed access to exposure analysis and dissemination functionalities. The user roles and responsibilities are defined based on the institutional, legal and social aspects of the early warning and response process. Therefore, the process view and the stakeholder view are used to define the nature of the user interface view.

The proposed user interface development will consider the following facts.

1. User interfaces should be specific for participating organisations, their roles and responsibilities.
2. User interfaces should be able to be customisable within the scope of the organisation.
3. The user interface should reflect the workflow of the flood warning and response process.
4. It should not lead to duplication among the roles and responsibilities of the organisations.
5. The user interface should be simple enough to learn and perform work easily.

Table 32 presents participating organisations' generic roles and responsibilities in each stage of a typical flood warning and response process as acquired from the primary data. However, the nature of an institution, its roles and responsibilities vary with the country's governing mechanisms and disaster risk management approach. A country-specific analysis is recommended for the detailed design of the user interfaces.

Table 32: Roles and responsibilities of organisations – A generic approach

Stage of Warning and Response	**Key User Role(s)**	**Potential User(s)**
Risk Knowledge	Risk information management	Technical agencies producing and updating risk information
Monitoring and Warning	Sensor management Sensor monitoring	The technical agency responsible for flood warning

	Food forecasting Warning generation	
Warning Dissemination	Warning evaluation Impact assessment Warning dissemination Declaration of evacuation	Disaster management authority
Response	User reporting Rescue coordination Medical assistance Camp management Relief distribution	Local government Police, Fire and Military Health authorities

7.3 System View

The System of Systems (SoS) is an inter-connected and inter-operating collection of systems that produces results that cannot be achieved by an individual system alone [(Arru et al., 2020; Chandana & Leung, 2010). FEWRS is, similarly, a collection of multiple systems established across all stages of the warning and response process to meet the business requirements of eac stage. The rapid growth of complexities and continuously changing requirements make the use of traditional design principles more challenging and complex. Therefore, this study employed an architectural development framework to overcome these issues.

The system view effectively demonstrates the integration of all the sub-systems and components into a unified entity. It illustrates the system as a whole, which integrates individual components (Figure 45), key users, actors and entities through process and data connectivities. This integration seamlessly embeds information, process, and technology dimensions, ensuring cohesiveness and synergy among these critical aspects. The process of deriving the system view is based on the user requirements gathered to fulfil objective 3 (Chapter 6), which consolidates all four co-processes into a single abstract level diagram that reflects functionalities, processes and data flows.

Each sub-system is denoted in a green box, while key partners are illustrated in purple. Blue arrows represent the abstract view of the process, while yellow coloured arrows indicate the data flow from each component. The components in light grey represent system interfaces available for the different user levels that are available for both authorised users and the general public. All the components are linked to the "shared information" platform, which leads to secure data in "data centres".

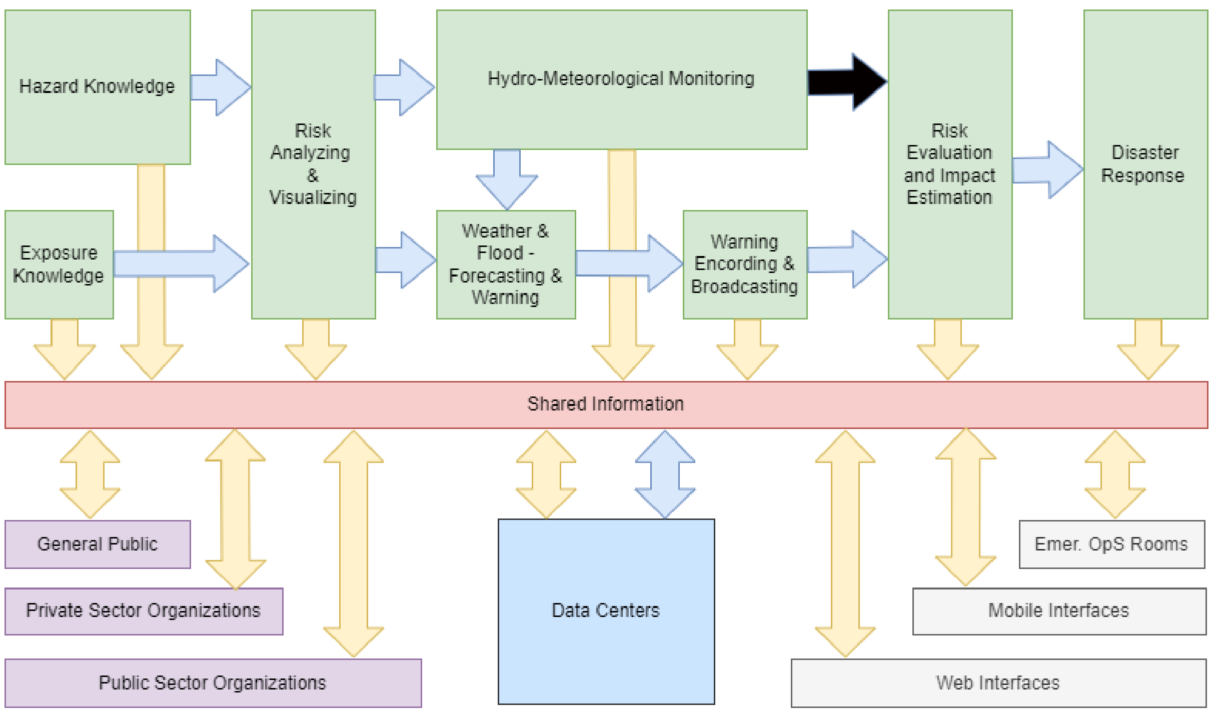


Figure 45: System view of the proposed FEWRS

In the proposed architecture, the author suggests embedding a reusable Service-Oriented Architecture (SOA) within a three-tier framework. A SOA with loosely coupled components independent of software development technologies, platforms and organisations offers a more novel approach to developing complex systems (Zhang et al., 2012), such as FEWRS. SOAs are widely used in enterprise applications, allowing organisations to integrate diverse systems into one. It also enables the reuse of components and creates more flexible and adaptable solutions. The SOA also provides a foundation to extend further the other architectural patterns, such as microservices, which take the idea of services to a more granular level. The use of SOA will ensure that the proposed system architecture presented in this study aligns with the latest software development paradigm. Since the proposed system is a collection of systems, interoperability is a vital aspect of the overall design. Data and information exchange within the inter-system should be facilitated through a pre-identified inter-operable framework.

The proposed FEWRS would encourage standardised communication protocols such as Hypertext Transfer Protocol (HTTP), Simple Object Access Protocol (SOAP), and Representational State Transfer (REST). These protocols ensure that different services can communicate and understand each other's messages, regardless of the technology they are built with. Data formats should not be overly regulated since digital information can be readily transformed into different formats using a variety of tools. Therefore, the primary design of this system encourages keeping the data open and in a machine-readable data format, which could be transferred into the desired format required for individual systems and tools.

The next section further elaborates on the 3-layer form of the system architecture.

7.4 Relationship of the Views and Layers

The previous sections presented the conceptual views of the proposed system architecture. This section presents the conceptual architecture with the layered representation of the proposed flood warning and response system.

Figure 46 shows the components of each layer that are mapped with the abstract views.

The architecture is encapsulated in a 3-tier architectural framework consisting of data, services, and application layers. This framework mirrors the conceptual architectural design, highlighting the structural organisation and interaction of these layers within the system, thereby providing a holistic understanding of the system's architecture.

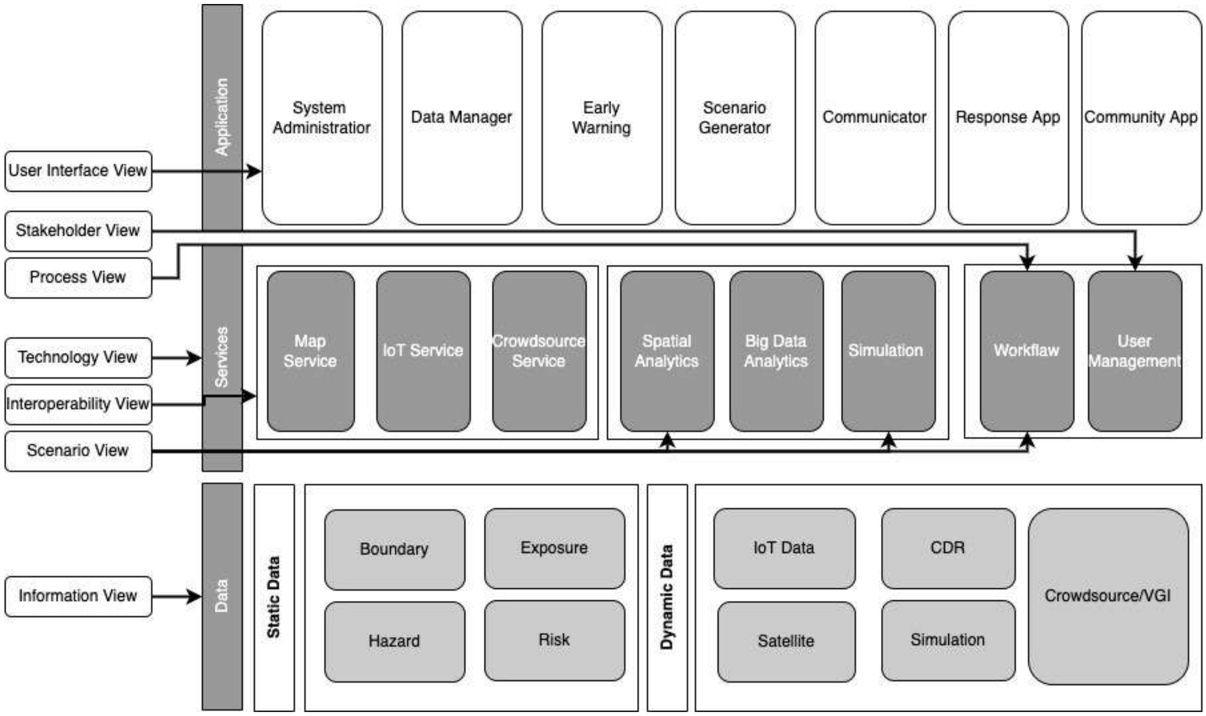


Figure 46: Representation of “Views” in the three-layered Conceptual Enterprise Architecture of FEWRS

7.4.1 Application Layer

The application layer maps individual applications reflecting the entire flood warning and response process. The user interfaces are separately identified as system administration, early warning, impact forecasting, communication and collaboration.

System Administration – The overall system administration will be conducted from this interface. This includes user management, user role definition, and allocation of interfaces to each institution, which are key responsibilities of the system administration interface.

Data Manager – The data manager will host, catalogue, and pre-prepare the data required for the system. The data manager will allow the user to define the level of access to each data set introduced to the system.

Early Warning – The EW interface will facilitate the respective user organisation to generate the flood warning. Three sub-modules have been proposed: the IoT monitor, the flood simulator and the warning generator will be employed to manage hydro-meteorological data, flood simulation and warning generation, respectively.

Scenario Generator – The scenario generator will facilitate the disaster management authorities to predict potential scenarios and identify the most vulnerable people and properties before a disaster occurs. This will allow disaster risk management and response partners to understand possible scenarios well in advance.

Communicator – The critical responsibility of the communicator is to disseminate early warning messages to the stakeholder organisations from the national level to the local level and the general public. It will connect with web services, SMS gateways and other communication channels such as HF, and VHF frequencies.

Response – This interface consists of the local-level stakeholder coordination for relief and response-related activities.

Community Module – The community app and web-based service are designed to collaborate with the community regarding warning services on potential disasters and obtaining feedback from the community on incidents. All the above-mentioned interfaces are solely available for government authorities and other stakeholder organisations before and during the flood warning and response phase; the community module is solely proposed for active community engagement. Therefore, rainfall, river water level heights, early warning and evacuation advisories, the status of evacuation routes, evacuation centres, and other community-level response activities will be coordinated through this module.

Furthermore, during non-emergency situations, this module will also provide regular awareness and education services.

7.4.2 Service Layer

The service layer will encapsulate the features and functionalities captured from all the views of the EA. This layer will facilitate the services to be consumed by the presentation layer. These services are categorised as (i) data management, (ii) data analytics, and (iii) workflow. The data management module is associated with the information view, the interoperability view, and the data analytics' service associated with the scenario view. In contrast, the workflow service is associated with the process view and the stakeholder view. The association and interlinkage of the components are shown in Figure 46. The following sub-services are proposed under the three service categories presented in Table 33:

Table 33: The functionality of the services and sub-services is defined

Service Type	**Functionality**
Data Management	Manage the databases
Map Service	Host and manage the spatial data
IoT Service	Host and manage the IoT data
Crowdsource Service	Host and manage crowdsource data
Data Analytics	Analytical functions
Spatial Analytics	Spatial analytical functions (clip, proximity and other spatial analysis)
Big Data Analytics	Big data analysis is performed here.
Simulation Service	Models and simulations are performed here
Workflow	Manage workflows and user management
Workflow	Manage the workflows of the FEWRS
User Management	User administration and roles are defined here

7.4.3 Data Layer

The data layer facilitates the data access to the sub-services of the service layer with the functions of data acquisition, storing and retrieval. The GIS and geo-referenced imagery data sets are stored in both raster and vector formats. Vector data may be stored in Postgres format, while raster data can be stored in GeoTIFF format. The coordinate reference system could be transformed into a country-specific projected coordinate system. The generic Geographic Coordinate System (GCS) with "WGS84 Spheroid" (Soler & Hothem, 1988) is proposed as the default coordinate system.

Table 34: Examples of the dynamic and static data that could be useful in flood response

Static Data	**Dynamic Data**
Population (census)	Current rainfall
Buildings (census)	Current river water flow
Roads	Current river/flood water level
Educational and healthcare facilities	Population dynamics
Utility/lifeline services	People affected (death, injuries, exposure)
Agriculture	Properties affected (name, number etc.)
Environment	People needing urgent rescue
Past flood inundations	People needing medical, healthcare and relief assistance
Past flood impact on people and properties	Roads affected

The purpose of the IoT service is to collect time-series data on river levels and rain to support flood forecasting and warning functions. A crowdsourcing platform that is used to capture community feedback on flood incidents and flood impact is logged into a separate database for real-time data analytics and model validation purposes.

Table **34** provides an example of the data that may be useful during flood warning and response. The data sets are classified as dynamic and static. Most of the static data can be acquired from the census and administrative databases, while the dynamic data is obtained from IoT, sensors and crowdsource techniques.

7.5 Summary

This chapter delves into the system design, drawing upon insights gathered from two structured literature surveys and requirements obtained from potential users. The proposed architectural framework has been meticulously crafted to encompass multiple perspectives of a Flood Early Warning and Response System (FEWRS).

The foundational element of this architectural framework is the process view of flood inundation events. The design of the system's architecture, as a whole, has been influenced by comprehensive secondary and primary data collection efforts. To clearly depict the envisioned FEWRS, 'to-be' process diagrams have been presented, complete with co-processes and sub-processes.

Subsequent views, including information, stakeholder, and technology perspectives, have been derived from the foundational process view. Beyond this, the scenario view, user interface, and system views have been employed to illustrate how the architecture will be utilised across various flood scenarios by different stakeholders.

Chapter 8 Evaluation of the System Architecture

8.1 Introduction

This chapter presents an evaluation of the proposed system architecture to provide the features necessary for developing an effective flood early warning and response system. The evaluation methodology employed in the evaluation was discussed in the methodology chapter and this chapter presents the results of the evaluation.

The flood warning and response system comprises a sequence of interconnected sub-processes encompassing four distinct stages. The initial stage, known as "Risk Understanding", involves a multitude of processes aimed at acquiring, processing, and delivering the underlying risk factors within a given geographical area. This exercise enables multi-agency teams to establish a common understanding of the social, economic, environmental, administrative, and physical risk landscape for a given hazard type. The subsequent stage, denoted as "Monitoring, Forecasting, and Warning", entails collaborative efforts by multi-agency teams to identify potential flood scenarios through forecasting and warnings. This is achieved through the aggregation, modelling, and interpretation of extensive hydrometeorological data within a collaborative environment. The third stage, titled "Warning Dissemination and Communication", involves translating flood warnings into “Impact-based” alerts, which are then disseminated to diverse user groups and the potentially affected community. The final stage, termed "Response Capacity", centres around the collaborative response involving multi-agency teams. It focuses on collaboratively identifying and rescuing individuals in distress, orchestrating requisite short-term coordination measures to ensure the well-being of both people and property.

The evaluation investigates whether the objectives of the proposed information system architecture solved the issues raised in objective one and improved the current position of FEWRS.

8.2 Evaluation Results

Figure 47 shows the summary values that reflect the individual participant's responses during the evaluation. The responses were rated from the scores 1 to 5, reflecting the values of strongly disagree, disagree, neutral, agree, and strongly agree, respectively. These questions were designed to cover the aspects of the FEWRS architectural framework to fulfil the objectives of (i) risk understanding, monitoring, forecasting and warning, (iii) warning dissemination, and (iv) response capacity.

With regard to the proposed artefact, the responses revealed that four participants rated the minimum value as “3” (neutral), while the other three participants rated it as “4” (agree). This implies that none of the participants expressed a "disagree" or "strongly disagree" sentiment towards the proposed artefact.

Notably, the mean values range from 3.7 to 4.65, and the median values fall between 4 and 5. This indicates that participants rated the proposed artefact from “agree” to “strongly agree”. As a result, the overall system received positive feedback during the evaluation phase.

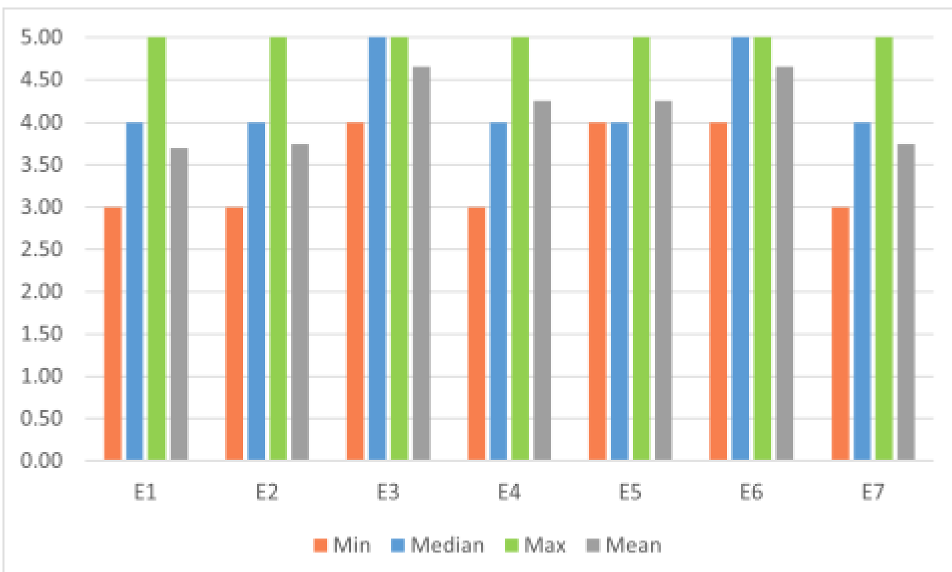
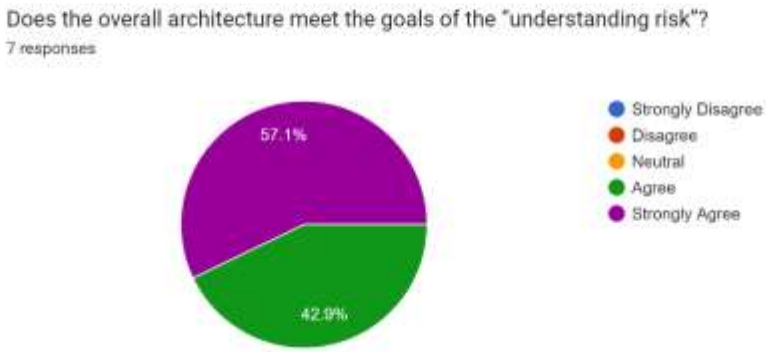
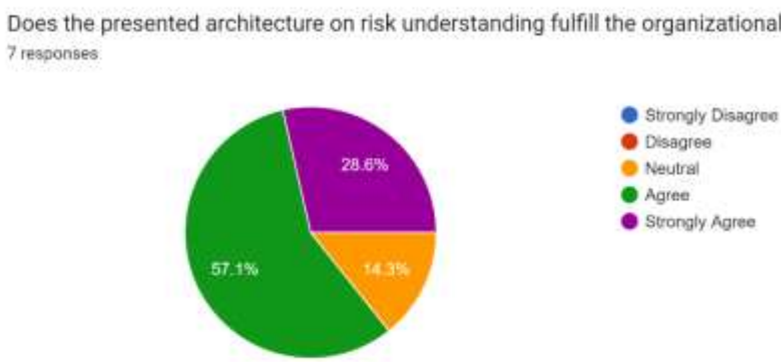


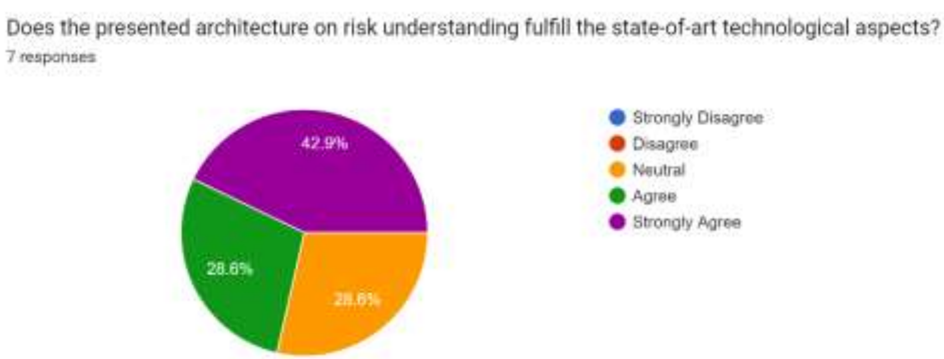
Figure 47: Evaluation Response of the Proposed Architecture of FEWRS

8.2.1 Risk Understanding

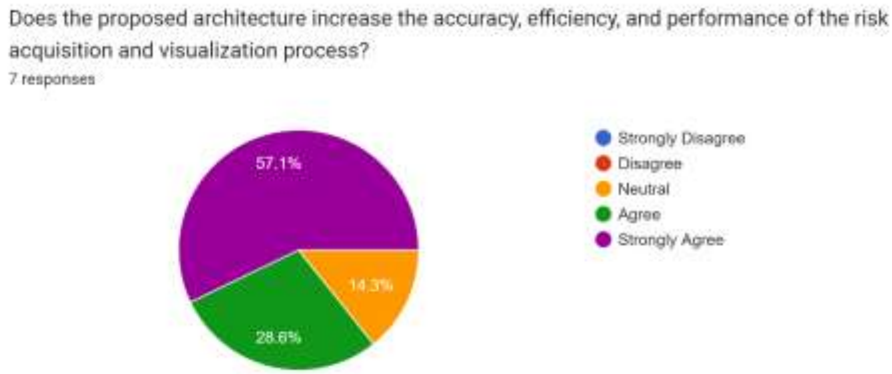


The participants unanimously agreed (100%) that the overall architecture effectively addresses "risk understanding," with no responses indicating "neutral," "disagree," or "strongly disagree."

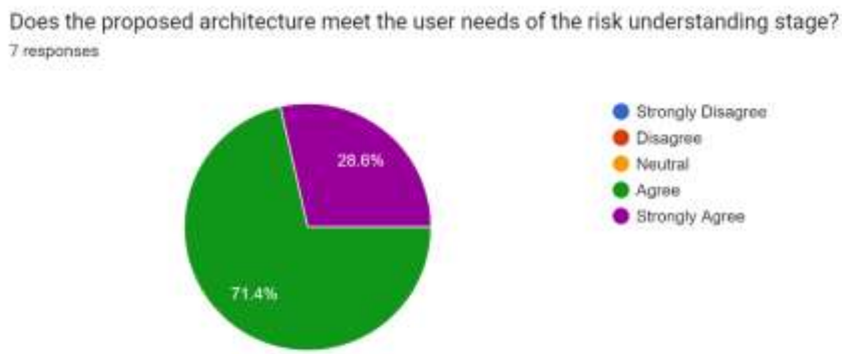




Additionally, the feedback indicated that the proposed artefact aligns well with the given framework, meeting organisational needs (85%) and leveraging state-of-the-art technological tools (70%) for an enhanced solution. This indicates that there may be room for improvement by introducing advanced tools and techniques (28.9%) in the risk understanding phase.



Approximately 76% of the participants believed that this framework will significantly improve the accuracy, efficiency, and performance of the FEWRS.



Furthermore, in terms of end-user requirements, all the participants either agreed or strongly agreed, in their responses, that the proposed architecture meets user needs.

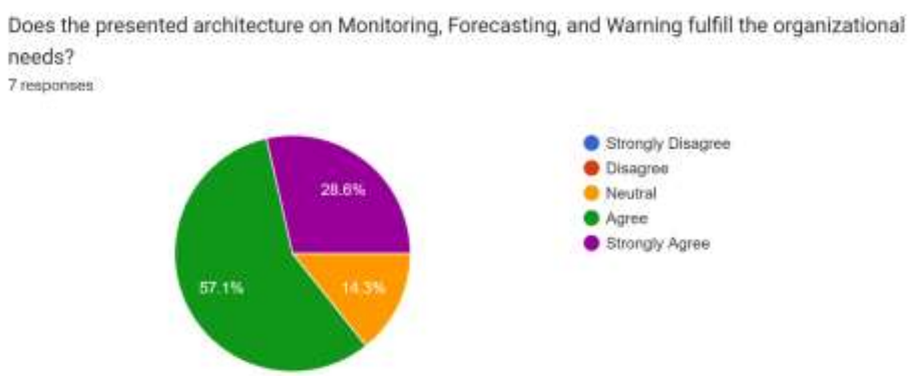
Therefore, in relation to risk understanding, the proposed artefact satisfactorily addresses (i) goal/efficacy, (ii) environment and (iii) activity.

During the brainstorming session, Co-Process 01 was the subject of a detailed discussion to validate the proposed system's processes and sub-processes. In this context, E4 suggested that incorporating remotely sensed data, along with aerial and drone data, would serve as valuable information sources to validate the model results. E1 emphasised that while a potential flooding scenario database is a good proposal, it is essential to strike a balance in complexity, aiming for tens rather than hundreds of scenarios.

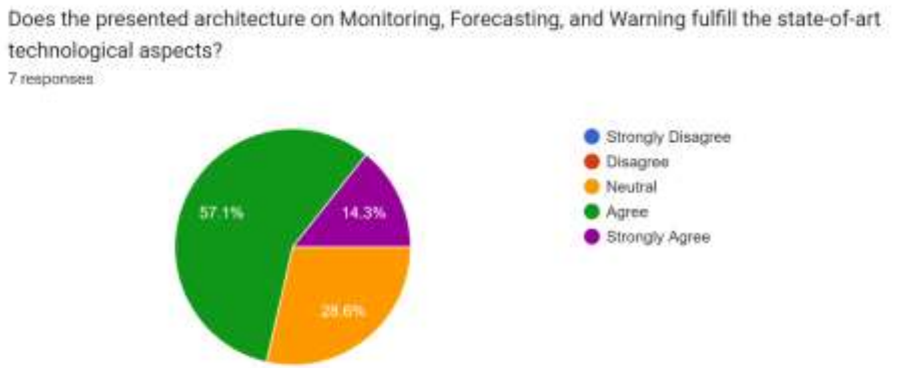
E4 also proposed integrating an event database within the system, feeding the annual event calendar for specific areas. He stated, "The event calendar should include known events where large crowds gather, warranting special attention. For example, musical or traditional community events are associated with unpredictable risks."

All responders emphasised the necessity for a common "exposure database" available in digital format for conducting impact-based forecasts and warnings. E4 further suggested establishing a link between this database and the impact analysis of Co-Process 2. E5 recommended making risk visualisations publicly accessible to everyone. Additionally, E3 advised including capacity assessment in the risk analysis process, a crucial aspect not currently represented in the architectural diagram.

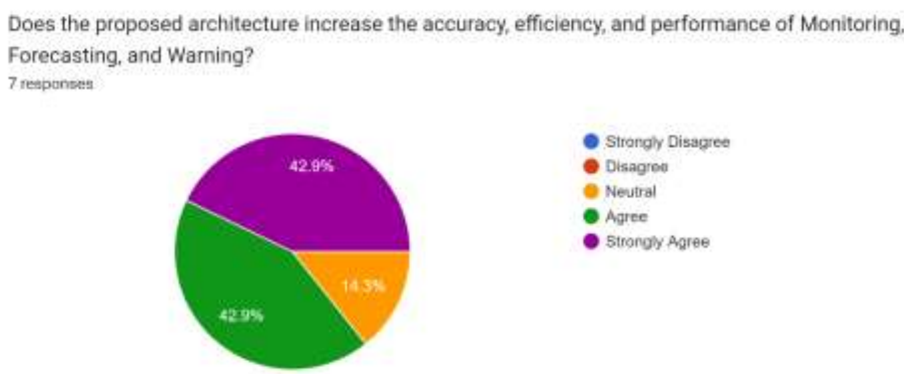
8.2.2 Monitoring, Forecasting and Warning

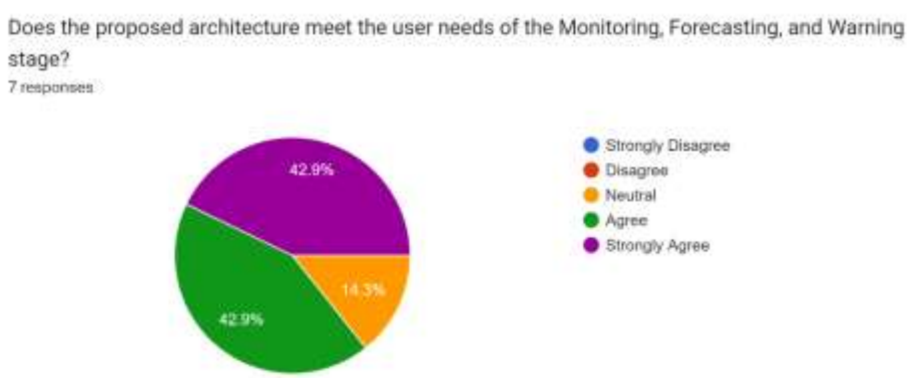


The responses indicate that approximately 85% of the participants agreed that the proposed artefact will effectively serve both the overall goals and meet the organisational needs of monitoring, forecasting, and warning generation.



Regarding the utilisation of state-of-the-art tools and technology in this component of the FEWRS, 70% of the responses affirmed its sufficiency, while 30% remain neutral on this matter.





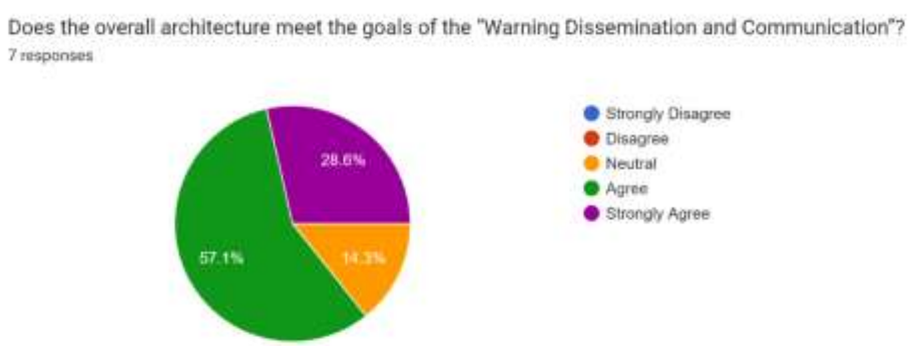
Approximately 85% of the respondents believed that the monitoring, forecasting, and warning component would significantly enhance both the system's effectiveness, efficiency and overall performance, as well as user needs to a high degree of satisfaction.

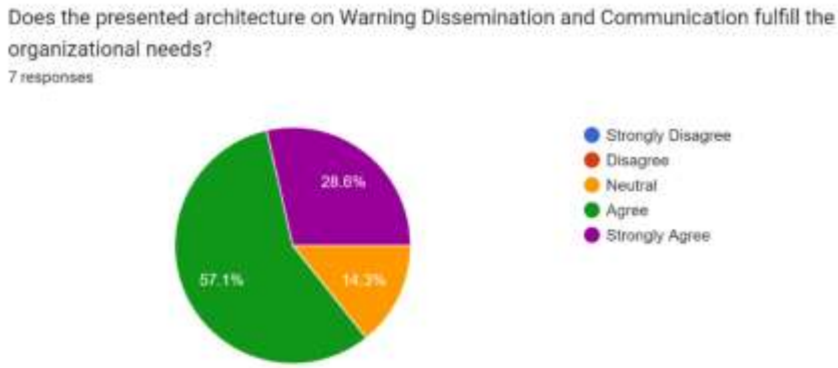
During the discussion, participants confirmed the necessity for a common hydro-meteorology observation network that integrates various sensor systems, established by multiple organisations. E7 proposed the establishment of a facility to archive the data generated through the platform for statistical purposes and model validation.

E4 suggested a few modifications to the weather forecasting and warning generation sub-process. Firstly, replacing ECMWF with Numerical Weather Prediction (NWP) to allow the use of any type of weather model in the forecasting process. Additionally, incorporating "nowcasting" alongside far-range and near-range forecasts was also suggested. All the participants suggested the incorporation of Artificial Intelligence (AI) and Machine Learning (ML) techniques within the flood forecast modelling process.

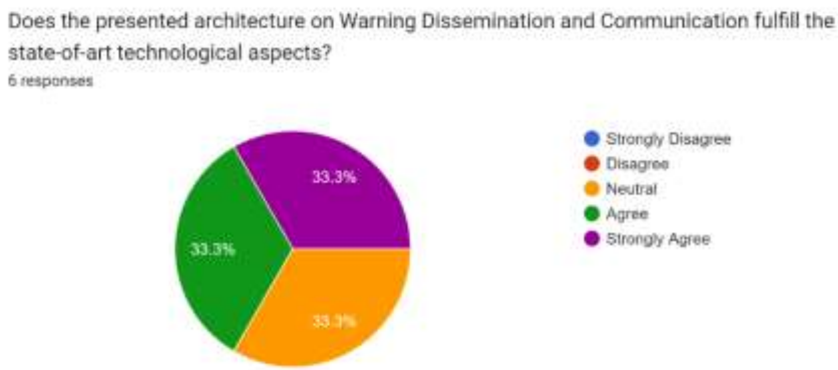
Both E1 and E2 recommended consolidating the flood forecasting activities under the "flood forecasting and warning sub-process". Furthermore, a majority of the participants suggested that the impact forecast should be a collaborative process coordinated by the DMC. E1 stated, “This aspect needs to be coordinated by DMC while participating with other stakeholders, including the Meteorology and Irrigation Departments”.

8.2.3 Warning Dissemination and Communication

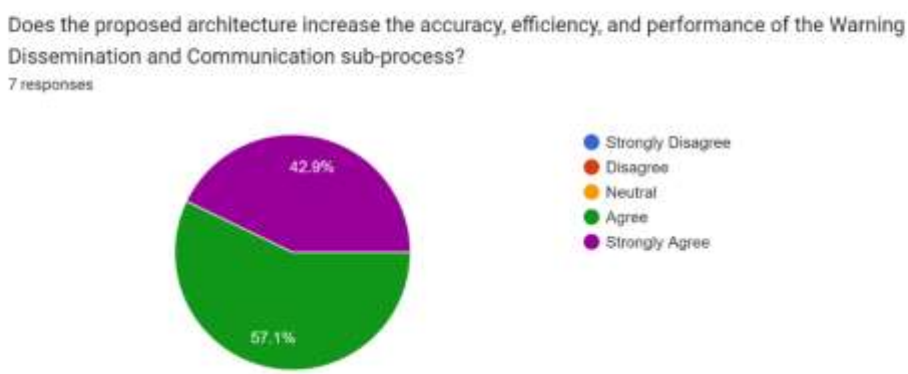




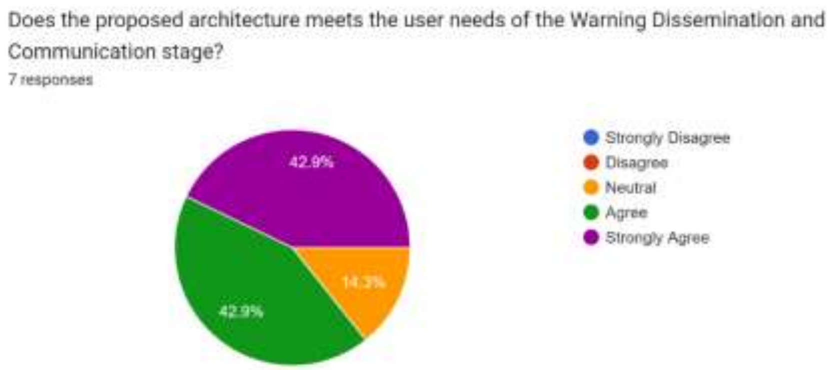
Over 85% of the responders affirmed that the proposed architecture fulfils the organisational needs as well as fulfilling the goals of the flood dissemination and warning communication phase.



However, only 66% agreed that this phase has adequately incorporated state-of-the-art technology and tools.



Nevertheless, all the respondents (100%) either agreed or strongly agreed that the proposed solution will significantly enhance the accuracy, efficiency, and overall performance of warning dissemination.



Approximately 85% of the responses confirmed that the architectural views of the warning dissemination and communication phase will meet user needs.

The above feedback suggests that the users are content with the architectural views of the warning dissemination and communication phase. This high level of confirmation suggests that the proposed architectural concepts align with the organisation, technical, and user requirements.

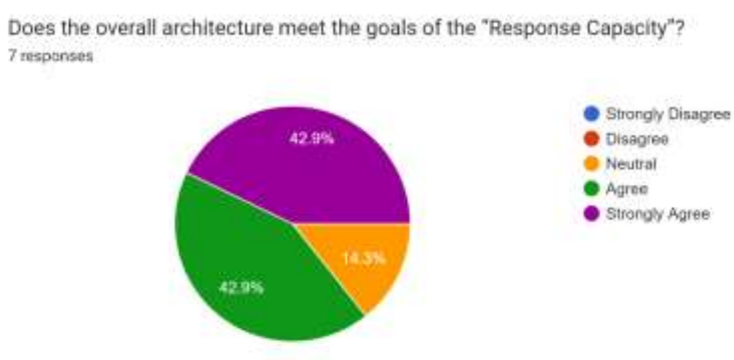
E1 highlighted that private media primarily operate with commercial targets, which may not always align with the objectives of warning authorities, as they tend to focus on their consumers. Overriding existing broadcast channels to transmit warning messages through radio or TV will require legal provisions (E1).

The majority of participants suggested implementing a hybrid warning dissemination mechanism, especially in rural areas during night-time, when electronic forms may not be effective. One suggestion was to "ring" fixed landline phones during this period. Hybridisation is proposed in order to disseminate warnings via village officers or military/police forces in rural contexts. Alternatively, participants proposed identifying and motivating community-level volunteers, and giving recognition to their valuable service.

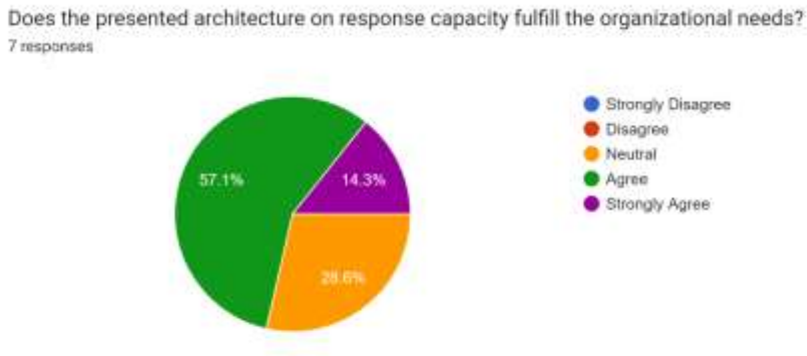
From a technological standpoint, only 33% expressed agreement with the proposed solution concerning the warning dissemination and communication phase, while 33% of responses were neutral, and the remaining percentage did not show agreement. This outcome suggests that users are comparatively less inclined to support the proposed architectural design. The discussion reveals that implementing the CAP system necessitates additional legal instruments for interaction with media agencies. The current legal framework does not permit disaster management agencies to override broadcasting forcibly for the inclusion of emergency warning messages. Therefore, E6 recommended that underlying policies are crucial for the optimal functioning of the proposed solution. Similarly, traditional warning dissemination methods, such as door-to-door communication, would be integrated with the electronic warning system during the nighttime when the community is in deep sleep. Mobile devices, media, and sirens may not be effectively utilized during the night to disseminate warning messages. Hence, messenger services facilitated by the military, police, and volunteers become essential to inform exposed communities.

E3 recommended integrating the warning dissemination mechanism with the call centres and the control centres established by the private sector to reach their workforce effectively. E3 also pointed out that the cell broadcast mechanism is not widely used among mobile users in the Sri Lankan context, suggesting its impact would be minimal. It was proposed to learn from the experiences of countries such as the USA and the UK to enhance cell broadcast effectiveness in warning dissemination.

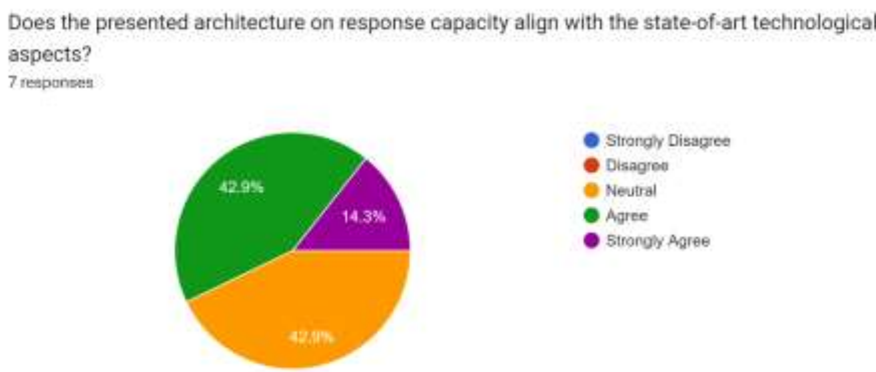
8.2.4 Response Capacities



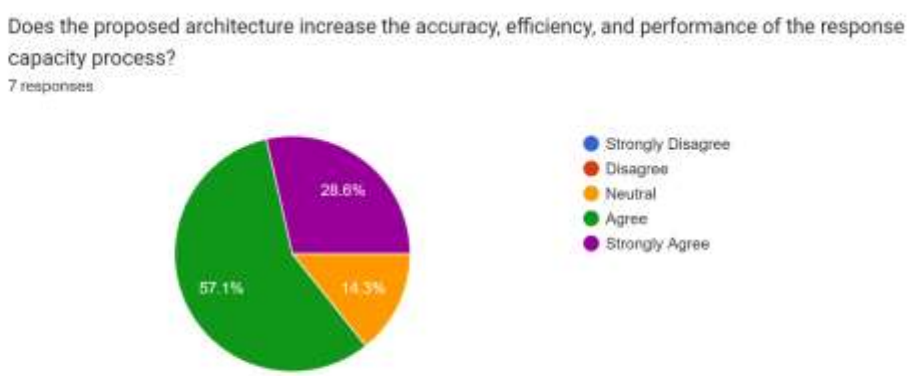
Approximately 85% of responses affirmed that the overall architecture aligns with the goals of the response capacity phase. However, this percentage is slightly lower compared to the responses concerning the participant's beliefs regarding achieving the goals in the other three phases.



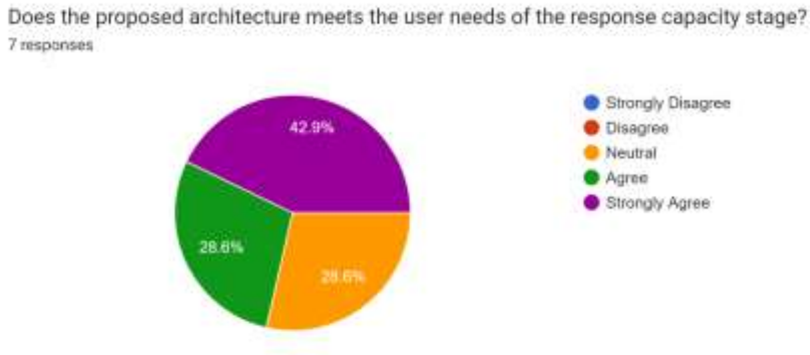
Only 72% of responders believed that the proposed solution meets organisational objectives, with the remaining 28% expressing neutrality.



Regarding the use of state-of-the-art tools and technologies, only 58% of the responses indicated agreement, while the remaining 42% remained neutral.



Nevertheless, 85% of the responses suggested that the proposed solution would enhance the efficiency and performance of the response process.



Approximately 72% of respondents believed that the framework would adequately meet user needs, while the remaining 28% expressed neutrality.

Overall, the responses indicate a slight weakness in the response capacity component of the proposed architecture. The author acknowledges that the research primarily focused on risk understanding, monitoring, warning generation, and warning dissemination, with limited coverage of the coordination aspects of the response. The response phase encompasses many more systems and processes beyond the scope of this research.

Further research is necessary to specifically study the improvement of the response system. E4 suggested that volunteers should be coordinated not only at the national level but also at the district and local levels. This recommendation should be reflected in the "to-be" process diagrams accordingly.

8.3 Discussion on the Overall System Architecture

The survey results, as discussed in the previous sections, indicate that each component of the overall architecture meets the objectives of the FEWRS with over 75% user agreement. This affirms that the overall design presented in this research aligns with organisational and user needs.

Responders E5, E6, and E7 further confirmed that it aligns with high-level system design solutions. The process view adequately covers the four core processes, their associated information flows, and technological tools. The generic representation of stakeholders in the design allows for the customisation of this system in different countries to meet their organisational expectations and improve performances.

The overall system framework presented in Figures 39, 40, 41, and 42 of Chapter 7 provides an abstract representation of the proposed FEWRS. Both the system view and the three-layered architecture conceptually visualise the FEWRS in its entirety (E7).

E7 also embraced the System of Systems (SoS) concept of this architectural framework, emphasising that multiple systems should be loosely coupled with other associated systems. Additionally, E7 proposed that, rather than relying on a rigid interoperable framework, individual systems should employ APIs to retrieve and adapt data for the recipient system. Additionally, E7 proposed that a microservice architecture could serve as a solution to integrate numerous systems into a conglomerate of FEWRS.

On the other hand, E6 suggested the introduction of interoperability standards to implement the overall system and recommended giving priority to system governance in implementing the proposed system.

Based on the responses, the following list has been formulated for incorporation into the design, as presented in Table 35. Some of the proposed adjustments require further research and go beyond the scope of this study and are, therefore, offered as suggestions for future work.

Table 35: The proposed changes within the FEWRS

#	Proposed Features	Process
1	The event calendar of major events should be reflected in the understanding risk component	Co-Process 1
2	Establish a link between the “Exposure Database” of Co-Process 1 and the impact analysis of Co-Process 2	Co-Process 1
3	Make risk visualisations publicly accessible to everyone	Co-Process 1
4	Provide capacity assessment in the risk analysis process	Co-Process 1
5	Provide a facility to archive the data generated through the platform	Co-Process 2
6	Replace ECMWF with Numerical Weather Prediction (NWP)	Co-Process 2
7	Incorporate "nowcasting" alongside far-range and near-range forecasts	Co-Process 2
8	Consolidate the flood forecasting activities in the Forecasting and Warning Process	Co-Process 2
9	Incorporate AI/ML techniques in the flood forecast modelling process.	Co-Process 2

10	Integrate the warning dissemination mechanism with the call centres and control centres established by the private sector	Co-Process 3
11	Enhance cell broadcast effectiveness in warning dissemination and enhance legal support in warning dissemination process.	Co-Process 3
12	Coordinate volunteers both at the national level and at the district and local levels.	Co-Process 4

In addition to the above changes to the proposed system, the participants also suggest the following additional recommendations during the evaluation to improve the overall system architecture. Some of these recommendations (items 2, 3, 4) are not associated with the system design and are supportive actions that can enhance the functionality of the overall design. Items 1, 5, and 6 are technical recommendations that can be adopted into the system to improve its functionality.

1. Override existing broadcast channels to transmit warning messages through radio or TV (which requires legal provisions) (E1). For example, the Emergency Warning Broadcast System (EWBS) used in Japan allows authorised organisations to broadcast emergency information through TV, radio, and other information channels. A similar service in the USA is available, which is referred to as the Emergency Alert System (EAS).
2. Consider the introduction of a hybrid warning dissemination mechanism, which may be useful to implement during night-time when electronic forms are unavailable.
3. Identify, motivate and train community-level volunteers and give them due recognition for their service.
4. Conduct further research to study the system improvements necessary for the response phase, which offers digital services for coordination to camp management and medical services.
5. Consider using interoperability standards to implement the system. Possible standards are Emergency Data Exchange Language (EDXL), Common Alerting Protocol (CAP), Open Geospatial Consortium (OGC) Standards, and WebEOC.
6. Consider adopting a microservice architecture concept and any appropriate technology to integrate the proposed system components seamlessly.

Based on the proposed changes, the corrected process diagrams of Figures 48 to 51 are presented below.

8.4 Summary

The chapter provides an overview of the results obtained from the evaluation of the artefact. It begins by outlining the criteria used for this assessment. Seven participants took part in the evaluation, and the overall feedback indicated a positive reception of the proposed artefact design.

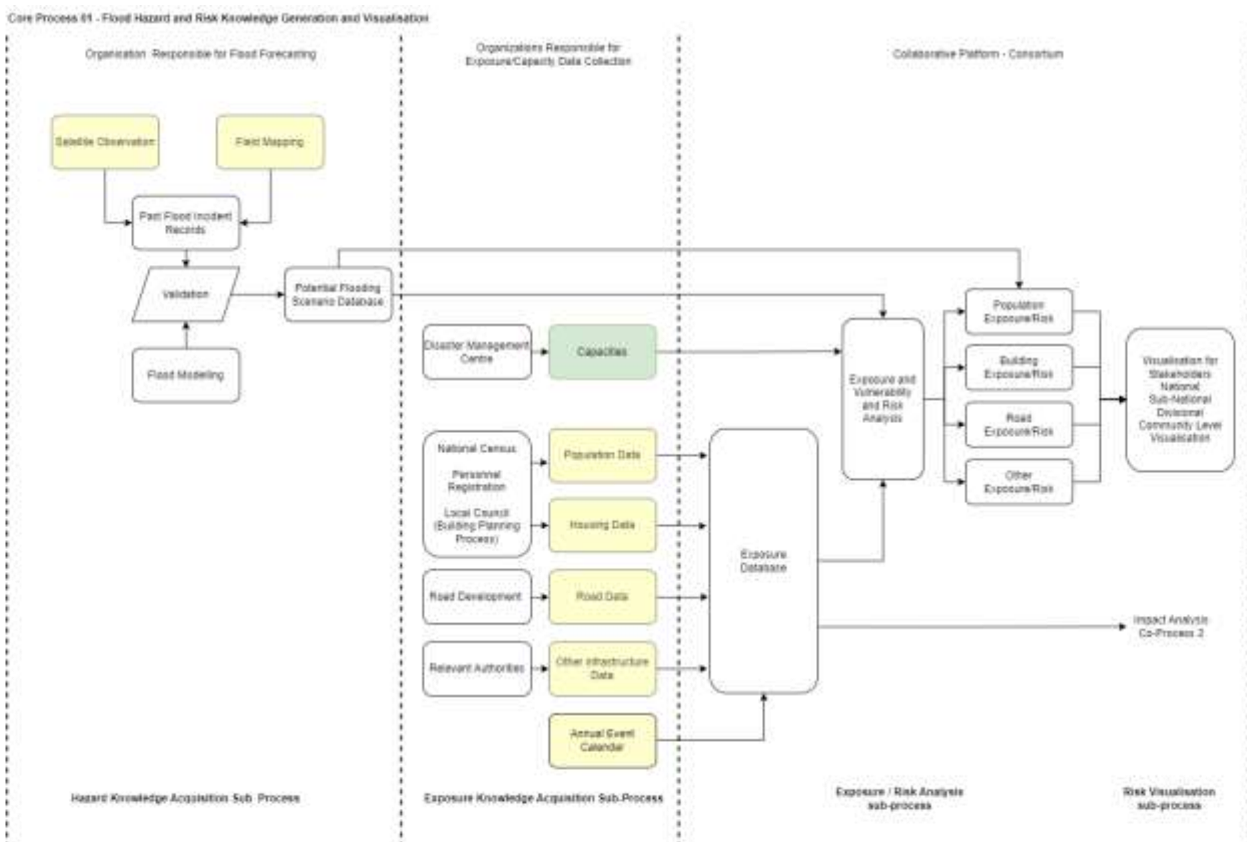


Figure 48: Revised flood hazard and risk knowledge generation and visualization co-process

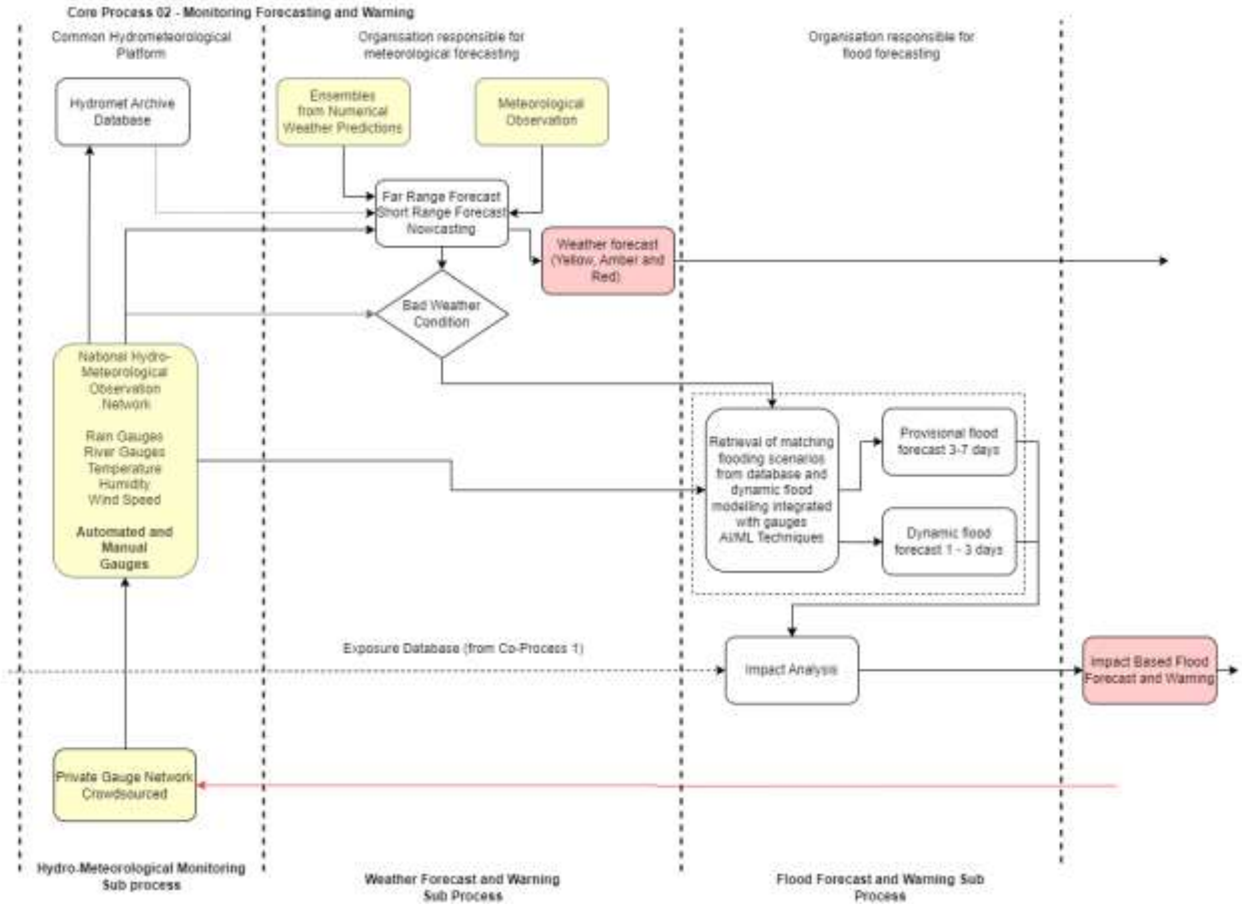


Figure 49: Revised monitoring forecasting and warning core process

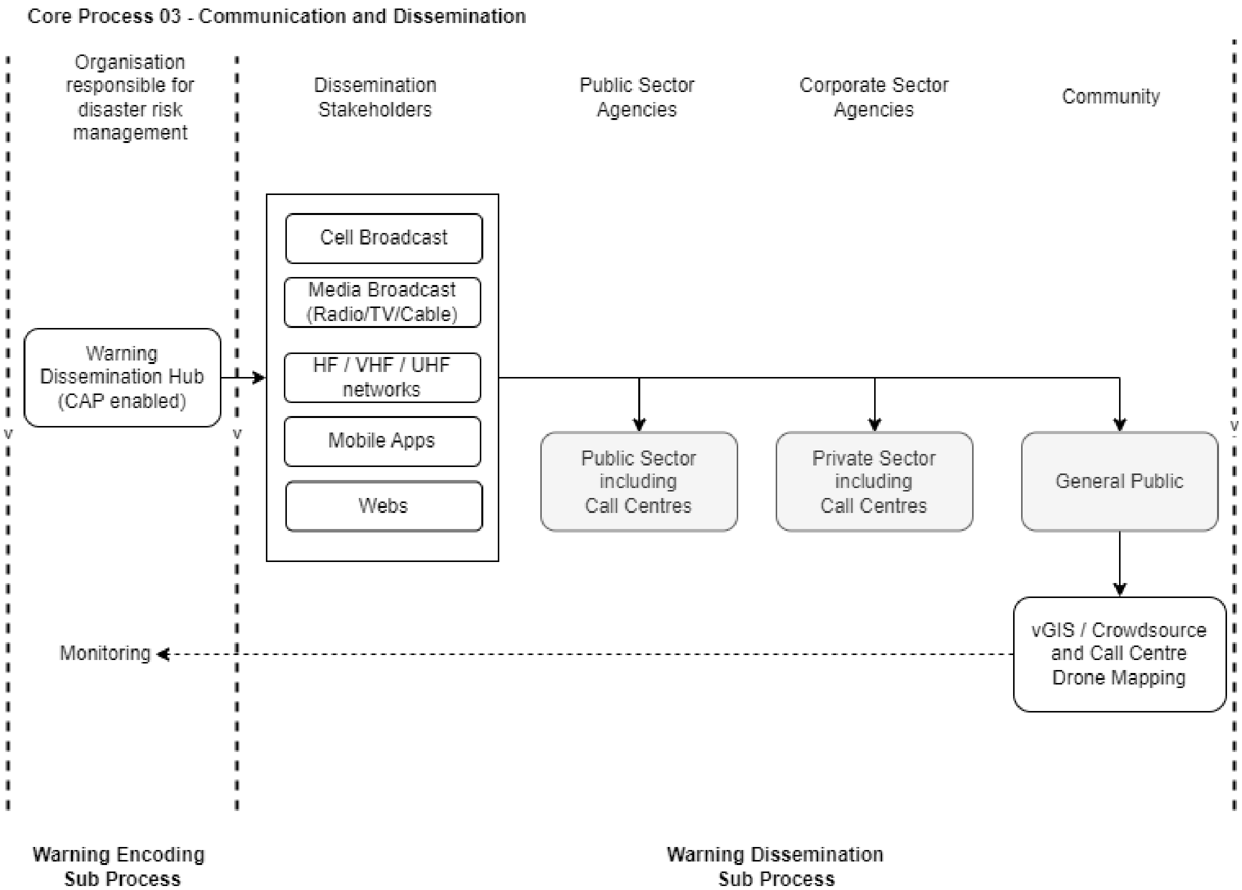


Figure 50: Revised warning dissemination and communication core-process

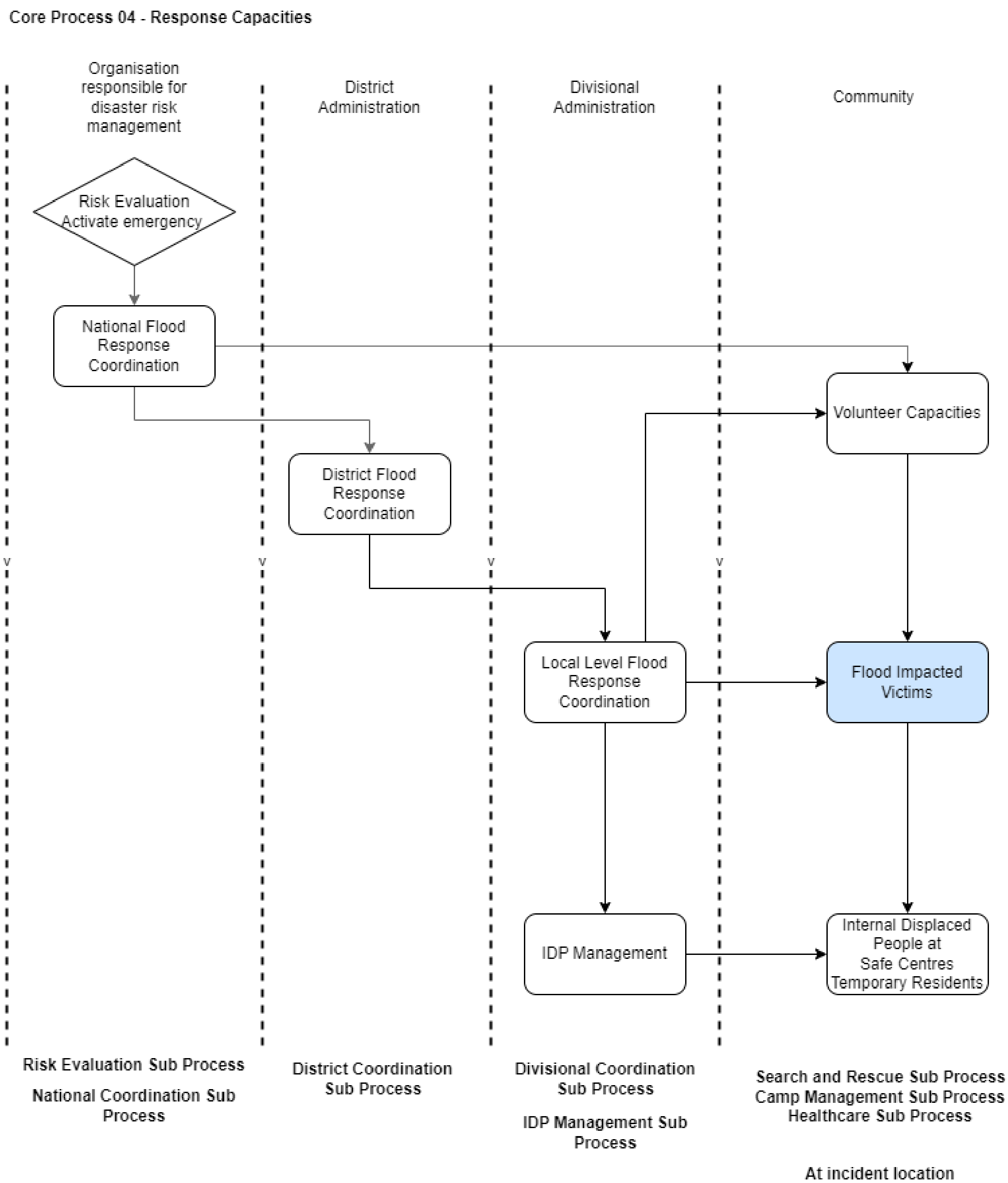


Figure 51: Revised Response capacities' core-process

Chapter 9 Discussion and Conclusion

9.1 Introduction

The following chapter intends to bring insight into the research by analysing and discussing the research outcomes in terms of primary and secondary data. The chapter also presents the limitations of the research and makes suggestions for further research.

The purpose of this research was to define the characteristics of an advanced flood early warning and response system (FEWRS) that offers accurate and timely intelligence for decision-makers in issuing flood warnings and responding to them more effectively. The research explored the nature of a FEWRS that can overcome current issues and challenges by capturing user requirements, designing the artefact and finally validating with the industry experts, process owners and end-user communities. By doing so, it studied how the power of advanced technologies such as information management systems, remote sensing, simulation technologies, advanced visualisation and mobile communication can be explored to design and build such a FEWRS.

This was achieved by focusing on four key areas: problem identification, requirement gathering, research design, and outcome validation. The research identified the critical failure factors of flood early warning and response systems through a comprehensive literature review. A second structured literature review was conducted to define the life cycle of a flood early warning and response system (FEWRS) and the necessary data, information and intelligence for making informed decisions in generating early warnings and responding.

Building upon the insights from these two structured reviews and drawing from theoretical frameworks, the characteristics of an advanced FEWRS specific to the Sri Lankan context were established. In-depth interviews were then carried out with senior officers involved in meteorological forecasting, flood forecasting, warning dissemination, emergency management, and local coordination to understand the current limitations of the FEWRS in Sri Lanka and the solutions for overcoming these limitations. Additionally, further input was collected from field experts and community users.

The characteristics identified from the literature survey and the user suggestions were then used to design an Information System Architecture (ISA) for FEWRS. This architecture was validated through feedback from seven participants. Among these participants, four were involved in the primary data collection process, while the remaining inputs were gathered from experts from within the ICT industry. Three group meetings were conducted to solicit feedback on the proposed FEWRS prototype, followed by one-to-one discussions to clarify the comments and suggestions. Subsequently, an online questionnaire shared among the seven review participants with closed-ended questions with a rating scale was administered to provide a brief individual perspective on the system. The findings of the primary data collection and verification processes were presented in the preceding chapters. The research design was modified in response to the feedback received during the verification stage.

The following sections discuss how the overall objectives have been met in achieving the overall aim of this research.

9.2 Current Gaps and Challenges of FEWRS (Objective 1)

The purpose of research objective 1 was to identify the current gaps, challenges, and limitations of the flood warning and response processes and how they can be addressed through advanced technologies. The outcome of this research objective is presented in Chapter 4. This section summarises the outcome of this research.

In order to fulfil this objective, an investigation was conducted to identify a broad spectrum of critical failure factors of flood warning systems through a structured literature survey from multiple sources. The structured survey captured 24 critical failure factors (CFFs) of flood warning and response systems from the articles published in the past 30 years.

Previous research shows that warning systems are, generally, a system of systems (Arru et al., 2020; Horita et al., 2019) operated in a multi-stakeholder environment, with the active involvement of authorised warning senders and receivers. Such warning systems are supported by numerous tools and technologies to improve the efficiencies of the entire process (Samansiri et al., 2022). However, the research highlighted that there is a considerable gap between 'warning senders' and 'warning receivers', and inefficient use of tools and technologies. Hence, in this structured review, the author has attempted to identify the most critical factors that affect the efficient implementation of FEWRS.

Flood warning and response systems are essential components of risk reduction strategies with a view to reducing loss of life and the impact on personal assets. However, recent flood incidents have caused significant loss of human lives due to failures in current flood warning and response mechanisms. Recent trend analysis has shown that climate change-induced flood incidents are gradually increasing, and both developed and developing nations feel its impact. Capturing critical failure factors affecting flood warning and response systems can provide opportunities for making corrective measures and for developing a more advanced and futuristic system for flood early warnings. By applying the interpretive structural modelling (ISM) approach, this research identified four types of failure factors (autonomous, dependent, linkage, and independent) with varying dependence and driving powers. Analysis shows that governance, leadership, finance, procedures (SoP), and community engagement are the most dominating factors with the highest driving factor, which can overcome other dependent factors. The outcome of this review could be helpful for policymakers and practitioners in overcoming failure factors and implementing effective early warning and response systems.

As illustrated in Figure 52, the study provides the overall relationship between institutional, technological and social factors.

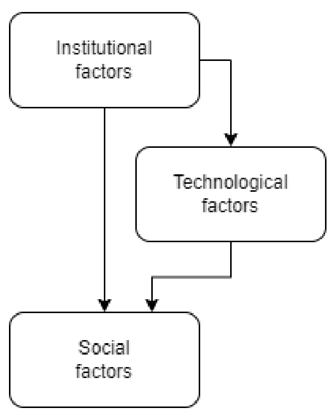


Figure 52: The relationship between institutional, technological and social factors regarding the failures of FEWRS

The structured literature review conducted in this research suggests that institutional factors trigger both technological and social factors. The top two factors affecting most other factors are weak institutional governance, coordination and custodianship, and the lack of political will and institutional leadership. This study has identified 11 factors that are categorised as institutional factors. Overcoming these factors will help to address the technological and social aspects. Several initiatives have proposed guidance for countries to overcome all three institutional, technological and social issues. For example, the Sendai Framework for Disaster Risk Reduction

(SFDRR) (UNISDR, 2015), the global policy that came into action in 2015, suggests the creation and improvement of multi-hazard, multi-sector, people-centred early warning systems. The global policy also provides directives to improve technology and communication mechanisms to forecast and communicate risks effectively. The process includes user participation and customisation to suit cultural and gender-specific requirements. Here, the focus is on affordable tools and broader channels for distributing early warnings on natural disasters. Moving forward, in November 2022, "Early Warning for All", a five-year programme (2022–2027), has been initiated by the United Nations to accelerate the objectives defined by Target G of the SFDRR by providing three-tier technical, financial, and political level support to the countries which do not have proper early warning systems.

The outcome of this research established a solid theoretical foundation to understand the critical failure factors of FEWRS and their inter-relationships. The findings suggest that the policy and institutional, technological, and social dimensions are equally important and must be carefully addressed to make such systems more efficient, inclusive, and user-centric. Identifying these critical failure factors (CFFs) and establishing inter-relationships among them serve as the fundamental bedrock of this research endeavour.

9.3 Identify Relevant Intelligence, Technology and Processes of FEWRS (Objective 2)

The second objective of this research focused on identifying the types and sources of the intelligence required for flood warning and response processes and the technology solutions that can offer such intelligence. This was achieved through a structured literature survey, and the outcome was presented in Chapter 5. The following paragraphs summarise the key outcome of this objective.

The review study identified the intelligence that is required at various FEWRS phases, which can be used for evidence-based decision-making. Twenty-seven different types of intelligence were found, along with the technologies that can be used to extract such intelligence. A conceptual layered architecture that illustrates how relevant technology solutions can be used to extract intelligence at various stages of a flood cycle for decision-making in issuing early warnings and planning responses was established as a part of this research.

The critical analysis of the literature showed that the situational intelligence obtained for flood warnings and responses is associated with rainfall, river flow, inundation, and impact on people, properties, and response capacities. Numerous tools and technologies which can be used to derive intelligence to inform decisions were identified in this research. The advanced technologies identified in this research include: gauges (IoT) and crowdsourcing for monitoring river levels, hydrodynamic modelling with AI that can predict potential flood inundation zones with flood arrival time, satellite and drone technology for capturing post-flood inundation mapping to conduct damage assessments, use of mobile data with active SIM locations (call detail records) to capture people's movement during evacuation, and crowdsourcing techniques for capturing information on trapped people and their needs.

The review study suggests that the natural flooding process, encompassing rainfall, river flow, and inundations, is comprehensively monitored and analysed using various tools and technologies (Samansiri et al., 2022). Rainfall and river flow data can be obtained through automated gauges, often utilising IoT (Internet of Things) technology to transform raw readings into real-time situational information. This data is then processed to generate intelligence regarding rainfall patterns and river flow conditions, providing a foundation for further analysis.

Crowdsourced systems (Castanhari et al., 2016) offer an alternative method for detecting these incidents, particularly in the absence of gauge data. They rely on human observations and experiences, effectively turning individuals into sensors. Hydrodynamic modelling, a well-established technology, is coupled with artificial intelligence (AI) to predict potential flood inundation zones, forecast river water levels, and estimate flood arrival times. The synthesis of multiple sources of intelligence allows decision-makers to derive comprehensive flood warnings.

Advanced tools such as satellites and drones play a crucial role in capturing post-flood inundation mapping data. This information is used to assess potential damage to people and properties, including residential buildings, roads, utilities, and the agriculture sector. Furthermore, mobile data, particularly call detail records from active SIM card locations, is leveraged to capture human dynamics and residential statuses. This information is vital for authorities when making evacuation plans. Crowdsourced data also serves as a valuable intelligence source for identifying individuals who are trapped and for determining those in need of basic necessities such as food, water, temporary shelters, and healthcare facilities.

Following these findings, the relationship between the flooding process, the required intelligence, and the tools and technology to derive this intelligence was presented as a conceptual system architecture for making informed decisions for early warnings and responses. Therefore, Objective 2 of the study was successfully achieved by identifying the relationships between each stage of the flooding process and the tools and techniques used to derive intelligence at each stage, facilitating timely decision-making.

The review stage uncovered four distinct process models to enhance our understanding of these complex interactions. The process models identified in this study were used to build entity relationship diagrams of the FEWRS, resulting in a four-layered architecture with the following layers: (i) physical process/data (ii) technology (iii) intelligence (iv) decision-making (Figure 53). From the literature, the findings of this structured survey are consistent with the information systems' modelling techniques and frameworks proposed in (Saad et al., 2013). However, the process models defined in this structured survey are unique and reflect new knowledge within the plethora of research.

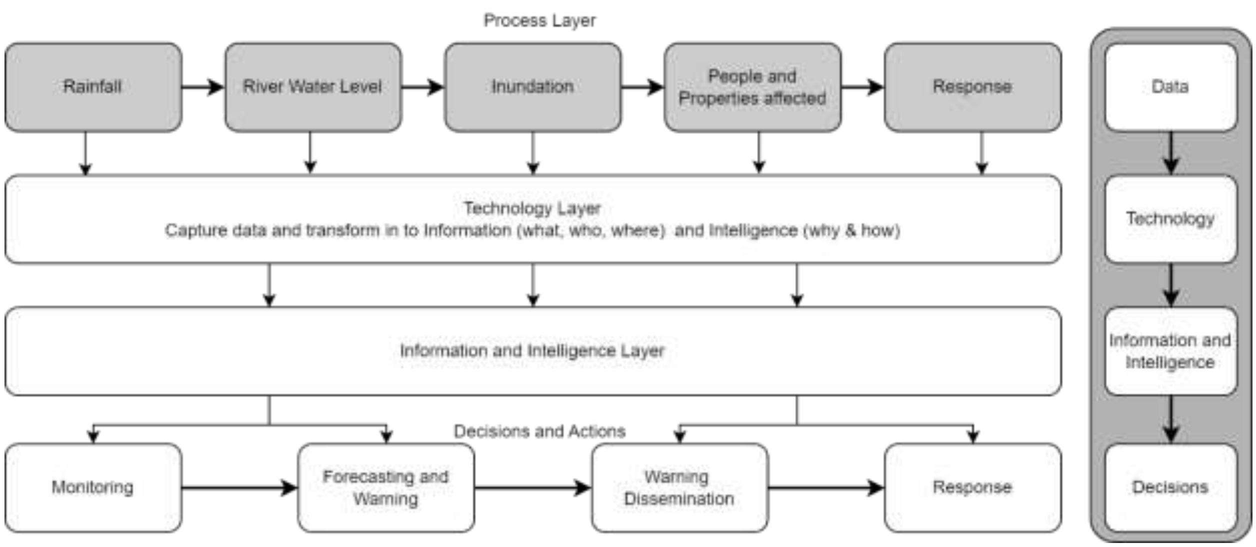


Figure 53: The generalised 4-layered conceptual architecture of the FEWRS

This overall four-layered architecture was validated and agreed upon by the experts during the verification process. This work contributes to the existing literature by providing a structured approach to developing a FEWRS and laying the foundation for building sound FEWRS in the future. The layered approach presented in this study offers a foundation for developing a technology platform that disaster management agencies can use to issue early warnings with sufficient time for people to evacuate, to better respond during floods, and to efficiently manage relief operations. Furthermore, the conceptual system architecture has captured a range of technology solutions that the decision-makers can deploy based on the availability of the technology. It offers a pathway to increase the accuracy and efficiency of receiving the necessary intelligence as the resources become available. It shows how information from sensors, databases, big data systems, GIS, hydrological simulations, and satellite remote sensing can be combined to offer a rich set of data for decision-making and interventions by various agencies. Integrating these technologies can potentially increase the effectiveness, efficiencies, and accuracy of the overall approach to flood monitoring, early warning, and evacuation.

This 4-layered architecture was used as the basis for defining the nature of a FEWRS from the process, information and stakeholder perspectives in Chapter 5. Furthermore, the conceptual models developed under this objective were used to develop a primary data collection strategy and as a foundation for the artefact-building process. This conceptual architecture was used for defining the layered architecture models presented in Figure 24, Figure 25, Figure 26 and Figure 27 of Chapter 5 to illustrate how the required intelligence during the flood cycle needs to be managed to inform, evacuate, rescue, and offer relief to citizens and safeguard property.

9.4 User Requirements' Capture (Objective 3)

Objective 3 was set out to identify user requirements for a technology platform that can capture necessary intelligence and also provide timely access to decision-makers for supporting flood warnings and responses. The outcome of this objective was presented in Chapter 6, and a summary of the outcome of this objective is presented below.

This objective was achieved by primary data collection from the interviews and document reviews. The data collection process was in two stages. In the first stage, the "as-is" process of the flood warning and response system was captured from the existing documents. Acts, policies and other project reports were used to identify the organisational process and data flow diagrams. The "as-is" process models captured the current status of the process of any organisation or system, by analysing existing documents and primary data. The outcome of the "as-is" processes was current flood warning and response process diagrams derived for the four stages of the FEWRS. The details of these diagrams are presented in Figures 29, 30, 32, 33, 34 and 35 of Chapter 6. The following "as-is" processes were derived:

1. Current weather forecasting process
2. Current flood risk and forecasting process
3. Flood warning dissemination and emergency response

In the second stage, the “to-be” process for the four stages of the proposed FEWRS was defined by capturing the user requirements. The “to-be” process is known as the "future state process model" which refers to a designed framework that outlines how a desirable operational state can be achieved. This was achieved through a consultative process with the process owners and the industrial experts in the field to overcome current issues and achieve anticipated goals. The “to-be” process model aims to enhance process performance and tackle existing challenges within the present process.

Fourteen participants, including process owners from relevant authorities, engaged in flood warning and response, disaster risk management experts, and community users, participated in the requirement analysis through interview sessions. The interviews were conducted with moderation, utilising open-ended questions to facilitate participants in articulating their proposed process enhancements. Each interview was then transcribed, and the responses were grouped into the warning system stage for better understanding. All the requirements were sorted, combined and generalised to derive more meaningful and unique requirements.

The requirement analysis captured the following salient points:

1. Avoid duplications of data collection at each stage of the warning and response process.
2. Reduce unnecessary controls and authorisations that hinder the effectiveness and efficiency of the process.
3. Improve muti-stakeholder collaboration through a virtual digital platform to collect, process and collaborate data and other knowledge products.
4. Integrate multiple processes, shared among numerous organisations, into a single process to streamline the decision-making process.

The "to-be” process, as an outcome of the user requirement analysis conducted in Chapter 6, was constructed and presented in Figures 39, 40, 41 and 42 of Chapter 7. Details on the key outcomes of these processes are summarised in the following section.

9.5 Overall System Architecture (Objective 4)

The purpose of Objective 3 was to conduct research to define the characteristics and develop the overall system architecture of the technology platform. The outcome of this objective is presented in Chapter 7, and a summary of the outcome of this objective is presented below.

Objective 4 was built on the outcome of the previous objectives. For example, Objectives 1 and 2 have established a sound foundation to justify the necessity for comprehensive FEWRS and process models. Objective 3 presented current ("as-is') and desired future ("to-be") processes through a consultative approach. Building on this understanding, Objective 4 analysed the user requirements in detail and further refined them to define a system architecture for an effective FEWRS, aligning with the envisioned "to-be" process.

Following the TOGAF framework, the overall system architecture of the FEWRS was defined as a set of views in order to reduce its complexity and focus only on a single aspect at once. The views used in this research include process, information, stakeholder, technology, scenario, user interface and system views.

Among these diverse "views," particular emphasis was given to the "process view" during the system development phase. Four co-processes of (i) risk understanding (ii) monitoring, forecasting and warning (iii) warning dissemination, and (iv) response were carefully delineated to align with each stage of the FEWRS, ensuring a one-to-one correlation. Furthermore, these co-processes were subdivided into several discrete sub-processes, thus simplifying the overall process into individual and coherent units. For example, the "Risk Understanding" co-process was subdivided into the following three distinct sub-processes: (i) flood risk acquisition (ii) exposure data acquisition, and (iii) exposure and risk analysis sub-processes. The "flood risk acquisition" sub-process was designed to produce a comprehensive flood database, incorporating multiple flood scenarios, instrumental for both preparedness and response activities. The sub-process "exposure data acquisition" was designed to hold comprehensive data such as population, housing, infrastructure and land use, through a unified "National Exposure Database". This database plays a pivotal role in identifying elements exposed to floods, assisting decision-making in both the preparedness and response phases. Lastly, the "exposure and risk analysis" sub-process involves the analysis of potential flood risks using data from the National Exposure Database, offering insights into elements at risk. Similarly, the second co-process, "Monitoring, Forecasting, and Warning," was subdivided into three sub-processes (i) hydrometeorological monitoring (ii) weather forecasting and (iii) flood forecasting. "Hydrometeorological monitoring" establishes a unified platform connecting diverse IoT and monitoring stations, allowing for the seamless sharing and consumption of data by multiple stakeholders. "Weather forecasting" generates long-range forecasts, short-range forecasts, and nowcasting. Meanwhile, "flood forecasting" integrates hydrometeorological observations, flood modelling and scenario matching with existing flood databases to calculate potential flood inundation and arrival times. Similarly, the third co-process, "Warning Dissemination" was subdivided into two sub-processes. The impact analysis sub-process transforms flood warnings into more meaningful impacts by identifying elements as risks using a national exposure database. The warning messages are further transformed and customised based on the end-user's contexts. The dissemination sub-process then shares the warning message among the dissemination partners and media agencies to distribute among the end-users. The final fourth sub-process, “Response”, focuses on national, sub-national, and local stakeholders' coordination among response partners and the victims by ensuring the safety of both people and properties.

The "stakeholder" and "information process" perspectives were derived from the process view, as both views inherently rely on stakeholder engagement and data/information aspects. The stakeholder view is instrumental in detailing the types of stakeholders associated with each sub-process, revealing which stakeholders initiate, and are involved in, the respective activities. Furthermore, each stakeholder has undergone a comprehensive assessment through stakeholder analysis, providing valuable insights into their roles and impacts.

Conversely, the information view delineates the types of data and information required and the outputs generated in each sub-activity. These data and information elements were categorised primarily as static and dynamic, reflecting the varying nature of information needs and outputs.

Static data primarily includes unchanging information, such as population census data, details about buildings and infrastructure (including roads and utilities), and environmental data. These data are considered static because they do not typically undergo frequent alterations. Most of these static data elements fall under the category of "exposure data," as they play a crucial role in exposure and risk analysis. Additionally, hazard knowledge, including historical inundation records and computed hazard maps at various return periods, is also classified as static.

In contrast, dynamic data is closely associated with the response phase of disaster management. These data exhibit rapid changes within specific timeframes. Dynamic data include real-time information such as rainfall, river water flow rates, and flood inundation heights. These dynamic data sets are instrumental in attributing ongoing hazards and guiding response efforts. Furthermore, data regarding post-disaster impacts are inherently dynamic, evolving over time. Understanding these dynamic changes is of paramount importance in the context of emergency response operations. Consequently, the dynamic and static attributes of the data and information required for FEWRS were considered in detail when constructing the "information view".

The "technology view" offers an in-depth exploration of the methodologies utilised to facilitate each sub-process within disaster management, aligning closely with the technological tools identified in Objective 2. These tools are of paramount importance, as they serve as critical enablers, greatly enhancing the efficiency and effectiveness of their respective processes. For instance, hydrodynamic models integrated with real-time inputs from numerical weather predictions (NWP) and the Internet of Things (IoT) contribute significantly to the accuracy of flood forecasting. This combination of advanced modelling and real-time data allows for timely and precise flood predictions, which are invaluable in mitigating the impact of floods and safeguarding vulnerable populations.

Post-flood impacts are effectively captured through the utilisation of remote sensing and crowdsourcing methods. Remote sensing provides a means of gathering detailed, real-time information about the affected areas, enabling rapid and informed decision-making during recovery. On the other hand, crowdsourcing leverages the collective intelligence of a community or the public to collect data and insights from affected individuals, further enhancing situational awareness and response efforts.

The proposed architecture proposes to capture the dynamic nature of human movement during emergency response through mobile SIM location followed by big data analytics. These sources of information allow responders to monitor and understand the movements and needs of affected populations in real-time, facilitating more targeted and efficient relief efforts.

The overarching objective of the "technology view" is to ensure the strategic association of the right technologies and tools for the extraction of situational intelligence to enhance preparedness and response processes. Disaster management practitioners and policymakers can make more informed decisions by harnessing technology and data-driven insights.

The scenario view provides clarity on the types of scenarios and thresholds used within the flood warning process, offering a glimpse into the decision-making parameters and criteria.

Subsequently, the system view effectively demonstrates the integration of all sub-systems and components into a unified entity. This integration seamlessly embeds information, process, and technology dimensions, ensuring cohesiveness and synergy among these critical aspects. Finally, the architecture was encapsulated in a 3-tier architectural framework consisting of data, services, and application layers. This framework mirrors the conceptual architectural design, highlighting the structural organisation and interaction of these layers within the system, thereby providing a holistic understanding of the system architecture.

As mentioned in earlier chapters, the FEWRS is a System of Systems (SoS). An SoS is an inter-connected and inter-operating collection of systems that produces results that cannot be achieved by an individual system alone (Zhang et al., 2012). FEWRS is, similarly, a collection of multiple systems established across all stages of the warning and response process to meet the business requirements of each stage. The rapid growth of complexities and continuously changing requirements make traditional design principles more challenging and complex. Therefore, this study employed an architectural development framework (Prasanna et al., 2017; Saad et al., 2013) to overcome these issues.

9.6 System validation (Objective 5)

The purpose of this objective was to validate the system architecture prototype for its potential to support disaster warning and response processes during floods. The outcome of this objective is presented in Chapter 8, and the outcome of this objective is summarised below.

The evaluation of the artefact is a critical step in design science research; hence, the outcome of this objective is important. Therefore, the overall system architecture was validated involving the users, process owners and experts. For this task, 7 participants were selected. Three participants from the respective technical agencies, one DRM expert, and three other participants from the ICT domain were involved. Except for the three ICT experts, all the other four participants were engaged in primary data collection. The role of the ICT experts was to verify and validate the technical representation of the proposed artefact. The discussions were held in three group meetings and in subsequent individual meetings to obtain individual responses.

The overall outcome of the verification process suggested that the participants were in agreement with the proposed architectural framework. Participants proposed several amendments, such as introducing AI and machine learning into the flood forecasting process utilising impact-based warning as a shared service that involves multiple organisations, and introducing bots for response coordination. Furthermore, proposals coming out of the verification process also suggested the tools and technology to address the vulnerable groups' inclusiveness and differently-abled conditions. Another key highlight of the verification meetings was the consideration of revising some legal and policy barriers to implement the system. For example, the implementation of the CAPs system requires additional legal instruments to interact with the media agencies. The current legal condition does not allow disaster management agencies to override broadcasting to include emergency warning messages forcefully. The other proposal was that manual methods integrated with the electronic warning system are necessary to disseminate the message during deep sleep. The mobile devices, media and sirens may not be effectively used during the night to disseminate the warning message. Therefore, military, police and volunteer-based messenger services are necessary to inform exposed communities.

The ICT experts were technically concerned with keeping the multiple modules in more loosely coupled systems. This will allow the designers to integrate various other systems whenever necessary. The use of service-oriented architecture and micro-services architecture was highlighted.

Overall, the verification process derived a positive response to the proposed system. A detailed discussion of this was recorded in Chapter 8. Therefore, the author believes that the procedures and activities adopted to achieve objective 5 were adequate.

9.7 Limitations

The critical limitation of this study is that the proposed architectural framework has a conceptual design that has not been implemented. Further enhancement and refinements may be necessary when implementing the proposed architecture. However, the proposed system architecture may provide a sound foundation for the implementation. The flooding scenarios considered in this research were hypothetical or informed by historical incidents. Therefore, more extreme hazard scenarios might demand different functionalities from the system architecture.

During the evaluation process, the participants were given an introduction to the overall system architecture, assuming conceptual and hypothetical settings. They were then asked to provide their feedback and its likely impacts on the system. Therefore, the feedback received from the users was purely based on their thoughts and hypothetical perceptions of potential flooding scenarios in conjunction with their past experiences. As a result, they may not have considered all the eventualities that occur in a real flood scenario.

The other limitation of this study is that the overall system architecture development focused on the physical, economic and social conditions and beliefs in the Sri Lankan context. Therefore, the findings may differ in other geographical, ethnical and cultural contexts.

Another aspect of this research relates to how primary data was gathered to identify system characteristics. The stakeholders were interviewed to gather the user requirements on four phases of the FEWRS. These interviews were held individually and in small groups from participating agencies and individuals representing the community and experts. The interview process may have missed some important stakeholder participation as well as their likely key requirements during the data collection.

Finally, this study investigated architecture in all parts of the flood warning and response process. In doing so, it provides an overview of warning systems but does not provide in-depth findings that apply to each aspect of the process.

9.8 Summary

The findings garnered widespread agreement. During discussions on the four stages of the Flood Early Warning and Response System (FEWRS), significant changes were proposed towards implementing an efficient FEWRS. Firstly, it emphasised inter-agency collaboration in a virtual space, facilitating the seamless engagement of various agencies. Secondly, it prioritised an open and easily accessible data-sharing mechanism among these agencies. Thirdly, it proposed the use of electronic forms to streamline information sharing and approval processes, thus enhancing overall efficiency.

The data and information produced were designated as shared assets among the relevant authorities. The three-layered architectural framework with multiple views was introduced to meet the distinct demands of each phase of the flood warning and response process. This architectural design aligns with prior works that have also advocated for a layered approach, affirming the alignment of this research's findings with established studies in the field (García et al., 2019; Prasanna et al., 2017).

Objective 1 was successfully accomplished through an in-depth investigation into the critical failure factors (CFF) of FEWRS. This comprehensive analysis yielded 24 distinct critical failure factors that were identified and documented. Building on this, Objective 2 was fulfilled by employing a thorough, structured survey approach. This survey delved into 28 different intelligences relating to flood management. Additionally, the study established vital connections between data, information, intelligence, technology, and the decision-making processes integral to flood warning and response scenarios. This understanding was further encapsulated through the creation of a range of process models. The outcomes of Objectives 1 and 2 provided the necessary foundation to tackle Objective 3. This involved crafting a data collection framework and conducting thorough user requirement assessments for an innovative system for FEWRS. Objective 4, a pivotal milestone, was reached by crafting the proposed Flood Exposure and Warning Resilience System (FEWRS). This involved the development of various view models and system architectures, process diagrams, each contributing to a comprehensive and detailed design. As a final validation step, the invented artefact underwent rigorous evaluation by both industrial experts and practitioners. This holistic assessment ensured the artefact's practical viability and effectiveness in real-world scenarios.

Collectively, the pursuit of these objectives concluded in the achievement of the overarching research aim. Through these systematic steps, a robust and multifaceted exploration of FEWRS was conducted, advancing the understanding and capabilities in the domain of flood warning and response systems.

9.9 Researcher's contribution to the body of knowledge

The researcher's contribution to knowledge via this study is multifaceted and aimed at enhancing flood warning and response systems for more effective decision-making during the emergency response phases of flood disasters. The specific contributions are as follows:

1. **Identification of Global Gaps and Challenges**: This research has identified and explored the existing gaps and challenges in flood warning and response systems on a global scale.

Establishing an interconnected understanding of these issues has contributed to establishing a foundation for addressing these gaps and developing a FEWRS that will overcome them.

2. **Intelligence for Effective Decision-Making:** The study has identified the crucial intelligence required for informed decision-making within the flood warning and response process. This intelligence is a vital component in developing an enterprise architecture for a FEWRS, ensuring that the right information is available at the right time for the decision-makers.

3. **Enterprise Architecture Development:** The research has developed an enterprise architecture with multiple views and tiers, tailored to the needs of flood warning and response systems. This architecture provides a structured framework for organising and integrating various components, processes, and stakeholders involved in managing flood emergencies. Furthermore, the research has validated the suitability of this enterprise architecture through engagement with participating organisations and individuals. This step ensures that the proposed framework can address real-world needs and is practical for implementation in the context of flood warnings and response.

In summary, this research contributes to the field by not only identifying global challenges but also by proposing a comprehensive enterprise architecture that addresses these challenges and facilitating effective decision-making in flood disaster situations. Moreover, the validation process ensures that the proposed solutions are theoretically sound, practically viable, and relevant to the stakeholders involved.

9.10 Future Research

Further research is essential to optimise the proposed Flood Early Warning and Response System (FEWRS) in practical environments. To this end, several research proposals have been identified.

It is suggested that a segment of the system be constructed and operationalised within a specific river basin. This real-world implementation will provide valuable insights into the final system's functionality and help researchers validate the system in real-world conditions.

The integration of Artificial Intelligence (AI) into the FEWRS mechanism should be explored. AI can enhance the analytical and decision-making capacity of FEWRS by re-evaluating and improving the accuracy of sensor and Internet of Things (IoT) gauge data. Machine learning algorithms can also be leveraged to refine flood modelling and forecasting capabilities by training the system with historical data, enhancing its predictive and responsive capabilities.

Further research should focus on enhancing the response capacity of FEWRS. While the initial study concentrated on risk knowledge, flood forecasting, and warning components, response processes encompass a broad array of functions, stakeholders, and systems. Therefore, further research is needed to enhance the response stage.

It is also proposed that there should be further investigations on the enabling environment for FEWRS implementation and on the development of policy guidelines to overcome current problems. Building upon the findings in Chapter 4, this extension of the research will help facilitate the effective implementation of FEWRS in various regions, particularly in Asian, African and South American areas susceptible to flooding, thereby bolstering disaster resilience.

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Appendix A – Ethical Approval

Monday, May 22, 2023 at 05:34:20 British Summer Time

Subject: Ethics Application: Panel Decision
Date: Tuesday, 7 December 2021 at 11:55:11 am Greenwich Mean Time
From: ethics
To: Rankothge Samansiri
CC: Terrence Fernando
Priority: Low

The Ethics Panel has reviewed your application: Characteristics of integrated flood warning and response system enabling intelligence-based decision making: A Case study from Sri Lanka
Application ID: 3159

The decision is: Application Approved.

If the Chair has provided comments, these are as follows:

Please use the Ethics Application Tool to review your application.

Appendix B – Interview Guideline

Characteristics of an Integrated Flood Warning and Response System Enabling Intelligence-based Decision Making: A Case Study from Sri Lanka

Interview Guideline

1. INTRODUCTION

This report aims to present the approach for collecting primary data for the above research project. These data will be collected from the industrial practitioners and community representatives involved in the flood warning and response process.

The interview consists of two sections; (i) identify gaps and challenges of flood warning and response systems (ii) Identify characteristics of future flood warning and response systems. In the first part of the interview, users will be asked about the current challenges and gaps that they face in the flood warning and response process and to validate the findings from a structured literature review conducted by the researcher. In the second part of the interview, responders will be asked to explain both the "as-is-process" as well as "to-be-processes" of the flood warning and response system, that can overcome the current limitations. These "to-be-processes" will be captured and translated into user requirements.

The interview questionnaire has been designed to gather requirements for each of the main stages of the flood warning and response system, as specified in UNDRR (UN Disaster Risk Reduction) terminology. The stages considered in the questionnaire design are: (i) risk knowledge, (ii) monitoring and forecasting (iii) warning dissemination and communication and (iv) response capabilities.

The approximate time required for this interview is two hours.

2. INTERVIEW QUESTIONNAIRE FORMAT

Personnel Information (10 mins)

I. Name
II. Organization
III. Designation
IV. Work Experience
V. Area of expertise
VI. Role and responsibilities

Survey Part I – Gaps and Challenges of Current Flood Warning and Response Systems
(Approx. time – 30 mins)

Explanation:

The structured and comprehensive literature survey revealed that 24 gaps and challenges are commonly available in implementing flood warning and response systems from the global perspective. However, these gaps and challenges may slightly vary from country to country depending on theor socio-economic and cultural background. Therefore, gaps and challenges identified from the literature need country-specific validation. Therefore, this section will gather responses from the practitioners and community representatives in Sri Lanka on the applicability of the identified gaps and challenges of flood warning and response systems within the Sri Lankam context. The key gaps and challenges are categorized as follows: (i) Policy and Institutional (ii) Technical (iii) Socio-cultural. Subjects will confirm the relevance of t factors by marking “Y”or “N”, and ranking them from least influential (value 1) to most influential (value 10).

Policy and Institutional

* Please use the ranking scale as follows: least influencing – 1 ; most influencing – 10

Gaps and Challenges	**Relvant to Sri Lanka (Y/N)**	**Rank if relevant (1-10)***
Week institutional governance, coordination and custodianships		
Lack of funding to operationalize, modernize, maintain of FEWRS systems		

Data sharing and data governance issues		
Lack of skilled human resources for data analysis, modelling and forecasting		
Lack of political will and institutional leadership		
Inadequate local level preparedness for response		
Lack of knowledge and awareness of key stakeholders and community		
Lack of access to warnings and less warning coverage		

Technology

* Please use the ranking scale as follows: least influencing – 1 ; most influencing – 10

Gaps and Challenges	**Relvant to Sri Lanka (Y/N)**	**Rank if relevant (1-10)***
Issues with physical protection of sensors / IoT installed		
Lack of inclusion of community and vulnerable groups in planning and decision making		
Lack of understanding of the risk and unavailability of risk information/maps		
Data / information errors		
Issues with flood forecast modelling accuracies and techniques		
Inadequate flood warning lead time and inefficiencies of warning generation and dissemination		
Issues with communication and dissemination systems		
SoPs, systems are not available for better warning and response		
Lack of appropriateness, completeness and understanding of warning message and dissemination in-efficiencies		
Limited computing capacity		

Social

* Please use the ranking scale as follows: least influencing – 1 ; most influencing – 10

Gaps and Challenges	Relvant to Sri Lanka (Y/N)	Rank if relevant (1-10)*
Lack of public awareness or ability to understand the warning		
Lack of trust and plans credibility on the warning system		
Lack of public interest and culture of neglect		
Lack of community understanding on risk		
Lack or neglect of community participation		
Lack of community capacities in the reception of warning and influence of digital divide and limited coverage of warning services		

Survey Part II – Diagnose current limitations and explore features of a future system for flood warning and response

(Approx. time - 30 mins)

Explanation:

This section will diagnose the current process and limitations of flood warning and response systems and identify potential solutions to overcome these issues. The overall objective is, therefore, to identify characteristics of future flood warning and response systems. Subjects will be asked to explain both the "as-is-process" and the "to-be-processes" of the flood warning and response system that can overcome the current limitations. For each questions under the "to-be-processes", user requirements will be captured and recorded in the form of "User Stories", by the researcher. The typical structure of "User Stories" is available in the Appendix.

User Stories is a popular requirement gathering method typically used for software and product development. It is a collection of a set of ideas of user requirements that are recorded in natural language, which is comprised of 3 essential components: (i) who it is for (*who*), (ii) what is expected (*what*) and (iii) why it is important (*why*) User stories will be developed under the each prbes of the User stories for each questions under the “to-be-process” will be prepared by the researcher during the interview, with the agreement of responder.

Risk Knowledge Stage

Acquisition of Risk Information

Category	Question	Probes
As is process	Could you please explain the process that you currently use to **acquire** the flood risk information?	-Stakeholder engagement -Process of acquiring the risk information -Type of data and data security -What technology is used to acquire risk knowledge - Intelligence derived from the risk information
Challenges	What are the challenges and gaps you face in acquiring flood risk information?	N/A
To be process	In future system, how would you like to acquire the flood risk information?	1. Stakeholder View – What stakeholder involvement in acquiring risk information? 2. Process View - What is the proposed process to acquire the risk information? 3. Data View – How risk information is acquired and shared? What are the data security aspects? 4. Intelligence View - What intelligence derived from the risk information? 5. Interface View - What is the suitable user interface to acquire the risk information?

Acquisition and Visualization of Risk Information

Category	Question	Probes
As is process	Could you please explain the process you currently use to acquire and visualize the flood risk information?	-Stakeholder engagement -Process of acquiring the risk information -Type of data and data security -What technology is used to acquire risk knowledge - Intelligence derived from the risk information
Challenges	What are the challenges and gaps you face in flood risk visualizations?	N/A
To be process	In future system, how would you like to visualize the flood risk information?	1. Stakeholder View - How stakeholders should view risk information? 2. Scenario View - In what scenarios risk knowledge is useful? 3. Process View - What is the proposed process to visualize the risk information?

		4. Data View - How risk related data is obtained and shared? What security aspects? 5. Intelligence View - What intelligence derived from the risk information? 6. Interface View - What is the suitable user interface to visualize the risk information?

Monitoring, Forecasting and Warning

IoT and Gauge Data

Category	Question	Probes
As is process	Could you please explain current process that is used to receive flood and rainfall information in order to generate flood warnings?	-Stakeholder engagement -Process of acquisition of gauge data -Data security concerns - Intelligence derived - Technology used
Challenges	What are the challenges and gaps you face in receiving rainfall and river gauge information real-time?	N/A
To be process	In future system, how would you like to acquire, visualize and consume rainfall and river flaw information in real time for flood forecast and warning process?	1. Stakeholder View - Who are the stakeholders should view real time IoT / gauge data? 2. Scenario View - In what scenarios rainfall / river gauge data is useful? 3. Process View - Briefly explain the process of consuming the automated gauge information for warning generation ? 4. Data View - How and to whom these IoT is shared? 5. Intelligence View - What intelligence derived from the rainfall and river flaw data? 6. Interface View - What is the convenient user interface to visualize and process IoT data?

Flood Forecast

Category	Question	Probes
As is process	Could you please explain the current flood forecast process?	-Stakeholder engagement -Process of acquisition of data -Data security concerns - Intelligence derived -Technology associated
Challenges	What are the challenges and gaps you face in flood forecasting ?	N/A
To be process	In future system, how would you like to develop numerical flood forecasting system to enable accurate warning with adequate lead time ?	1. Stakeholder View - Who are the stakeholders should view such flood forecast? 2. Scenario View - In what scenarios flood forecast outputs are useful? 3. Process View - Briefly explain the process of generating, authorization and sharing flood forecast? 4. Data View - How and to whom these forecast information is shared / restricted? What data is needed to generate the forecast?

		5. Intelligence View - What intelligence derived from the flood forecast ? 6. Interface View - What is the convenient user interface to generate, authorize and share flood forecast?

Potential Impact of Floods

Category	**Question**	**Probes**
As is process	Lets imagine, there is ongoing rainfall and increased river water level closer to inundation in upstream. Considering such situation, how do you estimate potential impact of the floods on people and infrastructure?	1. Stakeholder participation 2. Scenarios associated 3. Technology used 4. Data required and shared 5. Intelligence derived
Challenges	What are the challenges and gaps you face in flood impact assessment during the flood warning process?	N/A
To be process	In the future system, how would you like to estimate the potential flood impact?	1. Stakeholder View - Who are the stakeholders associated in generating flood impact information? 2. Scenario View - In what scenarios flood impact information is useful? 3. Process View - Briefly explain the process of generating, authorization and sharing flood impact information? 4. Data View - How and to whom this flood impact information is shared? What data is required? 5. Intelligence View - What intelligence could be derived from the flood impact information ? 6. Interface View - What is the convenient user interface to generate flood impact information?

Warning Dissemination and Communication

Warning dissemination

Category	**Question**	**Probes**
As is process	Could you please explain the current process of disseminating warning messages to stakeholders and the general public?	1. Stakeholder participation 2. Scenarios associated 3. Technology used 4. Data required and shared 5. Intelligence derived (if any)
Challenges	What are the challenges and gaps you face in disseminating warning messages to stakeholders and the general public?	N/A
To be process	In a future system, how would you like to disseminate the flood warning message?	1. Stakeholder View - Who are the stakeholders who need the warning message? 2. Scenario View - In what scenarios the warning message dissemination is required?

		3. Process View - Briefly explain the process of disseminating the flood warning message? What technology is used for dissemination? 4. Data View – What is the data requirement? 5. Intelligence View - What intelligence could be disseminated to the stakeholders? 6. Interface View - What is the convenient user interface to disseminate the flood warning message?

Response Capabilities

Actual Impact Monitoring

Category	**Question**	**Probes**
As is process	Could you please explain the actual flood impact monitoring process?	1. Stakeholder participation 2. Scenarios associated 3. Technology used 4. Data required and shared 5. Intelligence derived
Challenges	What are the challenges and gaps you face in flood monitoring the ground situation?	N/A
To be process	In future systems, how what sort of monitoring process to be established to get the actual ground situation in real-time?	1. Stakeholder View - Who are the stakeholders associated with flood situation monitoring? 2. Scenario View - In what scenarios the flood monitoring is necessary? 3. Process View - Briefly explain the process and technology used to monitor the current flood status? (Satellite / vGIS/Crowedsource/numerical modelling) 4. Data View - What data is needed to monitor the flood situation? 5. Intelligence View - What intelligence could be derived from the flood monitoring process? 6. Interface View - What is the convenient user interface to generate, authorize and share flood forecasts?

Rescue and Medical

Category	**Question**	**Probes**
As is process	Could you explain how you identify people who needs immediate medical and rescue support during a flood emergency?	1. Stakeholder participation 2. Possible scenarios 3. The technology used (if any) to identify and monitor 4. Intelligence derived
Challenges	What are the challenges and gaps you face in rescuing people?	N/A

To be process	In a future system, how would you like to disseminate the flood warning message?	1. Stakeholder View - Who are the stakeholders associated with rescue operations? 2. Scenario View - In what scenarios the rescue operations are involved? 3. Process View - Briefly explain the process of rescue operations in flood emergencies? 4. Data View – What is the data required for rescue operations related decision making? 5. Intelligence View - What intelligence could be derived from the data captured? 6. Interface View - What is the convenient user interface required for medical assistance/rescue operations?

Capacities

Category	**Question**	**Probes**
As is process	Could you explain how you coordinate the capacity (human resources, machinery and equipment) required for the emergency response missions?	1. Stakeholder participation 2. Possible scenarios 3. Technology used 4. Data required and shared 5. Intelligence derived
Challenges	What are the challenges and gaps that you face in finding the capacities during flood response time?	N/A
To be process	In a future system, how would you like to coordinate the capacities required for response?	1. Stakeholder View - Who are the stakeholders own and needs capacities 2. Scenario View - In what scenarios the capacity coordination is required? 3. Process View - Briefly explain the process of coordinating resources from owners to beneficiaries? 4. Data View – What is the data required? 5. Intelligence View - What intelligence is derived? 6. Interface View - What is the convenient user interface necessary to coordinate resources?

Relief and Internally Displaced Persons (IDP)

Category	**Question**	**Probes**
As is process	Could you explain how you coordinate the Internally Displaced Persons (IDP) and relief management process?	1. Stakeholder participation 2. Possible scenarios 3. Technology used 4. Data required and shared 5. Intelligence derived
Challenges	What are the challenges and gaps you face in relief management process?	N/A
To be process	In future system, how would you like to manage relief and IDPs?	1. Stakeholder View - Who are the stakeholders in relief and IDP management 2. Scenario View - In what scenarios the relief/IDP management is required? 3. Process View - Briefly explain the proposed process of managing relief and IDPs?

		4. Data View – What is the data required to manage relief and IDP? 5. Intelligence View - What intelligence is needed? 6. Interface View - What is the convenient user interface necessary to manage relief and IDPs?

User Story Template

The user stories will be captured in the survey part II of this interview. For each question under the "to-be-processes", user requirements will be captured for each probe and recorded in the form of "User Stories", by the researcher during the interview. Typically, "user stories" is a method that used to capture user requirements in software and product development.

The user story templates for each question will be filled by the researcher

Title:	Priority:	Estimate:
As a <type of user> I want to <perform some task> so that I can <achieve some goal>		
Acceptance criteria Given <some context> When <some action is carried out> Then < a set of observable outcomes should occur>		

Appendix C – Sample Interview

Transcribe of the Interview with C1
Date: 22 March 2023
Medium: Online

Survey Part I – Gaps and Challenges of Current Flood Warning and Response Systems
(Approx. time – 30 mins)

Explanation:

The first part of the interview aims to capture current gaps and challenges faced in the flood warning and response process in Sri Lanka. A structured and comprehensive literature survey revealed that 24 gaps and challenges are commonly available in implementing flood warning and response systems from the global perspective. However, these gaps and challenges may slightly vary from country to country, depending on the political, socio-economic and cultural settings. Therefore, gaps and challenges identified from the literature need country-specific validation. Therefore, this section will gather responses from the practitioners and community representatives in Sri Lanka on the applicability of the identified gaps and challenges of flood warning and response systems within the Sri Lankan context. The key gaps and challenges are categorized as follows: (i) Policy and Institutional (ii) Technical (iii) Socio-cultural.

1. According to your understanding, what are the **"policy and institutional"** related issues, gaps and challenges related to the flood warning and response system in Sri Lanka?

2. According to your understanding, what are the **"technology"** related issues, gaps and challenges related to flood warning and response systems in Sri Lanka?

3. According to your understanding, what are the **"socio-economic"** related issues, gaps and challenges related to the flood warning and response system in Sri Lanka?

Community – knowledge gap
Due to economic challenge community are in poor condition.
Behavioural issues are there – they are not preparing well. Taking too much of risk
No adequete economic condition to acquire smart phone

Policy & Institutional

Gaps and Challenges	Relevant to Sri Lanka (Y/N)	Rank if relevant
Week institutional governance, coordination and custodianships	Y	5
Lack of funding to operationalize, modernize, maintain of FEWRS systems	Y	5
Data sharing and data governance issues	Y	5
Lack of skilled human resources for data analysis, modelling and forecasting	No response	
Lack of political will and institutional leadership	Y	5
Inadequate local level preparedness for response	Y	5
Lack of knowledge and awareness of key stakeholders and community	Y	4
Lack of access to warnings and less warning coverage	Y	5

Technical

Gaps and Challenges	Relevant to Sri Lanka (Y/N)	Rank if relevant
Issues with physical protection of sensors / IoT installed	Y	3
Lack of inclusion of community and vulnerable groups in planning and decision making	Y	5
Lack of understanding of the risk and unavailability of risk information/maps	Y	5
Data / information errors	Don't know	NA
Issues with flood forecast modelling accuracies and techniques	Y	2
Inadequate flood warning lead time and inefficiencies of warning generation and dissemination	Y	5
Issues with communication and dissemination systems	Y	5
SoPs, systems are not available for better warning and response	Y	4
Lack of appropriateness, completeness and understanding of warning message and dissemination in-efficiencies	Y	5
Limited computing capacity	Don't know	na

Socio-economic

Gaps and Challenges	Relevant to Sri Lanka (Y/N)	Rank if relevant
Lack of public awareness or ability to understand the warning	Y	1
Lack of trust and credibility on the warning system	Y	5
Lack of public interest and culture of neglect	Y	5

Lack of community understanding on risk	Y	2
Lack or neglect of community participation	Y	4
Lack of community capacities in the reception of warning and influence of digital divide and limited coverage of warning services	Y	2

Survey Part II – Capturing User Requirements

Risk Knowledge

Q 1.1. Could you tell me what and how you expect to use the flood risk knowledge as a community member?

Answer: There are two key user groups who consume the risk knowledge: residents and newcomers. Residents, who have lived here for an extended period, possess local risk knowledge based on their experience with flood occurrences and their impacts. The second category comprises newcomers, who are either planning to stay temporarily or establish permanent residency. Additionally, there are those who frequently travel for work or business but do not reside here, and travelers who are unfamiliar with the area.

These four categories of citizens possess different levels of local risk knowledge. Long-term residents have prior experience with local hazard occurrences and understand the risks they face. Regular travelers have some knowledge of the area due to their familiarity with it over time. Newcomers intending to settle in a particular area need risk knowledge to select suitable lands for settlement. Meanwhile, temporary visitors or travelers require risk information for specific locations based on historical occurrences. Travelers also need current risk knowledge of a particular area or route. For instance, if I travel to Colombo, knowing the safest route for my visit enables me to plan my trip well in advance based on both past and current risks.

However, my concern lies in how users would become aware of a newly initiated system. Users may not always be informed of such initiatives or available systems. User awareness is of utmost importance. Users should be inclined to use such a system. For example, if the proposed system is an app, users should be made aware of its existence. Secondly, users should be willing to install it in order to access the service. Both of these factors need to be addressed. This poses a real challenge, as extra effort is required to introduce new users to the system and maintain their active participation. For instance, if a user is going to a supermarket, the proposed solution could be advertised within the store. "A mechanism should be available to provide users with risk information firsthand," possibly through guiding signboards.

Regarding risk awareness, users should be informed of the availability of an information system or mobile app that provides risk knowledge in a particular area. Before purchasing new land for settlement, users should be aware of how to evaluate the risk. How can users become aware of this? There should be a mechanism in place. Local authorities or councils should promote this awareness. Alternatively, awareness materials, brochures, or posters could be displayed in public areas to inform users (signing boards). Furthermore, for those with general risk knowledge, there should be a mechanism to obtain additional risk knowledge. Therefore, such systems should also facilitate access to additional or on-demand information.

Alternatively, we should be able to use information or knowledge from other means and sources. For example, there should be a facility to push information services through other popular e-services and mobile apps.

The quality of the information service should be maintained to retain users of the system. Therefore, the following key areas should be addressed: accuracy, relevancy, trustworthiness, currency, reliability, and, finally, the "wow factor".

The "wow factor" will serve as an attraction to keep users engaged with the system. This can be achieved through advanced analytics of the data to provide useful information or intelligence that can benefit end users. Such strategies will foster user loyalty to the system; the overarching goal is to enhance sustainability.

Q1.2. Could you explain how you need to visualize the risk information?

Answer:

Language is crucial. All users should be able to read and understand the information in their native language. Typically, web-based services and apps are designed by entering information in one language and then automatically translating it into other languages. I recommend avoiding this approach, as it can often lead to distortion of the original meaning. Instead, translations for each language should be done separately to ensure the accurate representation of each word and sentence. This will significantly enhance the user experience.

Customized interface - Another important consideration is that the service should cater to all possible user categories. Some users may be part of the general public with limited domain knowledge, while others may have a more specialized understanding. Users should have the ability to customize the interface to suit their individual preferences and desired complexity level.

Responsibility - For example, users often tend to uninstall apps, especially mobile ones. To address this, a follow-up mechanism should be put in place to keep users engaged. If a user uninstalls the app or stops using the system intentionally or unintentionally, there should be a way to reach out to them through personal contacts and encourage them to re-engage. Given that disaster information is critical for the day-to-day lives of the public, it's crucial to have a mechanism in place to re-engage users who may have uninstalled the app or left the system.

Users should derive additional benefits from the shared information. It's important to explore how the data collected for disasters can be useful in other aspects of daily life. For instance, a bakery owner who receives rainfall information could use it to make decisions about daily travel plans, routes, and timing for door-to-door visits by sellers. We should investigate whether the data generated in the flood early warning process could be applied to support other day-to-day decision-making needs of the public. This approach will not only increase the usability of the system but also ensure its continued relevance. For example, a bakery owner who distributes products to households through retail sellers could make use of this app for planning purposes.

Question – Do you have any design perspective on the proposed interface or presentation mode?

Answer:

The presentation mode should be adaptable to the individual's knowledge level and preferences. Customization for each user is key. Providing a range of tools for users to choose from based on their interests and level of understanding is essential. For example, some individuals may comprehend information better through visuals like pictures, while others may prefer maps, graphs, or text. Therefore, it's advisable to incorporate an administration panel or configuration facility where users have the freedom to select their preferred presentation mode.

Additionally, considering the effectiveness of emojis in conveying information, it might be a very practical and engaging way to share information. As seen in the case of the 2021 Olympics in Japan, a series of emojis were developed to offer basic information to international participants who may not understand Japanese characters. This approach could prove highly effective in communicating risk information to a wide audience.

Question – What type of monitoring, forecasting and warning mechanism do you expect?

Answer:

2.1 IoT/gauges are used to monitor the environment, and this data is usually consumed by the community. Do you have any idea how the community can use the outputs of the monitoring data? Can you suggest an appropriate proposal from the point of view of the end user?

The change in the environment is crucial to end-users. Engaging end-users can greatly support monitoring efforts. People often prefer to share data rather than just consuming it. We can leverage this interest of the general public to make the system more interactive and involve them as informers. Users could be ranked based on their participation, and some form of benefits could be offered to the most active users.

Question: How could information on environmental changes (IoT/gauge data) be useful for the public?

Users should have access to view IoT/gauge data as a basic principle. Instead of limiting the specific types of information, users should be provided with a wide range of information sources to choose from based on their interests. Users should have high flexibility in this regard. For instance, if I'm receiving information for my default residential area and I'm traveling, the system should start issuing information related to my current route. Imagine if I'm driving with the assistance of Google navigation, I might receive disaster data and warnings related to my route. Furthermore, if my daughter is traveling towards an area prone to high floods, I should be able to track her journey and assess the potential impact of the ongoing flood event.

Question: 2.2 Forecast – how do you like to receive flood forecasts and warnings?

The forecasts can be both positive and negative. Some people may need positive forecasts, while others may require negative forecasts. The forecast should be customizable from the user's perspective. For example, if a user is expecting rain, the system should provide a forecast for rain. On the other hand, if someone is concerned about dry conditions, the forecast should cater to that.

Regarding warnings, even in the absence of a formal warning, a form of information service or advisories could be issued regularly. While adhering to WMO traditional standards is important, I suggest that the system could also generate advisories. It's worth noting that sometimes adhering strictly to standard procedures can be limiting. As a researcher, there's room to propose innovative solutions that challenge traditional methods.

Warning – We should change the standard lead time by improving the process.

Improving the lead time for warnings is crucial. This means enhancing the processes involved in issuing warnings, possibly through the use of advanced technologies and methodologies.

Question: What would be the suitable interface for the warning?

The warning should be delivered promptly. If it's the final warning, the user may not have the opportunity to cancel it. In terms of media, warnings should be independent of specific platforms or devices. Alternatively, a multimedia warning system could be employed. For instance, if a user has a basic phone, warnings should be delivered through that device. If the user has a smartphone, the warning can be sent via advanced means. In the absence of a personal device, warnings should be issued through the nearest fixed device.

2.3 Potential impact

Do you have any idea about issuing and visualizing impact-based warnings?

I can classify users into three categories. The severity of the warning should be easily comprehensible to the user.

Technical individuals can understand potential impact by interpreting raw data such as rainfall intensity and water levels. They should be provided with more detailed raw data or information to allow them to derive forecasts or warning products.

The second category includes those who can understand processed technical data in simpler, everyday language.

The third category consists of users who may not understand the technical details. They should receive warnings in a way that forcefully alerts them, even if it means interrupting their current activities. For example, if a child is playing a game, the warning message could override the screen to get their attention.

Question: What user requirements do you expect for Warning Dissemination?

The objective of the warning is to provide advice on a potential danger. As mentioned earlier, everyone who is in danger should receive the warning, regardless of their current activities.

Considering the three categories of users receiving early warnings (DM-related professionals, other professionals not in the sector, and all other parties), it's important to identify the type of user based on their domain knowledge and educational level. The system should be able to customize warning messages based on these categories, providing at least two customized options. The system should also classify and select the receiver accordingly.

Additionally, there should be a confirmation or feedback loop to the sender based on the recipient's risk level. Facilities for live location tracking of the user's device or static address registration of potentially affected users could be implemented.

Capturing user responses to warnings is also crucial for evaluating the effectiveness of the warning system.

What strategies do you think can improve users' active participation?

The disaster-related information may be valuable for other domains. Sharing this information beyond the DM sector can help maintain user engagement.

Feedback and Ownership

Empowering users with a sense of ownership of the system can enhance feedback. Letting the public know that the system belongs to them can encourage more active participation. Each step of an incident, such as recording rainfall, water levels, capturing images of damage, and reporting water levels, should be shared by the public. The public is often eager to share data. For example, if there's heavy rain in my area, having a feature in a system or phone that allows me to click a button when the rain starts and stop it when it ends can make me feel that my data is contributing to flood warnings. This sense of ownership encourages user engagement.

To combat monotony, the system's interface could be periodically changed. Another proposal is to offer users rewards based on their interactions. Virtual recognition and benefits for crowdsourced partners, including public agencies in Disaster Management, Local Authorities, and Business Agencies, could be implemented. Utilizing sensor data combined with crowdsourced impact data through machine learning analysis can be valuable for various agencies in protecting their infrastructure and users, such as road authorities or insurance agencies. This creates a mutual benefit for both users and agencies.

Actual Impact Monitoring

Reporting during the response phase to capture flood impacts is crucial. Both citizens and government officers can contribute to updating the system. There are two types of data providers: official and unofficial. This information can be valuable for future forecasts. Additionally, the system's output can be utilized to assess damage and losses of properties, aiding in the claims process after the incident. It also ensures transparency in the claims process, as the system's outputs can serve as evidence.

Rescue and Medical

After authorities issue a warning, some people may evacuate the site, but others may remain in affected areas where rescue teams need to reach them. In Sri Lanka, the emergency hotline is 119. The proposed system could facilitate requesting ambulances, helicopters, and rescue support.

Camp management is another critical aspect. Determining where to locate rescued persons, managing the capacity of the camps, overseeing resource allocation in the camps, and arranging for the return of Internally Displaced Persons (IDPs) to their homes are all activities that can be supported by the proposed system.

Capacities

Question: How can we coordinate the capacity requirement?

You've aptly used the term "resources." Managing resources during an emergency is crucial. This involves estimating resource requirements - what is needed, how much, and when - during an emergency. The steps include:

Identifying available resources (boats, doctors, food, etc.).
Determining their locations or how to reach them.
Deciding when these resources are needed.
Specifying the location where these resources are needed.
Relief

Question: How can we manage Internally Displaced Persons (IDPs) in the future system?

If a particular family is affected by floods annually, authorities can use this information to permanently relocate them, thereby avoiding recurring flooding. This solution would take effect from the following year. The system can generate a potential list of users for this management process. In the meantime, the system can assist in evacuating the family well in advance. This proactive approach can help avoid last-minute rescues, ultimately reducing the risks and costs associated with emergency relocations.

Appendix D - Research Papers

1. Samansiri, S., Fernando, T., & Ingirige, B. (2023). Critical Failure Factors of Flood Early Warning and Response Systems (FEWRS): A Structured Literature Review and Interpretive Structural Modelling (ISM) Analysis. *Geosciences*, *13*(5), 137.

2. Samansiri, S., Fernando, T., & Ingirige, B. (2022). Advanced technologies for offering situational intelligence in flood warning and response systems: A literature review. *Water*, *14*(13), 2091.