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Translating early warning into early action in Indonesia

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Research Article

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Abstract

Non-technical summary. Floods repeatedly disrupt lives, livelihoods, and public services across Indonesia, while available warnings do not always lead to timely action. This article shows how rainfall forecasts can become practical early actions before flood impacts escalate. Evidence from four Indonesian regions highlights that rainfall thresholds can support earlier decisions, while stakeholder engagements reveal the procedures, coordination, and community readiness needed to act on warnings. The study demonstrates that linking forecasts with clear responsibilities and prepared local systems can reduce avoidable losses, improve disaster governance, and strengthen resilience to elevating climate-related risks.

Technical summary. Despite advances in weather forecasting and flood warning systems, the operational translation of early warning into anticipatory action remains limited in Indonesia. This gap constrains the effectiveness of disaster risk reduction, particularly in regions exposed to recurrent hydrometeorological hazards. To address this challenge, historical rainfall, flood occurrence, and impact records from Gresik Regency, Samarinda City, South Barito Regency, and Medan City were analyzed using Log Pearson III return-period estimation and cumulative distribution functions to identify locally relevant trigger thresholds. The results indicate that rainfall exceedance levels around the 90th, 95th, and 99th percentiles provide technically credible benchmarks for preparedness escalation and resource mobilization, with marked variation across hydroclimatic settings. Stakeholder consultations further reveal that forecasting information is increasingly available, but implementation shall be supported by standard operating procedures, systematic communication pathways, functional role clarity, and sufficient local validation mechanisms. An operational framework is proposed, which links forecast thresholds, impact monitoring, verification processes, and predefined actions. The findings provide evidence for embedding forecast-based action within decentralized disaster governance systems in Indonesia and comparable flood-prone settings of other countries.

Social media summary. Operationalizing warnings into action can strengthen anticipatory disaster governance.

1. Introduction

Global spending on emergency response continues to outpace investment in preparedness, underscoring the need for greater investment in disaster risk reduction (DRR). Disasters generate substantial direct economic losses, strain public expenditures, and cause indirect GDP losses that significantly affect essential facilities and people's lives (Bevan & Cook, 2015; Shabnam, 2014). By contrast, DRR is a no-regret investment that protects lives, property, livelihoods, schools, businesses, and employment. The Sendai Framework for Disaster Risk Reduction (SFDRR), adopted by the UN member states in 2015, emphasizes investment as a priority for decreasing disaster risks and losses. The SFDRR encourages strengthening institutional modalities to address disaster risk (UNISDR, 2015).

Indonesia is widely recognized as a disaster-prone country, experiencing numerous events each year. Over the last decade, the National Disaster Management Authority (Badan Nasional Penanggulangan Bencana, BNPB) has reported an upward trend in annual disaster occurrences. Between 2010 and 2020, the highest number of events occurred in 2019 (approximately 3,814), with the numbers of missing persons and fatalities reaching into the hundreds to thousands. Another peak occurred in 2018 with 3,397 events, affecting 6,240 people. That year saw a sequence of major disasters, including the Lombok earthquake (West Nusa Tenggara), the Palu earthquake and tsunami (Central Sulawesi), and the Sunda Strait tsunami. Updated data on disaster events and impacts are available from BNPB's portal (https://dibi.bnpb.go.id/).

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Given the adverse implications for national development targets, Indonesia must strengthen capacities from national to local levels to anticipate future disasters. This endorsement is in line with the recent efforts of ASEAN to encourage anticipatory action across countries in Southeast Asia (ASEAN, 2022).

The UNDRR (2023) urges countries worldwide to address the systemic disaster risks containing cascading and compounding risks (Sulfikkar Ahamed et al., 2023). Cascading risks involve impacts that can propagate within and across systems and sectors, potentially leading to existential consequences and, in the worst case, system collapse over varying time horizons (Lawrence et al., 2020). Compounding risks arise when two independent hazards interact to create new risks. Recognizing both components supports improved prediction, analysis, and risk communication for designing early actions (De Risi et al., 2022; Sillmann et al., 2022). Systemic risk can undermine economies and disrupt social cohesion, hindering progress toward key intergovernmental agendas, including the Paris Agreement, the SFDRR, and the Sustainable Development Goals (Arrighi et al., 2021; Renn et al., 2022).

Theoretical and practical debates increasingly emphasize bridging early warning with anticipatory action as part of disaster risk governance and adaptive governance frameworks (Hurlbert, 2017; Kelman et al., 2015). While studies have advanced rainfall thresholds and community-level preparedness (Mentzafou et al., 2023; Shah et al., 2022; Tarchiani et al., 2020), relatively few have translated these insights into institutional mechanisms for anticipatory action. This constitutes a critical gap: forecast-based approaches remain underutilized in informing standard operating procedures (SOPs) within disaster management systems (Wilkinson et al., 2018). Anticipatory action, also framed as early warning for early action, responds to this gap by emphasizing reliable early warning systems, preparedness plans, and timely interventions triggered by forecasts and risk assessments (Sillmann et al., 2022; Tozier et al., 2023).

The ASEAN Framework on Anticipatory Action in Disaster Management seeks to ensure that early warnings are systematically translated into effective anticipatory action to reduce disaster impacts across the region (ASEAN, 2022). Typically, this approach integrates data analysis, community engagement, and coordinated response strategies. In the context of systemic and cascading risk, anticipatory action entails identifying and addressing interconnected risks before they escalate into larger-scale disasters, recognizing potential ripple effects and interdependencies among hazards that may amplify consequences. Anticipatory measures, such as early warning systems, contingency planning, and coordinated response, enable authorities and communities to more effectively avoid or limit catastrophic losses to lives and infrastructure.

In Indonesia, disaster events are predominantly hydrometeorological. BNPB reports that floods, landslides, and whirlwinds have been the dominant hazards in the past decade, with floods being the most frequent. Indonesia's disaster data system (https://dibi.bnpb.go.id/) recorded about 500 flood events from 2007 to 2021, with the affected population reaching up to 4 million people annually and damage to thousands of residential structures. Floods cause both direct and indirect impacts that differ between urban and rural settings (Chanut et al., 2019): urban areas tend to experience residential and infrastructure losses, whereas rural areas commonly face agricultural impacts. Resulting damages include loss of life and injury; destruction of residential, commercial, industrial, and agricultural areas; and impairment of infrastructure such as drainage and irrigation systems, roads and railways, bridges, and telecommunications (Chanut et al., 2019).

The Indonesian context illustrates the operational gap. While capacities to generate weather forecasts and flood warnings are expanding, the use of this information to trigger predefined actions remains at an early stage. This study addresses three research questions: (a) What rainfall thresholds can serve as anticipatory action triggers? (b) What institutional capacities and gaps influence the operationalization of these thresholds? and (c) How do key stakeholders perceive the translation of early warning into early action? By addressing these questions, the study contributes to refining Indonesia's disaster governance and to international debates on institutionalizing anticipatory action.

International experience offers relevant lessons. In Bangladesh, flood forecasts inform pre-agreed humanitarian interventions (Lopez et al., 2020); in Uganda, drought triggers have been tested to release cash transfers (Coughlan de Perez et al., 2016); and in Japan and the Netherlands, established institutional models for flood preparedness demonstrate how structured governance can reduce systemic risk (Kerstholt et al., 2017; UNDRR, 2023). The Indonesian case adds to this global dialogue by showing how statistically derived rainfall thresholds can be validated through multi-stakeholder engagement, while also drawing lessons from contexts where early action protocols (EAPs) are already institutionalized (Weingärtner & Wilkinson, 2019).

This study focuses on translating flood early warning systems into early actions (EWEAs) in Indonesia. EWEA, as a stage of flood risk management, remains in an initiative phase in the country and requires further exploration. Gaps persist in utilizing weather forecasts to inform flood early warnings and in classifying them into disaster early warnings that are actionable for decision-making. These latter warnings are critical for determining what anticipatory actions are needed to minimize or avoid adverse consequences, particularly catastrophic losses affecting essential facilities and human lives. In particular, gaps exist in defining the elements and processes required to operationalize the translation of early warnings into early actions. This research explores existing modalities that can meet Indonesia's needs for EWEA operationalization; these modalities are key to proposing an appropriate scheme or mechanism for EWEA implementation.

The study explored the country's capacities for developing an operational EWEA mechanism using selected study areas. The areas are (a) Gresik Regency, (b) Samarinda City, (c) South Barito Regency, and (d) Medan City. These areas were selected to represent different climate types, watershed sizes, and flood consequences across urban and rural settings in Indonesia. The goal is to provide countrywide insights to identify feasible rainfall thresholds that can trigger early action and to inform a flood early warning system that supports proactive disaster management. EWEA comprises three major elements: early warning, early action, and resource mobilization. The action is aimed to avoid or at least mitigate disaster impacts. Therefore, the study results will enhance the knowledge and understanding of anticipatory action among all parties involved in flood risk management, i.e., technical agencies, related institutions, and communities (Rosmadi et al., 2023; Shah et al., 2023). Cooperation among these parties (Rozi et al., 2021) is essential to ensure the implementation of both structural and nonstructural measures to mitigate or avoid the adverse impacts of floods (Conitz et al., 2021).

2. Methodology

A recent study on the conceptual theory of the early warning system (Alcántara-Ayala & Oliver-Smith, 2019) criticized the need to

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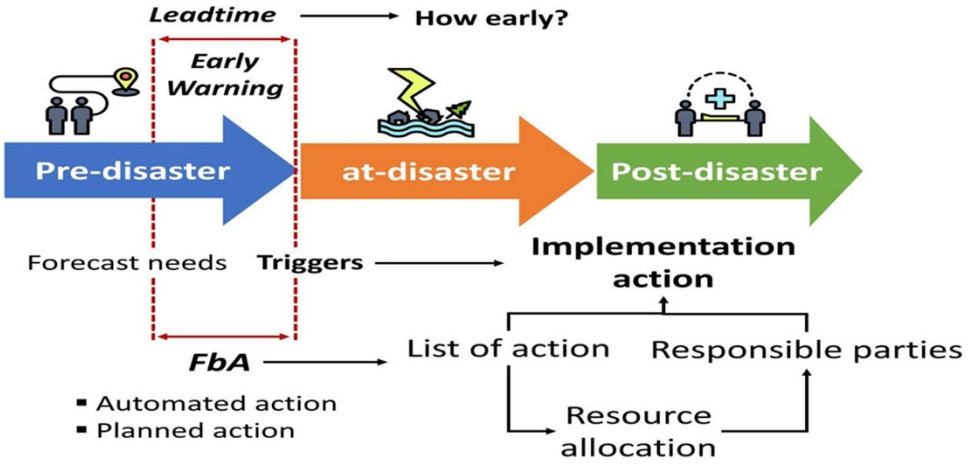


Figure 1. Illustration of early warning to early action (EWEA), i.e., forecast-based actions (FbAs) or anticipatory action in Indonesia.
Source: Modified from Perdinan et al. (2020).

consolidate the early warning system targeted for reducing damages from hazard onset and reducing disaster risks. The different speed of hazard onset provides information on the different lead times required for forecasting the events. These different speeds of hazard onset also signify the need to identify what actions within the time speeds (i.e., early action) can be done to avoid or minimize catastrophic or massive damages or losses (Staupe-Delgado & Rubin, 2022). Response to a predictable hazard to avoid or mitigate the adverse impacts of hazard events to safeguard lives and livelihoods is endorsed to be embedded in disaster risk management (DRM; Keim, 2015). Forecast-based action (FbA) or anticipatory action is an initiative to take steps to protect people before a disaster strikes based on early warnings or forecasts. Many anticipatory action initiatives and projects exist in more than 60 countries worldwide (CERF, 2021). Specifically for Indonesia, Perdinan et al. (2020) illustrated the position of early warning within the pre-disaster action that is essential to consider lead time (i.e., forecasting capacity) as the element for trigger actions, either autonomous or planned actions, to mobilize resources. This illustration describes the three elements of anticipatory action (ASEAN, 2022), focusing more on the disaster impacts for devising proper actions (Vahlberg et al., 2022). In Indonesia, the implementation is challenged by several factors related to available and accessible data, adequate knowledge, proper capacity and skills, operational tools and systems, and public understanding and participation (Fig. 1).

This study evaluated existing data and information explored from the study areas to construct a proposed mechanism for FbAs or EWEAs in Indonesia. This research started by collecting available data and information required to fulfill the elements of EWEA from relevant sources in the country. The data and information are related to historical rainfall, flood occurrences, and their impacts. The statistical analyses were applied to assess the return period of rainfall and the association of rainfall intensity with flood events. The stakeholders' engagements are also approached to validate the findings and explore indicators or triggers used for the development of EWEA operationalization. The engagement was conducted in the form of stakeholders' consultations or focus group discussions (FGDs), which involved various stakeholders. Participants were government officials, nongovernmental organizations, and meteorological experts, who provided valuable feedback to refine the required elements and processes to operationalize the EWEA in the country.

2.1. Study areas

The study areas, i.e., Gresik Regency, Samarinda City, South Barito Regency, and Medan City, are dominantly flat, less than 40 m above sea level (Fig. 2). Medan City is prone to floods, exacerbated by minimal water absorption and flood control policies that only focus on the river channel without maintenance in the upstream area. The damage to the watershed area increases surface runoff and decreases groundwater filling, resulting in a drastic increase in river flow, particularly during the rainy season. In conditions of extreme damage, there will be significant floods in the rainy season. This condition is exacerbated by the occupancies of Medan City as the residential area (Fig. 3), with minimal infiltration capacity. Samarinda City has characteristics that are similar to Medan City. The high population growth has led to massive infrastructure development. The flood events in Samarinda City occur due to degraded watersheds in the upstream area and local rainfalls, causing river overflows and tides on the Mahakam River (Sulaiman et al., 2020). Generally, residential areas are very close to water bodies such as rivers, which increase the potential for losses due to abundant water inundations (Zain et al., 2014). Furthermore, South Barito and Gresik are generally characterized as rural areas and located downstream. The land use of South Barito and Gresik is dominated by agricultural lands and plantation (Fig. 3). In these regencies, flood events cause losses and damages to the agricultural sector.

The availability of climate stations in the study areas is essential as data on historical rainfalls are employed to assist in determining thresholds to trigger early action. Implementation of FbAs requires the availability and accessibility of data on rainfall events and totals (Perdinan et al., 2020). The climate stations employed in this study are operated by the Indonesian Bureau of Meteorology, Climatology, and Geophysics, named in Bahasa as *Badan Meteorologi, Klimatologi, dan Geofisika* (BMKG; Table 1). The climate data are obtained from the BMKG online data system by downloading the data every month. The climate variables include rainfall averages, monthly air temperature averages, and daily rainfall.

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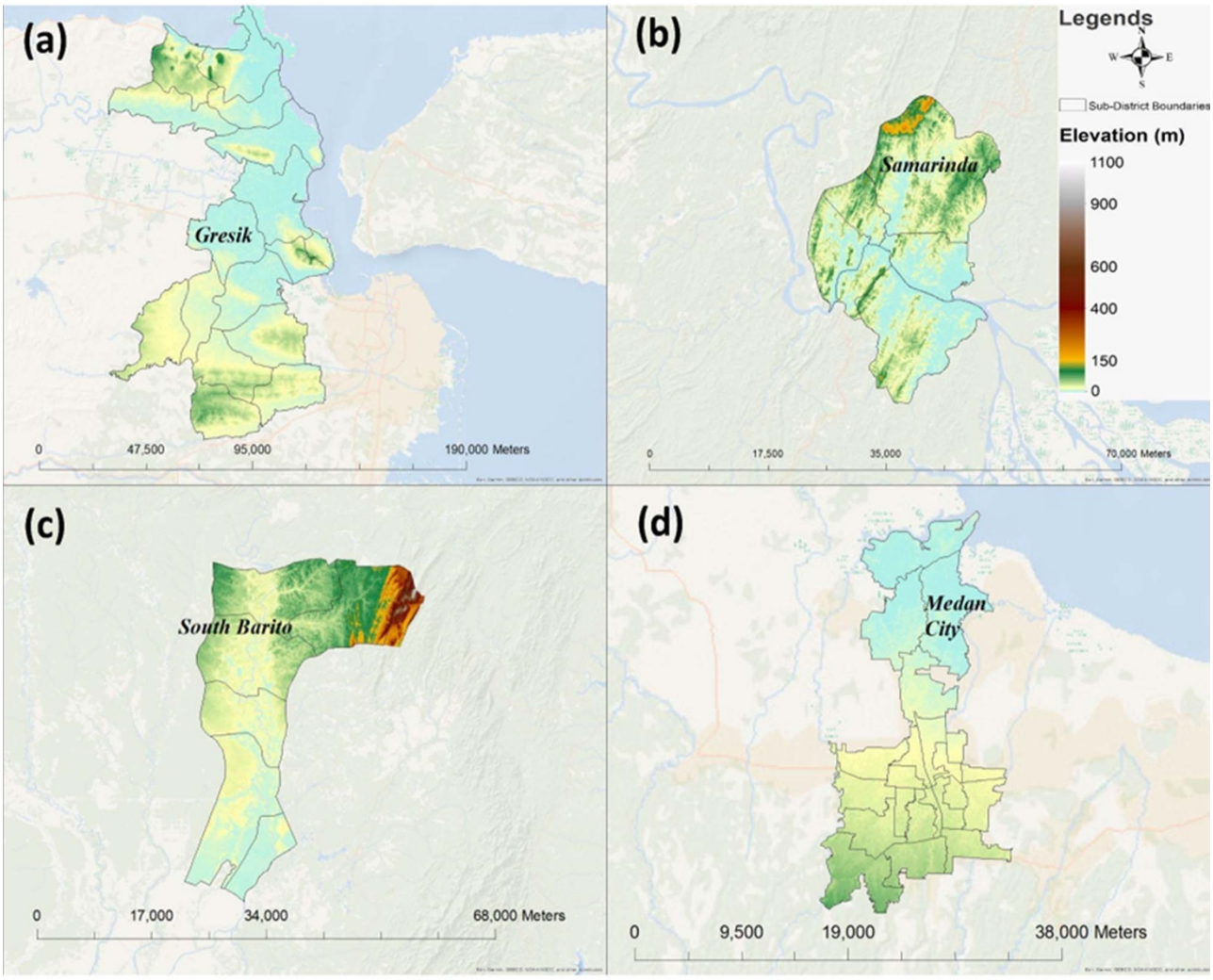


Figure 2. Topographical information in the study area. (a) Gresik Regency, (b) Samarinda City, (c) South Barito Regency, and (d) Medan City.
Source: Geospatial Information Agency (2021).

2.2. Method of analysis

2.2.1. Return period of rainfall

The analysis of the return period aims to determine the extreme rainfall events based on historical rainfall events recorded by the climate station. The return period is defined using the method of Log Pearson III with the formula:

$$Log\ X_t = \underline{Log\ X} + (G \times S)$$

where

X_t = The amount of rainfall with period t (mm),

Log X = The average value of the logarithm of the observed data X (mm), and

S = Standard deviation of the logarithmic value of the observed data.

Three important parameters for the Log Pearson III are the standard deviation (S) and the coefficient of tension (G). The return period analysis was completed using the Spreadsheet applied to rainfall data from the climate station operated by BMKG (Table 1).

2.2.2. Rainfall intensity and flood events

The rainfall intensities impacted by flood events are identified using rainfall events on the 0, 1, and 2 days before the flood occurrences. The flood incidents obtained from BNPB are reported based on the date of the flood incidents. The rainfall intensity is categorized into six classes (Table 2) measured in millimeters per day following BMKG.[1] The analysis is applied to create a matrix to plot rainfall intensities 2-day (D-2), 1-day (D-1), and 0-day (D-0) before the date of the flood occurrences.

Extreme rainfall can be defined as the cumulative probability of daily rainfall in a certain period exceeding a threshold. Extreme values can be defined based on daily rainfall intensity above certain percentiles, i.e., 90th, 95th, and 99th percentiles (Bodini & Cossu, 2010). This study employs the cumulative distribution function (CDF) to describe the probability that the rainfall intensity, represented by x, with a given probability distribution, will have a value less than or equal to x. This CDF calculation is completed based on the relationship with the probability density function (Kokoska & Zwillinger, 2000).

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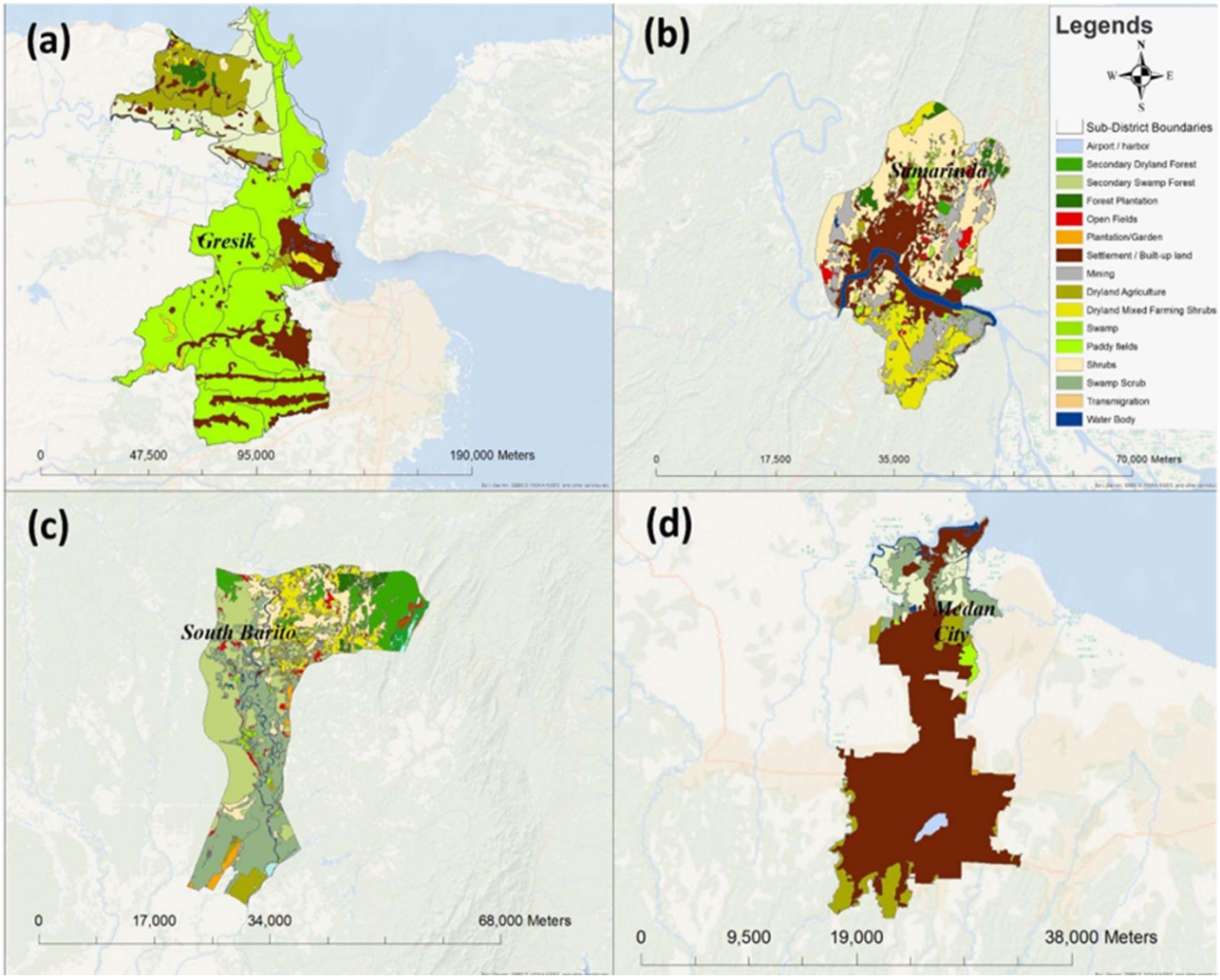


Figure 3. Land-use information in the study area. (a) Gresik Regency, (b) Samarinda City, (c) South Barito Regency, and (d) Medan City.
Source: Ministry of Environment and Forestry (2019).

Table 1. Climate stations used in this study

City/District	Climate station	Coordinate	Climate variable	Period
Medan City	Maritime Meteorological Station Belawan	3.781, 98.702	Rainfall and temperature	2010–2021
Samarinda City	Meteorological Station Temindung	−0.482, 117.156	Rainfall and temperature	2002–2021
South Barito Regency	Meteorological Station Sanggu	−1.668, 114,897	Rainfall and temperature	2000–2021
Gresik Regency	Silver Meteorological Station I	−7.223, 112.724	Rainfall and temperature	1991–2021

Table 2. The categorization of rainfall intensities into six classes

Rainfall intensity (mm/day)	Class
0	Cloudy
0.5–20	Light rain
20–50	Moderate rain
50–100	Heavy rain
100–150	Very heavy rain
>150	Extreme

2.3. Stakeholders' engagement

This study conducted workshops and FGDs to explore current knowledge and operational modalities related to anticipatory action. The process was coordinated by the Indonesian Red Cross (*Palang Merah Indonesia* [PMI]) with support from the International Federation of Red Cross and Red Crescent Societies (IFRC). Stakeholder engagement served both to validate the study design and results, particularly the indicators and rainfall thresholds proposed as triggers for early action, and to assess practical opportunities and challenges in operationalizing early warning into early action.

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Table 3. Stakeholder consultations on translating early warning into early action in Indonesia

Consultation	Date	Participant	Topics (key questions)
First consultative meeting	October 19, 2021	Red Cross Indonesia (10 people)	**Research design and criteria for study location determination** – What needs to be considered in choosing the study locations – Do IFRC and Red Cross Indonesia named in Bahasa Palang Merah Indonesia (PMI) have capacity in the target area?
Second consultative meeting	9 February 2022	Climate Center of IFRC (8 people)	**Climate characteristics and initial findings** – Does the target area represent the climate type in Indonesia? – Is the flood event at the location due to heavy rain or from the upstream flow? – Are the triggers to be used consistent with weather and disaster information from official agencies in Indonesia (i.e., BMKG and BNPB)?
Third consultative meeting	June 21, 2022	Red Cross Indonesia, Regional Disaster Management Authority (BPBD), and IFRC (30 people)	**Lessons learned from early action at the regional level** – How are early warnings disseminate to the community? – When is the early warning activated? What triggers? – Who are the stakeholders involved in early action efforts? – What gaps and modalities does each region have?
Fourth consultative meeting	October 13, 2022	Climate Center of IFRC (8 people)	**Formulation of early action strategies** – What is the focus of early action? Life-saving, health, etc. – What are the priorities? – What early actions can society take? – What assistance is required for early action?
Fifth workshop consultative meeting	November 11, 2022	Red Cross Indonesia, Regional Disaster Management Authority (BPBD), Red Cross Indonesia at Subnational level, and IFRC (35 People)	**Research challenges and opportunities** – Best practice from regional red crosses for determining threshold considerations and list of early actions? – How to integrate research findings with national government modalities?

Table 4. Analysis of the return period for the study area

	Rainfall intensities (mm/day)			
Return period (years)	Gresik	Medan	Samarinda	South Barito
2	84.04	93.02	84.68	65.30
5	104.56	108.97	110.13	103.62
10	118.76	123.85	134.87	146.04
15	127.77	135.16	154.40	182.84
25	137.46	147.51	176.76	228.91
30	144.52	155.39	191.08	271.07
50	151.95	163.69	206.57	321.00
100	166.94	193.36	266.81	449.68
200	182.55	221.82	328.10	629.47
1,000	221.97	308.22	490.75	1,378.40

Between October 2021 and November 2022, a series of five consultative meetings were held with representatives from PMI, IFRC, the National Disaster Management Authority (BNPB), local disaster management authorities (Badan Penanggulangan Bencana Daerah [BPBD]), and other humanitarian actors. Participants were purposively selected through institutional partnerships to ensure relevant expertise and operational experience. The consultations captured a wide range of institutional perspectives, although individual attendees varied across sessions. Each meeting addressed specific themes aligned with the study objectives (Table 3).

Despite the strengths of combining statistical analysis with participatory engagement, this study presents several limitations. First, the FGDs and workshops, while involving a range of national and subnational institutions, were limited in number and scope, meaning the perspectives captured may not fully represent the diversity of stakeholders across Indonesia. Second, although the case study areas were chosen to reflect different hydrological and climatic conditions, the identified rainfall thresholds and early action triggers remain context-specific and require local validation before broader application. Third, while the statistical methods employed (Log Pearson III and CDF) are robust for analyzing historical rainfall patterns, they depend heavily on the completeness and accuracy of available data, which may be constrained in some regions. These limitations highlight the need for further longitudinal and comparative research to refine and generalize the proposed early action framework.

3. Result

3.1. Thresholds and triggers

Daily data analysis from climate stations in the study area provides information on the maximum rainfall value in a specific return period (Table 4). Information on the value of extreme rainfall can be used to identify rainfall intensities contributed to flood events. If there is a specific rainfall value with a frequency faster than the return period, this can be considered an extreme condition. A rainfall value occurring at a frequency faster than its return period can be considered an extreme condition, making the area more prone to flooding. For example, the 5-year return period provides rainfall intensities over 100 mm per day, which

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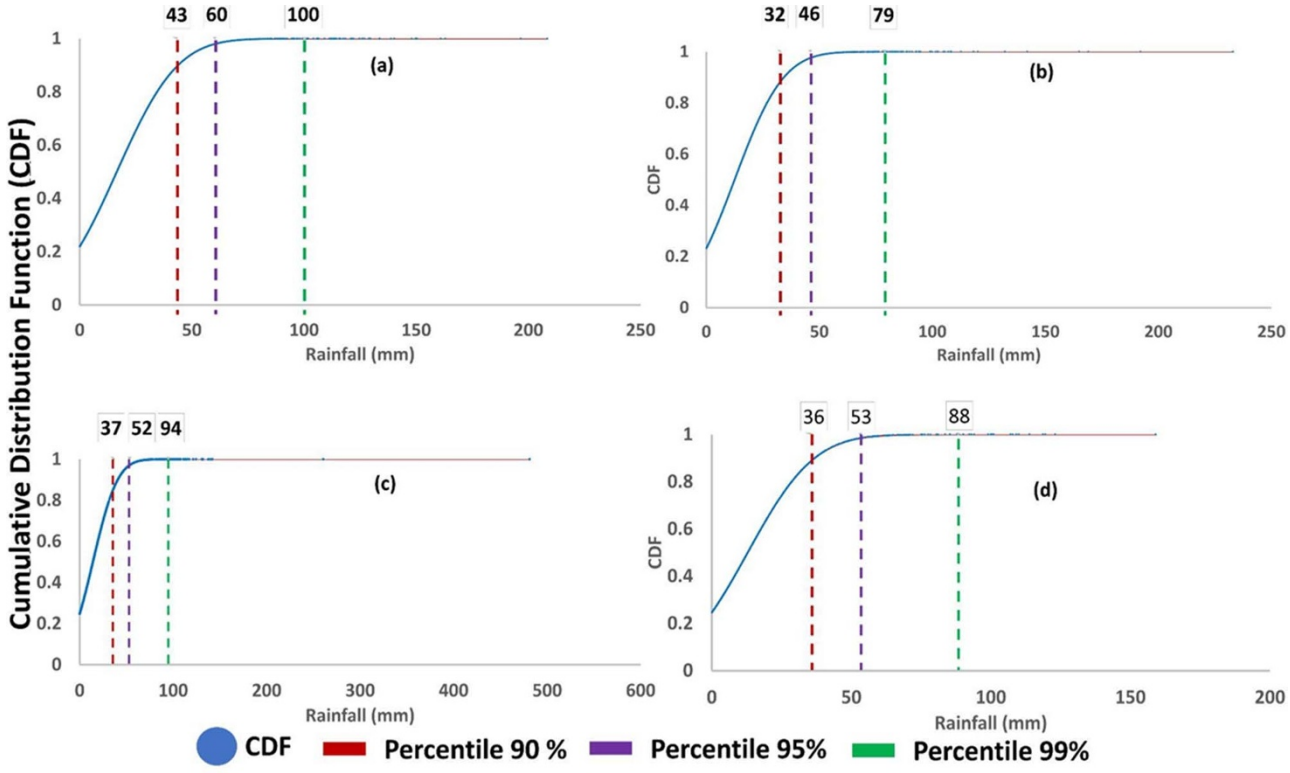


Figure 4. Cumulative distribution functions for determining the daily rainfall thresholds in the study area. (a) Gresik Regency, (b) Samarinda City, (c) South Barito Regency, and (d) Medan City.

may be considered for the thresholds of early warning to flood events. Furthermore, CDF (Fig. 4) is applied to determine the rainfall intensities for specific percentiles. The intensities for the 90th, 95th, and 99th percentiles in Gresik Regency are 43, 60, and 100 mm/day, respectively. Samarinda City's rainfall intensities are 32, 46, and 79 mm/day. The values for South Barito Regency are 37, 52, and 94 mm/day. For Medan City, the rainfall intensities are 35, 53, and 88 mm/day. These percentile thresholds provide a statistical basis for anticipatory action: exceedance of the 95th percentile indicates a high-probability event requiring preparedness measures, while the 99th percentile corresponds to conditions that justify pre-positioning of emergency resources.

The CDF results show rainfall thresholds ranging from 32–94 mm/day (90th–95th percentile) to more than 100 mm/day (99th percentile), with local variation reflecting differences in hydrological response, topography, and watershed size. For instance, in Gresik Regency, rainfall above 100 mm/day (99th percentile) has historically been associated with widespread flooding. On the contrary, Samarinda City exhibits lower percentile thresholds (32–79 mm/day), yet still experiences severe flooding due to poor drainage and rapid urban expansion. For example, the flood that occurred on January 11, 2020, in Samarinda City illustrates how statistical extremes interact with human-induced vulnerabilities. In this event, rainfall exceeded the 95th percentile, causing extensive damage, including the destruction of 31 infrastructures, which was further exacerbated by urban development pressures, reduced infiltration from land-use changes, and limited drainage capacity.

This highlights that while rainfall thresholds are scientifically robust, they must be contextualized within socio-environmental conditions and institutional readiness (Hirabayashi et al., 2013; Winsemius et al., 2016). In operational terms, integrating percentile-based rainfall triggers with local vulnerability assessments can enhance the design of anticipatory actions, ensuring that thresholds are both meteorologically valid and practically actionable.

3.2. The impacts of flood events

There were 73 flood disaster events from the period 2011 to 2021 that occurred in Gresik Regency (Fig. 5). The most enormous impact occurred on January 30, 2011, caused by the high intensity of rainfall, leading to cause Kali Lamong overflows. The impacts damaged 726 infrastructures. Two peaks of high rainfall intensity (112 and 111 mm) caused Kali Lamong to evaporate. About 40 flood events occurred from 2011 to 2021 in Samarinda City. The most considerable impact in Samarinda City occurred on January 11, 2020, damaging 31 infrastructures. This flood was due to the high rainfall intensity that occurred the previous day. Figure 5 shows that South Barito experienced 16 flood events from 2011 to 2021. The peak of rainfall intensity occurred on November 9, 2017 and hit the Barito River. Floods in the North Hamlet District impacted people's infrastructure and homes. The floods also affected community activities and road access around the Barito River. Figure 5 shows a light rainfall that informs the occurrence of floods. This situation can be caused by a flood of shipments from the upstream areas, leading to an increase in the water discharge of the Barito River in the downstream area. For Medan City, there were 49 flood events from 2011 to 2021. The most immense impact in Medan City occurred on April 1, 2011. The most extensive loss was caused by damage to 250 infrastructures or buildings. The high intensity of rainfall earlier in the day caused the overflow

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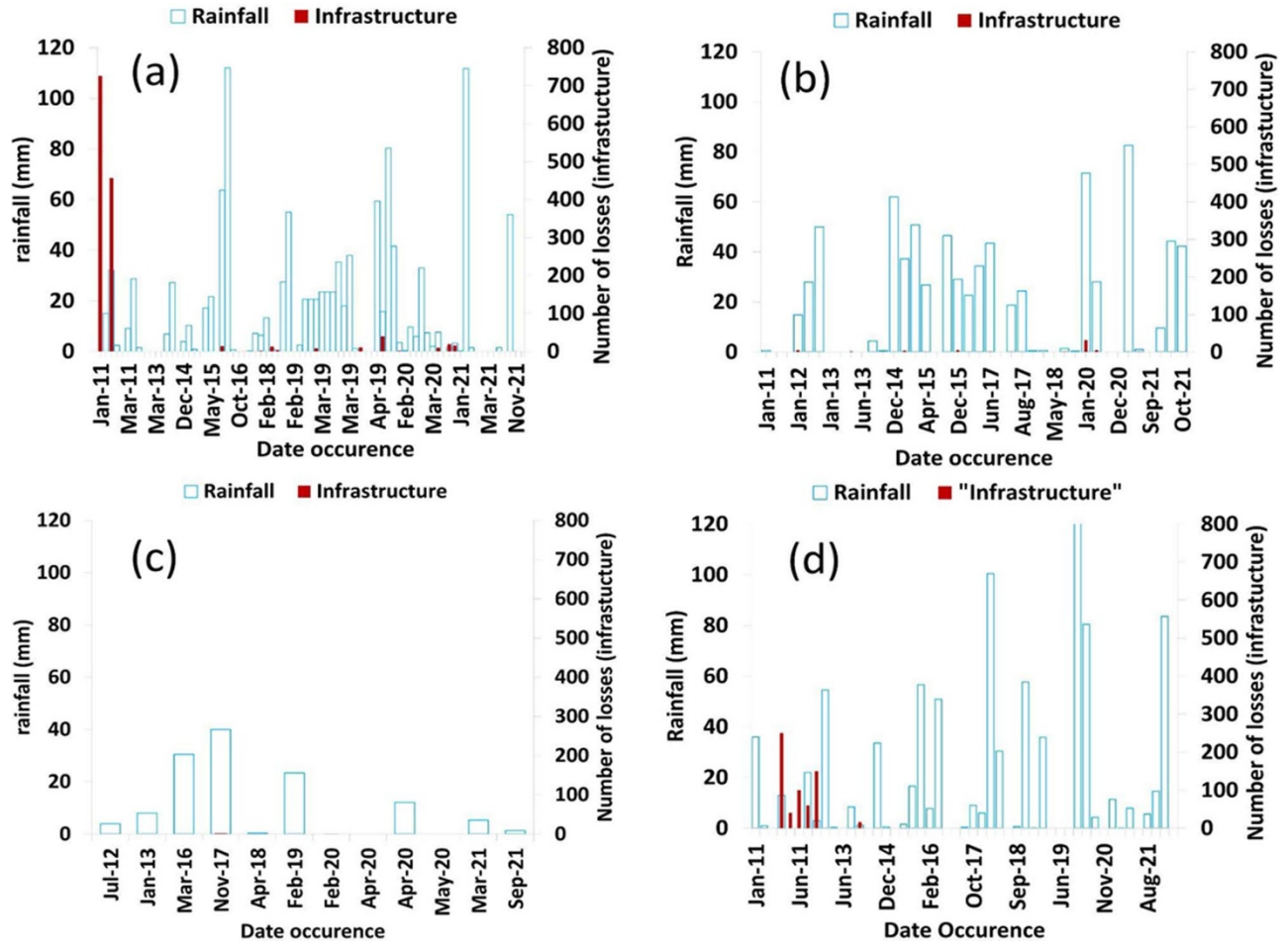


Figure 5. Historical dates of flood events (*x*-axis), recorded rainfall amount (*y*-axis), and reported number of losses (affected infrastructures categorized as minor, moderate, and severe damages, *y*-axis) based on Indonesia Disaster Data and Information (dibi.Bnpb.Go.Id) for the study sites: (a) Gresik Regency, (b) Samarinda City, (c) South Barito Regency, and (d) Medan City.

of two large rivers passing through Medan City and its surroundings, namely the Deli River and Babura River. On January 29, 2020, a high rainfall intensity of 159 mm caused buildings with a 50–80 cm puddle depth.

Extreme rainfall that causes flooding can significantly impact building infrastructure, both in terms of physical damage and functional disruption. Physically, floods can damage foundations, building materials, and electrical and mechanical systems, potentially leading to structural collapse and operational failure. Additionally, the functionality of buildings is often compromised, with schools, hospitals, and other public facilities rendered unusable, and access to buildings is hindered due to damaged transportation infrastructure. These impacts also result in substantial economic losses from repair costs and the loss of productivity and essential services. The data presented, sourced from the National Disaster Management Agency named in Bahasa BNPB, record the number of building infrastructures damaged due to flooding and categorize them as minor, moderate, and severe based on Indonesian disaster data and information (dibi.bnpb.go.id).

The size of rivers, rainfall intensity, and the upstream runoff determined flood risks in the study sites. River size affects its capacity to retain incoming water volumes. Regardless of the river sizes, the rivers are still susceptible to flooding when rainfall exceeds their capacity (Miller et al., 2021). Rainfall intensity, defined as the amount of precipitation over a specified period, serves as a key indicator for determining flood occurrences. High-intensity rainfall can cause a rapid water flow, overwhelming river and drainage capacities, and increasing the risk of flooding. The upstream runoff contributes to flood risk in downstream areas (Lee et al., 2024). Rainfall in upstream regions can augment water flow into main rivers (Johnson & Chen, 2023), exacerbating flood conditions in the downstream even if rainfall intensity in the downstream is moderate.

3.3. *Baseline situation for translating early warning into early action*

The stakeholder engagement was carried out by inviting relevant agencies to the implementation of translating EWEA. The agencies are the Meteorological, Climatological, and Geophysical Agency (BMKG), Ministry of Public Works (*Kementerian Pekerjaan Umum dan Perumahan Rakyat* [PUPR]), National Disaster Management Agency (BNPB), Indonesian Red Cross (PMI), National Search and Rescue Agency (*Badan Nasional Pencarian dan Pertolongan*/BASARNAS), River Management Authority of the Ministry of Public Works (*Balai Besar Wilayah Sungai* [BBWS]), Regional Disaster Management Authority (BPBD), and PMI's volunteers from the study area. The participants provided

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Table 5. The existing or baseline condition for the translation of early warning to early action in Indonesia is summarized based on the conducted stakeholder engagements

Location	Result
Medan City	**General or Regular Actions** • Cleaning the Deli River. **Early Warnings** • Provide information as soon as possible to the public. • Early warning refers to information about high rainfall from BMKG via WhatsApp. • Dissemination of TMA information to the community through the WhatsApp group with each village's head of the environment. **Early Actions** • There is coordination between institutions or communities (covering BPBD, BMKG, BASARNAS, PMI, flood task force, firefighters, and others). • BPBD carries out monitoring and evaluation of flood events. • When a flood disaster occurs in Medan City, BPBD will create disaster posts consisting of various components. Prioritization of aid recipients refers to data collection by principals.
Samarinda City	**General or Regular Actions** • Check the condition of the building and its surroundings. • Conduct debriefing in the form of training in the field of disaster. **Early Warning** • The threshold for early warning of flood events in Samarinda City is based on Water Level (TMA). • TMA monitoring can be monitored directly using a mobile phone online. • Using information from BMKG for rainfall monitoring and early warning of rainfall. • Utilization of TMA information when the threshold is alert, alert, and alert, namely officers (PMI), gives more vigilance to agencies handling floods before going to the community. **Early Action** • Coordination of BMKG, BPBD, PMI, and Basarnas. • Appeals to the media and even local journalists to be able to inform the public so that when the rainfall starts to get heavy, they can anticipate. • Basarnas mechanism for aid providers, namely coordinating with BNPB and BPBD to map out which locations require assistance channels and what can be provided or needed. • The PMI mechanism for assisting affected communities is to conduct an assessment first and distribute it to affected districts, especially the most vulnerable communities, and then to other communities.
Gresik District	**Early Warning** • Early warning information will be communicated via WhatsApp and available on the BBWS Bengawan Solo website. **Early Action Stakeholders** • Coordination of BMKG, BPBD, BBWS, PMI, and volunteers. • Every time it rains with high rainfall intensity (>50 mm), there will be a BBWS warning status (green, yellow, and red). What each warning does is: ◦ Green: BPBD prepares equipment such as cars, boats, tires, and pumps. ◦ Yellow: Coordinate with village officials and volunteers and provide information on locations that will be affected. ◦ Red: Volunteers are already on site; inventory of needs (aid and evacuation tents). A command post will be developed if the flood occurs for more than 3 days.
South Barito District	**Early Warning** • BMKG always reports on the daily weather in the upstream and downstream areas through the WhatsApp group (PMI, BPBD, volunteers, social services, and tagana). • TMA observations are carried out in the upstream and downstream areas. **Early Action** • Coordination of BMKG, BPBD, TRC, Basarnas, PMI, and volunteers. • Through TRC (Quick Reaction Team), convey it to the village level. • Assistance area for evacuation.

information regarding the existing conditions and modalities for implementing EWEA. The responses are summarized in Table 5.

The stakeholder engagement identified modalities and gaps regarding information on hazards, impacts, and actions related to implementing FbA in Indonesia. The identification was made for each rainfall type included in the study, namely: (a) equatorial type (Samarinda City and Medan City) and (b) monsoonal type (Gresik and South Barito). The summaries of the findings are presented in Fig. 6 for the equatorial type and in Fig. 7 for the monsoonal type. The stakeholders were generally informed that the primary information of early warnings is from the BMKG, and disseminated rainfall prediction via WhatsApp. However, the early warning information still needs to have an SOP for updating schedules, causing the early warnings to often be known by relevant stakeholders and circulated too late. The BBWS of PUPR employs water-level monitoring (in Bahasa named *Tinggi Muka Air* [TMA]) and reports the monitoring results to BPBD. When there is a warning of flood events, the information may be spread

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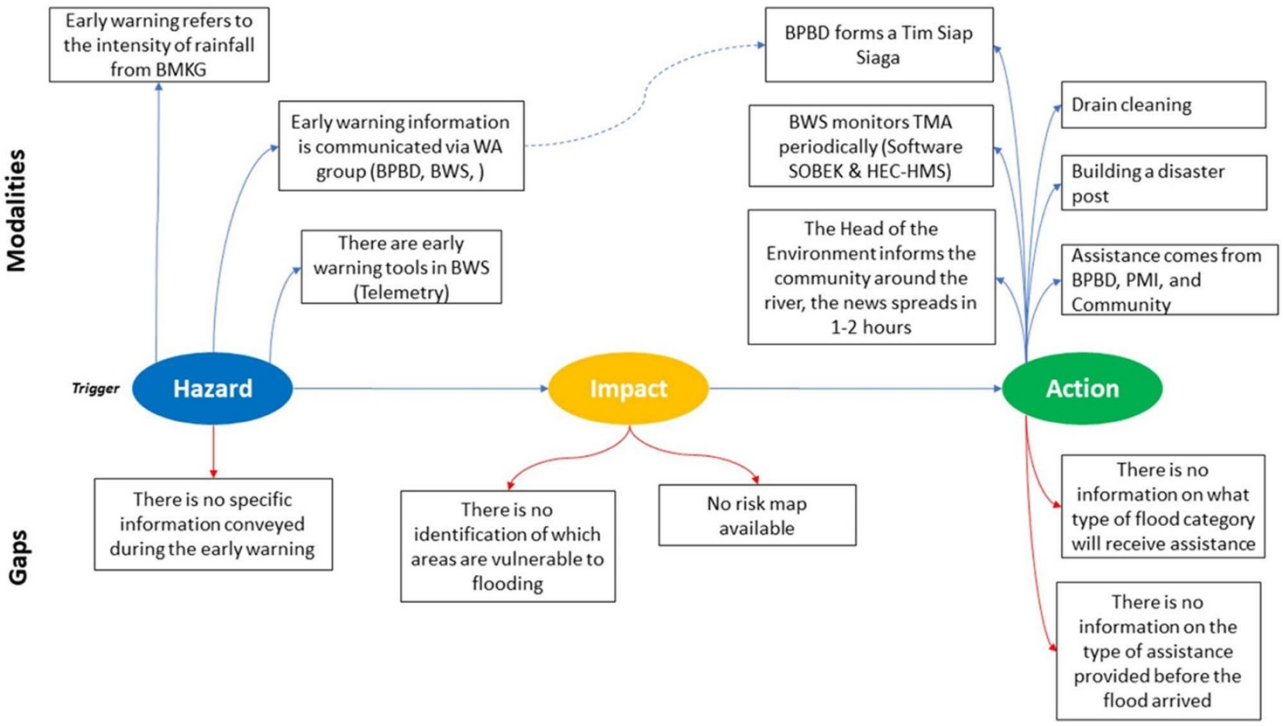


Figure 6. The modalities and gaps of translating early warning into early action were identified from the stakeholder engagement with participants grouped for the equatorial region, i.e., Samarinda City and Medan City.

to the community via WhatsApp, environmental groups, and traditional tools such as mosque speakers and alarms sounded by drums. BPBD usually coordinates the rapid reaction team to the community about evacuation routes, the whereabouts of vulnerable groups, and the possible affected areas. Unfortunately, risk and vulnerability maps have yet to be widely used for delineating the flood impact assessment. The community may take early action regarding the alerts. For example, the PMI branch took early action with the local government. The actions include cleaning drains, preparing tools and infrastructure for aid posts, and making embankments to divert the path of water overflow. The communities are urged to save their property. The different responses for the two groups (Figures 6 and 7) are merely the details on accessible information and responded actions.

4. Discussion

4.1. Utilization of weather data and information

The preparation of EAPs in Indonesia is based on early warning information regarding floods available in Indonesia. The trigger modality is rainfall intensity. The classification of rain between 50 and 125 mm/day is indicated to be a trigger for flood events in Indonesia. BMKG, as the responsible authority at the national level, already has a BMKG 'Signature' (https://signature.bmkg.go.id/) that provides information on potentially affected areas based on weather information released since 2020. The next part is the identification of the rainfall, which will have a detrimental effect if a flood hazard occurs. Therefore, reference data are needed that can be used as a reference for estimating the impact of loss and damage if a flood hazard occurs in a location. INARISK of BNPB (https://inarisk.bnpb.go.id/) provides data on potential losses, including the affected population, physical losses, economic losses, and environmental damage. Analysis of flood triggers based on rainfall that becomes a reference, including rainfall on the day (D-0), D-1, and D-2 before the flood events. The triggering intensity that causes flooding is rainfall intensities of 50–125 mm/day. This range is obtained from the heavy rainfall defined by BMKG and the cumulative rainfall of 2 days before the rain day until the day of the rain day, causing flood events. Therefore, the 50 mm of rainfall amount can be used as a reference for early action at the community level and the 100 mm for early action for resource mobilization, including the financing scheme. The illustration is in Figure 8.

The use of existing modalities offered in this study initiates the development of EAPs for the operationalization of EWEA in the country. The protocols can be developed using the rainfall records and flood impact analyses of the related early warning systems discussed above. The connection of historical data on rainfall and flood events can be employed to define the trigger thresholds (Fig. 8). The protocols can also be tailored to address weather extremes caused by flood events to design the required early actions effectively. The use of rainfall intensities as thresholds can refine early warning triggers, ensuring timely and appropriate responses. The available real-time monitoring tools, such as weather radar and observed water-level stations, can be employed to complement the implementation of the protocols for tracking the forecasted rainfall intensities caused by flood events. The protocols can also be part of training programs and public education initiatives to enhance our understanding of early action measures, ultimately improving capacity on flood risk management based on rainfall forecasts.

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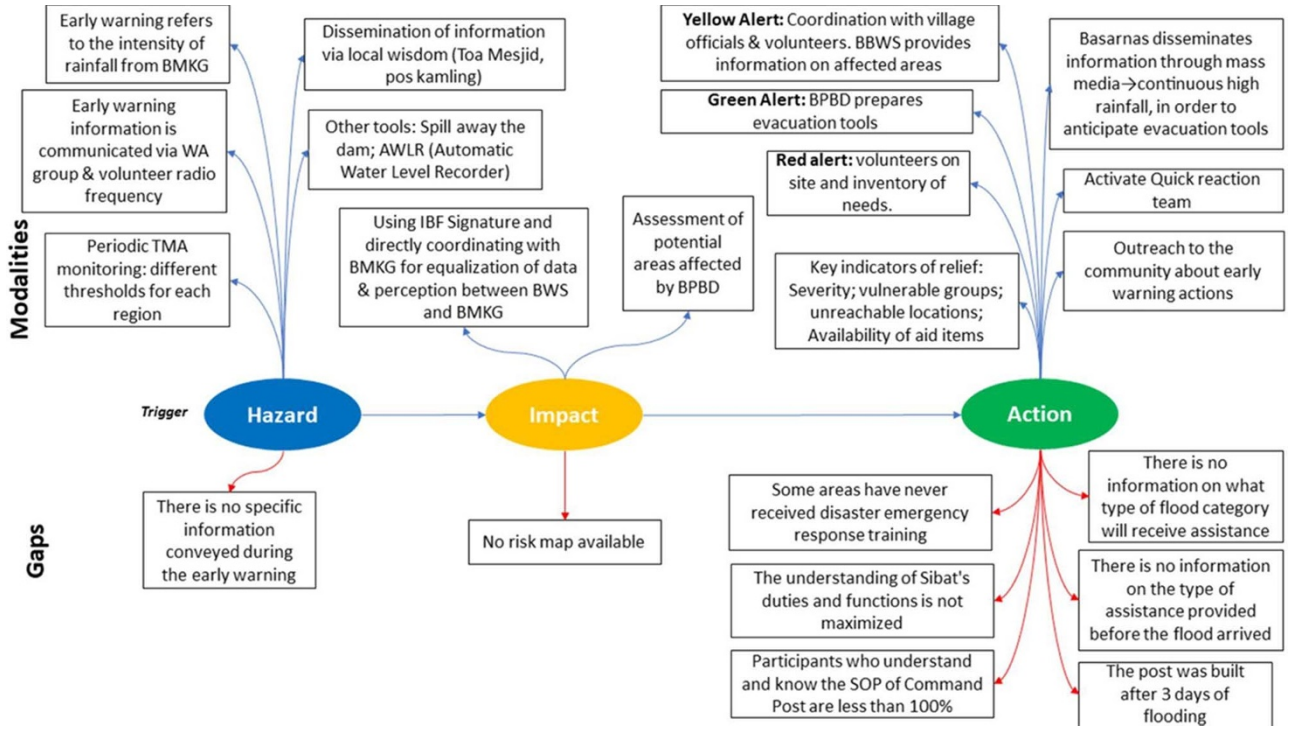


Figure 7. The modalities and gaps of translating early warning into early action were identified from the stakeholder engagement with participants grouped for the monsoonal region, i.e., Gresik Regency and South Barito Regency.

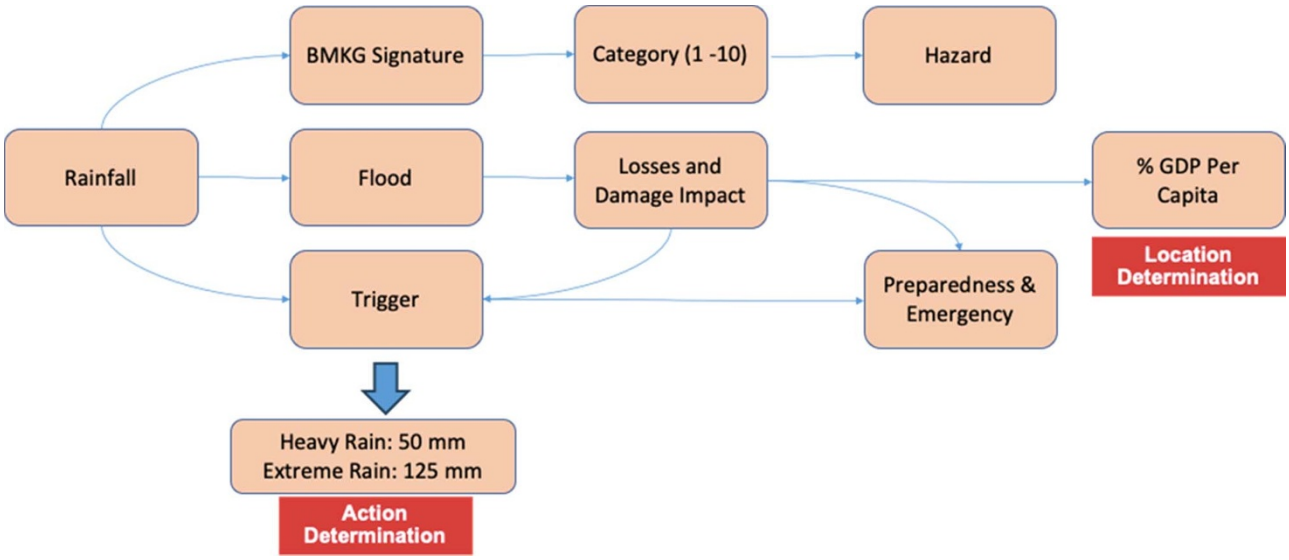


Figure 8. The connection of rainfall intensities, their impacts on flood events, and their implications for losses and damages is illustrated for developing early action protocols in Indonesia.

4.2. The proposed implementation

This study identified the proposed mechanism for operationalizing the FbA or EWEA approach in Indonesia (Fig. 9). The FbA or EWEA is an approach that utilizes weather forecasting capacities and a pre-agreed threshold to pre-allocated funds, enabling a set of planned early actions to reduce impacts (Pilli-sihvola et al., 2020). The proposed mechanism is constructed by considering the following three primary components (Vahlberg et al., 2022):

- **Triggers:** Based on detailed risk analysis of relevant natural hazards, impact assessments of past events, and vulnerability data, 'danger levels' for a region are identified. Then, a forecast trigger is identified that will give notice before the 'danger level' is reached.
- **Selected early actions:** The predefined actions that will be implemented during a triggering forecast to reduce the humanitarian impact of an event.
- **Financing mechanism:** an ex ante financing instrument that automatically allocates funding once a forecast is triggered,

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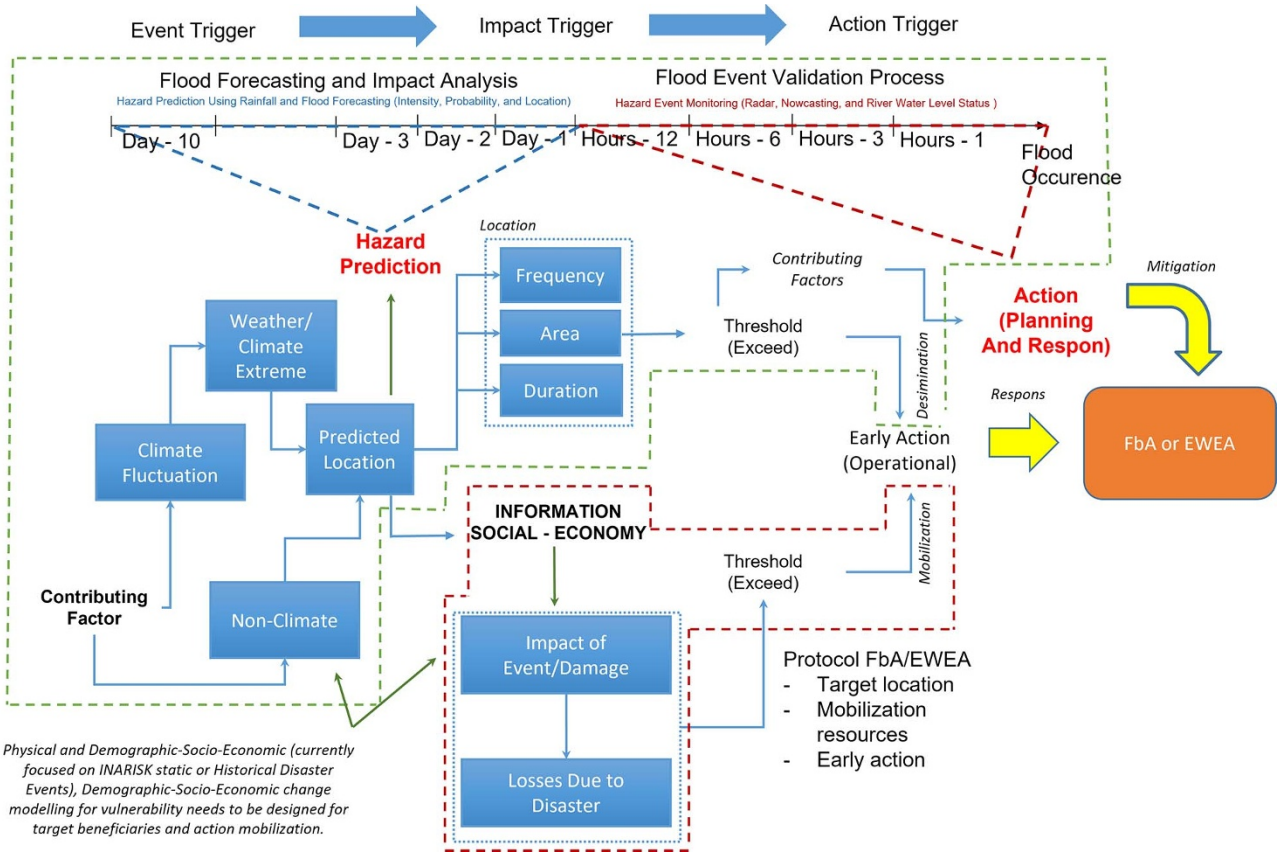


Figure 9. The proposed mechanism and required elements for translating early warning, i.e., a prediction of hazard events, into the potential impacts (*event trigger*), to early action, i.e., the predicted impacts that are determined to cause potential damages or losses (*impact trigger*), that require an autonomous and systematic action (*action trigger*) for mobilizing resources to avoid or minimize the potential damages or losses affected to essential facilities or people lives to manage flood risks.

which enables the effective implementation of early actions. These components are summarized in an EAP. The EAPs serve as action guidelines delineating roles and responsibilities for quick action when a trigger is reached.

The proposed mechanism hopes to shift the current disaster management mindset of response to a disaster to a 'response to a forecast' – a shift that leverages current capacities and strengths and applies them to anticipatory approaches. The translation of EWEA for managing flood risk in Indonesia (Fig. 9) can be operationalized based on available modalities. Recent rainfall predictions, available up to 10 days in advance, provide information on rainfall intensity and the probability of occurrence under normal and extreme weather conditions (e.g., 20 mm of rainfall in 6 hours or 50 mm in 24 hours). These forecasts can be tracked through radar estimation and nowcasting outputs from the BMKG. The observed rainfall totals leading to flooding are monitored through observing water levels in the rivers by the PUPR, categorized into four alert levels: Alert Level IV (Normal), Alert Level III (Caution), Alert Level II (Alert), and Alert Level I (Danger). The validation process for predicted flood events is based on monitoring weather radar, nowcasting, and water levels, which should be tracked 24 hours before the flood occurrence. The monitoring and tracking (within 12 hours to 1 hour before the flood occurrence) provide inputs as a trigger for actions by the authorities. If the action trigger is not met, an early action stop mechanism will be implemented in response to the early warning that has been issued.

The use of rainfall probability based on extreme weather forecasts in stop mechanisms for flood early action has been successfully implemented in several countries. In Peru, rainfall probability forecasts determine whether to initiate or halt early action (Lala et al., 2021). This mechanism is employed to prevent unnecessary resource allocation when the probability of extreme rainfall decreases (Jones & Patel, 2020). Another example is in Australia, where preventive measures adjust in response to changes in rainfall probability over time (Australian Bureau of Meteorology, 2021). This approach allows for flexible action that is updated based on real-time information. Other countries, such as Germany and the Netherlands, combine rainfall probability forecasts with real-time observational data from radar or satellites to refine decisions in the stop mechanism (Müller & Schumann, 2022). In Germany, stop mechanisms are activated earlier if forecasted rainfall is not corroborated by observational data (German Federal Institute of Hydrology, 2020). In the Netherlands, an automatic system halts warnings when the probability of extreme rainfall drops below a threshold that could cause significant infrastructure damage (Dutch Water Authority, 2021). This integrated approach enhances flood response, reduces costs, and improves the overall effectiveness of early warning and early action strategies (UNDRR, 2021).

Learning from the existing country's modalities and the other countries' experiences, the operationalization of the FbA or EWEA (Fig. 9) at the national and subnational levels requires a multi-stakeholder collaboration among relevant agencies. Further research is still required to evaluate the translation of weather

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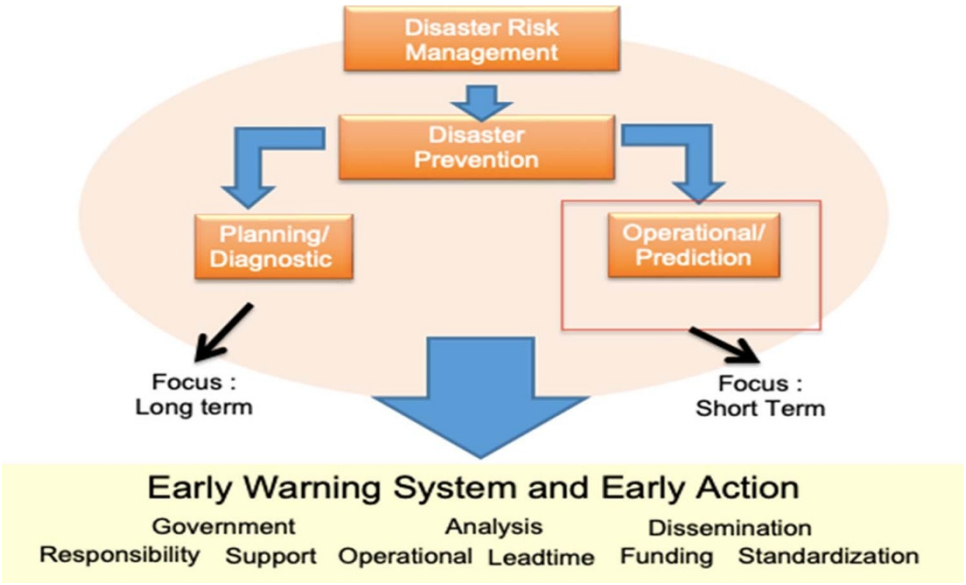


Figure 10. The elements of disaster prevention about early warning and early action.

information to hazard warnings into possible disaster events, from which early action can be taken. The main element is understanding the different rainfall threshold levels for hazard warnings and trigger actions. This information is needed to identify the thresholds and triggers required to translate early warning into early action in Indonesia.

Our findings highlight that the absence of clearly defined SOPs is a major barrier to translating EWEA. While this study does not prescribe SOPs, it emphasizes their necessity for institutionalizing EWEA in Indonesia. The results demonstrate that percentile-based rainfall thresholds are technically feasible, but their translation into anticipatory action requires embedding within SOPs that regulate update schedules, clarify institutional roles, and formalize communication protocols. To ensure that early warning systems are not only technically reliable but also operationally effective, SOPs should be designed to cover several essential elements:

1. **Clear update schedules**: Forecasts and warnings should be refreshed at consistent and predefined intervals (e.g., every 6–12 hours), with more frequent updates during high-risk periods.
2. **Defined roles and responsibilities**: The SOP should clearly specify which institutions are accountable for generating, validating, and disseminating early warning information at national, subnational, and local levels.
3. **Trigger-based communication protocols**: Predefined thresholds (such as rainfall intensity or probability) should automatically activate a communication chain and initiate preparedness or response actions.
4. **Verification and feedback mechanisms**: Procedures should ensure that warning messages are received, acknowledged, and acted upon by all relevant stakeholders, particularly at the community level.
5. **Integration with local decision-making**: SOPs should support timely coordination among technical agencies, disaster management authorities, and frontline responders, enabling locally grounded actions such as community alerts, evacuation planning, and resource mobilization.

By outlining these operational elements, this study provides guidance for relevant agencies, such as BMKG, BNPB, BPBD, and PMI, to develop context-specific SOPs. Embedding such procedures would reduce delays and miscommunication, thereby enhancing the reliability, timeliness, and effectiveness of early warning systems as enablers of anticipatory action.

4.3. Way forward strategies for collaborative effort

Anticipatory action within the framework of DRM refers to a proactive approach or measures in addressing and mitigating the impacts of disasters (i.e., prevention) (ASEAN, 2022). Disaster prevention expresses the concept and intention to avoid potential adverse impacts of hazardous (i.e., disaster) events. While certain disaster risks cannot be eliminated, prevention aims at reducing vulnerability and exposure in such contexts where, as a result, the risk of disaster is removed (UNDRR, 2015). Disaster prevention promotes the early warning system and early action, which contain several indicators in Fig. 10. This figure illustrates that early warning and early action are integral to disaster prevention. Early warning involves the timely dissemination of information about impending hazards or risks. Early warning systems use various data sources and forecasting models to provide advance notice to communities and authorities, allowing them to prepare and respond effectively (ISDR, 2006). Early action refers to the proactive measures taken in response to early warning information. When potential hazards or risks are identified through forecasting, early action involves implementing preparedness plans and interventions before the disaster strikes, reducing its impact and saving lives (Kiptum et al., 2023).

Early warning systems and early action endorsers start from global to national policies. The SFDRR 2015–2030 justified the Global Target (point g): 'Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to communities by 2030' (Sulfikkar Ahamed et al., 2023). The Multi-hazard Early Warning Conference, held from May 22 to 23, 2017, in Cancún Mexico, by the World Meteorology Organization, produced a checklist according to the

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four main elements of an early warning system: (a) disaster risk knowledge based on systematic data collection and disaster risk assessment; (b) detection, monitoring, analysis, and forecasting of hazards and their possible consequences; (c) dissemination and communication, by official sources, of authorized, timely, accurate, and actionable warnings and related information on likelihood and impact; and (d) preparedness at all levels to respond to warnings received. Article 8 anchored loss and damage in the Paris Agreement, adopted at COP 21 (2015), also encourages areas of cooperation and facilitation to enhance understanding, action, and support, including (a) early warning systems and emergency preparedness; (b) slow onset event; (c) event that may involve irreversible and permanent loss and damage; (d) comprehensive risk assessment and management; (e) risk Insurance facilities, climate risk pooling, and other insurance solutions; (f) noneconomic losses; and (g) resilience of communities, livelihood, and ecosystems.

As an example of feasible implementation, the vision for FbA or EWEA is to shift the current disaster management mindset of response to a disaster to one that is 'response to a forecast' – a shift that leverages current capacities and strengths and applies them to anticipatory approaches. The envisaged approach factor in the decentralized governance approach is to build an FbA or EWEA architecture that embraces the expertise and local knowledge of the community. In the words of the community level, 'Locals know what locals need'. The desire is for FbA or EWEA in Indonesia to become a multi-stakeholder process in which collaboration and knowledge-sharing are embedded into program design. Therefore, the overall outcome will be a regime shift toward anticipatory approaches that empower those impacted to take action to mitigate the effects of a disaster, with the systems and finances in place to support locally. To further translate this vision into practice, EWEA must be embedded in a systematic DRM framework that ensures coherence between global guidance and local implementation. Building on the findings of this study and international experience, eight interlinked elements are identified as essential for institutionalizing anticipatory approaches:

1. **Early warning systems:** Establishing reliable and timely mechanisms to detect and forecast hazards, ensuring actionable information reaches both authorities and communities.
2. **Risk assessment and vulnerability analysis:** Systematically assessing exposure and vulnerability to identify priority areas and populations for early action.
3. **Preparedness plans:** Developing pre-agreed action plans, including evacuation, resource allocation, and communication protocols.
4. **Community engagement and awareness:** Promoting public understanding, trust, and participation so that warnings translate into timely actions.
5. **Resource allocation and pre-positioning:** Ensuring that supplies, equipment, and personnel are ready for rapid mobilization once triggers are met.
6. **Interagency coordination:** Strengthening horizontal and vertical linkages across agencies and actors to reduce fragmentation and duplication.
7. **Policy formulation and implementation:** Embedding anticipatory action within DRM policies and aligning them across national to subnational levels.
8. **Monitoring and evaluation:** Establishing feedback loops to assess effectiveness, refine thresholds, and improve protocols over time.

5. Conclusion

Translating EWEA remains at an initiative phase in Indonesia, and the gap between warnings and timely responses continues to limit the effectiveness of DRR. This study addressed that gap by examining how rainfall thresholds can be operationalized as triggers for anticipatory action, assessing institutional capacities and barriers, and exploring stakeholder perspectives on the integration of early warning into early action. The combining statistical rainfall analysis with multi-stakeholder consultations across diverse hydroclimatic contexts offers an evidence on the feasibility of EWEA in Indonesia.

The study's findings show that percentile-based rainfall thresholds (90th, 95th, and 99th) provide technically credible triggers for anticipatory action, validated through engagement with relevant institutions. However, the effectiveness of these thresholds is constrained by institutional barriers, particularly the absence of SOPs. The SOPs define update schedules, roles and responsibilities, and communication protocols. Stakeholders acknowledged the importance of translating EWESs but highlighted challenges in coordination, timeliness, and local-level validation. These results confirm that operationalizing EWEA requires not only technical thresholds but also institutional embedding through clear procedures and coordinated governance.

The implications of this study are threefold. For policy, agencies such as BNPB, BMKG, BPBD, and PMI should formalize SOPs that align rainfall thresholds with predefined early actions, supported by multi-stakeholder coordination and community engagement. For management, disaster authorities must establish systematic procedures for timely updates, trigger-based communication, and verification mechanisms that reach communities effectively. For science, the integration of statistical rainfall analysis with participatory engagement offers a transferable methodology for operationalizing early warning systems in other disaster-prone settings. Together, these contributions demonstrate that EWEA is a feasible pathway to strengthen disaster risk governance, reduce losses, and enhance resilience in Indonesia and beyond.

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Author contributions. P. conceived the study, developed the analytical framework, supervised the research, and led manuscript preparation. R.F.A. contributed to study analysis, stakeholder engagement, interpretation of findings, and manuscript writing. S.D.P. contributed to data collection, analysis, and reporting. A.A. supported stakeholder coordination, institutional consultation processes, and interpretation of operational findings. S.A. contributed to data processing, literature review, and manuscript development. R.R. contributed to statistical analysis, figure preparation, and manuscript drafting. All authors reviewed and approved the final manuscript.

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Competing interests. R.F.A., S.D.P., and S.A. are employed by PIAREA. The remaining authors declare that the research was conducted in the absence of

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any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability. The data supporting the findings of this study were obtained from publicly available and institutional sources cited in the manuscript, including BMKG and BNPB databases. Processed data and supporting materials are available from the corresponding author upon reasonable request.

Note

1. https://www.bmkg.go.id/cuaca/probabilistik-curah-hujan.bmkg?mm=20&hour=24&gen=9j71iru6vi97g3ygzx.

References

Alcántara-Ayala, I., & Oliver-Smith, A. (2019). Early warning systems: Lost in translation or late by definition? A FORIN approach. *International Journal of Disaster Risk Science*, *10*(3), 317–331. https://doi.org/10.1007/s13753-019-00231-3

Arrighi, C., Pregnolato, M., & Castelli, F. (2021). Indirect flood impacts and cascade risk across interdependent linear infrastructures. *Natural Hazards and Earth System Sciences*, *21*(6), 1955–1969. https://doi.org/10.5194/nhess-21-1955-2021

ASEAN. (2022). *ASEAN framework on anticipatory action in disaster management*.

Australian Bureau of Meteorology. (2021). *Rainfall and flood forecasting in Australia: Recent developments*. https://www.bom.gov.au

Bevan, D., & Cook, S. (2015). *Public expenditure following disasters. World Bank Policy Research Working Paper, 7355*. World Bank. https://doi.org/10.1596/1813-9450-7355

Bodini, A., & Cossu, Q. A. (2010). Vulnerability assessment of central-east Sardinia (Italy) to extreme rainfall events. *Natural Hazards and Earth System Science*, *10*(1), 61–72. https://doi.org/10.5194/nhess-10-61-2010

CERF. (2021). *CERF anticipatory*. Retrieved November 2021, from https://cerf.un.org

Chanut, P. C. M., Datry, T., Gabbud, C., & Robinson, C. T. (2019). Direct and indirect effects of flood regime on macroinvertebrate assemblages in a floodplain riverscape. *Ecohydrology*, *12*(5), e2095. https://doi.org/10.1002/eco.2095

Conitz, F., Zingraff-Hamed, A., Lupp, G., & Pauleit, S. (2021). Non-structural flood management in European rural mountain areas—Are scientists supporting implementation? *Hydrology*, *8*(4), 167. https://doi.org/10.3390/hydrology8040167

Coughlan de Perez, E., van den Hurk, B., van Aalst, M. K., Amuron, I., Bamanya, D., Hauser, T., Jongma, B., Lopez, A., Mason, S., Mendler de Suarez, J., Pappenberger, F., Rueth, A., Stephens, E., Suarez, P., Wagemaker, J., & Zsoter, E. (2016). Action-based flood forecasting for triggering humanitarian action. *Hydrology and Earth System Sciences*, *20*(9), 3549–3560. https://doi.org/10.5194/hess-20-3549-2016

De Risi, R., Muhammad, A., De Luca, F., Goda, K., & Mori, N. (2022). Dynamic risk framework for cascading compounding climate-geological hazards: A perspective on coastal communities in subduction zones. *Frontiers in Earth Science*, *10*, 1023018. https://doi.org/10.3389/feart.2022.1023018

Dutch Water Authority. (2021). *Flood mitigation strategies and the use of automated systems in the Netherlands*. https://www.dutchwaterauthority.nl

German Federal Institute of Hydrology. (2020). *Hydrological data and forecasting systems in Germany*. https://www.bafg.de

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*, 816–821. https://doi.org/10.1038/nclimate1911

Hurlbert, M. A. (2017). Adaptive governance (management, co-management and anticipatory). In M. A. Hurlbert (Ed.), *Adaptive governance of disaster. Water governance – Concepts, methods, and practice* (pp. 21–45). Springer. https://doi.org/10.1007/978-3-319-57801-9_2

ISDR. (2006). *Developing early warning systems: A checklist*. Third International Conference on Early Warning, Bonn, Germany, 27–29 March 2006.

Johnson, D., & Chen, X. (2023). Impact of upstream rainfall on downstream flood risk: A comprehensive review. *Water Resources Research*, *59*(1), e2022WR033789. https://doi.org/10.1029/2022WR033789

Jones, M., & Patel, S. (2020). Early warning systems for climate resilience. *Journal of Disaster Risk Management*, *15*(2), 105–118. https://doi.org/10.1007/s10113-020-01698-3

Keim, M. E. (2015). Disaster preparedness. In R. A. Ciottone (Ed.), *Ciottone's disaster medicine* (pp. 200–214). Elsevier. https://doi.org/10.1016/B978-0-323-28665-7.00032-7

Kelman, I., Gaillard, J. C., & Mercer, J. (2015). Climate change's role in disaster risk reduction's future: Beyond vulnerability and resilience. *International Journal of Disaster Risk Science*, *6*(1), 21–27. https://doi.org/10.1007/s13753-015-0038-5

Kerstholt, J., Duijnhoven, H., & Paton, D. (2017). Flooding in the Netherlands: How people's interpretation of personal, social and institutional resources influence flooding preparedness. *International Journal of Disaster Risk Reduction*, *24*, 52–57. https://doi.org/10.1016/j.ijdrr.2017.05.013

Kiptum, A., Mwangi, E., Otieno, G., Njogu, A., Kilavi, M., Mwai, Z., MacLeod, D., Neal, J., Hawker, L., O'Shea, T., Saado, H., Visman, E., Majani, B., & Todd, M. C. (2023). Advancing operational flood forecasting, early warning and risk management with new emerging science: Gaps, opportunities and barriers in Kenya. *Journal of Flood Risk Management*, *16*(1), e12884. https://doi.org/10.1111/jfr3.12884

Kokoska, S., & Zwillinger, D. (2000). *CRC Standard Probability and Statistics Tables and Formulae*, Student Edition (1st ed.) CRC Press. https://doi.org/10.1201/b16923

Lala, J., Bazo, J., Anand, V., & Block, P. (2021). Optimizing forecast-based actions for extreme rainfall events. *Climate Risk Management*, *34*, 100374. https://doi.org/10.1016/j.crm.2021.100374

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. *Climate Risk Management*, *29*, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lee, J., Thompson, R., & Robinson, M. (2024). River flow and flood management in urban areas: Case studies and future directions. *Urban Water Journal*, *21*(3), 345–359. https://doi.org/10.1080/1573062X.2023.2153348

Lopez, A., de Perez, E. C., Bazo, J., Suarez, P., van den Hurk, B., & van Aalst, M. K. (2020). Bridging forecast verification and humanitarian decisions: A valuation approach for setting up action-oriented early warnings. *Weather and Climate Extremes*, *27*, 100218. https://doi.org/10.1016/j.wace.2018.03.006

Mentzafou, A., Papadopoulos, A., & Dimitriou, E. (2023). Flood generating mechanisms investigation and rainfall threshold identification for regional flood early warning. *Environmental Earth Sciences*, *82*, 242. https://doi.org/10.1007/s12665-023-10938-8

Miller, C., Smith, L., & White, P. (2021). Effects of river size and rainfall intensity on flood occurrences. *Journal of Hydrology*, *600*, 126789. https://doi.org/10.1016/j.jhydrol.2021.126789

Müller, A., & Schumann, P. (2022). The integration of satellite data in flood forecasting. *Journal of Hydrology*, *594*, 125829. https://doi.org/10.1016/j.jhydrol.2021.125829

Perdinan, E., Arini, E. Y., Adi, R. F., Siregar, R., Clatworthy, Y., Nurhayati, & Dewi, N. W. S. P. (2020). Meteorological services for forecast-based early actions in Indonesia. In W. L. Filho, & D. Jacob (Eds.), *Handbook of climate services* (pp. 353–382). Springer. https://doi.org/10.1007/978-3-030-36875-3_18

Pilli-sihvola, K., Laitila, T., & Win, M. T. (2020). *Feasibility assessment on forecast-based action in the Republic of the Union of Myanmar*. Myanmar Red Cross Society.

Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R. W., & Schweizer, P. J. (2022). Systemic risks from different perspectives. *Risk Analysis*, *42*(9), 1902–1920. https://doi.org/10.1111/risa.13657

Rosmadi, H. S., Ahmed, M. F., Mokhtar, M. B., & Lim, C. K. (2023). Reviewing challenges of flood risk management in Malaysia. *Water*, *15*(13), 2390. https://doi.org/10.3390/w15132390

Rozi, S., Ritonga, A. R., & Januar, J. (2021). Local community based disaster management in West Sumatra. *Proceedings of the International Conference on Disaster Management*, 1–7. https://doi.org/10.4102/jamba.v13i1.1020.

https://doi.org/10.1017/sus.2026.10062 Published online by Cambridge University Press

Shabnam, N. (2014). Natural disasters and economic growth: A review. *International Journal of Disaster Risk Science*, *5*(2), 157–163. https://doi.org/10.1007/s13753-014-0022-5

Shah, A. A., Ullah, A., Khan, N. A., Pal, I., Alotaibi, B. A., & Traore, A. (2022). Gender perspective of flood early warning systems: People-centered approach. *Water*, *14*(14), 2261. https://doi.org/10.3390/w14142261

Shah, A. A., Ullah, A., Khan, N. A., Shah, M. H., Ahmed, R., Hassan, S. T., Tariq, M. A. U. R., & Xu, C. (2023). Identifying obstacles encountered at different stages of the disaster management cycle (DMC) and its implications for rural flooding in Pakistan. *Frontiers in Environmental Science*, *11*, 1088126. https://doi.org/10.3389/fenvs.2023.1088126

Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J. T., Juhola, S., Kornhuber, K., Mahecha, M. D., Mechler, R., Reichstein, M., Ruane, A. C., Schweizer, P.-J., & Williams, S. (2022). Briefing note systemic risk: Review and opportunities for research, policy and practice from the perspective of climate, environmental and disaster risk science and management. *Progress in Disaster Science*, *13*, 100233. https://doi.org/10.1016/j.pdisas.2021.100233

Staupe-Delgado, R., & Rubin, O. (2022). Challenges associated with creeping disasters in disaster risk science and practice: Considering disaster onset dynamics. *International Journal of Disaster Risk Science*, *13*(1), 1–11. https://doi.org/10.1007/s13753-022-00391-9

Sulaiman, M. E., Setiawan, H., Jalil, M., Purwadi, F., Brata, A. W., & Jufda, A. S. (2020). Analisis penyebab banjir di Kota Samarinda. *Jurnal Geografi Gea*, *20*(1), 39–43. https://doi.org/10.17509/gea.v20i1.22021

Sulfikkar Ahamed, M., Sarmah, T., Dabral, A., Chatterjee, R., & Shaw, R. (2023). Unpacking systemic, cascading, and compound risks: A case-based analysis of Asia Pacific. *Progress in Disaster Science*, *18*, 100285. https://doi.org/10.1016/j.pdisas.2023.100285

Tarchiani, V., Massazza, G., Rosso, M., Tiepolo, M., Pezzoli, A., Ibrahim, M. H., Katiellou, G. L., Tamagnone, P., De Filippis, T., Rocchi, L., Marchi, V., & Rapisardi, E. (2020). Community and impact based early warning system for flood risk preparedness: The experience of the Sirba River in Niger. *Sustainability*, *12*(5), 1802. https://doi.org/10.3390/su12051802

Tozier, A., De Poterie, E. C., Rahaman, H., Heinrich, D., Clatworthy, Y., & Mundorega, L. (2023). Climate risk management anticipatory action to manage climate risks: Lessons from the Red Cross Red Crescent in Southern Africa, Bangladesh, and beyond. *Climate Risk Management*, *39*, 100476. https://doi.org/10.1016/j.crm.2023.100476

UNDRR. (2015). *Proposed updated terminology on disaster risk reduction: A technical review*. United Nations Office for Disaster Risk Reduction.

UNDRR. (2021). *Global assessment report on disaster risk reduction*. United Nations Office for Disaster Risk Reduction. https://www.undrr.org

UNDRR. (2023). *Words into action: Implementation guide for early warning systems*. United Nations Office for Disaster Risk Reduction.

UNISDR. (2015). *Sendai framework for disaster risk reduction 2015–2030*. United Nations International Strategy for Disaster Reduction.

Vahlberg, M., Khan, R., Heinrich, D., & Jjemba, E. (2022). *Early Warning Early Action (EWEA) in Secondary Cities in South Asia.* Guidance Note 2022. Red Cross Red Crescent Climate Centre, 1–74.

Weingärtner, L., & Wilkinson, E. (2019). *Anticipatory crisis financing and action: Concepts, initiatives, and evidence*. Overseas Development Institute.

Wilkinson, E., Weingärtner, L., Choularton, R., Bailey, M., Todd, M., Kniveton, D., & Mowjee, T. (2018). *Forecasting hazards, averting disasters: Implementing forecast-based early action at scale*. Overseas Development Institute.

Winsemius, H. C., Aerts, J. C. J. H., van Beek, L. P. H., Bierkens, M. F. P., Bouwman, A., Jongman, B., Kwadijk, J. C. J., Ligtvoet, W., Lucas, P. L., van Vuuren, D. P., Ward, P. J., & Ward, J. H. (2016). Global drivers of future river flood risk. *Nature Climate Change*, *6*(4), 381–385. https://doi.org/10.1038/nclimate2893

Zain, Z., Hutabarat, S., Prayitno, S. B., & Ambaryanto, A. (2014). Potency of Mahakam Delta in East Kalimantan, Indonesia. *International Journal of Science and Engineering*, *6*(2), 126–130. https://doi.org/10.12777/ijse.6.2.126-130

https://doi.org/10.1017/sus.2026.10062 Published online by Cambridge University Press