



Flood Early Warning Systems: A Literature Review of Concepts, Evolution, and Implementation in Indonesia

Calvin Wimordi, Doddi Yudianto^{1*}, and Obaja Triputera Wijaya

Department of Civil Engineering, Parahyangan Catholic University, Bandung, Indonesia

*) Email corresponding author: doddi_yd@unpar.ac.id

Received: 19 May 2026 Revised: 9 September 2026 Accepted: 15 September 2026

Abstract

Rapid urbanization and intensifying climate change significantly escalate flood risks in Indonesia, yet the effectiveness of current early warning systems is often hampered by technological fragmentation and regional implementation disparities. This study evaluates the evolving landscape of Flood Early Warning Systems (FEWS) through a comprehensive review of its five fundamental components. A systematic literature review was conducted by analyzing academic research and technological prototypes implemented across the archipelago between 2015 and 2026. The findings indicate substantial technical progress in localized monitoring and predictive modeling; however, implementation remains geographically uneven and predominantly concentrated in metropolitan regions. Furthermore, a persistent silo effect prevents the cohesive integration of monitoring, forecasting, and risk assessment into a unified operational framework. This study concludes that achieving a truly resilient FEWS requires bridging the functional gap through multi-agency synergy and the integration of technical precision with local social capital. Such an integrated approach is vital for ensuring that technological alerts translate into effective community protective actions within a diverse geographical context.

Keywords: Flood risk, flood early warning system, disaster mitigation, risk management

Abstrak

Urbanisasi yang pesat dan perubahan iklim yang intens meningkatkan risiko banjir secara signifikan di Indonesia, namun efektivitas sistem peringatan dini saat ini sering terhambat oleh fragmentasi teknologi dan ketimpangan implementasi regional. Penelitian ini mengevaluasi lanskap Sistem Peringatan Dini Banjir (FEWS) yang sedang berkembang melalui tinjauan komprehensif terhadap lima komponen fundamentalnya. Tinjauan pustaka sistematis dilakukan dengan menganalisis penelitian akademik dan prototipe teknologi yang diimplementasikan di seluruh kepulauan antara tahun 2015 hingga 2026. Temuan menunjukkan kemajuan teknis yang substansial dalam pemantauan lokal dan pemodelan prediktif; namun, implementasinya tetap tidak merata secara geografis dan didominasi oleh kawasan metropolitan. Selain itu, efek silo yang persisten menghambat integrasi kohesif antara pemantauan, prakiraan, dan asesmen risiko ke dalam satu kerangka kerja operasional yang bersatu. Studi ini menyimpulkan bahwa untuk mencapai FEWS yang benar-benar tangguh, diperlukan upaya menjembatani celah fungsional melalui sinergi lintas instansi serta integrasi antara presisi teknis dan modal sosial lokal. Pendekatan terintegrasi tersebut sangat krusial untuk memastikan bahwa peringatan teknologi dapat diterjemahkan menjadi aksi perlindungan masyarakat yang efektif dalam konteks geografis yang beragam.

Kata kunci: Sistem peringatan dini banjir, risiko banjir, mitigasi bencana, manajemen risiko

Introduction

Flooding is among the most frequent and destructive natural hazards affecting communities worldwide. Inland floods alone caused more than 175,000 fatalities and affected over 2.2 billion

people globally between 1975 and 2002 (Jonkman, 2005), and they continue to generate substantial economic losses, infrastructure damage, and human casualties every year. Population growth, urban expansion, land-use change, and the increasing occurrence of extreme rainfall have further

intensified flood risk in both urban and rural environments (Huang & Xiao, 2025).

Flood mitigation has traditionally relied on structural measures such as dams, levees, drainage systems, and flood control channels (Jonkman, 2005). These works reduce flood impacts but are rarely sufficient on their own under extreme hydrometeorological conditions. Non-structural measures have therefore gained attention as complementary strategies, and among them Flood Early Warning Systems (FEWS) have become critical in reducing flood-related losses by providing timely information that enables early protective actions by communities and authorities (Rana et al., 2021).

Indonesia represents one of the most urgent contexts for examining flood risk and early warning implementation. Its tropical monsoon climate, high annual rainfall, and intense seasonal variability across more than 17,000 islands make the country inherently susceptible to hydrometeorological hazards (Aldrian & Susanto, 2003). Rentschler et al. (2022) rank Indonesia among the top four countries globally in population exposure to flood risk, with approximately 76 million people, representing roughly 27% of the national population, living in zones categorized as high risk, the highest exposure in Southeast Asia. Jakarta has experienced catastrophic flood events with annual expected damages estimated in the hundreds of millions of US dollars (Budiyo et al., 2015), and projections indicate a median risk increase of up to 180% by 2030 under combined scenarios of climate change and land subsidence (Budiyo et al., 2016). BNPB has recorded more than 1,200 flood events annually in recent years, making floods the most frequent disaster type in Indonesia and the primary cause of casualties and displacement.

To be effective, Flood Early Warning Systems must operate as integrated, end-to-end systems connecting scientific monitoring with community-level response (Alfieri et al., 2012; Perera et al., 2020). Under the *Early Warnings for All* initiative, WMO and UNDRR define four essential pillars of a people-centered multi-hazard early warning system: disaster risk knowledge and management; detection, observation, monitoring, analysis, and forecasting; warning dissemination and communication; and preparedness and response capabilities (UNDRR and WMO, 2024). Technically sound warnings nevertheless do not automatically translate into effective emergency response. Perera et al. (2020) demonstrated that warnings issued with adequate lead time frequently fail to reach vulnerable populations because of incomplete information, language barriers, and

weak inter-agency coordination, so that FEWS effectiveness depends as much on institutional governance and last-mile communication as on technological sophistication.

Implementation of reliable and integrated FEWS nevertheless remains highly uneven, and translating forecasts into actionable warnings is especially difficult where institutional arrangements are fragmented, observational networks are limited, and community preparedness is insufficient (Perera et al., 2020). In Indonesia these constraints are compounded by geographic complexity, diverse socioeconomic conditions, and the involvement of BMKG for weather forecasting, the Ministry of Public Works and Housing (PUPR) for river monitoring, and BNPB as coordinating body, each operating on distinct platforms with varying levels of technical capacity (Djalante, 2012). The absence of a fully interoperable national framework has thus constrained flood warning delivery in many regions.

While numerous studies have examined individual components of FEWS, including hydrological modeling, sensor networks, or community response, a consolidated synthesis tracing the global conceptual evolution of FEWS and examining its implementation within the Indonesian context remains limited. This study reviews the fundamental concepts underpinning flood early warning systems, traces their development from early technical approaches to contemporary people-centered frameworks, and examines the current state, progress, and challenges of FEWS implementation in Indonesia.

Methodology

This study employed a Systematic Literature Review combined with policy analysis to assess the global evolution of FEWS and its implementation in Indonesia. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P), integrating four main stages: literature identification, screening, eligibility assessment, and qualitative synthesis.

Data were obtained from peer-reviewed academic publications and national water governance documents. Scientific articles were retrieved through Scopus, Web of Science, the Directory of Open Access Journals (DOAJ), and Google Scholar using the Boolean search string '*Flood Early Warning System*' OR '*FEWS*' AND '*Indonesia*'. The strategy was designed to capture both foundational historical frameworks and contemporary technological advancements. Policy documents and technical reports were further

collected from BMKG, BNPB, and the Ministry of Public Works and Housing, alongside strategic publications from global institutions such as the World Bank and OTCA. The inclusion and exclusion criteria were structured using the SPICE (Setting, Perspective, Intervention, Comparison, Evaluation) framework, and the adapted criteria used in this study are summarized in Table 1.

Tabel 1. Adapted SPICE structure for formulating inclusion and exclusion criteria

Criteria	Definitions (Contextualized)
Setting	Global flood-affected regions (for tracing FEWS evolution) and national/subnational flood contexts throughout the Indonesian archipelago (for implementation analysis).
Perspective	Key actors including national and local government agencies (BMKG, BNPB, PUPR), technical specialists, researchers, and at-risk communities.
Intervention	Implementation of FEWS components including hydrometeorological monitoring, hydrological modeling, warning dissemination, institutional coordination mechanisms, and community preparedness measures.
Comparison	Studies comparing different FEWS approaches (technology-driven vs. community-based; centralized vs. decentralized), or contrasting FEWS performance across different regions, scales, or time periods.
Evaluation	Operational effectiveness in terms of warning accuracy, lead time, dissemination reach, community response, and identification of implementation barriers.

A quality assessment procedure was subsequently applied to all records that passed title and abstract screening. Each record was appraised against four criteria: *publication credibility*, whether it appeared in a peer-reviewed journal, an indexed conference proceeding, or an official institutional report; *thematic relevance*, whether it addressed at least one of the five core FEWS components in an Indonesian or comparable archipelagic context;

methodological clarity, whether it reported a traceable methodology, dataset, or analytical procedure; and *sufficiency of evidence*, whether it provided empirical data, a technical prototype, or an implementation case rather than conceptual commentary alone. Applying this procedure to the 100 screened records excluded one purely conceptual study, yielding the final corpus of 99 studies.

Results and Discussions

A total of 107 records were initially identified through systematic database searching across Scopus, Web of Science, and Google Scholar, supplemented by manual screening of policy documents and institutional reports. Following the removal of 7 duplicate records, 100 studies proceeded to title and abstract screening, and full-text assessment excluded 1 study due to insufficient relevance, resulting in a final corpus of 99 studies (Figure 1). This selection covers studies addressing the five core FEWS components in the Indonesian context, while foundational literature on global concepts was identified through purposive manual searching and is not reflected in the PRISMA count.

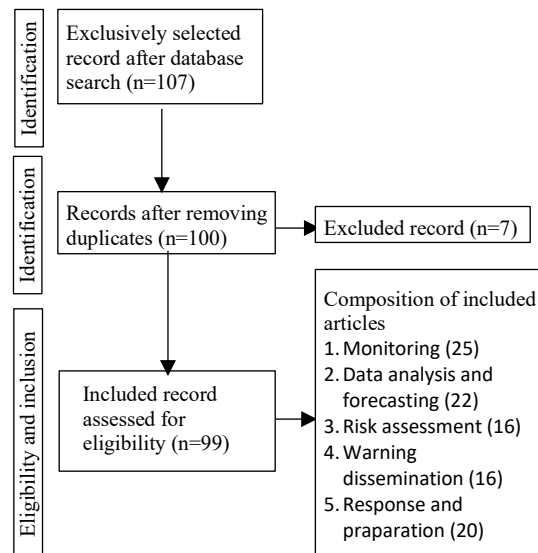


Figure 1. Data charting comprised of the PRISMA flow-chart

The discussion first traces the fundamental concepts and evolutionary trajectory of Flood Early Warning Systems in both global and Indonesian contexts, then presents a thematic synthesis organized into five core components: Monitoring, Data Analysis and Forecasting, Risk Assessment, Warning Dissemination, and Response and Preparedness. Most of the reviewed studies were not originally framed within an explicit FEWS context, having been conducted as standalone investigations into flood hazard mapping, hydrological modeling,

sensor networks, or community disaster response; connecting them analytically, and identifying where integration has been achieved and where it has not, is the role of this review.

Concepts and evolution of FEWS

Flood Early Warning Systems have been conceptualized since the early stages of modern disaster risk management as observation-driven approaches aimed at providing timely alerts to reduce community vulnerability to flood hazards (Basher et al., 2006). Growing international recognition during the 1990s led to the establishment of the International Strategy for Disaster Reduction, which structured early warning around four interdependent components: risk knowledge, monitoring and forecasting, warning dissemination, and response capability (ISDR, 2006). The framework was subsequently reinforced under the Sendai Framework for Disaster Risk Reduction 2015–2030, which positioned people-centered early warning systems as a critical pillar of disaster resilience and called for universal access to multi-hazard early warning systems by 2030 (Morote, 2015).

From a technical standpoint, FEWS have evolved substantially in their underlying methodologies. The earliest systems relied on direct field observation and simple threshold-based rules, issuing alerts only after monitored variables such as river water levels or rainfall intensity exceeded predefined critical limits (Pumo et al., 2024). Such systems were inherently reactive, since warnings could be generated only after hazardous conditions had already developed, which sharply constrained the lead time available for preparedness and evacuation.

Hydrological and hydraulic models were subsequently incorporated so that rainfall-runoff processes, river discharge, and inundation extents could be simulated before critical thresholds were physically reached (Varlas et al., 2024), a shift from reactive to predictive operation that allowed longer lead times and spatially explicit forecasts. More recently, real-time data networks, remote sensing, geographic information systems, and machine learning have further expanded system capabilities (Wang et al., 2024). Significant gaps nevertheless remain in translating technical sophistication into accessible warnings, particularly in developing countries where data scarcity and weak institutional coordination constrain performance.

In Indonesia, FEWS development was catalyzed by the catastrophic 1966 Solo River flood, which exposed the absence of organized flood

management mechanisms and prompted the establishment of the Bengawan Solo River Basin Agency in 1969. The Bengawan Solo River Basin Development Master Plan of 1974, prepared in cooperation with the Overseas Technical Cooperation Agency of Japan, laid the initial hydrological groundwork for predictive systems. Disaster management nevertheless remained predominantly reactive through the late twentieth century, with Bakornas PB prioritizing emergency response over proactive risk reduction (Lassa, 2013). Major disasters between 2002 and 2005, including the 2002 Jakarta flood and the 2004 Indian Ocean Tsunami, exposed deficiencies in warning dissemination and inter-agency coordination and precipitated Law Number 24 of 2007 on Disaster Management, which mandated the integration of early warning into the national disaster risk reduction strategy (Republik Indonesia, 2007). The law transformed Bakornas PB into the Badan Nasional Penanggulangan Bencana (BNPB) and established Badan Penanggulangan Bencana Daerah (BPBD) at the regional level, creating a multi-tiered institutional architecture with FEWS as a central component.

Within this framework, FEWS development is coordinated by BMKG for weather and climate monitoring, PUPR for hydrological modeling and river basin management, and BNPB for disaster risk coordination. Despite the legal mandate, implementation across the archipelago remains uneven, constrained by fragmented monitoring networks, limited data availability in ungauged and remote areas, insufficient integration between forecasting and dissemination, and varying subnational technical capacity, reflecting the broader global gap between technological advancement and practical implementation.

State of research on FEWS components in Indonesia

Figure 2 conceptualizes these five components not as isolated domains but as a continuous operational cycle in which each stage supplies the functional input required by the next. Monitoring generates the raw hydrometeorological data that anchor forecasting; forecasting outputs are translated into hazard and vulnerability estimates within risk assessment; risk assessment findings define the thresholds and target audiences for warning dissemination; and dissemination is complete only once it activates preparedness and response actions at the community level.

The cycle is closed by a feedback loop through which the outcomes of community response are channeled back to recalibrate sensor placement,

warning thresholds, and model parameters. This feedback mechanism distinguishes a genuinely integrated FEWS from a linear sequence of disconnected technical outputs, and it is precisely here that the reviewed literature is most conspicuously thin.

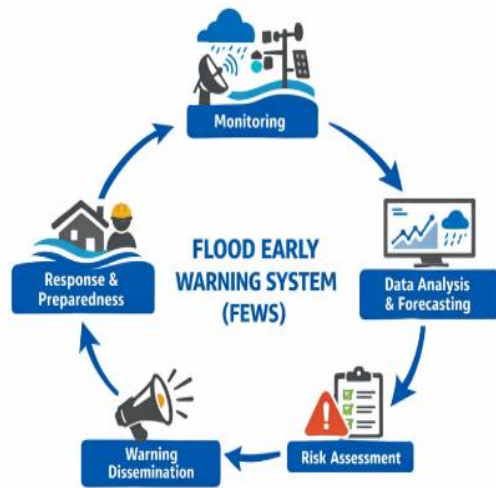


Figure 2. Flood early warning system cycle

Monitoring

The monitoring component in Indonesia has developed into a multi-scale framework that responds to the geographic complexity of the maritime continent. At the macro level, satellite precipitation products remain indispensable for capturing rainfall anomalies and extreme climate trends across the archipelago. CHIRPS data have proven highly effective for assessing long-term spatial-temporal variability and tracing extreme episodes such as the drought of 2015 (Marzuki et al., 2025), while GPM IMERG products have been extensively validated across various time scales for analyzing extreme events over the Indonesian Maritime Continent (Ramadhan et al., 2022). These satellite sources establish the primary data foundation for rainfall-runoff modeling and broad-scale rainfall estimation throughout Indonesia (Hidayah et al., 2024).

Because satellite observations often exhibit regional biases, ground-based telemetry has been developed to provide immediate localized validation, and the proliferation of the Internet of Things has made real-time observation both accessible and cost effective. Locally built mini weather stations and microcontroller frameworks now deliver live data through platforms such as MIT App Inventor and automated Telegram messaging (Ulum, 2023), bridging the gap between raw environmental detection and immediate local awareness.

The deployment of physical sensors is most critical within highly vulnerable aquatic and coastal environments. Customized Automatic Water Level Recorders have been implemented to monitor fluctuating river levels and specifically to mitigate the persistent risk of tidal flood disasters in the coastal areas of Jakarta (Pianto et al., 2023). Such localized hardware implementations provide the direct physical verification required to confirm the broader alerts generated by national meteorological agencies.

The monitoring ecosystem is completed by advanced spatial analytics that synthesize satellite and ground observations. When a disaster unfolds, cloud computing platforms and multi-temporal Sentinel-1 Synthetic Aperture Radar data are used to generate rapid flood inundation maps in urban centers such as Kendari (Aldiansyah et al., 2024). Together, broad satellite detection, accessible ground telemetry, and advanced spatial computation establish a monitoring foundation capable of driving the entire flood early warning mechanism.

Data analysis & forecasting

The analytical framework for flood forecasting in Indonesia relies increasingly on numerical and hydrodynamic models capable of replicating complex inundation patterns. The Rainfall-Runoff-Inundation (RRI) model has been applied extensively in strategic basins such as the Upper Citarum to simulate large-scale flood events using satellite-derived rainfall data (Nastiti et al., 2018), an approach well suited to Indonesian watersheds because it tightly couples two-dimensional rainfall-runoff and inundation processes in areas with limited ground-based data. Determination of critical rainfall thresholds using HEC-HMS and HEC-RAS has likewise provided essential benchmarks for establishing early warning levels in the Bandung Basin (Harlan et al., 2018).

The performance of meteorological inputs determines how far the lead time of a warning can be extended. Evaluations of the BMKG-WRF numerical weather model indicate that it is effective for daily rainfall accumulation forecasting but requires categorical verification to address inherent overestimation over the Indonesian maritime continent (Fatkhuroyan et al., 2019). In regions with sparse rain gauge networks, GPM-IMERG data have demonstrated superior performance in HEC-HMS hydrological modeling compared with traditional observational data, particularly when analyzed using the Thiessen polygon method (Hidayah et al., 2024).

Machine learning and deep learning architectures are redefining the precision of hourly water level and discharge forecasting. Long Short-Term Memory networks have proven more effective than traditional statistical models for predicting hourly discharge in the Upper Citarum River (Enung et al., 2022), while Multiple Input Bidirectional LSTM architectures combined with outlier-handling frameworks have significantly improved forecasting accuracy for the Ciliwung River, achieving high Nash-Sutcliffe Efficiency values (Octaviana et al., 2025).

On a national scale, Random Forest classification has achieved accuracy rates of 94.93% by processing three-day rainfall rates, forest ratios, and streamflow data (Puspasari et al., 2023). The synergy between hydrodynamic modeling, reliable satellite-based meteorological inputs, and deep learning algorithms therefore forms a robust foundation for flood analysis in Indonesia, bridging raw environmental data and actionable early warning insights for both large-scale and localized flood events.

Risk assesment

Comprehensive flood risk assessment in Indonesia is shifting toward a multi-dimensional framework that integrates physical hazard data with complex socio-economic realities (Sigit et al., 2023). In coastal metropolises such as Jakarta and Medan, land subsidence acts as a critical risk amplifier, with projections indicating substantial increases in inundation extent and economic exposure under combined scenarios of climate change and continued ground deformation (Budiyo et al., 2016).

Relative sea level rise of approximately 4.79 mm/year in North Sumatra significantly exceeds the global mean and is capable of reclassifying large proportions of urban areas into the highest vulnerability categories (Lumban-Gaol et al., 2024). Land use and land cover transformation, including the clearing of plantation forests for the new capital of Nusantara, similarly increases peak discharge and expands high-hazard zones, reinforcing the need for regularly updated risk assessments (Handyastono et al., 2025).

Methodologically, the field is evolving from traditional hydraulic approaches toward data-driven paradigms capable of producing high-resolution spatial outputs from limited datasets. Random Forest has emerged as a dominant tool for flood susceptibility mapping at both national and regional scales, classifying hazard zones by processing conditioning variables such as geology, rainfall

intensity, slope, and land cover (Ismanto et al., 2023). For data-constrained urban settings such as South Jakarta, Frequency Ratio and Logistic Regression provide reliable alternatives when validated using receiver operating characteristic analysis (Puspitasari et al., 2026). Combining these models with the Analytic Hierarchy Process further allows evidence-based weighting of physical, economic, and environmental variables at a scale suitable for local spatial planning (Rendana et al., 2025).

A critical focus of modern risk assessment is the Social Vulnerability Index, which evaluates human exposure to flood impacts beyond simple monetary asset loss. Research in the Samin watershed indicates that social vulnerability is spatially non-homogeneous, driven largely by demographic characteristics such as the proportion of child and elderly populations and by the prevalence of informal sector livelihoods that lack institutional safety nets (Suryanto et al., 2026). This aligns with a broader global pattern in which flood exposure intersects most acutely with conditions of extreme poverty (Rentschler et al., 2022), while studies in Central Java suggest that community strategies grounded in local wisdom are often more effective than high-cost infrastructure investments in low-income flood-prone areas (Sigit et al., 2023).

The integration of risk assessment results into administrative policy frameworks is increasingly recognized as essential for sustainable urban management. High-resolution risk data is now being mainstreamed into Strategic Environmental Assessments and Detailed Spatial Plans in cities such as Palembang, ensuring that development permits are aligned with flood mitigation policies (Rendana et al., 2025). This policy-oriented application positions risk knowledge as the foundational input that drives all subsequent FEWS components.

Warning dissemination

The warning dissemination landscape in Indonesia is transitioning from manual river monitoring to automated systems that utilize Internet of Things technology to provide immediate updates (Ratmini et al., 2025). Prototype designs across the archipelago frequently integrate ESP32 microcontrollers with ultrasonic sensors to detect water levels and transmit information through digital platforms (Mahardhika et al., 2025), significantly reducing the time required to inform vulnerable populations in regions where river overflows occur rapidly during intense rainfall events.

Telegram bots and WhatsApp messaging have emerged as dominant channels for flood warning dissemination because they provide a lightweight and responsive interface accessible to a broad range of residents (Lailul Fikri et al., 2025). Many systems trigger automated notifications once water levels reach specific thresholds, with delivery latencies reported to be as low as 1.2 seconds in controlled testing environments (Ratmini et al., 2025).

Social media integration through Twitter and Facebook further extends the reach of mass warnings in metropolitan areas such as Jakarta and Surabaya (Riama et al., 2021), and this multi-channel approach has achieved over 83 percent successful message delivery in community-based implementations (Lailul Fikri et al., 2025).

Intelligence layers further improve the clarity and actionability of warning messages. Systems utilizing the Fuzzy Sugeno method classify water status into categories such as Safe, Alert, or Danger, translating complex sensor readings into guidance that communities can act upon without technical expertise (Mahardhika et al., 2025).

The reliability of dissemination in remote Indonesian locations is being improved through alternative power sources and robust communication modules. Solar-powered early warning systems address the challenge of electricity scarcity in mountainous and rural areas, ensuring that sensors and transmitters remain operational during storms when grid power is most likely to fail (Athirah et al., 2020). Such hardware innovations are essential to bridging the last mile gap in information delivery for isolated coastal and headwater communities that are often among the most flood-vulnerable yet least connected populations in the archipelago.

Despite these technological advances, effectiveness remains contingent on the degree to which systems are socially accepted and culturally integrated within the communities they serve. Research in Jakarta indicates that public acceptance of coastal flooding early warning systems is generally high, yet strongly mediated by prior knowledge, community attitudes, and trust in the issuing institution (Riama et al., 2021). Socialization at the neighborhood level must therefore precede and accompany the rollout of IoT-based alert systems, so that digital outreach combined with existing community networks reinforces the social trust necessary for warnings to translate into coordinated protective action (Permatasari & Sinduwiatmo, 2024).

Response & preparedness

Disaster risk reduction in Indonesia has shifted from reactive emergency response toward a more proactive and systematic preparedness approach, supported by legal frameworks that increasingly prioritize integrated disaster management across multiple levels of government (Djalante & Garschagen, 2017). Adaptive governance serves as a critical model in this context, advocating polycentric institutions capable of handling recurring hydrometeorological and geophysical hazards (Djalante, 2012). True resilience nevertheless depends on the ability of local institutions to translate these broad strategies into actionable preparedness plans that reflect specific regional risks (Ayuningtyas et al., 2021).

Community empowerment is identified as the most vital component of an effective early warning and response system across the archipelago. Programs such as Desa Tangguh Bencana (Destana) mobilize local resources so that residents can manage the critical early hours after a disaster strikes (Danar et al., 2022). Effective preparedness at the village level is measured through indicators such as the existence of disaster risk maps, established evacuation routes, trained volunteers, and clearly defined standard operating procedures (Kusumastuti et al., 2022), while training and simulation programs based on modified emergency response models significantly improve the practical skills of community members (Subandi et al., 2019). These initiatives nevertheless face bottlenecks caused by limited maintenance budgets, under-capacity volunteer teams, and inconsistent participation of local youth (Danar et al., 2022).

The relationship between risk perception and actual preparedness behavior reveals a complex paradox within vulnerable Indonesian communities. Increased awareness of climate change and flooding typically raises concern, yet it can inadvertently lead to psychological paralysis or a decrease in proactive efforts if the level of worry becomes overwhelming (Christia et al., 2026). In many regions, residents exhibit a high degree of desensitization due to repeated exposure to seasonal floods, which leads to reliance on spontaneous reactions rather than systematic planning (Aksa & Afrian, 2022). In these settings, social capital and the spirit of gotong royong often provide a stronger safety net than formal infrastructure (Ningtias et al., 2025), and the integration of local wisdom, such as traditional building materials, elevated dwellings, or indigenous early warning signs, remains essential for community acceptance (Subandi et al., 2019).

Modern digital communication strategies matter not merely as channels for disseminating hazard information but as instruments for shaping preparedness attitudes and behavior. The use of social media platforms by regional disaster management agencies fosters more positive preparedness orientations, particularly among younger demographics such as Generation Z, when information is delivered in a timely, accurate, and action-oriented manner (Hotimah & Sitanggang, 2025). Their effectiveness nevertheless depends on being accompanied by culturally integrated communication that accounts for the diverse socioeconomic and educational backgrounds of local communities (Permatasari & Sinduwiatmo, 2024), so that hazard awareness is translated into concrete protective actions rather than technical data alone.

The overarching architecture of disaster resilience in Indonesia demonstrates that formal technological infrastructure and regulatory frameworks must be deeply intertwined with grassroots social dynamics to be truly effective (Ayuningtyas et al., 2021). Across various vulnerable regions, communities heavily utilize social capital, mutual cooperation, and local wisdom to compensate for the limitations of institutional early warning systems (Aksa & Afrian, 2022; Ningtias et al., 2025), and sustaining this preparedness requires communication strategies that avoid triggering psychological fatigue or desensitization (Christia et al., 2026). Optimizing disaster response ultimately relies on an adaptive governance model in which scientific early warning data, local institutional capacity, and communitydriven initiatives operate synergistically (Djalante, 2012), a balance that remains aspirational in many parts of the country.

Discussion

Synthesis of cross-component integration

The collective advancement documented across the five components reflects a research landscape that is technically ambitious yet structurally fragile. The majority of contemporary systems reviewed in this study rely on continuous internet connectivity and stable electrical supply to transmit sensor readings, activate automated notifications, and operate IoT-based monitoring nodes. Yet flooding events of sufficient severity to require early warning are precisely the conditions under which power grids fail, communication towers lose function, and mobile networks become congested or inoperable, so that the most technologically sophisticated systems may be the first to fail when they are most urgently needed.

Traditional community-based mechanisms such as kentongan, beduk, or manually operated sirens, which require no electricity, no internet connection, and no technical literacy, may therefore possess a form of operational resilience that their digital counterparts fundamentally lack. The reviewed literature contains no systematic comparison between the two under actual disaster conditions, a significant gap in understanding which approach better protects lives in the critical minutes before inundation.

A second and equally pressing concern involves the relationship between forecasting model reliability and long-term community trust. Community-based early warning systems are effective only to the extent that the populations they serve believe in and act upon the warnings they receive, yet this trust is asymmetric and fragile. Validation studies reviewed above consistently document high false alarm ratios in satellite precipitation products and numerical weather models, with IMERG data showing FAR values approaching 0.50 for daily rainfall detection and even higher for hourly data across the Indonesian Maritime Continent. When these uncertain inputs cascade through hydrological models and trigger automated community alerts, the probability of false warnings is non-trivial.

Repeated false alarms produce the cry-wolf effect, whereby populations progressively reduce their protective response. In Indonesia, where seasonal flooding recurs annually and desensitization has already been documented, automated systems that increase warning frequency without guaranteed accuracy may paradoxically reduce preparedness, and a single failed high-profile prediction that triggers costly and unnecessary evacuations can erode years of institutional trust-building.

The assumption of universal digital access embedded in most dissemination systems also warrants critical examination. Telegram, WhatsApp, and web-based monitoring dashboards presuppose smartphone ownership, adequate mobile data coverage, and a baseline level of digital literacy, an assumption inconsistent with the socioeconomic realities of many flood-vulnerable populations, which the risk assessment component identifies as disproportionately composed of elderly residents, informal sector workers, and low-income households.

A dissemination architecture that reaches only the technologically connected fraction of a vulnerable community is not an inclusive early warning system regardless of its sophistication. The reviewed IoT literature further reveals prototype-level implementation in which systems are deployed and

documented during active research but rarely evaluated for long-term sustainability; battery maintenance, sensor calibration drift, hosting costs, and institutional ownership after project completion are largely absent from these studies, raising concern over whether locally developed devices become durable infrastructure or abandoned prototypes.

Implications for research and policy

The institutional architecture governing flood early warning in Indonesia introduces systemic vulnerabilities that technical innovation alone cannot address. Dividing responsibility among BMKG for meteorological monitoring, PUPR for hydrological modeling, BNPB for disaster coordination, and BPBD at the regional level creates a warning chain with multiple potential points of failure: when each agency operates on distinct data platforms, employs different threshold criteria, and communicates through separate channels, the risk of conflicting warnings, delayed dissemination, or complete information gaps increases substantially. Numerous local FEWS implementations have also been developed independently of national systems, deepening interoperability challenges, so that without standardized protocols and unified data sharing agreements the technical achievements documented above remain functionally disconnected.

The reviewed literature further reveals a systematic geographic concentration of research effort that introduces structural bias into the evidence base upon which any national FEWS strategy must be built. The preponderance of studies focusing on Jakarta, the Citarum basin, Bandung, and Semarang reflects the clustering of academic institutions, research funding, and government monitoring infrastructure on Java, while Papua, Maluku, Nusa Tenggara, and the interior of Kalimantan and Sumatra remain substantially underrepresented despite facing equally severe flood risks under highly distinct hydrological and topographic conditions. Methodologies, threshold values, and system architectures validated in Javanese contexts are therefore routinely recommended for outer island settings where their transferability has not been empirically established.

Read against the conceptual framework introduced in Figure 2, these cross-cutting concerns converge on a single structural diagnosis: each stage of the monitoring-to-preparedness cycle has developed in relative isolation, while the feedback loop that would allow community-level outcomes to recalibrate upstream monitoring and forecasting remains almost entirely undocumented. Closing this

feedback gap is therefore the single research and policy priority through which the remaining synthesis findings could be most efficiently addressed.

Conclusions

The synthesis of research across the five core components of the Indonesian Flood Early Warning System reveals a substantial body of academic work that has achieved a high level of technological innovation within individual sectors yet remains systemically fragmented. Current literature has begun to bridge certain gaps by integrating two or three elements, such as linking monitoring with forecasting or analysis with risk assessment, but research encompassing the full five-component framework in a single cohesive implementation is absent, which prevents the system from functioning as a true end-to-end disaster management solution.

The identified pattern of development is characterized by a profound technological divide in which sophisticated infrastructure, including advanced forecasting models and real-time IoT networks, is predominantly concentrated in major urban centers and on the island of Java. This uneven implementation creates a significant disparity in disaster resilience between metropolitan hubs and remote regions or outer islands, and highlights the need for a more equitable distribution of technological resources so that every province has access to the same level of protection.

A persistent and cross-cutting challenge identified in this study is the functional gap between advanced technical detection and actual community response. High-precision forecasting and automated dissemination do not inherently translate into timely evacuation or effective preparedness at the grassroots level, and this disconnect is exacerbated by the recurrent bottleneck of ground-based data scarcity which continues to hinder the calibration of monitoring and forecasting tools. Technology alone cannot solve the crisis if the data input is insufficient or if the social translation of the warning is ignored.

To bridge these gaps, inter-agency synergy must be prioritized to dismantle the institutional silos currently separating meteorological detection, public safety, and infrastructure management. Future governance models should focus on integrated platforms that unify the operational roles of national and regional agencies, while policy making should transition from infrastructure-centric investments toward holistic strategies emphasizing both hybrid observation networks and culturally grounded disaster communication,

bringing BMKG, BNPB, and PUPR under a unified digital and administrative umbrella.

This study positions itself as a critical synthesis of the current state of the Indonesian early warning landscape by identifying that, while many studies exist for each component, they remain fundamentally unintegrated. A significant opportunity for future research lies in developing a unified framework that holistically connects monitoring, forecasting, risk assessment, warning dissemination, and response capabilities into a singular operational chain, treating warning systems not as isolated technical components but as a socially embedded and fully integrated multi-agency ecosystem.

Acknowledgement

The authors gratefully acknowledge the Water Resources Engineering Group of Parahyangan Catholic University for its institutional support, and thank colleagues and mentors for their constructive discussions throughout the preparation of this paper. The authors also acknowledge the institutions, researchers, and practitioners whose publicly available data and previous studies formed the essential foundation of this review, as well as the anonymous reviewers whose comments helped improve this manuscript.

References

- Aksa, F. I., & Afrian, R. (2022). Community adaptation strategies toward tidal flood: A Case study in Langsa, Indonesia. *Jamba: Journal of Disaster Risk Studies*, 14(1).
<https://doi.org/10.4102/JAMBA.V14I1.1258>
- Aldiansyah, S., Saputra, R. A., Wahid, K. A., Madani, I., Setiyo, D., & Ningsih, W. (2024). Rapid Flood Inundation Mapping Using Multi-Temporal Sentinel-1 SAR: An Example from Kendari City. *Jurnal Geosains Dan Remote Sensing*.
<https://doi.org/10.23960/jgrs.ft.unila.205>
- Aldrian, E., & Dwi Susanto, R. (2003). Identification of Three Dominant Rainfall Regions Within Indonesia and Their Relationship to Sea Surface Temperature. *International Journal of Climatology*, 23(12). 1435-1452.
<https://doi.org/10.1002/joc.950>
- Alfieri, L., Salamon, P., Pappenberger, F., Wetterhall, F., & Thielen, J. (2012). Operational early warning systems for water-related hazards in Europe. In *Environmental Science and Policy*, 21, 35-49.
<https://doi.org/10.1016/j.envsci.2012.01.008>
- Athirah, N. A., Radzi, N. H., Abdullah, M. N., Jumaat, S. A., & Mohamad, N. Z. (2020). Solar-powered flood early warning system with short message service (SMS) notifications. *Indonesian Journal of Electrical Engineering and Computer Science*, 18(3). <https://doi.org/10.11591/ijeecs.v18.i3.pp1156-1162>
- Ayuningtyas, D., Windiarti, S., Sapoan Hadi, M., Fasrini, U. U., & Barinda, S. (2021). Disaster preparedness and mitigation in indonesia: A narrative review. In *Iranian Journal of Public Health*, 50(8).
<https://doi.org/10.18502/ijph.v50i8.6799>
- Basher, R., Page, J., Woo, J., Davies, M. L., Synolakis, C. E., Farnsworth, A. F., & Steacey, S. (2006). Global Early Warning Systems for Natural Hazards: Systematic and People-Centred. In *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 364(1845).
<https://doi.org/10.1098/rsta.2006.1819>
- Budiyono, Y., Aerts, J., Brinkman, J. J., Marfai, M. A., & Ward, P. (2015). Flood Risk assessment for Delta Mega-cities: A Case Study of Jakarta. *Natural Hazards*, 75(1) 389-413.
<https://doi.org/10.1007/s11069-014-1327-9>
- Budiyono, Y., Aerts, J. C. J. H., Tollenaar, D., & Ward, P. J. (2016). River Flood Risk in Jakarta Under Scenarios of Future Change. *Natural Hazards and Earth System Sciences*, 16(3) 757-774.
<https://doi.org/10.5194/nhess-16-757-2016>
- Christia, M., Setiawan, T., Van Kempen, L., & De Jong, E. (2026). Flood risk perception paradox: balancing awareness and worriedness of Indonesian vulnerable communities in disaster preparedness. *Environmental Hazards*, 1-23.
<https://doi.org/10.1080/17477891.2026.2617610>
- Danar, O. R., Anggriawan, T., & Prameisa, D. (2022). Evaluasi Program Desa Tangguh Bencana dalam perspektif flood risk management. *Jurnal Manajemen Dan Ilmu Administrasi Publik (JMIAP)*, 4(2), 101-110.
<https://doi.org/10.24036/jmiap.v4i2.492>
- Djalante, R. (2012). " Adaptive governance and resilience: the role of multi-stakeholder platforms in disaster risk reduction". *Natural Hazards and Earth System Sciences*, 12(9), 2923-2942.
<https://doi.org/10.5194/nhess-12-2923-2012>
- Djalante, R., & Garschagen, M. (2017). *A Review of Disaster Trend and Disaster Risk Governance in Indonesia: 1900–2015*.

https://doi.org/10.1007/978-3-319-54466-3_2

Fatkhuroyan, Praja, A. S., & Wati, T. (2019). A preliminary results of assessment of BMKG-WRF numerical model daily rainfall forecasts performance using categorical verification. *IOP Conference Series: Earth and Environmental Science*, 284(1).
<https://doi.org/10.1088/1755-1315/284/1/012013>

Handyastono, B., Alghoul, M. A., Rizki, A., Djambek, N. P., Kusuma, M. S. B., Kuntoro, A. A., Harlan, D., Nugroho, E. O., Munthe, H. M., Hazmi, M., Wisanggeni, D. H., & Rizqy, M. A. (2025). Flood hazard assessment in Pemaluan Village due to land use change in IKN (Ibu Kota Nusantara) as the New Capital City of Indonesia. *Case Studies in Chemical and Environmental Engineering*, 11.
<https://doi.org/10.1016/j.cscee.2025.101211>

Harlan, D., Hadihardaja, I. K., Kuntoro, A. A., Enung, & Faturachman, D. (2018). Derivation of the critical rainfall level needed for an early flood warning in the Upper Citarum river basin Indonesia. *International Journal of GEOMATE*, 14(43).
<https://doi.org/10.21660/2018.43.50926>

Hidayah, E., Saifurridzal, S., Wiyono, R. U. A., Widiarti, W. Y., Martini, R., Juliastuti, J., & Riduwan, M. (2024). Performance of GPM-IMERG satellite precipitation for rainfall-runoff modeling in Indonesia. *Water Practice and Technology*, 19(10).
<https://doi.org/10.2166/wpt.2024.240>

Hotimah, O., & Sitanggang, N. A. R. (2025). The Relationship Between Disaster Communication Through @bpbddkijakarta Instagram Account on Gen Z's Preparedness Attitudes in Facing Potential Floods in DKI Jakarta. *Journal of Digital Marketing and Communication*, 5(1).
<https://doi.org/10.53623/jdmc.v5i1.641>

Huang, D., & Xiao, G. (2025). Exploring Urban Expansion Pattern Associations with Flood Vulnerability: Spatial Heterogeneity in Multidimensional Linkages Across China's Min Delta Urban Agglomeration. *Journal of Environmental Management*, 394.
<https://doi.org/10.1016/j.jenvman.2025.127449>

ISDR. (2006). Developing Early Warning Systems : A Checklist. *Third International Conference on Early Warning*, (March).

Ismanto, R. D., Fitriana, H. L., Manalu, J., Purboyo, A. A., & Prasasti, I. (2023). Development of Flood-Hazard-Mapping Model Using Random Forest and Frequency Ratio in Sumedang Regency, West Java,

Indonesia. *Geomatics and Environmental Engineering*, 17(6).
<https://doi.org/10.7494/geom.2023.17.6.129>

Jonkman, S. N. (2005). Global perspectives on loss of human life caused by floods. *Natural hazards*, 34(2), 151-175.
<https://doi.org/10.1007/s11069-004-8891-3>

Kusumastuti, R. D., Nurmala, N., Arviansyah, A., & Wibowo, S. S. (2022). Indicators of community preparedness for fast-onset disasters: a systematic literature review and case study. *Natural Hazards*, 110(1).
<https://doi.org/10.1007/s11069-021-04970-9>

Lailul Fikri, M., Dharmawan, A., & Agung Prakoso, S. (2025). Implementation of the Internet of Things (IoT) for Water Level Monitoring Using Ultrasonic Sensors and Telegram Bots as an Early Flood Warning System in Loireng Village, Sayung District. *Journal of Information Technology and Computer Science (INTECOMS)*, 8(2025).

Lassa, J. A. (2013). Disaster Policy Change in Indonesia 1930–2010: From Government to Governance? *International Journal of Mass Emergencies & Disasters*, 31(2).
<https://doi.org/10.1177/028072701303100202>

Lumban-Gaol, J., Sumantyo, J. T. S., Tambunan, E., Situmorang, D., Antara, I. M. O. G., Sinurat, M. E., Suhita, N. P. A. R., Osawa, T., & Arhatin, R. E. (2024). Sea Level Rise, Land Subsidence, and Flood Disaster Vulnerability Assessment: A Case Study in Medan City, Indonesia. *Remote Sensing*, 16(5).
<https://doi.org/10.3390/rs16050865>

Mahardhika, P., Sari, Z., Akbi, D. R., Kunci, K., Sugeno, F., Air, M. K., Bot, T., & Dini Banjir, P. (2025). Rancang Bangun Prototype Sistem Monitoring Ketinggian Air Sungai Berbasis Mikrokontroler ESP32 dan Telegram Sebagai Upaya Deteksi Banjir Secara Dini. *REPOSITOR*, 7(4).

Marzuki, M., Ramadhan, R., Yusnaini, H., Vonnisa, M., Muharsyah, R., Nugraha, Y., Sari, A. Y., & Erjalita, A. (2025). Long-Term Spatial–Temporal Variability, Trends and Extreme Rainfall Events Over Indonesia Based on 43 Years of CHIRPS Data. *International Journal of Climatology*, 45(14).
<https://doi.org/10.1002/joc.70107>

Morote, Á. F. (2015). Sendai Framework for Disaster Risk Reduction 2015–2030. *Australian Journal of Emergency Management*, 30(3).
<https://doi.org/10.4018/979-8-3693-7185-5.ch004>

- Nastiti, K. D., An, H., Kim, Y., & Jung, K. (2018). Large-scale rainfall–runoff–inundation modeling for upper Citarum River watershed, Indonesia. *Environmental Earth Sciences*, 77(18). <https://doi.org/10.1007/s12665-018-7803-x>
- Ningtias, Y. R., Noviani, R., Wijayanti, P., & Osza, A. A. (2025). Preparedness through social capital in Bengawan Solo River Communities, Surakarta City. *Jamba: Journal of Disaster Risk Studies*, 17(1). <https://doi.org/10.4102/jamba.v17i1.1857>
- Octaviana, S., Sartono, B., & Notodiputro, K. A. (2025). Enhancing Water Level Forecasting in the Ciliwung River Using Multiple Input BiLSTM. *Communications in Mathematical Biology and Neuroscience*, 2025. <https://doi.org/10.28919/cmbn/9343>
- Perera, D., Agnihotri, J., Seidou, O., & Djalante, R. (2020). Identifying societal challenges in flood early warning systems. *International Journal of Disaster Risk Reduction*, 51. <https://doi.org/10.1016/j.ijdrr.2020.101794>
- Permatasari, T. O., & Sinduwiatmo, K. (2024). Improving Disaster Response in Indonesia Through Culturally Integrated Communication Strategy. *Journal of Geosciences and Environmental Studies*, 1(2). <https://doi.org/10.53697/ijgaes.v1i2.3346>
- Pianto, T. A., Akbar, H. I., Sutejo, B., Rudiastuti, A. W., Sumargana, L., Purwandani, A., Santikayasa, I. P., Ambarwulan, W., Priyadi, H., & Nurdiansyah. (2023). Design and implementation of an IoT-based Automatic Water Level Recorder (AWLR) as a tool to mitigate the risk of tidal flood disasters in the coastal area of Jakarta. *IOP Conference Series: Earth and Environmental Science*, 1266(1). <https://doi.org/10.1088/1755-1315/1266/1/012061>
- Pumo, D., Avanti, M., Francipane, A., & Noto, L. V. (2024). An Early Warning System for Urban Fluvial Floods Based on Rainfall Depth–Duration Thresholds and a Predefined Library of Flood Event Scenarios: A Case Study of Palermo (Italy). *Water (Switzerland)*, 16(18). <https://doi.org/10.3390/w16182599>
- Puspasari, R. L., Yoon, D., Kim, H., & Kim, K. W. (2023). Machine Learning for Flood Prediction in Indonesia: Providing Online Access for Disaster Management Control. *Economic and Environmental Geology*, 56(1). <https://doi.org/10.9719/eeg.2023.56.1.65>
- Puspitasari, D., Hizbaron, D. R., & Mei, E. T. W. (2026). An urban flood-risk assessment of South Jakarta, Indonesia: A methodological approach through frequency ratio, receiver operating curve and analytic hierarchy process. *Jamba: Journal of Disaster Risk Studies*, 18(1). <https://doi.org/10.4102/jamba.v18i1.1873>
- Ramadhan, R., Yusnaini, H., Marzuki, M., Muharsyah, R., Suryanto, W., Sholihun, S., Vonnisa, M., Harmadi, H., Ningsih, A. P., Battaglia, A., Hashiguchi, H., & Tokay, A. (2022). Evaluation of GPM IMERG Performance Using Gauge Data over Indonesian Maritime Continent at Different Time Scales. *Remote Sensing*, 14(5). <https://doi.org/10.3390/rs14051172>
- Rana, I. A., Bhatti, S. S., & Jamshed, A. (2021). Effectiveness of Flood Early Warning System from the Perspective of Experts and Three Affected Communities in Urban Areas of Pakistan. *Environmental Hazards*, 20(3). 209-228. <https://doi.org/10.1080/17477891.2020.1751031>
- Ratmini, Y., Atina, V., & Purwanto, E. (2025). Flood monitoring and early-warning system based on the Internet of Things (IoT). *Jurnal Ilmiah Teknologi Informasi Asia*, 19(1).
- Rendana, M., Mohd Razi Idris, W., Abdul Rahim, S., Abdo, H. G., Almohamad, H., & Abdullah Al Dughairi, A. (2025). Flood risk and shelter suitability mapping using geospatial technique for sustainable urban flood management: a case study in Palembang city, South Sumatera, Indonesia. *Geology, Ecology, and Landscapes*, 9(2). <https://doi.org/10.1080/24749508.2023.2205717>
- Rentschler, J., Salhab, M., & Jafino, B. A. (2022). Flood Exposure and Poverty in 188 Countries. *Nature Communications*, 13(1).3527 <https://doi.org/10.1038/s41467-022-30727-4>
- Republik Indonesia. (2007). *Undang-Undang Republik Indonesia Nomor 24 Tahun 2007*.
- Riama, N. F., Sari, R. F., Rahmayanti, H., Sulistya, W., & Nurrahmat, M. H. (2021). The level of public acceptance to the development of a coastal flooding early warning system in Jakarta. *Sustainability (Switzerland)*, 13(2). <https://doi.org/10.3390/su13020566>
- Sigit, A., Koyama, M., & Harada, M. (2023). Flood Risk Assessment Focusing on Exposed Social Characteristics in Central Java, Indonesia. *Sustainability (Switzerland)*, 15(24). <https://doi.org/10.3390/su152416856>
- Subandi, A., Alim, S., Haryanti, F., & Prabandari, Y. S. (2019). Training on modified model of programme for enhancement of emergency

response flood preparedness based on the local wisdom of Jambi community. *Jamba: Journal of Disaster Risk Studies*, 11(1).

<https://doi.org/10.4102/JAMBA.V11I1.801>

Suryanto, S., Sholeh, S., Utomowati, R., & Hidayat, A. (2026). Assessment of social vulnerability to floods in the Samin watershed, Indonesia. *Jamba Journal of Disaster Risk Studies*, 18(1).
<https://doi.org/10.4102/jamba.v18i1.1947>

Ulum, M. bahrul. (2023). Sistem Monitoring Cuaca dan Peringatan Banjir Berbasis IoT dengan Menggunakan Aplikasi MIT App Inventor. *Jurnal Informatika Dan Teknik Elektro Terapan*, 11(3).
<https://doi.org/10.23960/jitet.v11i3.3088>

UNDRR and WMO. (2024). Global Status of Multi-Hazard Early Warning Systems. In *United Nations*

Office for Disaster Risk Reduction and World Meteorological Organization (Vol. 53, Number 41).

Varlas, G., Papadopoulos, A., Papaioannou, G., Markogianni, V., Alamanos, A., & Dimitriou, E. (2024). Integrating Ensemble Weather Predictions in a Hydrologic-Hydraulic Modelling System for Fine-Resolution Flood Forecasting: The Case of Skala Bridge at Evrotas River, Greece. *Atmosphere*, 15(1). <https://doi.org/10.3390/atmos15010120>

Wang, L., Bian, L., Leon, A. S., Yin, Z., & Hu, B. (2024). Integrating Policy Instruments for Enhanced Urban Resilience: A Machine Learning and IoT-Based Approach to Flood Mitigation. *Water (Switzerland)*, 16(23).
<https://doi.org/10.3390/w16233364>