Proposal of Dynamic Critical Line Algorithm by Real-time Monitoring with IoT sensors for Early Weather Warning System

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Abstract

Even today, predicting weather warnings such as floods and landslides due to heavy rainfall remains challenging. The current early warnings rely on the statistically estimated Critical Line based on the historical weather data. However, the weather has dramatically changed through the time, which could impact the effectiveness of the evacuation measures. Therefore, the Critical Line needs to be dynamically adjusted by real-time monitoring besides the existing weather forecasting system, and this paper proposes the Dynamic Critical Line algorithm with IoT sensors for the Early Weather Warning System. In the proposed methods, IoT sensors are introduced to the observed rivers or mountains, and the abnormal data is classified by the proposed MQTT-Drain methods. Then, this paper discusses the possibility of the proposed methods by simulating the case of the overflood disaster caused by Typhoon No.10 in 2016, and the future studies are also presented in this paper.

Keywords: Disaster Information System, Early Weather Warning System, IoT, Wireless Network

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1 Introduction

The recent developments of IoT technology expect new applications, such as the Early Warning System for landslides or overflood by unexpected heavy rain. In this background, the recent impact of catastrophic landslides or overflood disasters urges quick and smooth emergency response measures worldwide. In the case of Japan, for example, the Atami landslide disaster in July of 2021 caused 27 people's deaths, 580 evacuators, and 136 damaged houses [1]. Also, the Iwaizumi overflooding disaster caused by Typhoon No. 10 in 2016 caused nine deaths in the nursing home because of the evacuation delay [2].

Nevertheless, predicting weather warnings such as floods and landslides due to heavy rainfall remains challenging even today. As a result, weather forecasting services typically rely on statistical models that analyze historical weather data, including rainfall patterns for predicting landslides and flooding events. For example. in the case of Japan, the current early warnings rely on the statistically estimated CL (Critical Line) based on the historical weather data. Japan Metrological Agency (JMA) defines the five criteria for issuance of emergency warnings, and each level at the location is decided by the threshold of forecasting rainfall by the historical weather data [3]. Currently, the CL is determined based on forecasted rainfall levels, and warnings are typically issued one hour before the CL is expected, allowing time for evacuation. However, the weather has dramatically changed through the time, which could impact the effectiveness of the evacuation measures. Furthermore, this delay in issuing warnings could result in situations like the Iwaizumi flooding disaster caused by Typhoon No. 10 in 2016, where evacuations may come too late.

Therefore, this paper proposed the Dynamic Critical Line Algorithm by real-time monitoring with IoT sensors for the Early Weather Warning System. In the proposed method, this paper assumes to apply the IoT networks such as the ELWS (Early Landslide Warning System) with the Enhanced MQTT (Message Queueing Telemetry Transport) [4], since it is necessary to consider the scalability and reliability of the IoT data transmission. The Enhanced MQTT is the transmission control methods by the IoT data priority, and the previous paper presents the great improvements of data transmission rate and their latency. Then, in the proposed methods, many IoT sensors, such as flood sensors or 3-axis accelerometers, are first introduced to the observed rivers or mountains. Secondly, many observed values are classified by the proposed MQTT-Drain methods due to the quick processing, and the normal distributions for the Enhanced MQTT prioritize abnormal values. Finally, if there are a series of abnormal detections, the absolute emergency warning issues to mobile phones in the dangerous area by using ETWS protocol [5].

In the following, the proposed system configuration is explained in section II, and section III explains the original CL for early weather warnings based on weather forecasting. Then, Section IV proposes the Dynamic Critical Line algorithm, and Section V explains the IoT sensors and the abnormal detections by the proposed MQTT-Drain method. Finally, Section VI discusses the simulation of the proposed method by the previous overflood disaster, and Section VII presents the conclusions and the future works in this research.

2 Proposed System Configuration

This paper assumes to apply the early warning system with IoT sensors such as the ELWS with the Enhanced MQTT [6], and the system is shown as Figure 1.

The assumed system consisted of IoT network, IP network, and IoT getaway. In the system, many IoT sensors are settled in observed points, and they are connected with 920MHz LoRa radio band [7]. Then, the observed data are transmitted to the IP network through the gateway, and the abnormal observed data is observed in the servers at the disaster headquarters.

Moreover, the system connects with Web APIs on weather forecasting services such as JMA [8] and Open Weather Map [9] to acquire weather data and warnings. Then, if there are the abnormal

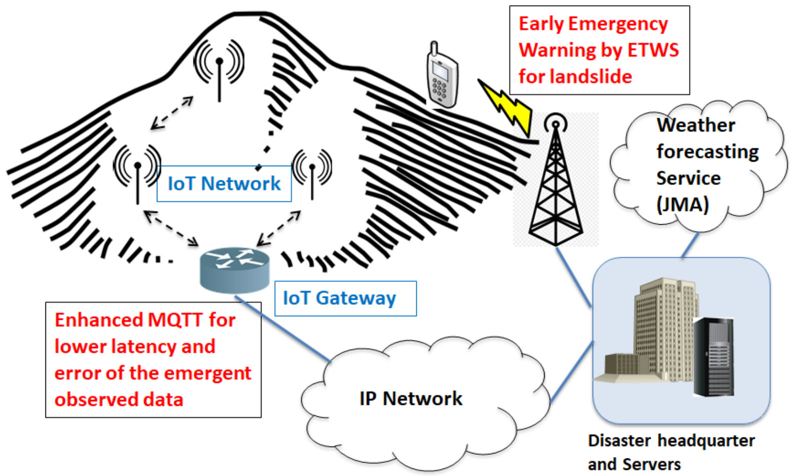

Figure 1: Assumed Early Landslide Warning System

values from IoT sensors in the servers, the absolute emergency warning would be issued to the mobile phones in the target areas by ETWS protocol [5].

In the system, while IoT transport protocols like MQTT [10] were originally designed for small data transmissions with numerous connections, the extensive coverage required for rivers and mountains necessitates a large number of IoT sensors. Therefore, this paper assumes to introduce the Enhanced MQTT protocol prioritizing observed values within the system. Figure 2 shows the proposed protocol.

In Figure 2, the proposed protocol first introduces the priority values to the meta-data field in the MQTT header, and the values are used for buffering the data in the priority queues of the broker node. Then, the subscriber subscribes to the broker to receive data from the higher-priority queues.

Moreover, the previous paper [6] reported the significant improvements in the scalability and reliability of the IoT data transmission since it is necessary to cover whole mountain area by a number of IoT sensors to detect the beginning of the landslide disaster.

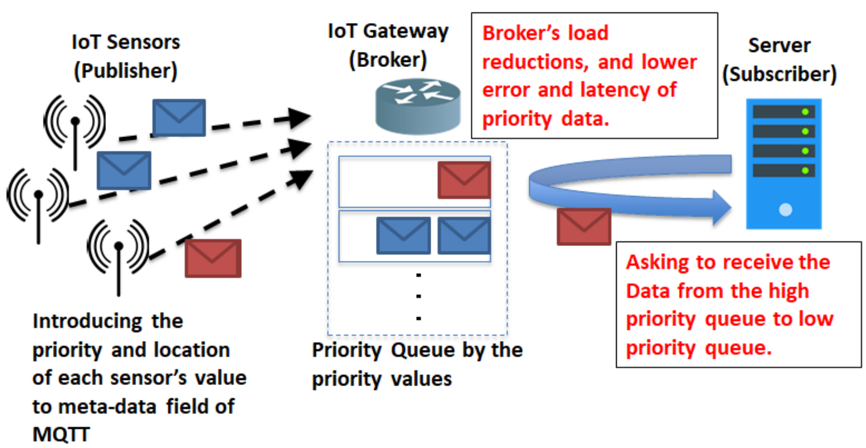

Figure 2: Enhanced MQTT Protocol

3 Critical Line for Early Weather Warning

However, it still needs to be improved by forecasting emergency warnings such as landslides or overflood, although it might be possible to detect the very beginning of the disaster. Figure 3 shows the time sequence of landslide warnings in Japan and the proposed ELWS with IoT sensors.

As shown in Figure 3, there are mainly two reasons for landslide disasters. One is the debris slide by gravity, and it usually takes many years to cause the landslide disaster. Another is slope failure or landslides caused by heavy rain, which usually takes some hours to cause the landslide disaster [11]. Moreover, in case of a disaster by gravity, it is challenging to forecast the disaster because the debris usually moves a few centimeters every year, and it is necessary to observe the very long period [12].

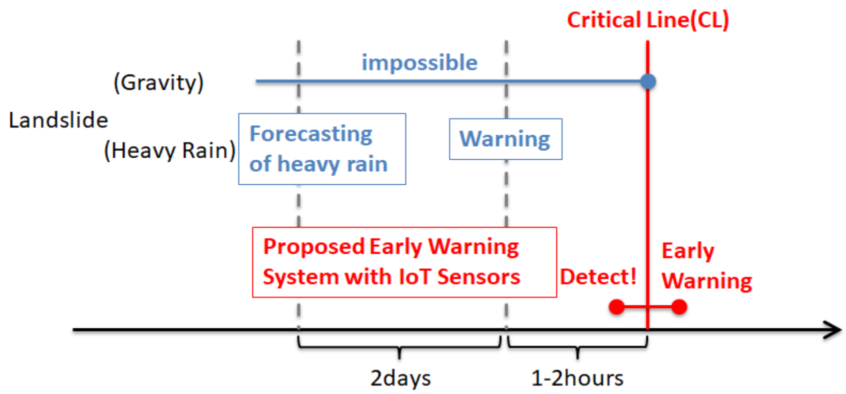

Figure 3: Time Sequence of Critical Line (CL) for Landslide Warning

However, it is currently considered that landslide disaster by heavy rain is possible to forecast by observing rainfalls. For example, JMA applies the previous weather data to forecast for landslide warnings [13]. JMA uses the soil rainfall index with the three-step tank model [14] in every 1km^2 area over the nation, and emergent warnings would be issued if the forecasting rainfall is more than the soil rainfall index. Especially, JMA usually issues heavy rain forecasting two days before the CL, and the early warning with five levels one hour before the CL to consider the evacuating period, as shown in Figure 3.

On the other hand, the proposed ELWS aims to detect the signs of the landslide, and it is possible to issue an early warning immediately, and it is considered to apply both landslide types including other disasters such as overfloods. Besides, although the current JMA warnings are issued one hour before the CL based, the proposed system is able to issue the emergency warnings immediately if the abnormal values are observed by IoT sensors. Therefore, unlike the emergency warning before the static CL, this paper proposed the Dynamic Warning Critical Line with IoT sensors for the Early Weather Warning System

4 Proposed Methods

As previously mentioned, the current weather warning, such as landslide or overflood, issues the emergency warning at a certain period before CL based on the statistics with the previous weather data. However, the weather conditions might dramatically change with the time sequence, and it is necessary to consider new warning protocols such as the dynamic CL with real-time monitoring by many IoT sensors for the security of evacuators.

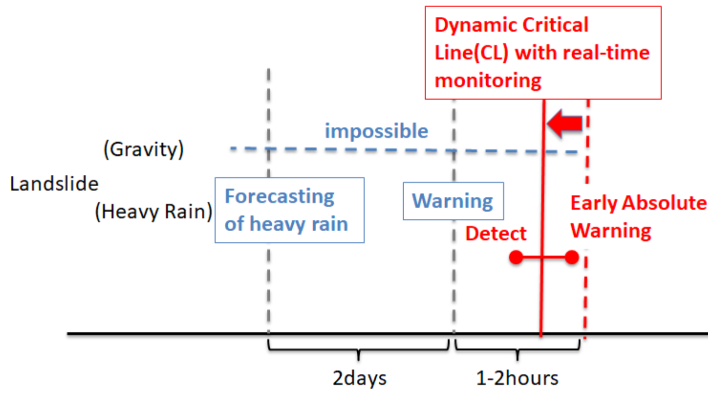

Figure 4: Dynamic Critical Line Algorithm

As shown in Figure 4, in the case of landslides, the proposed method first moves the CL when the IoT sensors detect abnormal data. Then, the early absolute warnings such as ETWS (Earthquake and Tsunami Warning System) [5] immediately issued to the evacuated area through mobile phones. ETWS is the simple broadcasting alert protocol for mobile phones, and the paging signal transmits the alert signal. The paging is the mechanism that the first broadcasting signal from the cellular station when the mobile phone is activating, and ETWS has the emergent codes in the header signal. Therefore, the emergency warning can be sent to all smartphones in the area of the specific cellular station, and the warning is possible to activate in very short periods.

5 IoT sensors and Abnormal Detection Methods

For the detections of disasters, it is also necessary to suppose the types of IoT sensors. The followings are the considerable IoT sensors for landslide and overflood disaster as shown in Table 1.

Disaster	IoT Sensors
Landslide (by heavy rain)	Soil moisture, 3axis Accelerometer, Camera
Landslide (by gravity)	Soil pressure, 3axis Accelerometer, Camera
Overflood (in river)	Flood sensor, Camera, Rainfall (cloud service)

Table 1: Types of IoT Sensors for the Dynamic CL

Also, the prototype IoT sensors are shown in Figure 5 for the proposed system. The system is implemented by Green House GH-EVARDLRB (Arduino Bootloader Atmega328PB, LoRa GH-WM92LRA(920MHz)), 3 axis accelerometer (Akizuki KXR94-2050), temperature & humidity sensor (Osoyoo DHT11), and soil moisture (DFRobot SEN0193). The broker was also implemented by Raspberry PI 4B (8MB).

Figure 5: Prototype IoT Sensors for Proposed Early Warning System

Moreover, the MQTT-Drain method is proposed for the detection of abnormal values from IoT sensors. As mentioned in the assumed system, many IoT sensors would be needed to observe mountains or rivers for early emergency warnings. The processes of abnormal detection should be quick and applicable to various types of sensor logs. The Drain method [15] is one of the log parsing algorithms especially considered in a streaming and timely manner. To accelerate the parsing process, the Drain method uses a fixed depth parse tree defined by the following *simSeq* (similarity sequences).

Here, seq_1 and seq_2 is the log messages, and *seq(i)* is the *i*-th token of the sequence. Also, function *equ(a, b)* is defined as *equ(a, b) =1 (when a=b)* and *equ(a, b) =1 (when a≠b)*.

$$\boldsymbol{simSeq} = \frac{\sum_{i=1}^{n} \boldsymbol{equ}\left(\boldsymbol{seq_1}(\boldsymbol{i}), \boldsymbol{seq_2}(\boldsymbol{i})\right)}{n} \tag{1}$$

Input:
①2023/1/18 13:21:01 Client device51 received PUBLISH: 'FIT/Bldg.D/5F/temp' 20.8
②2023/1/18 13:21:01 Client device109 received PUBLISH: 'FIT/ Bldg.D /3F/temp' 18.5
Preprocessing
① FIT Bldg.D 5F temp *
② FIT Bldg.D 3F temp *

Figure 6: Examples of Log Message from IoT sensors

For example, if the two logs as shown in Figure 6, the Drain method firstly preprocess as the simple tokens. Here, the different values are expressed as * token.

Then, the examples of update parsing trees are shown in Figure 7. After generating the parsing tree by the first log with five length tokens, the *simSeq* of two logs is calculated by equation (1). Then, if the value is more than the threshold values previously configured in the system, "5F" and "3F" are defined as the same branch in the tree. On the other hand, if the value is less than the threshold, "5F" and "3F" are defined as the different branches in the tree. Therefore, even if many types of IoT sensors exist in different locations, the proposed drain method is supposed to classify many logs into optimal storage quickly. At last, the normal distribution is calculated in the IoT gateway for the priority controls of the Enhanced MQTT protocol. Here, the abnormal observed values such as less than five percent are classified as the highest priority data, and the data from ten percent to five percent are classified as the second priority data. Then, the data is transmitted to the publisher (the headquarter server) from the highest priority data.

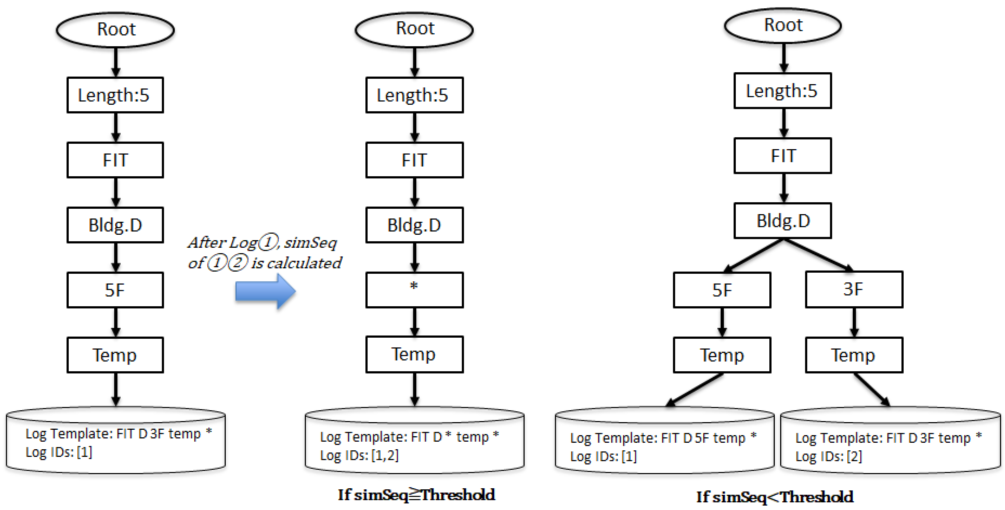

Figure 7: Examples of Update Parsing Tree

6 Simulations

For the evaluations of the proposed methods, this paper considered the disaster case of Typhoon No.10 at Iwaizumi Town in Japan on August 26, 2016. The disaster caused 26 deaths and 1916 overflood houses in Japan. In particular, Iwaizumi Town is located in Pref. Iwate in Japan, and nine persons in the care house were dead in the overflood of the Omoto river [2]. Moreover, it is pointed out that the tragedy was caused by the lack of an emergency warning for the nursing home because of the rapid overflood level changes of the Omoto river. The progress of the overflood disaster and the issued warnings are shown in Table 2 [16].

Date (8/26/2016)	Early warnings
5:16	JMA announce the heavy rain warning in Iwaizumi Town.
9:00	Iwaizumi Town issued the evacuation preparation.
10:16	JMA announced the heavy rain and flood warning in Iwaizumi Town.
14:00	Evacuation advisory issued around the Omoto river.
Just before 18:00	Typhoon No.10 made landfall in Pref. Iwate (Ofunato City).
About 18:00	The nursing home was flooded

Table 2: Progress of Typhoon No.10 Disaster in Iwaizumi Town

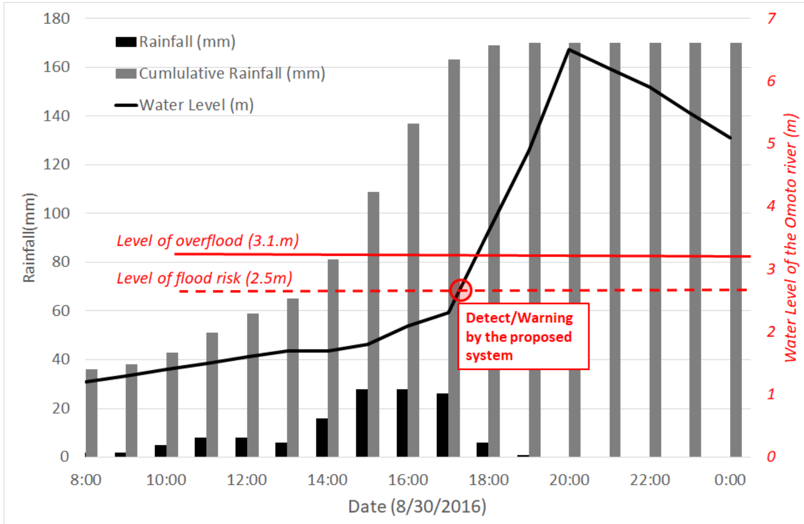

Figure 8: Rainfall and Overflood in Typhoon No.10 Disaster in Iwaizumi Town

As mentioned before, according to JMA, there are five levels of warnings based on the weather forecasting, JMA issued the heavy rain warning (level 3) in the early morning of that day. Then, JMA also announced the overflood warning (level 3) at 10:16, and the town properly reacted to issue the evacuation advisory around the Omoto river. However, the typhoon made landfall just before 18:00, and the nursing home was suddenly overflooded without the emergency warning of level 4 and 5 because of the unexpected heavy rainfall.

Thus, Figure 8 shows the simulations of the rainfall and overflood in the disaster with the proposed Dynamic CL algorithms with IoT sensors. According to Figure 8, although the heavy rainfall occurred around 14:00, it is understood that the water level of the river did not reach to the risk level. However, after 17:00, the water level suddenly rose up to the risk level, and the river was overflooded before 18:00. Therefore, if the proposed IoT sensors, such as the flood sensor, were introduced for observing the flood risk level along the river, the overflood was detected. Then, it may be expected that the absolute emergency warning could be received by the mobile phones at the nursing home.

7 Conclusions and Future Study

Even now, it is difficult to predict weather disasters such as landslides and overfloods, and weather forecasting and statistical calculations such as the soil rainfall index with the three-step tank model estimate the CL. Then, the early warnings are issued at a certain period before the estimated CL.

However, the weather conditions might be dramatically changed through the time, and it is necessary to consider the CL with real-time monitoring, including the current forecasting system. Therefore, this paper proposed the Dynamic CL algorithm with IoT sensors for the Early Weather Warning System for the security of evacuators. In the proposed methods, this paper firstly assumes to introduce the Early Weather Warning System with the Enhanced MQTT protocol because of the scalability and reliability of many IoT connections. Then, the Dynamic CL algorithms by real-time monitoring with IoT sensors are discussed for the absolute emergency warning by ETWS protocol. In the methods, in case of overflood warnings, IoT flood sensors, as well as the rainfalls and the forecasting warnings from Web API, are used for abnormal detections. Then, these data are classified by the MQTT-Drain method, and the normal distributions classify the priority values of the data. Also, these data are transmitted to the headquarters server by the Enhanced MQTT, and the absolute emergency warning is transmitted to mobile phones in dangerous areas by ETWS protocol.

Then, this paper discussed the possibility of the proposed methods considered with the previous overflood disaster in Iwaizumi Town, Japan. The simulation results suggest that the victims could be evacuated if the proposed system was properly worked for the security of the evacuations.

For future studies, we are working on the implementations of the proposed MQTT-Drain method for the abnormal detections from the sensor's observations, and the field experiments of the prototype system are also planning for the evaluation of the proposed methods.

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