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Trends and Research Opportunities For Microcontroller-Based Flood Warning Systems: A Bibliometric Analysis

Aulia Rahman Isti[1,*], Asrizal[1], Harman Amir[1], Leni Aziyus Fitri[1], Syafri[1]
[1] Department of Physics, Universitas Negeri Padang, Padang 25131, Indonesia

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Corresponding Author
*Author Name: Aulia Rahman Isti
Email: auliarahmanisti08@gmail.com

Abstract: Indonesia as an archipelago has a high level of vulnerability to flood disasters, which is worsening due to climate change, rapid urbanization, and weak mitigation systems. Ideally, an early warning system that is responsive, accurate, affordable and easy to implement in vulnerable areas is needed. While microcontrollers offer a potentially effective technological solution, most research is still limited to small prototypes without regard to long-term predictability or community participation. This study aims to evaluate the development, focus, and prospects of microcontroller-based flood warning system research using a quantitative bibliometric approach. A total of 200 articles from 2015-2025 were collected through Publish or Perish and analyzed using VOSviewer. The results showed, first, a significant increase in publications occurred in 2024, namely 29 articles. Second, word network visualization resulted in the mapping of 87 keywords in 7 clusters. Third, data overlay visualization resulted in a shift in focus to IoT integration, the latest microcontrollers, cloud-based monitoring. Fourth, data density analysis confirms the dominance of technical aspects, where keywords such as microcontroller, flood early warning system, and flood become the center of attention with the highest density level. The implications of these findings provide direction for the development of a more adaptive, inclusive, and applicable flood warning system in disaster mitigation.

Keywords: Floods, Flood Warning System, Microcontroller, Bibliometric Analysis, Disaster Mitigation.

1. Introduction

The protection of human safety is a universal principle that forms the basis of social policies and sustainable development strategies. In the context of disaster management, safety is positioned not only as an end goal but also as a fundamental element in shaping resilient communities. The Sendai Framework for Disaster Risk Reduction emphasizes ensuring safety by strengthening mitigation capacity based on accurate risk information systems and the active participation of local communities in risk management. Accordingly, the effectiveness of safety measures hinges on integrating warning technology, local knowledge, and swift, accurate responses. Therefore, life protection efforts form the basis for developing adaptive, technology-based disaster warning systems [1].

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Efforts to improve safety, particularly from the threat of flooding, require more than just the construction of physical infrastructure such as embankments or water channels. Technological advances have enabled the design of early warning systems that are not only cost-effective but also responsive and widely accessible. The use of microcontrollers, digital sensors, and wireless communication networks has become an important element in forming real-time flood monitoring systems. Microcontrollers are miniature computers integrated into a single integrated circuit (IC) chip, consisting of a processor, memory, and programmable interfaces [2]. For example, developing a Telegram bot-based flood warning system connected to water level sensors that can instantly notify the public [3]. Another study implemented a combination of ultrasonic sensors with GSM modules to detect water elevation and automatically send warning messages. Microcontrollers have superior capabilities because they can store and execute programs [4]. The consistent use of this technology demonstrates the effectiveness of microcontroller-based approaches in directly supporting disaster risk mitigation at the community level [5,6].

Indonesia's geographical characteristics inherently increase its vulnerability to hydrometeorological disasters, particularly floods. As an archipelago with a complex hydrological system and a dominant topography of densely populated lowlands, Indonesia is highly vulnerable to the accumulation of uncollected rainwater. Global climate change exacerbates the situation through increased rainfall anomalies that are difficult to predict conventionally. According to BNPB (2023), flooding is the most frequent type of disaster in Indonesia in recent years. This kind of tropical condition requires a detection system that is able to integrate spatial data, sensory sensing, and application-based information delivery systems in order to produce warnings that are fast, precise and easy to understand [7]. Therefore, the development of an early warning system that is contextualized with geographical characteristics is an urgent need.

The annual incidence of flooding in Indonesia consistently surpasses that of other types of disasters, with the highest number of flood events recorded. A significant number of major cities in Indonesia are susceptible to flooding, a phenomenon attributable to a combination of factors, including but not limited to: inadequate drainage systems, elevated rainfall intensity, and topographical conditions characterized by low-lying areas. In certain regions, flooding can also occur abruptly due to the overflow of rivers and the obstruction of waterways. The risk of flooding is not confined to the rainy season; it is also precipitated by the repercussions of climate change, which engenders extreme weather conditions. This condition renders flooding a complex and recurring threat, necessitating serious management. A critical strategic imperative is the development of an early warning system that can mitigate the consequences of disasters. The system must facilitate the expeditious transmission of information, ensuring its precision, thereby enabling individuals to promptly undertake rescue or preventive measures.

A substantial body of research has previously examined the primary causes of the high incidence of flooding in Indonesia, attributing it to a combination of natural factors and human activities. A frequently cited cause is suboptimal spatial planning, wherein development is executed without consideration for the environment's capacity. In many cases, areas that are susceptible to flooding have been developed into residential zones without the incorporation of adequate drainage systems, thereby diminishing the soil's capacity to absorb water naturally [8]. Furthermore, the conversion of green open space due to urban development has been shown to accelerate surface runoff, thereby increasing the risk of sudden flooding events. The underutilization of meteorological and hydrological data in urban planning also weakens warning systems and necessary mitigation measures [9]. A further complicating factor in the efforts to mitigate the risks posed by flooding is the limited public awareness regarding the threats posed by this phenomenon. The absence of a comprehensive disaster information system has also been identified as a contributing factor to the challenges experienced in cross-regional coordination. Consequently, the flood problem must be regarded as a multidimensional challenge that cannot be adequately addressed solely through technical solutions.

A body of research has been conducted on microcontroller-based flood early warning systems, yielding a range of innovative solutions designed to provide rapid and precise information. Such systems typically consist of water level measurement sensors in conjunction with communication modules, such as GSM or Wi-Fi, which are connected to a monitoring platform. One solution that has been proposed involves the automatic transmission of sensor data to a cloud-based platform, enabling real-time monitoring [10]. Another system integrates a Telegram Bot to transmit alerts directly to user devices [11]. The merits of this approach are evident in its ease of implementation, cost-effectiveness, and adaptability to local environments. This technology has demonstrated its efficacy in regions with limited infrastructure. Consequently, microcontroller-based solutions emerge as a rational and efficient option for enhancing community flood preparedness.

In theory, a microcontroller-based flood warning system is an example of the implementation of cyber-physical systems (CPS), the integration of physical and digital components within a system that can automatically detect, analyze, and respond to environmental parameters. This approach is highly relevant for flood risk management because it can respond to changes in field conditions in real time in an energy- and cost-efficient manner. Devices such as NodeMCU and ESP32, when combined with cloud platforms such as Firebase, can produce a fast, accessible notification system for the wider community [10, 11]. However, the absence of systematic mapping of research developments in this field has resulted in fragmented research and a lack of long-term collaborative strategies [12].

Various studies on flood warning systems have been conducted, although many studies have been developed in this area, most of them still face limitations in terms of scalability and sustainability. Many of the existing studies only produce technical prototypes without including system designs that enable integration with cloud platforms or geographic information systems. As an illustration, limiting system implementation to a single location, without cross-regional testing or multi-risk scenarios [8]. Meanwhile, using IoT but not including predictive processing based on historical data [9]. This indicates a gap between the available technological innovation capacity and the need for nationally-oriented mitigation system development. In addressing this challenge, the importance of warning system design that is modular, collaborative and supports interoperability across regions and institutions is emphasized [13].

The decision to employ a bibliometric analysis approach in this study is predicated on the pressing need to devise a systematic, data-driven, and pertinent scientific framework for the development of microcontroller-based flood warning systems. This approach has the capacity to thoroughly explore the intellectual landscape of research, including the mapping of collaboration networks between researchers, the identification of main keywords, and the dynamics of technological evolution in the last decade. In the national context, bibliometric analysis serves as a strategic tool to assess the strengths and weaknesses of the established scientific structure, especially in Indonesia, where research fragmentation and interoperability across institutions are still a problem. This approach represents more than a mere academic contribution; it also has the potential to inform the development of disaster technology policies grounded in scientific evidence and a reflexive consideration of global research trends.

This research aims to establish a strong scientific basis for planning and developing an adaptive, efficient, and widely applicable flood warning system at the national level through the use of software such as VOSviewer and Publish or Perish. Technical approaches without research maps often lead to project duplication, technological inconsistencies, and an inability to integrate data across regions, so this solution was chosen. This research's main objective is to thoroughly map the scientific structure of microcontroller-based flood warning systems to provide a conceptual basis for developing innovations, fostering strategic scientific collaborations, and formulating data-based, nationally contextualized technology policies.

2. Materials and Method

This study applies a bibliometric analysis approach to examine trends, dynamics, and research potential in the field of microcontroller-based flood warning systems. This method was chosen because it provides a quantitative overview of published scientific publications, such as research trends by year, data network visualization, data distribution visualization, and data density visualization. The research data consists of scientific journal articles and international conference proceedings that have undergone a peer-review process. Non-academic publications such as theses, technical reports, and popular documents are excluded. To maintain consistency in terminology and international relevance, this study only included publications in English. The criteria for selecting data sources were based on articles that explicitly discussed flood early warning systems using the keywords "flood warning system" AND "microcontroller" to search for relevant literature. These articles were taken from scientific journals published between 2015 and 2025. The search process was conducted through the Google Scholar database, accessed using the Publish or Perish (PoP) application. Google Scholar was chosen because it has broad coverage of publications in the fields of applied engineering, embedded systems, and the Internet of Things (IoT), which are often not fully indexed in curated databases such as Scopus or Web of Science. However, the limitations of Google Scholar regarding metadata curation and search reproducibility are acknowledged as limitations of this study.

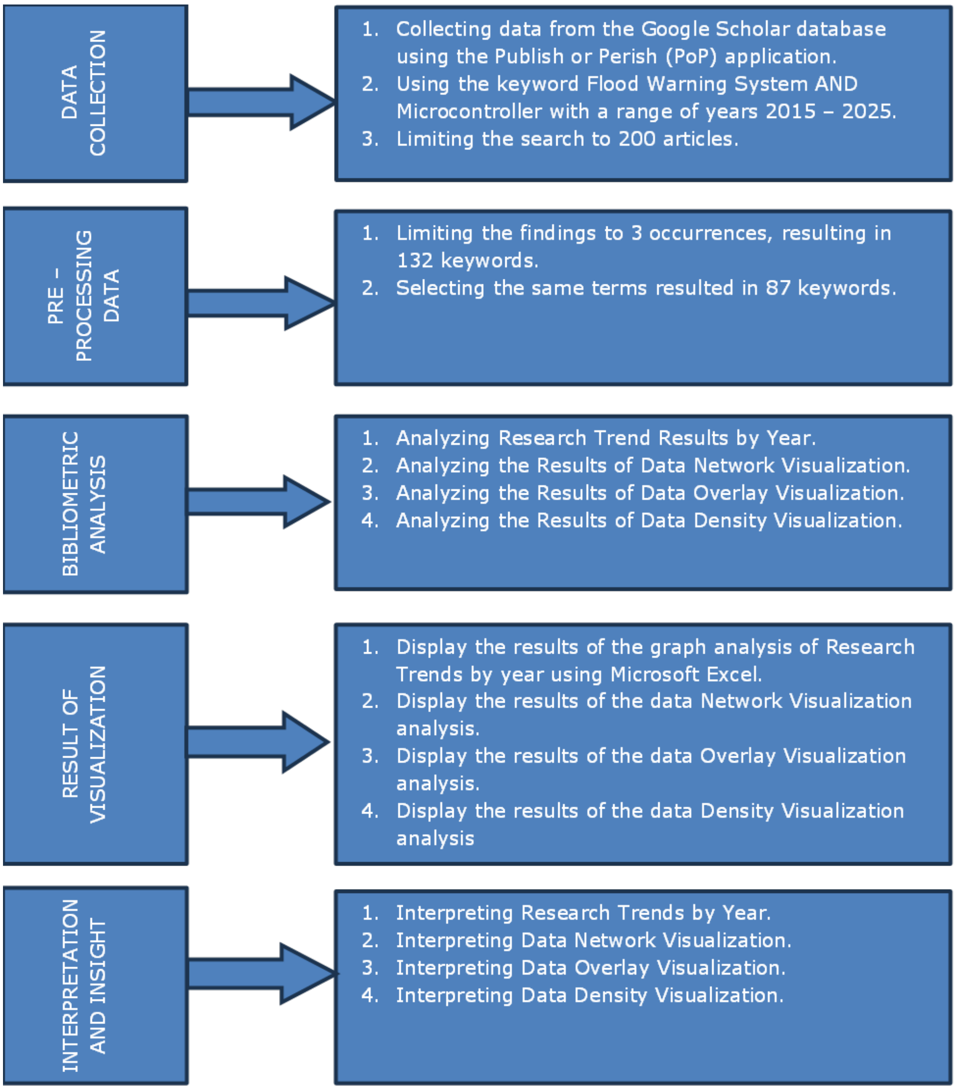

Figure 1. Research Stages of Bibliometric Analysis

a. The first stage of this research involved collecting data using the Google Scholar platform with the Publish or Perish (PoP) application. The search keywords were "Flood Warning System" and "Microcontroller," limited to publications from 2015 to 2025. To keep the analysis process focused and relevant, the maximum number of articles collected was limited to 200 documents.
b. The second stage was data preprocessing, which involved filtering keywords from the publication metadata results. Only keywords that appeared three or more times were included in the analysis. Additionally, a normalization process was carried out to unify words or phrases with similar meanings and avoid duplication in the results. This stage yielded 87 clean keywords, which was a reduction from the initial total of 132 words that passed the initial selection.
c. The third stage is a bibliometric analysis conducted using the VOSviewer software program. At this stage, the co-occurrence method was employed to identify relationships between keywords that frequently appear together in documents. This analysis enabled us to map thematic structures and identify emerging research foci.

d. The fourth stage of the process entails the visualization of the analysis results. The visualization of this data is achieved through the utilization of network maps, overlay maps, and keyword density maps. Furthermore, the annual trend in the number of publications was visualized using Microsoft Excel. This visualization offers a more comprehensible depiction of the relationship patterns among research topics.
e. The fifth stage is interpreting the results. At this point, the researcher explains the meaning of the visualizations and analyses performed. The main focus is identifying dominant themes, research trends, collaboration opportunities, and potential research gaps that have not been widely explored. These interpretations form the basis for research conclusions and recommendations.

Bibliometric analysis was conducted using VOSviewer software with the co-occurrence method to identify relationships between keywords and form thematic clusters of research. The resulting visualizations included network maps, time span maps, and keyword density maps.

To improve interpretability, the analysis was organized based on a three-dimensional bibliometric framework, including:

1. Technology Dimension, covering microcontrollers, sensors, and IoT.
2. System Function Dimension, covering detection, monitoring, warning, and prediction.
3. Application Dimension, covering prototype scale, social readiness, and disaster policy integration.

This framework is used as a basis for interpreting results and identifying research gaps.

3. Results and Discussion

3.1. Results

The data generated in this study includes analysis to determine publication trends over the past 10 years, data network visualization, data overlay visualization, and data density visualization. The results of the analysis are used to identify trends, research development dynamics, and future research potential in the field of microcontroller-based flood warning systems.

3.1.1 Trends in Flood Warning System Research by Year

An analysis of publication trends by year provides an overview of the development of research on microcontroller-based flood warning systems. Figure 2 summarizes the number of articles from 2015 to 2025 based on Google Scholar data analyzed using Publish or Perish (PoP) and Microsoft Excel. These results provide an initial basis for exploring the direction and opportunities for further research development. From the data in Figure 2, it can be explained that the growth pattern of the number of publications of articles discussing microcontroller-based flood warning systems during the period 2015 to 2025. At the beginning of the period, namely 2015 and 2016, the number of publications was still stable with 10 articles each. The increase began to appear in 2017 with a total of 12 publications, then experienced a significant increase in 2018 which reached 23 articles. Although there was a slight decline in 2019 and 2020, which amounted to 22 and 21 publications respectively, these figures still show the high interest in research in this field. 2021 recorded the lowest decline with only 14 articles, but the positive trend reappeared in 2022 with 19 articles, and continued to increase until reaching 27 articles in 2023. Publication activity reached its highest point in 2024 with a total of 29 articles. The drastic decline that occurred in 2025, with only 5 articles, was most likely due to data limitations due to the unfinished publication process for the current year.

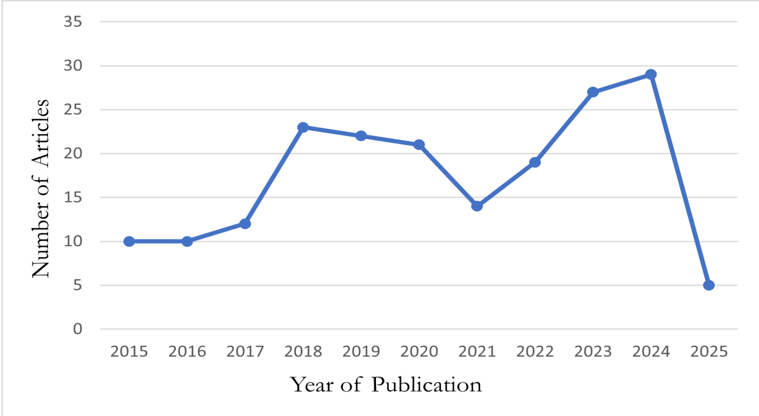

Figure 2. Research Trends by Year

3.1.2 Data Network Visualization

In bibliometric studies, keyword network visualization plays an important role in revealing the conceptual structure of a research field. Not only does it display word frequencies, but it also shows how important terms are interconnected and form thematic clusters in the scientific literature. This kind of visualization helps researchers see the knowledge map more systematically, as well as recognize dominant, interrelated, or even underexplored research areas. Figure 3 is the result of a mapping using VOSviewer software of publications that discuss microcontroller-based flood warning systems in the last decade. Through the co-occurrence approach, keywords that often appear together in scientific documents are visualized as a network, with a certain size and color representing their role and connection. From this, an assessment can be made of the orientation, strength of linkages, and diversity of research focus within the topic under review.

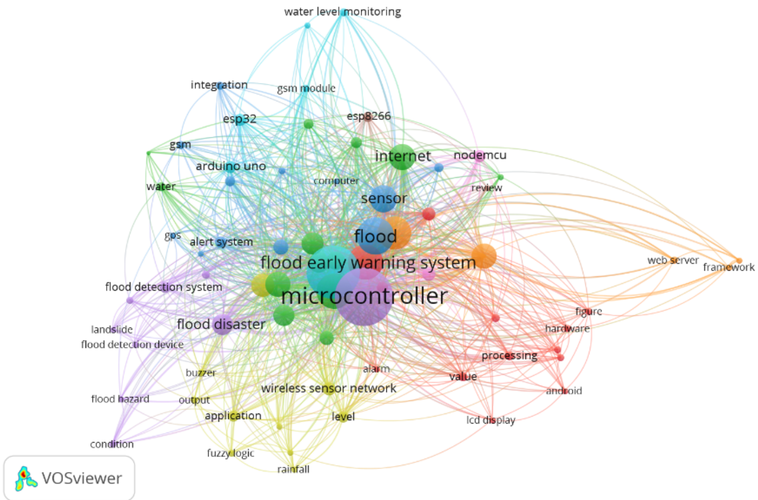

Figure 3. Data Network Visualization

Figure 3 shows the results of mapping keyword relationships using the co-occurrence method with the VOSviewer application. This method is based on a collection of scientific publications on microcontroller-based flood warning systems. The map shows the connections between keywords that appear together in a document. Node size shows how often a term is used, and node color shows specific research clusters or themes. Core keywords such as "microcontroller," "flood early warning system," and "flood" occupy central positions in the network, reflecting their role as the primary focus of the analyzed research. Green, blue, and cyan colors represent technical topic groups, including devices such as "esp32," "esp8266," and "arduino uno," as well as communication components like "gsm module," "internet," and "sensor." This suggests that the development of most microcontroller-based flood warning systems is closely tied to Internet of Things (IoT)-based approaches.

On the other hand, the purple and yellow groups contain keywords that describe the application of the system in the context of disasters, such as “flood detection system,” “alert system,” “buzzer,” and “flood disaster,” which show the research orientation toward direct implementation in the field. The red and orange clusters expand the research dimension to aspects of data processing and user interface development, with words such as “processing,” “framework,” “web server,” and “android,” indicating the importance of integration between hardware systems and digital monitoring platforms. The density and connectivity between keywords suggest that research in this field involves various disciplines, from hardware engineering and data communication to disaster mitigation aspects. This map illustrates that flood warning system research is not only advancing technically but is also beginning to move toward more connected, adaptive, and practical systems.

3.1.3 Data Overlay Visualization

In bibliometric analysis, knowing the relationship between keywords is not enough to understand how the direction and development of a research field is formed. Other methods are needed that not only show the interconnectedness of topics, but also illustrate the changing focus of studies over time. Figure 4 visualization of the data overlay is one effective method to see these dynamics, as it can show when a term starts to be widely used, lasts for a long time, or even starts to be abandoned. Through the help of color gradations that represent the time period of keyword occurrence, this visualization is able to provide a clearer picture of the development and shift of topics in a field of science. As such, this analysis helps researchers see not only what is frequently researched, but also how those themes change and evolve over time.

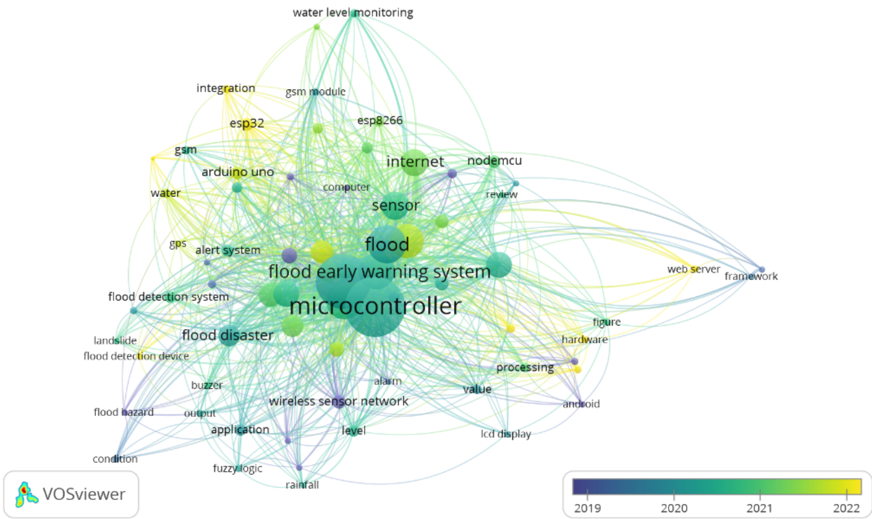

Figure 4. Data Overlay Visualization

Based on the data in Figure 4, it can be stated that the visualization results created using VOSviewer software, based on a collection of scientific publications that discuss the topic of microcontroller-based flood warning systems. In this visualization, the color of each node indicates the estimated average time of keyword appearance in the literature with blue representing early appearance (around 2019), green depicting the transition phase (2020 - 2021), and yellow indicating emerging or dominant topics in recent publications (2022 and above). Therefore, this visualization not only displays thematic relationships between words, but also reflects the dynamics of topic evolution in the past decade.

Some key terms such as “microcontroller”, “flood early warning system”, and “flood” are located in the central area of the network in greenish color, indicating that they have been part of the core of scientific conversations since the beginning and continue to be used consistently until now. Around them, terms such as “sensor”, ‘internet’, and “wireless sensor network” are similarly colored, indicating their stable use as an important part of supporting flood monitoring technology. Meanwhile, keywords in yellow such as “esp32”, “alarm”, ‘integration’, and “water level monitoring” indicate new focuses that have begun to emerge in recent years. This indicates that recent studies are shifting towards the adoption of more advanced IoT technologies and the enhancement of real-time warning system capabilities.

On the other hand, some terms such as “processing”, ‘framework’, “web server”, and “hardware” appear in the blue-colored area at the edge of the network, indicating that these themes were the focus of attention during the early stages of system development (around 2019-2020). This reflects that the early phase of the research focused more on system architecture design, hardware components, and data processing as the technical foundation. However, over time, the research direction shifted to more practical and integrated aspects, such as the efficient use of the latest microcontrollers and wireless and cloud-based monitoring capabilities. Thus, the color changes in this visualization reflect the shift in scientific focus from basic system design to smart integration and responsiveness to modern disaster needs.

3.1.4 Data Density Visualization

Density visualizations are used to show how often a keyword appears and how strongly it relates to other keywords in a collection of scientific articles. The color on the map, from purple to bright yellow, indicates its intensity, the lighter the color, the more often and important the word is discussed. Figure 5 below shows the results of the density visualization of the studies that discuss microcontroller-based flood warning systems. Through this map, we can see the main topics that are most researched, what keywords are most prominent, and how they are positioned and related to other themes in the same field.

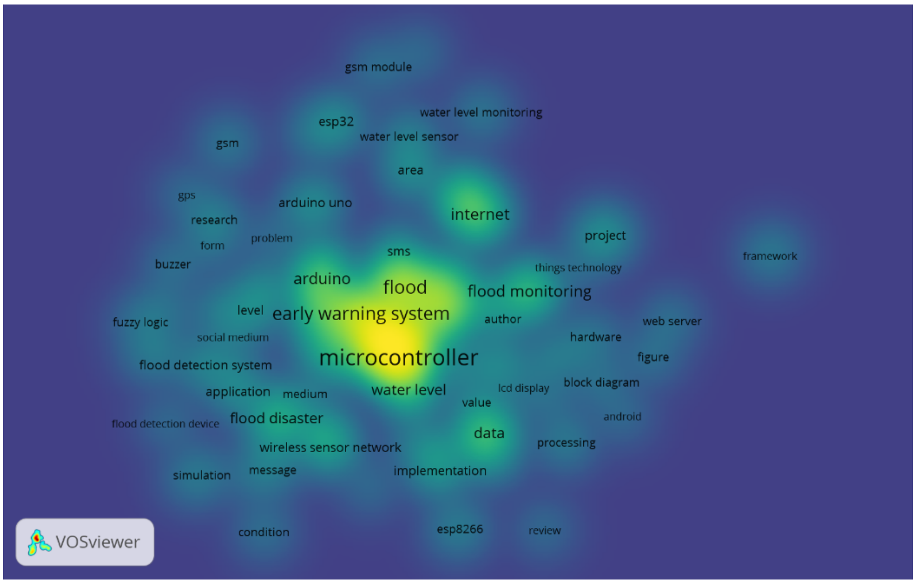

Figure 5. Data Density Visualization

Based on the data in Figure 5, it can be revealed that the results of visualizing data density using VOSviewer, which shows the intensity of occurrence and connectedness between keywords in scientific publications on microcontroller-based flood warning systems. The bright yellow color represents high density - meaning that the keyword appears frequently and is highly connected to other terms - while the purple color indicates low frequency and minimal connection. It is clear that "microcontroller", "flood early warning system", and "flood" are the main centers of research attention, with the highest density, confirming that the technical aspects and disaster context are the main focus in the literature.

The surrounding dense areas show keywords such as "sensor", 'internet', and "wireless sensor network", indicating the importance of IoT integration in flood warning systems. Outside of this core, terms such as "esp32", "arduino uno", and "alert system" are in medium-density areas, reflecting a technology trend that is used quite frequently, but has not yet become a central point. Meanwhile, words like "web server", 'framework', and "android" are in the dark and remote areas, indicating that these topics are still rarely discussed or not yet a top priority.

3.2 Discussion

The results of the discussion in this study show that the study of microcontroller-based flood warning systems has shown a significant increase in the last ten years. The increase in the number of publications began to be seen since 2018 and reached its peak in 2024. This shows that researchers' attention to affordable and effective microcontroller-based technology in disaster mitigation is getting higher. Several important terms such as “microcontroller”, “flood early warning system”, and “sensor” were the main keywords in the articles, indicating a strong focus on the technical aspects of the system. The visualization of the keyword network shows a close connection between the use of devices such as ESP32 and Arduino Uno, with various water level sensors and communication modules such as GSM and Wi-Fi, all connected to a cloud-based monitoring platform or smartphone app [14]. The study also showed that the system was able to transmit data efficiently and in real-time [15]. In addition, there are many developments of systems that directly connect with users through Telegram Bot [16], WhatsApp Gateway [8], or mobile phone-based IoT interfaces [17], which shows that the direction of technology development is increasingly prioritizing ease of access, energy efficiency, and speed of notification. However, there are still a number of gaps in this research, especially regarding the limitations of the system when it is widely deployed. Most studies only focus on developing small-scale prototypes, without considering aspects of scalability or integration with larger disaster information systems. Some studies only measure water levels and transmit the data, without conducting predictive analysis based on historical data [8]. Some even only tested the system in one location without cross-regional simulations or complex disaster scenarios [18]. Yet, with Indonesia's diverse geographical conditions and vulnerabilities, a flexible system that can be adapted to various environments is crucial. On the other hand, prediction-based approaches or artificial intelligence (AI) modeling are still rarely applied, although various studies have shown that the use of predictive models can help improve community preparedness [19]. Several studies have shown the success of AI-based systems in urban areas with rapid response to water dynamics [20], as well as the effective use of Wi-Fi-based sensors and dynamic data processing for flood mitigation [21]. Even systems that use self-sustaining energy such as solar power have been tested in remote areas [22].

Another weakness that is also a concern is the lack of discussion related to social, cultural and policy aspects. Most research still focuses on the technical side, without assessing the extent to which people understand and accept the technology [23]. This is a challenge, especially in areas with limited digital literacy and communication infrastructure. Another study even shows that systems using buzzers and SMS are more easily accepted by rural communities because they are simpler and do not rely on the internet [5]. In addition, there are still few studies that develop systems that can deal with more than one type of disaster, even though floods often occur together with landslides or storms [1]. Another bibliometric study revealed that warning systems that do not anticipate different types of risks can fail when faced with large-scale disasters such as those in Turkey [12]. Another issue is the system's dependence on a stable internet connection. Some studies show that when the connection is disrupted, the system fails to send alerts [24]. Another study found that the system can also fail to deliver information if it does not have alternative features such as buzzers or SMS [25].

In general, the development of microcontroller-based flood warning system research has now led to more interactive and adaptive systems. The system not only collects data, but is also able to provide warnings to users directly and process data automatically. To answer the increasingly complex needs of the field, future research approaches must be more integrated-not only involving technical aspects, but also paying attention to spatial planning, policies, and social readiness of the community. Research opportunities are wide open, ranging from the application of AI for flood prediction [5], the use of visualization and GIS platforms [26], to system designs that are inclusive of vulnerable groups. In addition, cross-sectoral collaboration and data-driven regulatory support are needed for this technology to be widely adopted and sustainable [3]. One example of system integration worthy of national adoption is the development of IoT-based alerts with real-time notifications [9]. Therefore, in addition to being a technical solution, future flood warning systems should be part of a sustainable development strategy that encourages community resilience to disasters [11].

The results of bibliometric analysis show that research on microcontroller-based flood warning systems is still dominated by technical approaches, particularly the development of prototypes based on water level sensors and IoT communication. Large clusters centered on the keywords microcontroller, flood early warning system, and sensor reflect a research orientation focused on hardware and real-time data transmission. The dominance of this technical cluster indicates research redundancy, where many studies develop relatively similar system architectures using ultrasonic sensors, popular microcontrollers, and IoT-based notifications, but test them in limited locations and scales. This condition shows that the increase in the number of publications has not been fully accompanied by an increase in system complexity or significant conceptual contributions. The time series visualization shows that topics such as ESP32, IoT integration, and digital application-based notifications have emerged as trends in recent years. However, the emergence of these topics reflects the adoption of popular technologies rather than fundamental methodological innovations. Conversely, topics such as artificial intelligence-based flood prediction, multi-disaster system integration, and community preparedness assessment remain in areas with low density.

Although this analysis does not specifically map the countries of origin of the publications, the patterns of themes and technologies that emerge indicate the dominance of universal and engineering-oriented approaches. This suggests that research in this field is developing globally with relatively homogeneous characteristics, especially in the development of low-cost IoT-based systems. However, this homogeneity also implies a lack of local contextualization and a dearth of research linking technology to national disaster policies or the social characteristics of specific regions. The lack of connection between technical clusters and social clusters indicates that most research is still device-oriented rather than system-oriented. Early warning systems tend to be viewed as mere technical devices rather than part of a disaster mitigation ecosystem involving people, institutions, and policies. These findings underscore the importance of shifting the research paradigm toward a more holistic and sustainable flood warning system. Based on the results of bibliometric analysis and identified research gaps, this study proposes a conceptual model of a microcontroller-based flood warning system that is viewed as a cyber–physical–social system. This model consists of three main layers, namely the physical layer (sensors and microcontrollers), the digital layer (data processing, communication, and prediction), and the social layer (users, communities, and disaster policies). The physical layer functions as a real-time environmental data collector through sensors and microcontrollers. The digital layer plays a role in processing, analyzing, and delivering warning information, including the potential integration of artificial intelligence for flood prediction. The social layer emphasizes the role of users, community preparedness, and system integration with disaster policies and institutions.

Based on this model, the future research roadmap is directed at four main focuses:
(1) development of a flood warning system based on smart predictions,

(2) design of a user- and community-oriented system,
(3) development of an integrated multi-disaster warning system, and
(4) synchronization of technology with national disaster policies and platforms.

The authors' findings show a significant increase in the development of microcontroller-based flood warning systems over the past decade, especially in the utilization of IoT technology, sensor integration, and real-time notification based on digital applications. The direction of research has begun to develop into the application of artificial intelligence, GIS visualization, and strengthening systems that are inclusive of affected communities. This study is still limited to data from Google Scholar and the majority of the publications analyzed only focus on the development of small-scale prototypes without widespread deployment tests. In addition, the study has not explored the social, regulatory and community readiness dimensions that are important in the effective implementation of a flood warning system.

4. Conclusion

This study presents a comprehensive bibliometric mapping of the development of microcontroller-based flood warning system research during the period 2015–2025. The analysis results show that the number of publications has increased significantly, with a strong dominance of technical approaches based on sensors, microcontrollers, and the Internet of Things (IoT). The main keyword clusters confirm that research is still oriented towards the development of prototypes and real-time monitoring systems. However, the mapping results also reveal structural imbalances in the direction of research. Aspects of flood prediction based on artificial intelligence, integration into multi-disaster systems, and community preparedness and adoption are still relatively unexplored. These findings indicate that the increase in the quantity of publications has not been fully accompanied by conceptual deepening and expansion of the scope of early warning systems.

As a scientific contribution, this research not only maps scientific trends and structures, but also proposes a conceptual model of a microcontroller-based flood warning system as a cyber physical social system. This model emphasizes the importance of integration between physical components, digital intelligence, and social factors in building an effective and sustainable early warning system. Based on these findings, the future research roadmap is directed towards the development of a flood warning system that is predictive, inclusive, integrated across risks, and aligned with national disaster policies and systems. Thus, this research is expected to serve as a conceptual and strategic basis for the development of research and implementation of microcontroller-based flood warning systems in the future.

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