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Big Data Challenges and Opportunities for Disaster Early Warning System

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Abstract: The application of big data in early warning systems (EWS) for multi-hazard risk management is becoming increasingly popular due to its enormous potential. Nevertheless, despite noteworthy achievements, there are still several enduring obstacles. This study aims to evaluate the advantages and difficulties through a comprehensive SWOT (strengths, weaknesses, opportunities, threats) analysis and the use of existing literature. An extensive literature analysis was conducted, incorporating perspectives of researchers from diverse background investigating both technical and social elements. The study results showed several notable strengths, such as unmatched accuracy and comprehensiveness, the incorporation of several data sources to improve prediction and forecasting, and the exploitation of up-to-the-minute data. On the other hand, problems, such as insufficient monitoring of hazards and a scarcity of interconnected sensors, especially common in less developed countries, were recognized. Lack of adequate coverage leaves a substantial percentage of the population vulnerable to disaster risks as a result of inadequate early warning systems. Ultimately, although big data offers significant possibilities, its complete capacity remains unexplored in the least developing nations due to existing obstacles, such as shortage of skilled worker, data accuracy and privacy which can be solved by enhancing technology education, capacity building, and practice. The objective of this study is to help such nations identify and overcome underlying challenges by implementing suitable measures.

Keywords: disaster; early warning system (EWS); big data; SWOT

1. Introduction

Geological, hydrological, biological, and climatic variables are causing disasters, which result in catastrophic events with disastrous consequences on environments and human social orders [1]. In such conditions, big data technologies can play a tremendous role in early warning systems by monitoring hazards, determining the exposure of human societies to disaster risk, tracking the impacts of disasters and monitoring recovery efforts, mitigating vulnerabilities, and strengthening the resilience of communities [2]. However, how to define big data? Some people argue that big data is "an inherently vague concept". Therefore, it is important to define it [3]. This is important to explain for readers that big data is not only simply "lots of data" and the term "big data" does not take size as its defining feature, despite what its name suggests. If not size, what makes big data "big"? One of the challenges to answer this question is that "there is no rigorous definition of 'big data'" [4]. Several researchers have identified certain vital features for describing big data. The 3Vs, or variety, volume, and velocity, are the three primary characteristics used to define big data. Variety refers to the presence of data from many categories, including raw data, structured data, semi-structured data, and unstructured data. This data is obtained from various sources such as websites, social media platforms, emails, and documents [5]. In recent days, big data has been used for disaster management because, with the continuous development of information technology and computing science, the application research of big data and artificial intelligence (AI) technology has been involved in various fields in recent decades, including hydro-meteorological forecasting, typhoon-related disaster risk prevention and early warning [6]. One pivotal study emphasizes an integrated approach to managing big data within a landslide early warning system through the application of ground-based interferometric radar technology [7]. Another study explores the development of a real-time natural hazard monitoring system that utilizes time data series of automated Interferometric Synthetic Aperture Radar (InSAR) as part of the geoscience framework project [8] Similarly, one more noteworthy study shows the use of Google Earth Engine for forecasting runoff in snow areas, developing flood prevention and response systems, and assessing drought occurrences by using global soil moisture indicators [9].

Various studies have shown that the application of big data and AI may effectively improve the level of disaster risk prediction and early warning, and disaster risk prevention, preparedness, and reduction [10]. Moreover, big data can increase social resilience to disasters caused by natural hazards, and enhance early warning systems by providing functionalities such as monitoring hazards, predicting exposure and vulnerabilities, managing disaster response, assessing the adaptability of natural systems, as well as engaging communities throughout the disaster cycle [11].

However, due to serious policies, operational, and even philosophical issues, the integration of big data into existing workflows has become very challenging. 40% of the countries indicated that two or more of the four elements in an effective early warning system were missing; 55% of them reported that at least one element is missing. These findings make it clear that most countries must strengthen their capacities in this field [12].

As crisis response teams are strengthening their ties with the formal emergency management sector, it is expected that big data technology can offer aids that will suit the needs of responders [13]. While the use of big data for an early warning system is highly beneficial, it poses significant challenges particularly in the least developed countries [14]. This research reviews several case studies from different countries that have deployed big data systems for early warning to mitigate potential losses. The aim is to identify the major challenges and opportunities while employing big data for early warning systems. Additionally, this study focuses mainly on the following three questions:

- How big data is used to strengthen early warning systems for disasters?
- What are the challenges in using big data for early warning systems?
- What could be done more in the case of the least developed countries?

The above mentioned questions have been analyzed in this study by using a SWOT analysis from the existing literature which allows for the evaluation of big data potential in early warning systems for disaster management. This study includes five sections. Firstly, an introduction that explains the background, big data definition, and characteristics. The next section provides a SWOT analysis for big data in early warning systems describing strengths, weaknesses, opportunities, and threats. Lastly, the discussion and conclusion, including a reflection on the analysis previously presented and final considerations, respectively.

2. Review Methodology

2.1. Data Sources

The data for this study were primarily sourced from academic journals, conference proceedings, reports, and reputable online repositories focusing on disaster management, big data analytics, and early warning systems. The selection criteria for literature include relevance to the study topic. Additionally, case studies and empirical research articles detailing the application of big data in disaster management were prioritized. A comprehensive literature review was conducted by using academic databases such as Scopus, ScienceDirect, and Google Scholar with the keywords and phrases including "big data" and "early warning systems" and "disaster management", and "SWOT analysis", and their variations were used to identify relevant articles. Although over 182 articles were found through the selected keywords, under consideration of the article type (review and research) and recent publications within the last decade (2010–2024), only 25 were assessed as appropriate for the initial review. The first phase of the review involved evaluating articles based on their abstracts. In the second phase, the focus shifted to the use of big data for disaster management, particularly in early warning systems. Additionally, a further 25 reviews, were conducted from other sources to meet the objectives of the article.

2.2. Application of SWOT Analysis to Early Warning Systems for Disaster Management

The SWOT analysis was applied specifically to evaluate the integration of big data into early warning systems for disaster management. Strengths were identified by examining the capabilities of big data analytics in enhancing the speed and accuracy of disaster risk assessment and prediction. Weaknesses were identified by analyzing challenges such as data quality issues, interoperability concerns, and resource constraints. Opportunities were identified by exploring the potential for utilizing big data technologies, including machine learning and artificial intelligence, to improve early warning systems' effectiveness. Threats were identified by assessing risks such as data privacy breaches, network security vulnerabilities, and ethical dilemmas associated with the use of sensitive personal information in disaster management. The findings from the literature review and SWOT [15] analysis was synthesized to provide a comprehensive understanding of the challenges and opportunities associated with integrating big data into early warning systems for disaster management. The themes and patterns identified from the data were analyzed to draw meaningful conclusions and insights, which were presented in subsequent sections of this article form the basis of the discussion. This methodology ensured the use of rigorous and systematic approaches for the SWOT analysis, thereby enhancing the credibility and validity of the study findings.

3. SWOT Analysis

3.1. Big Data Strengths and Opportunities in Early Warning Systems

Big data technologies offer information with unprecedented resolution and comprehensive coverage. They also collect and process data from various sources, including weather forecasts, tide gauges, and rainfall measurements, to generate accurate and timely flood forecasts. For instance, the system, called the Macao Flood Information Management System (MFIMS), was developed by the Macao Water Supply Company, and uses big data and AI technology to predict flooding caused by typhoons. This system uses big data to push emergency alerts as early warning and help emergency responders better allocate resources during a typhoon [16–18]. In the context of disaster risk management, early warning systems can make use of such big data to mitigate the risks effectively.

Disaster monitoring and forecasting are the first steps of disaster risk management. For example, satellite remote sensing technologies can provide real-time or near-real-time data which can help in detecting disasters more effectively [19]. Remote sensing data from satellites and radars is a major source of big data helping to detect any climate abnormalities and disaster probability [20]. However, it is worth noting that not only volume but also the variety of data matters in ensuring the accuracy of the system. Remote sensing data can be complemented and integrated with field observations and other varieties of data to ensure the accuracy and reliability of the systems [21]. For example, to predict flash floods, flood early warning systems can also use relevant information and data from other sources such as social media data, digital elevation models, and online water sensors [22]. The volume and variety of big data enable early warning systems to have a more comprehensive understanding of potential hazards, leading to more accurate and timely warnings.

Big data, particularly when combined with AI, can also contribute to a better understanding of patterns and trends, which can in turn lead to enhanced prediction and forecasting of the occurrence and intensity of hazards by the early warning systems [23]. The combination of big data (e.g., vast amount of historical data and socio-economic data), and AI has the potential to reveal such patterns and trends, which was difficult with a conventional approach. By using deep learning mathematical models, AI could learn from past weather records to predict the future. Such findings can contribute to more accurate and speedy forecasting through better modeling. For example, The Tamil Nadu System for Multi-Hazard Potential Impact Assessment, Alert, Emergency Response Planning and Tracking (TNSMART) Platform and app use big data analytics and machine learning to develop hazard and impact forecast [22]. Big data analytics and machine learning are essential components of the system in managing sizeable data from various institutes and sources on a single platform. For example, the flood early warning system of the TNSMART platform incorporates social media data streams, digital elevation models, and water sensors with other information to predict flash floods. During the 2020 Northeast Monsoon season, the potential flood scenario for the vulnerable locations in 37 districts was computed, based on the cyclone forecasts. During the Nivar and Burevi Cyclones, communities vulnerable to the potential flood scenario were identified and it was disseminated to district administrators to take necessary precautionary measures which helped emergency responders and decision-makers to have a better understanding of the impact and severity of the hazard, enabling them to allocate resources and coordinate response efforts more effectively.

Social media can also supply useful real-time data that can help in identifying disaster hotspots [24]. In addition, a case study from Huangshan, China shows that establishing a regional model has multiple benefits, as it can show accuracy as per the geography. The established model not only has an early warning accuracy of 85% but also has a false alarm rate of only 15%. It can effectively warn whether a geological hazard will occur in any location of the study area after the next 3 hour in every 1 hour [25]. Social media can facilitate information flow related to the probability of damages, location, and duration of natural hazards [26]. For example, it was found that the social media content about ongoing or upcoming flood was available several days before these events were reported to humanitarian organizations in Pakistan, and the Philippines tested a landslide detection system integrating physical sensors as well as social media (Instagram, YouTube, and Twitter) to explore the real origins and locations of natural hazards which were found to be effective to an extent [27].

3.2. Big Data Weaknesses and Threats in Early Warning Systems

The advancement of information and communication technology (ICT) has enabled the generation and collection of massive amounts of data from various sources, such as satellites, radars, and sensors, but there are also challenges associated with it. Foremost, coverage range of hazard monitoring and interconnected sensors is a major issue, particularly in developing countries. In the 73 countries out of 138 countries in World Meteorological Organization that shared data, one-third of every 100,000 people are not covered by early warning systems, mainly due to a lack of adequate hydrological and meteorological monitoring systems [28]. Hema Chandra et al. and WMO 2020 emphasized the critical importance of government investment in multi-hazard early warning systems. Recognized as a pivotal component in numerous disaster risk reduction measures, such systems have been proven effective in saving lives and minimizing economic losses.

Shah et al. outlined various challenges in data management, including issues related to data accessibility, timeliness, credibility, accuracy, and completeness [29]. Additionally, Šakić et al. identified significant challenges that must be confronted by multi-hazard early warning system (MHEWS) in integrating and amalgamating data from diverse and disparate sources, which involves the combination of data from different sensors, models, and platforms, as well as the resolution of conflicts that may arise during this process.

Given data heterogeneity, integration, fusion, and the utilization of diverse thresholds in analysis and interpretation, one challenge arises in the form of potential false alarms, as noted by Thirugnanam et al. [30]. Scheerlinck et al., 2018 [31] listed the following challenges in terms of data interoperability: poor data quality, considerations regarding data protection (including confidentiality and privacy regulations), complexities in data integration especially when dealing with a large number of sources, data processing to produce near-real-time analytics, and difficulties related to interfacing mechanisms between systems, including different communication protocols and data formats. Šakić et al. emphasized the imperative for decisions to be grounded in evidence, the necessity for performance monitoring, and the importance of addressing errors and false information.

One of the challenges faced for the proper operation of an early warning system is the reliability of sensors. Many early warning systems have been proposed for multiple hazards [32–34]. Esposito et al. analyzed flood, earthquake, landslide, and tsunami early warning systems and listed the challenges such as sensor installation in difficult places, sensors' energy requirement and consumption, sensor accuracy, calibration and upgradation [35].

Furthermore, next issue that has emerged in recent years on the use of the big data analysis for MHEWS is data security and privacy [36–38]. EWS based on cloud computing allows data storage and access through the internet because the data will be stored outside a country, which may not be permitted by the government's data privacy and security protocols [39]. Against this backdrop, the paramount significance of data governance is highlighted to guarantee the ethical and effective management of data, and several principles have been suggested for the ethical utilization of big data analytics to mitigate potential threats [40].

Another significant challenge confronting operational systems is the shortage of technical expertise and workforce [41–44]. Many governments, particularly those in developing nations, have shown hesitancy in embracing big data solutions due to the substantial investment required in terms of technical human resources. Achieving the objective of a functioning multi-hazard EWS necessitates ongoing political and institutional dedication, appropriate adjustments in policies and procedures, and investment in appropriate technology and human resources [45].

Despite the widespread interest and growing adoption of big data analytics, it is important to note that the result may not be perfect. For instance, while there is a vast amount of both historical and real-time data on earthquakes, predicting them remains exceedingly challenging, as highlighted by Silver [46]. Figure 1 further summarizes the strengths, weaknesses, opportunities, and threats of using big data in early warning systems for multi-hazard risk management.

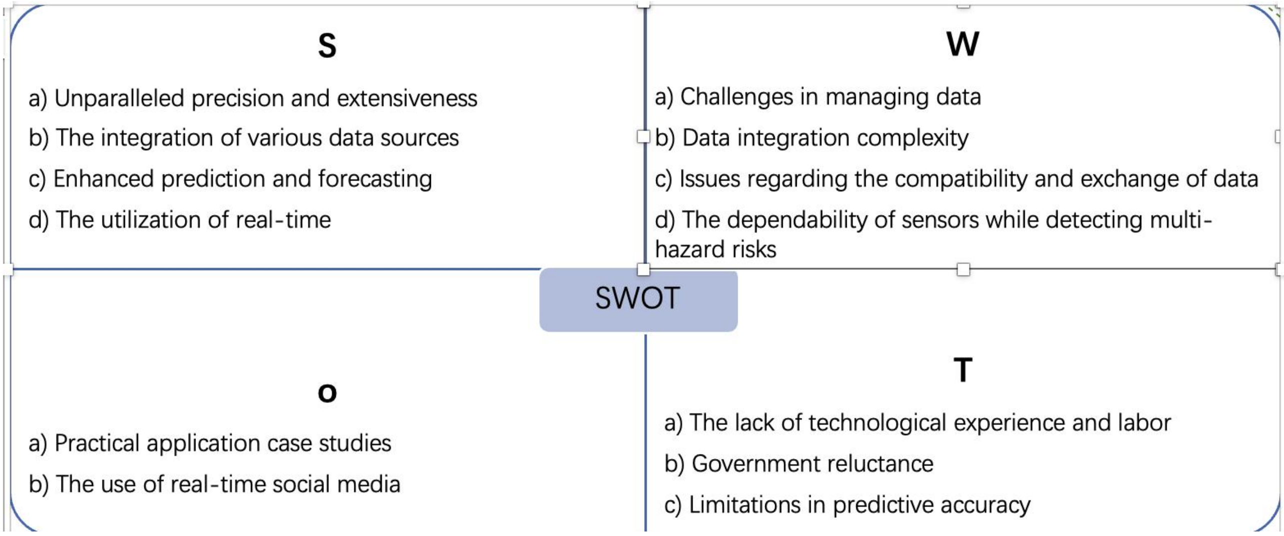

Figure 1. Summary of SWOT analysis.

3.3. SWOT (Brief of Figure 1, Summary of SWOT)

3.3.1. Strengths

- Unparalleled precision and extensiveness
  Big data technologies provide complete and detailed coverage, allowing early warning systems to get a deeper understanding of potential dangers. This result provides precise and fast alerts.
- The integration of various data sources
  The integration of various data sources, such as satellite remote sensing, radar data, social media data, digital elevation models, and online water sensors, is made possible by big data. This integration improves the accuracy and reliability of early warning systems.
- Enhanced prediction and forecasting
  The coupling of big data with AI offers a better understanding of patterns and trends, leading to enhanced prediction and forecasting of hazard incidence and intensity. This can enhance the precision and efficiency of forecasting by system effectiveness, which includes challenges relating to poor data quality, and the improvement of the modeling techniques.
- The utilization of real-time
  Social media data can enhance the early warning capabilities of systems by providing immediate information about disaster hotspots, the possibility of damages, and other pertinent details. This presents a chance to enhance the speed and precision in handling disasters.

3.3.2. Weaknesses

Coverage disparities refer to the inadequate monitoring of hazards and lack of networked sensors, which is particularly common in underdeveloped nations. This poses a serious drawback. The absence of proper coverage exposes a significant segment of the population to the risk of disasters as a result of inadequate early warning systems.

- Challenges in managing data
  The challenges identified by Shah et al. regarding data accessibility, timeliness, reliability, quality, and completeness pose substantial obstacles in efficiently handling the extensive data collected from many sources.
- Data integration complexity
  Data integration complexity arises when attempting to combine and merge data from several sources that are different and unrelated, such as data from different sensors, models, and platforms. This presents a significant difficulty in comparison to other challenges. The intricacy of this situation can result in problems such as possible erroneous alerts and challenges in resolving disagreements while integrating.
- Issues regarding the compatibility and exchange of data
  Scheerlinck et al. have identified several shortcomings in data interoperability and data protection, complexity in data integration, and difficulties in data processing.
- The dependability of sensors while detecting multi-hazard risks
  The dependability of sensors while detecting various dangers is a notable vulnerability. Obstacles, such as the installation in challenging locations, energy demands, precision, calibration, and upkeep, all contribute to the lack of reliability in sensor data.

Data security and privacy concerns arise when using cloud computing systems that store data outside of a country's boundaries, which can be a serious vulnerability. This encompasses possible clashes with government data privacy and security rules, emphasizing the necessity for strong data governance systems.

3.3.3. Opportunities

- Practical application case studies
  Case studies like the Tamil Nadu System for Multi-Hazard Potential Impact Assessment, Alert, Emergency Response Planning, and Tracking (TNSMART) Platform show how big data technologies can be effectively used to manage and predict hazards. These case studies provide concrete examples of how similar implementations can be beneficial in other regions or contexts.
- The use of real-time social media data
  The use of real-time social media data offers the potential to improve early warning systems by integrating supplementary sources of information, reducing response time, and increasing accuracy in disaster management.

3.3.4. Threats

- The lack of technological expertise and skilled labor
  Especially in poor countries, the lack of technological experience and labor poses a risk to the successful adoption and maintenance of the early warning systems driven by big data. This poses a threat to the system's functionality and effectiveness because of inadequate human resources.
- Government hesitancy
  Governments, particularly in underdeveloped countries, are reluctant to adopt big data solutions because of the significant expenditure needed for technical human resources, which is a danger. This hesitancy impedes the advancement and use of cutting-edge technologies in disaster risk management, thereby exposing populations to vulnerabilities and dangers.
- Limitations in predictive accuracy
  Despite significant progress in big data analytics, there are still significant challenges in accurately predicting certain risks, such as earthquakes. The abundance of historical and real-time data, despite its availability, presents a challenge to the efficacy of early warning systems in accurately predicting future events.

4. Discussion

This research analyzed the strengths, weaknesses, opportunities, and threats of using big data for a multi-hazard early warning system. The overall findings revealed that the significance of big data in early warning systems is very high; however, it is equally important to address the challenges associated with it. These outcomes align with the idea proposed by Emmanouil D et al. that big data helps manage disasters by enhancing effective early warning systems [10]. Research also presents the usefulness of the analysis of big data management for all stages of disasters and briefly an analysis of the data sources collected during the crisis, the technological means, and the tools for storing and processing big data. The Hurricane Weather Research and Forecasting model, which uses big data and AI techniques, has been used in various disaster risk reduction efforts, such as the deployment of resources and evacuation plans. For example, during Hurricane Florence in 2018, the Federal Emergency Management Agency used the HWRF model to predict the storm's track and intensity, which allowed them to deploy resources and personnel to the areas expected to be hit the hardest [47]. However, our research is slightly different because it particularly focuses on early warning systems, which participate in the preliminary and important stage of disaster management.

The findings, especially on challenges of employing big data for multi-hazards such as coverage disparities, difficulties in managing data, complexity in data integration regarding compatibility and exchange, and concerns regarding data security and privacy, are important challenges that should be understood in advance when working with big data for early warning systems. These findings help to understand the nature of challenges and provide insights for actively solving problems and taking action. Several previous studies have focused on specific hazards, such as landslides or floods exclusively [48]. In certain areas prone to earthquakes, floods, landslides, and multiple hazards, our research has found that addressing challenges about big data in early warning systems from a multi-hazard perspective is essential for enhancing effectiveness.

In addition, our research also found that from analysis of previous research unparalleled precision and extensiveness, the integration of various data sources, and enhanced prediction and forecasting are strong parts of big data for multi-hazard early warning systems which was highlighted in previous research. For example, the Korea Meteorological Administration has installed an AI-based flood forecasting model that can predict flooding in real time and provide early warning alerts [49,50]. However, our research benefits all concerned departments by providing ideas for the action and effectiveness of early warning installation.

There are few limitations in this research on reviews, because it has taken available reviews through the search based on topic instead of systematic literature to gather as much information as possible. The research primarily examines the effectiveness and difficulties of utilizing big data for early warning systems, specifically from a multi-hazard standpoint. However, it may not provide an in-depth exploration of the precise technical or methodological components of data analysis. Additionally, it is important to note that the research findings may be context-specific or region-specific. Therefore, they may not have universal applicability across all situations. There may be differences in infrastructure, resources, and technological capabilities among different regions.

Further investigation should explore the identified obstacles in more detail, such as discrepancies in coverage, intricacies in data integration, and issues related to privacy. This may entail investigating novel solutions and technology to successfully tackle these difficulties. Additional research is necessary to increase the integration of diverse data sources and optimize prediction and forecasting models for early warning systems. Future research endeavors could prioritize the validation of the effectiveness of suggested solutions and techniques for tackling big data difficulties in early warning systems by conducting real-world implementation and evaluation studies.

5. Conclusions

To summarize, study results showed that the use of big data is increasing and how much it should be integrated into early warning systems. With over half of the countries worldwide advocating for improved systems, the importance of understanding and enhancing this integration cannot be overstated. Big data's potential in early warning systems is immense, so it requires a deep understanding of how big data can be effectively used and the challenges that need to be addressed in this aspect. The opportunities, such as practical application case studies like the TNSMART platform, show how big data technologies can be effectively used to manage and predict hazards. Moreover, challenges, such as shortage of skilled workers, and data accuracy and privacy issues, can be solved by enhancing technology education, capacity building, and practice. Therefore, the finding from this research provides crucial information for deploying an early warning system addressing multi-hazards risk through a SWOT analysis.

Author Contributions

R.S.: conceptualization; methodology; original draft preparation. N.P.: review and editing. Y.C., Y.Z., Y.S., A.M.D.: investigation. N.P., Y.S., A.M.D.: formal analysis.

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Conflicts of Interest

The authors declare no conflicts of interest related to this research.

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