Field Validation of Multiple IoT Sensors for Detecting Geographical Phenomena in an Early Warning System for Heavy Rainfall*

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Abstract

In recent years, sudden heavy rain has caused serious problems in cities and rural areas, leading to flooding, damaging crops, and even threatening human lives. Because of this, micrometeorological forecasting technology is getting more attention for its potential to predict localized weather phenomena. However, effective countermeasures against heavy rain disasters require a comprehensive approach that considers not only atmospheric changes but also geographical changes such as terrain and built environments. Therefore, this study proposes the Early Warning System for heavy rainfall that considers both atmospheric factors from cloud-based micrometeorological prediction services and geographical factors collected by numerous IoT sensors. Especially, this paper reports on the deployment of IoT sensors, including 3-axis accelerometers, flood sensors, and soil moisture sensors, to monitor water flow. Also, anomaly detection approach with the Kalman Filter is proposed for the proposed system, and ongoing field experimental results are discussed for future works aimed at refining and expanding the system.

Keywords: Early Warning System for Heavy Rainfall, Disaster Information System, IoT, Wireless Network, Kalman Filter

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1 Introduction

In recent years, sudden heavy rain has caused serious problems in cities and rural areas, leading to flooding, damaging crops, and even threatening human lives around the world. For example, in Iwaizumi Town, Iwate Prefecture, Typhoon No. 10 in 2016 brought unexpected heavy rain that flooded a nursing home (Yamamura, n.d.). In the disaster, nine people died before a flood warning was issued. More recently, in July 2024, sudden rainstorms in Akita and Yamagata Prefectures caused five deaths, damaged over 1,000 houses, and led to economic losses of more than 10 billion yen (CabinetOfficeJapan, n.d.).

Therefore, micrometeorological forecasting technology is getting more attention for its potential to predict localized weather phenomena. Unlike traditional systems using AMeDAS (Automated Meteorological Data Acquisition System) and rain cloud radar, which operate at the kilometre scale, recent research has shifted toward high-resolution, real-time micrometeorological forecasting at the meter scale using AI (Yuki, 2023) and social media (Umaga, Mikami, Goto, & Yoshikai, 2018).

However, to respond to heavy rain disasters more effectively, it is important to consider not only atmospheric changes but also geographical changes such as rivers, mountains, and buildings. Therefore, this study proposes the Early Warning System for Heavy Rainfall (EWSHR) that considers both micrometeorological factors from cloud-based weather prediction services and geographical factors collected by numerous IoT sensors to provide faster and more accurate alerts to help reduce damage and protect lives.

In detail, the Enhanced MQTT (Message Queuing Telemetry Transport) protocol (Uchida, Endo, Ishida, Yuze, & Shibata, Enhanced MQTT Method with IoT Data Priority Controls for Scalability and Reliability on Early Landslide Warning System, 2022) is proposed to enable scalable and reliable wireless communication across diverse terrains, including mountains or rivers. By prioritizing high-importance data, the Enhanced MQTT ensures low-latency and low-error transmission even in environments with a high density of IoT sensors and drones.

Also, the system is designed to detect anomalies by applying the Kalman Filter (Hagiwara, Makiyama, Uryu, & Ishida, 2018), which utilizes a time-series state-space model to analyze both atmospheric and geographical variables. This approach improves prediction accuracy by continuously adjusting estimates based on observed discrepancies and calculating abnormality scores using Gaussian distribution models (Ide, 2015). The system then assesses risk levels and issues in real-time, high-confidence warnings.

The structure of this paper is as follows: Section II reviews the proposed system architecture considering both atmospheric and the geographic factors. Section III details the Enhanced MQTT protocol for IoT networks. Section IV and Section V outline the atmospheric factors with the cloud-based micrometeorological predictions and the geographical factors with numerous IoT sensors. Section VI describes the implementations of IoT sensors, and it presents the results of the field experiments. Finally, Section VII concludes with a summary and future research directions.

2 Proposed System

This paper proposes a practical EWSHR using a large number of IoT sensors and micrometeorological predictions. The system is designed to consider both atmospheric and geographical factors, making it more accurate and reliable for disaster prevention. Figure 1 shows the overall structure of the proposed system.

As shown in Figure 1, the system includes three main network layers: an IoT network, an IP network, and cloud-based weather forecasting services. The IoT sensors, such as 3-axis accelerometers, GPS modules, flood sensors, and soil moisture sensors, are connected through the 920 MHz LoRa radio band (Semtech.com, n.d.), which is suitable for long-range and low-power communication. Agricultural drones are also used to collect visual data for analyzing terrain and water flow. All observed data are sent to disaster management servers via IoT gateways, allowing real-time monitoring at the disaster response center.

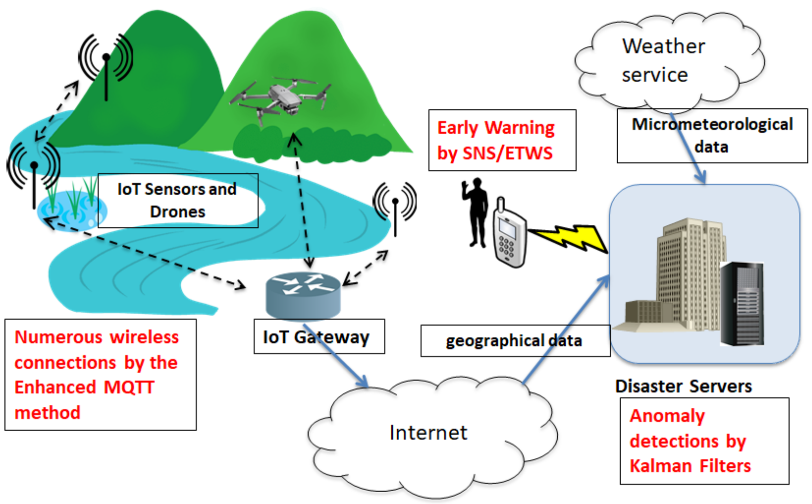

Figure 1: Proposed Early Landslide Warning System

The server connects to Web APIs from weather forecasting services like JMA (JMA, Advanced use portal site of weather data, n.d.), Yahoo Japan's Weather Information (YahooJapan, n.d.), and cloud-based AI platforms such as Google GraphCast to collect micrometeorological data. These data are combined with geographical observations, and the system checks for anomalies. If abnormal values are detected, early heavy rain warnings are sent to mobile phones in the affected areas using the ETWS (Earthquake and Tsunami Warning System) protocol (3GPP, n.d.) or LINE notify (LINE, n.d.).

Two key technologies are used in the system. First, the Enhanced MQTT protocol (Uchida, Endo, Ishida, Yuze, & Shibata, Proposal of Early Landslide Warning System considering Scalability and Reliability with Emergent IoT Data Priority, 2022) is applied to support many wireless connections. While standard MQTT (OASIS, 2019) is designed for small data and many devices, monitoring large areas like rivers and mountains requires more sensors. The Enhanced MQTT adds priority control to make sure important data is sent quickly and reliably.

Second, the system uses anomaly detection with the Extended Kalman Filter (Hagiwara, Makiyama, Uryu, & Ishida, 2018). This method analyses multiple types of data, such as acceleration, water level, and rainfall, using a time-series model. It improves prediction accuracy by adjusting estimates based on differences between predicted and observed values. Abnormality scores are calculated using a Gaussian distribution (Ide, 2015), and the system can then assess danger levels and send real-time warnings with high confidence.

3 Enhanced MQTT Method

A previous study (Uchida, Endo, Ishida, Yuze, & Shibata, Proposal of Early Landslide Warning System considering Scalability and Reliability with Emergent IoT Data Priority, 2022) introduced the Enhanced MQTT method, which was applied to an Early Landslide Warning System utilizing a large number of IoT sensors. The research demonstrated that this enhanced protocol could support up to 600 IoT connections, doubling the capacity of the standard MQTT protocol, which managed fewer than 300 devices (Uchida, Endo, Ishida, Yuze, & Shibata, Enhanced MQTT Method with IoT Data Priority Controls for Scalability and Reliability on Early Landslide Warning System, 2022). Additionally, the study explored the potential integration of this system with existing weather warning infrastructure to develop a more advanced Early Weather Warning System (Uchida, Ishida, Yuze, & Shibata, Early Weather Warning System with Real-Time Monitoring by IoT Sensors Considering Scalability and Reliability, 2023).

Figure 2 illustrates the data transmission mechanism of the proposed method. The protocol assigns priority levels to metadata within the MQTT header, allowing IoT data to be sorted into corresponding priority queues at the broker node. Subscribers then receive data asynchronously from the higher-priority queues, ensuring that critical information is delivered promptly.

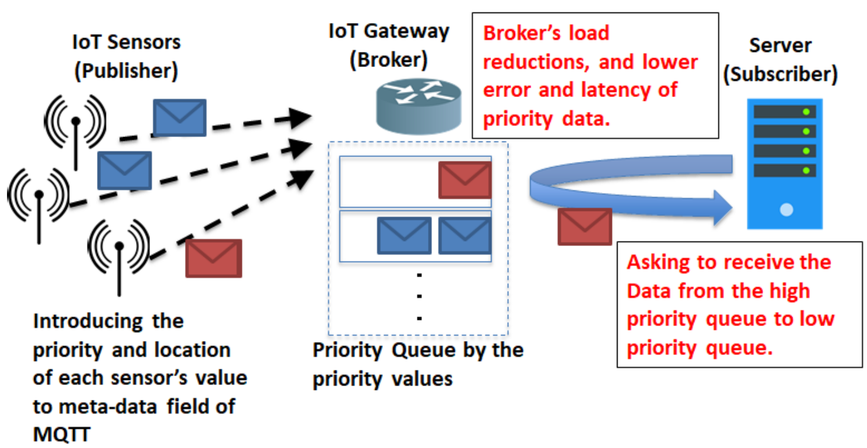

Figure 2: Enhanced MQTT Protocol

By prioritizing abnormal sensor readings such as those indicative of landslides or flooding, the method reduces the processing burden on the broker node, minimizes transmission errors, and lowers latency for essential data. Furthermore, the MQTT-Drain technique (Uchida, Endo, Ishida, Yuze, & Shibata, Enhanced MQTT Method with IoT Data Priority Controls for Scalability and Reliability on Early Landslide Warning System, 2022) is also employed to efficiently parse system logs, enabling rapid data calculations on the server.

4 Atmospheric Factors with Micrometeorological Data

As previously noted, micrometeorological forecasting has recently focused on the advancement of weather prediction technologies. This field examines atmospheric behaviour at very localised scales, typically within tens of meters, and near the Earth's surface (Foken, 2008). In Japan, conventional forecasting methods rely on systems such as AMeDAS, rain cloud radars, and satellite images. AMeDAS consists of ground-based observation stations equipped with instruments like thermometers, rain gauges, and anemometers. These data are combined with radar and satellite inputs to generate weather forecasts.

However, AMeDAS stations are distributed at intervals of several tens of kilometers, and rain cloud radar operates at a similar spatial resolution. Moreover, radar-based cloud analysis typically requires at least one hour to complete. As a result, recent studies have proposed more accurate and real-time micrometeorological forecasting derived by artificial intelligence (Yuki, 2023) or observation data from social media platforms (Umaga, Mikami, Goto, & Yoshikai, 2018).

In detail, the previous paper (Yuki, 2023) proposed a deep learning-based approach to micrometeorological forecasting. The study employed neural networks to perform 3D super-resolution processing on existing weather data, achieving a resolution eight times higher than the original, without increasing computational time. Additionally, Google has introduced GraphCast (Google, n.d.), which is a cloud-based AI system capable of global weather forecasting. This service enables micrometeorological predictions with significantly reduced computational overhead.

In addition, some studies have also explored the use of social media (Umaga, Mikami, Goto, & Yoshikai, 2018) and IoT sensors (Kunimi, Tomii, Ito, Abe, & Suganuma, 2024) to derive micrometeorological data. In fact, Yahoo Japan already provide the weather information service for the mobile applications and Web API, and the service use customer's SNS postings to derive the micrometeorological forecasting including the disaster phenomena (YahooJapan, n.d.).

Despite these advancements, accurate heavy rainfall warnings must still account for local geographical features such as rivers, agricultural reservoirs, and terrain-induced flooding. Currently, the Japan Meteorological Agency (JMA) incorporates historical weather data to issue landslide warnings (JMA, Criteria for Issuance of Emergency Warnings, n.d.). JMA utilizes a soil rainfall index based on a three-layer tank model (Ishihara & Kobatake, 1979), applied to 1 km^2 grid cells across the country. Emergency alerts are triggered when forecasted rainfall exceeds the threshold defined by the index. However, during Typhoon No. 10 in Iwaizumi Town on August 26, 2016, nine individuals in a care facility tragically died due to flooding from the Omoto River, which was intensified by underground water surges and runoff from nearby mountains (Uchida, Ishida, Yuze, & Shibata, Early Weather Warning System with Real-Time Monitoring by IoT Sensors Considering Scalability and Reliability, 2023).

5 Geographical Factors with Numerous IoT Sensors

This paper also proposes the early warning system for heavy rain disasters that combines atmospheric data from microclimate forecasting with geographical data collected by various IoT sensors. While traditional hazard maps require significant effort to create such as surveying terrain and geology in advance to identify flood-prone areas, recent disasters have shown that unexpected factors can also cause flooding (Uchida, Ishida, Yuze, & Shibata, Proposal of Dynamic Critical Line Algorithm by Real-time Monitoring with IoT sensors for Early Weather Warning System, 2023). For example, our past investigations revealed that underground water eruptions, overflow from agricultural reservoirs, and clogged drains due to fallen leaves in urban areas have all contributed to flooding. These events highlight the need to monitor changing geographical conditions in real time.

To address this, the proposed system uses multiple types of sensors, including temperature and humidity sensors, accelerometers, flood sensors, and soil moisture sensors. These sensors help detect abnormal conditions as they happen. By applying the Enhanced MQTT method, the system significantly improves the simultaneous connectivity and reduces the latency of IoT devices. It allows for efficient and timely monitoring of dynamic geographical factors, which is essential for accurate and fast disaster alerts.

Building on this foundation, the study proposed leveraging a dense network of IoT sensors to monitor geographical features such as water flow. To enhance the system's responsiveness to environmental changes, the authors introduced an anomaly detection mechanism based on the Kalman Filter (Hagiwara, Makiyama, Uryu, & Ishida, 2018).

The Kalman Filter is a widely used algorithm for estimating hidden or unobservable states in dynamic systems, based on noisy or incomplete observations. It operates within the framework of state-space models, where sensor data serve as observed inputs to infer underlying geographical states. This method enables the detection of anomalies by continuously updating and refining state estimates in real time.

One of the key strengths of the Kalman Filter lies in its recursive nature: it calculates the current state estimate and predicts the next state using both the latest observation and the previous prediction. This iterative process allows for accurate tracking of time-varying phenomena, even when observations are subject to noise and uncertainty.

In the Kalman Filter, the state Equation and the observation equation are expressed as shown in Figures (1) and (2).

$$\boldsymbol{x_t = Ax_{t-1} + B\mu_t + \varepsilon} \quad (1)$$

$$\boldsymbol{y_t = Cx_t + \sigma} \quad (2)$$

Here, x_t represents the state variable at time t, u_t is the control variable, and ε is the process noise followed by Gaussian distribution. Also, y_t is the observed variable at time t, and σ is the process noise followed by Gaussian distribution. *A*, *B*, and *C* are coefficients for each value. Also, Figure 4 shows the Kalman filter's prediction and update process.

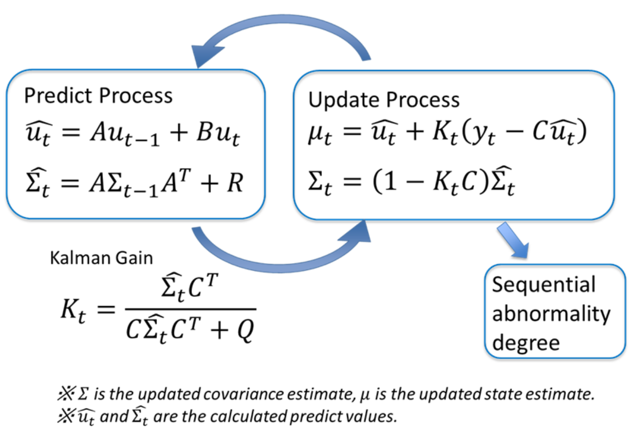

Figure 4: Processes of Kalman Filter

This paper proposed to introduce the multiple IoT observed values to x_t, and the micrometeorological rainfall to ε in the process, and it is supposed to calculate more reliable warning levels for the system.

In this study, the Kalman Filter is integrated into the EWSHR to detect abnormal environmental conditions. Given the complexity of sudden rainfall events and diverse terrain characteristics, the Kalman Filter, a linear variant of the standard model, is employed. This version accommodates nonlinear relationships in the data and uses Gaussian distributions to quantify the degree of abnormality (Ide, 2015), enabling more precise and adaptive forecasting for future works.

6 Experiments

This paper focused on testing the proposed EWSHR by using multiple IoT sensors to measure acceleration, soil moisture, and flooding phenomena during heavy rainfall. The goal was to evaluate how well the system could detect early phenomena of disaster in real time.

In the experiments, the IoT sensor devices are implemented by the Green House GH-EVARDLRB, which includes an Arduino Bootloader Atmega328PB and a LoRa GH-WM92LRA (920MHz) module for wireless communication. The sensors used were a 3-axis accelerometer (Akizuki KXR94-2050), a temperature and humidity sensor (Osoyoo DHT11), and a soil moisture sensor (DFRobot SEN0193). Also, for the IoT gateway, a Raspberry Pi 4B (8MB) was used to implement the proposed Enhanced MQTT communication method using the Go programming language. Figure 3 shows the implemented multiple IoT sensors.

These sensors were placed in different environments to monitor changes during rainfall. The system was able to collect data such as soil moisture increase, ground vibration, and water level changes. The Enhanced MQTT method helped improve the speed and reliability of data transmission, allowing the system to detect abnormal conditions quickly and efficiently.

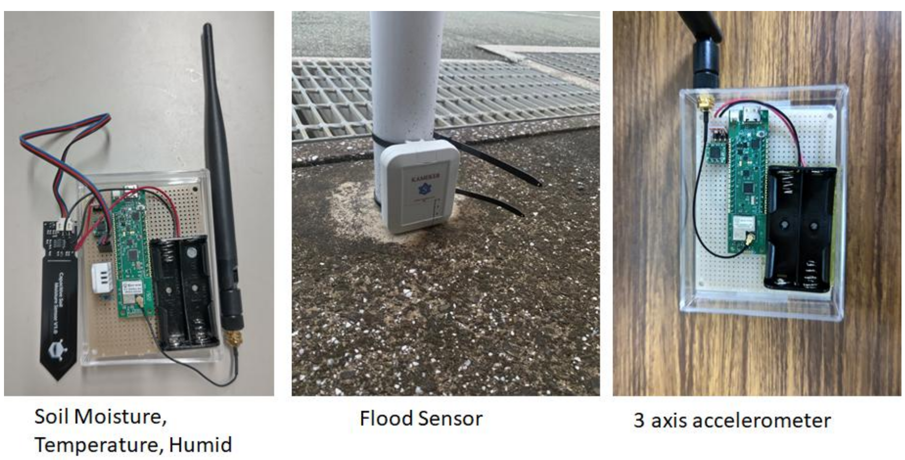

Figure 3: Prototype IoT Sensors for Proposed Early Warning System

Figure 4 shows the installation of the implemented three accelerometers (points A, B, and C in the Figure) on the slope behind Fukuoka Institute of Technology, Japan. To ensure these sensors were sensitive to environmental influences such as running water and rainfall, they were wrapped in bubble sheets and tied to a pile with string. This setup was designed to enhance the sensor's ability to detect motion effectively from our previous experiments.

Figure 4: Field Experiments with Prototype System

The experimental results are presented in Figure 5. The graph in the upper right corner shows the angular velocity recorded on a day without rainfall. The remaining graphs illustrate the data collected during a sudden downpour with a rainfall intensity of 17.5 mm/h, which occurred between 18:00 and 18:10 on July 13, 2025, at observation points A through C.

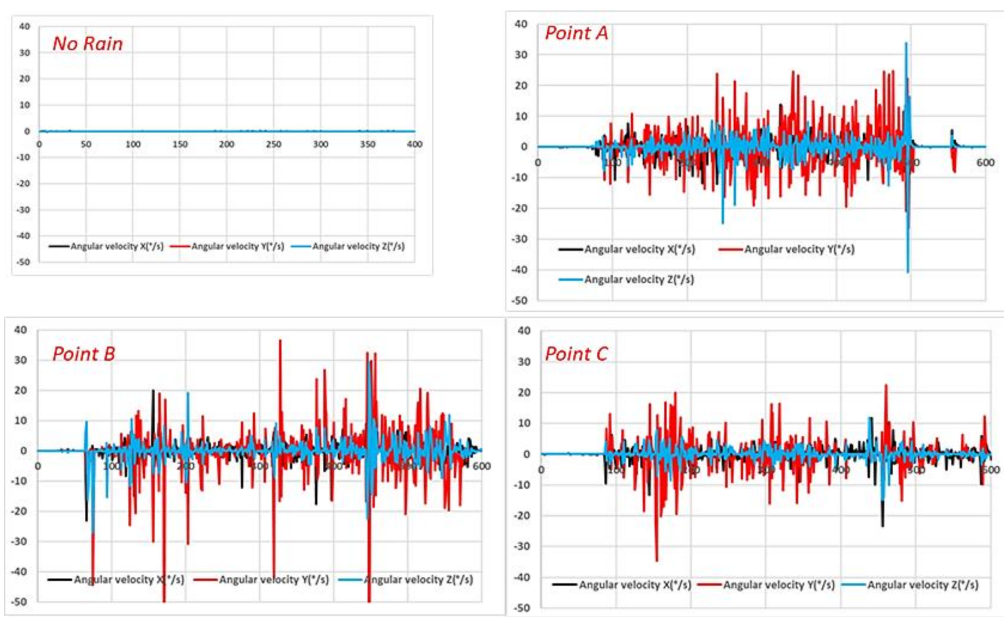

Figure 4: Experimental Results of Angular Velocity

These results demonstrate that the proposed IoT sensor successfully detected angular velocity changes caused by rainfall or flowing water. In detail, Point B exhibited the highest values, likely because it was not obstructed by vegetation. In contrast, Points A and C showed lower values, presumably due to being partially covered by grass.

Similarly, the soil moisture sensor, which typically measures around 50% moisture content, recorded an increase to an average of 86%. Meanwhile, the flood sensor did not respond, as the water level did not reach the threshold for inundation.

These results suggest that not only can the effects of rainfall and flowing water be detected using accelerometer sensors, but also that combining them with soil moisture and flood sensors enables the observation of surface-level geographical phenomena caused by heavy rainfall. Furthermore, by integrating highly accurate rainfall predictions derived from micrometeorological forecasting into the prediction stage of a Kalman filter, it is suggested that the system can reliably reflect dynamic hazard levels in real-time within an early warning framework for heavy rainfall disasters.

7 Conclusions and Future Study

Recently, heavy rainfall disasters have caused significant damage to human life and agricultural and livestock products. Therefore, this paper proposes the Early Warning System for heavy rainfall that considers both atmospheric factors from cloud-based micrometeorological prediction services and geographical factors collected by numerous IoT sensors. This paper mainly reports on the deployment of IoT devices, including 3-axis accelerometers, flood sensors, and soil moisture sensors, to monitor water flow. Also, ongoing field experiments are explained to validate the proposed anomaly detection approach, with future work aimed at refining and expanding the system.

Then, the experiments showed that the IoT sensors efficiently detected the symptoms of sudden heavy rainfalls, and it is supposed that the multiple IoT sensors enable the observation of surface-level geographical phenomena caused by heavy rainfall. Furthermore, by integrating highly accurate rainfall predictions derived from micrometeorological forecasting into the prediction stage of a Kalman filter, it is suggested that the system can reliably reflect dynamic hazard levels in real-time within an early warning framework for heavy rainfall disasters.

For future studies, we are working on implementing the proposed anomaly detection with the Kalman Filter using geographical IoT observations and micrometeorological prediction from weather clouds. Moreover, the field experiments are also planned for the evaluation of the proposed Early Heavy Rain Warning System.

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