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Research on Key Technologies of Debris Flow Real-time Monitoring and Early Warning System

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Abstract. The establishment of a real-time monitoring and early warning system (EWS) can effectively reduce the risk of debris flow. Based on the analysis of real-time rainfall data and the automatic identification of rainfall processes, this paper presents a solution and a system for the real-time monitoring and early warning of debris flows (DEWS). Rainfall intensity (RI) and cumulative rainfall (CR) are the main parameters for the debris flow EWS. Thus, determining how to correctly identify a rainfall process is of great significance for improving the accuracy of debris flow EWSs. Based on the store procedure of database and C# development language, combined with the characteristics of rainfall data and the classification criterion of a rainfall process presented by Jan and Lee, the automatic identification of a rainfall process is realized. Developing a method of achieving early warning processes without manual intervention via a completely automatic, real-time and stable operation has represented a difficult problem in the early warning process. The proposed solution introduces “system services” technology to achieve accurate automatic real-time monitoring and early warning for debris flows. This system was applied to the debris flow in Zoumaling gully and successfully predicted the debris flow events on July 8, 2013.

Keywords: debris flows, early warning system, rainfall process, automatic

1 Introduction

Debris flows are natural disasters with great potential for harm, and they have seriously threatened the sustainable development of the national economy and society in China [1-2]. After the 2008 Wenchuan earthquake, the mountains and surfaces in disaster areas were strongly damaged, and the accumulation of loose deposits provided more favorable conditions for the occurrence of debris flows [3-5]. The occurrence of debris flow events in the earthquake area has obviously increased, especially in the three major areas (Yingxiu Town, Qingping Town, and Longchi Town) of Sichuan Province. On August 12-14, 2010, a large-scale mass debris flow appeared in this area and caused heavy casualties [6-10]. Research indicates that debris flows will become the main secondary geological disasters in the three main areas after the Wenchuan earthquake. Moreover, multiple studies have confirmed that post-earthquake effects will persist over a long period of time (usually 10 to 30 years) and disaster-affected areas will experience active periods of geological disaster and recovery until the stable period is reached [11-13]. Therefore, all levels of government have invested in the control and prevention of debris flow geological hazards every year. However, because of the complex conditions underlying post-earthquake debris flows, the occurrence and location of debris flows are subject to considerable uncertainties, which leads to the high cost of debris flow control. Therefore, conducting large-scale debris flow control is difficult. To address this problem, debris flow real-time monitoring and early warning represent important methods of debris flow control.

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Many methods are widely used for debris flow monitoring, and they involve monitoring rainfall and mud levels and recording infrasound, ground sound, and video data [14-15]. Different types of monitoring data provide powerful support for real-time monitoring and early warning of debris flows. With the wide application of a new generation of information technology and the development of geohazard monitoring technology, debris flow early warning systems (EWSs) have gradually played an important role in improving the control and mitigation of debris flow geohazards [14-16]. Many scholars have developed debris flow monitoring and early warning systems based on B/S (Browser/Server) or C/S (Client/Server) architectures, and the applications have been successful [14-20].

Nonetheless, in practical applications, an EWS needs to process data in real time, which is of important significance. When an EWS has been running without interruption, the time for early warning accounts for less than 1% of the EWS's running time (taking our EWS as an example). The entire warning operation will fail if the EWS crashes within this time frame. However, few EWSs have been developed to perform automatic and stable operations under long-term operating conditions.

Currently, debris flow monitoring and EWSs mainly analyze rainfall monitoring data to provide early warning information. Cumulative rainfall (CR) and rainfall intensity (RI) are the key factors in debris flow early warning models. Developing a method of automatically addressing rainfall data is important for classifying rain events and directly affects the CR value. However, rain events are not considered in many EWSs; instead, these systems directly sum the rainfall data recorded from the current time to previous days or even months as the CR. Therefore, an algorithm must be developed that can automatically search for the start time of a rainfall process in a real-time early warning system (REWS).

This paper first introduces the key technologies of debris flow automatic real-time monitoring and early warning system, and then studies the automatic identification of rainfall process based on the characteristics of real-time rainfall monitoring data. As a solution, a system for automatic real-time monitoring and debris flow early warning based on automatic identification of the rainfall process is developed. Thorough research on the key technology for long-range wireless automatic monitoring and early warning of debris flows has been conducted via the construction of an early warning demonstration site for debris flow monitoring in recent years. This paper also presents the research process and results on the wireless automatic monitoring and EWS for debris flow, and these findings could be used as a reference for others to conduct further research in this area.

2 Background and Related Work

Monitoring and early warning of geohazards is an important means to achieve disaster reduction and prevention of geological disasters. In the field of debris flow monitoring, there are many research results of model theory. Many scholars have also developed debris flow monitoring and early warning system based on monitoring data [14-20]. At present, many monitoring and early warning systems are based on C/S or B/S architecture, which requires a lot of manual participation, so it is difficult to achieve automatic and real-time monitoring and early warning of debris flow. Based on the project of debris flow monitoring and early warning in Wenchuan earthquake disaster area of Sichuan Province, this paper focuses on how to realize unattended real-time early warning. In order to realize the automatic and real-time warning of debris flow, three important research contents are involved: (1) automatic processing of monitoring data, (2) algorithm realization of model parameters, (3) automatic generation and transmission of early warning information. In the preliminary work, we have developed the basic system framework of debris flow monitoring and early warning [21]. This paper mainly studies the key technology and implementation of debris flow automatic monitoring and early warning.

3 Key Technologies of Early Warning System

3.1 Automatically Run the Early Warning Process

Most desktop applications terminate when the user logs out of the system and do not automatically run unless the operating system (OS) is restarted. However, a system service can run when the user is not logged in or has logged out. When the OS is restarted after an abnormal shutdown, the system service can automatically run without user intervention.

Most EWSs are designed as normal desktop programs [22-23]. When the EWS terminates or quits abnormally (e.g., because of server downtime, memory overflow or other issues), manual intervention is required to restart it. If the technical staff does not immediately identify the EWS abnormalities, then an interruption of the entire early warning process can result, with unpredictable consequences. Therefore, to solve this problem and realize the automation of the debris flow early warning process, system service technology [24-25] has been introduced in the design of the debris flow EWS. Along with the implementation of the system service technology, the debris flow EWS could be set up as a system service to guarantee the stability of the automatic early warning process.

The debris flow automatic warning process is shown in Fig. 1. Based on the algorithm of the early warning model, three system services (Table 1) were developed by using C# programming technology, system services, and the functions of the database itself (such as view, job, trigger, or custom functions). These services can perform real-time analyses of debris flow real-time monitoring data and real-time warnings of debris flow based on existing thresholds. Among all three system services, ServiceWatcher was specifically developed to monitor the debris flow real-time early warning service (Real Time Early Warning) and the send warning messages (SMSs) service (AutoSMS). If the other two services close or operate abnormally, ServiceWatcher will automatically issue a command to restart the other two services to ensure the normal operation of the entire early warning process.

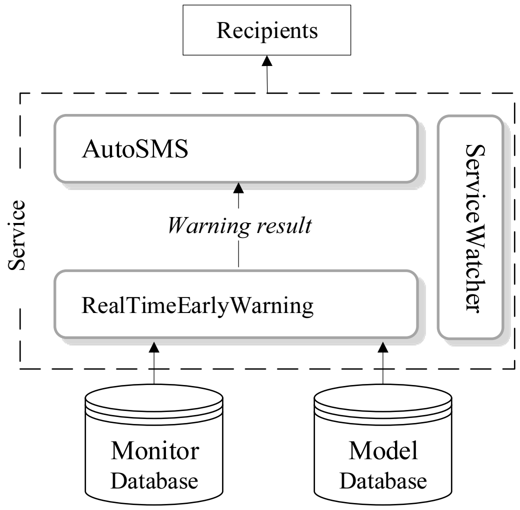


Fig. 1. Debris flow automation early warning process

Table 1. System services in the early warning system

#	System Service Name	Function
1	RealTimeEarlyWarning	Process monitoring data; calculate the warning level in combination with the early warning model; and generate early warning send warning message (SMS)
2	AutoSMS	Generate SMS
3	ServiceWatcher	Monitor whether the two system services are working properly

3.2 Automatically Generate Early Warning Messages

Four alert levels have been defined in this paper: Null, Outlook, Watch, and Warning [17, 26]. According to the level, warning message templates and their sending rules have also been defined. The message templates are listed in Table 2. Different alert levels correspond to different warning messages. The system administrator can edit the message templates according to their actual needs and may add words as required before sending the message to the recipients.

{%name%}: geohazard name; {%t1%}: start time of the rain event; {%t2%}: start time of the warning process (usually equals current time); {%cr%}: cumulative rainfall (mm), {%ri%}: rainfall intensity (mm/h). The tags will be replaced by the actual values when the “Real-time early warning” service generates the warning messages.

Table 2. Templates of early warning messages

Alert level	Templates
Null	[{%name%}], alert level: Null, {%t1%}~{%t2%}: Cumulative rainfall {%cr%} mm, rainfall intensity {%ri%} mm/h. The possibility of the outbreak of debris flow is very low. Please pay attention to rainfall trends.
Outlook	[{%name%}], alert level: Outlook, {%t1%}~{%t2%}: Cumulative rainfall {%cr%} mm, rainfall intensity {%ri%} mm/h. The possibility of the outbreak of debris flow is low. Please pay attention to rainfall trends.
Watch	[{%name%}], alert level: Watch, {%t1%}~{%t2%}: Cumulative rainfall {%cr%} mm, rainfall intensity {%ri%} mm/h. The possibility of the outbreak of debris flow is moderate. Please pay attention to rainfall trends.
Warning	[{%name%}], alert level: Warning, {%t1%}~{%t2%}: Cumulative rainfall {%cr%} mm, rainfall intensity {%ri%} mm/h. The possibility of the outbreak of debris flow is high. Please pay attention to rainfall trends.

To establish an effective early warning and alert system, the recipients have also been divided into four categories as shown in Fig. 2: manager, duty officer, responsible person, and leader. Different levels of warning messages are sent to different recipients.

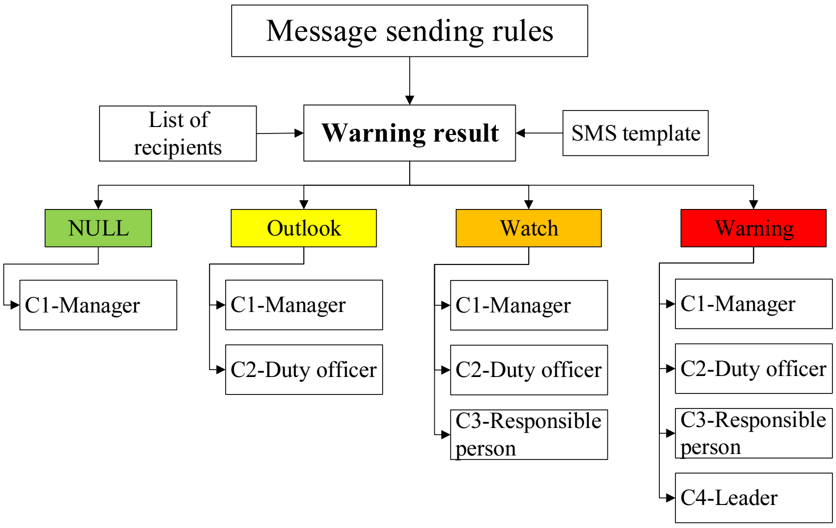


Fig. 2. Sending rules for warning messages

The real-time early warning service will automatically generate early warning messages according to the warning results, the SMS template, and the message sending rules and then will write them to the corresponding table in the warning result database.

3.3 Automatically Publish Early Warning Messages

The AutoSMS service (Table 1) reads the messages from the database and then sends them to the corresponding user's mobile phone according to the corresponding interface. This service contains a variety of SMS send interfaces. Users can configure the interface to use according to the actual situation as shown in Fig. 3.

The AutoSMS service monitors the changes of early warning messages stored in the warning database in real time. Once a new warning message is written to the database, the SMS sending module is immediately started to ensure the timely delivery of early warning messages to the corresponding recipient's mobile phone.

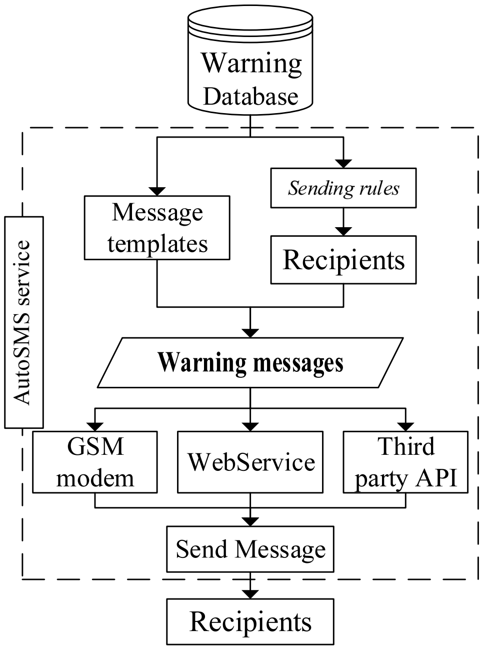


Fig. 3. System service for automatically sending short messages

4 Data Analysis and Methods

4.1 Data Serialization with Equal Time Intervals

In general, the program for the real-time monitoring and debris flow EWS is automatically calculated every 10 minutes. The original rainfall data must be processed with equal time intervals (10 minutes) to obtain the 10-minute rainfall, hourly rainfall, and cumulative rainfall of a rain event. The rainfall monitoring data are considered cumulative data and represent a cumulative amount of measured monitoring data over a given time period. As shown in Fig. 4, the monitoring value is affected by the previous monitoring value and time.

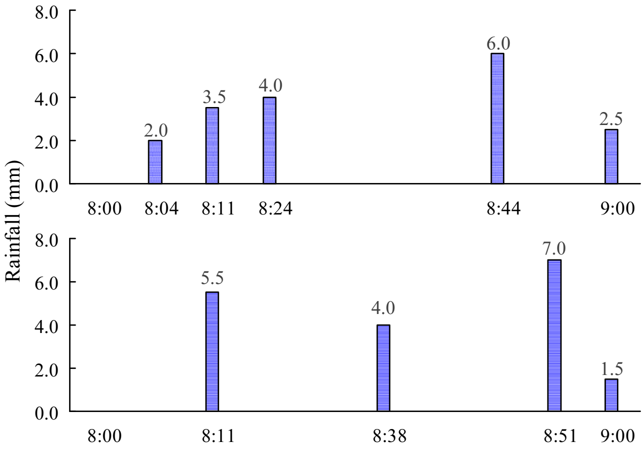


Fig. 4. Cumulative rainfall monitoring values, which are affected by the previous monitoring value and time

The monitoring data time periods are affected by the characteristics of rain gauges, and they are disorganized (Table 3). The values in Table 3 represent the minimum precision of the rainfall gauge (such as 0.5 mm). Therefore, the data will be serialized with equal time intervals before use.

Table 3. Original rainfall data from rain gauge #2

ID	Monitor equipment code	Time	Rainfall (*mm*)
1	520121030001YL0201	2017-3-22 09:34	0.5
2	520121030001YL0201	2017-3-22 09:42	0.5
3	520121030001YL0201	2017-3-22 09:46	0.5
4	520121030001YL0201	2017-3-22 09:47	0.5
5	520121030001YL0201	2017-3-22 09:56	0.5
6	520121030001YL0201	2017-3-22 10:01	0.5
7	520121030001YL0201	2017-3-22 10:02	0.5
8	520121030001YL0201	2017-3-22 10:03	0.5

Rainfall monitoring data serialized with equal time intervals are usually generated by the following steps:

Generate time series. The time series T will be generated according to the starting and ending time combined with the actual demands of the time interval, such as 5 minutes, 10 minutes, or 1 hour:

$$\begin{aligned} &\Delta t = 5 \ \ \text{min}(10 \ \ \text{min}, 1 \ h...) \\ &t_i = t_0 + (i-1)\Delta t, i = 1,2,\dots n \\ &T = \{t_1, t_2, \dots, t_n\} \end{aligned} \tag{1}$$

Calculate the cumulative value. The cumulative value will be easily calculated when combined with T and the original monitoring data. V is the monitoring data set serialized with equal time intervals:

$$\begin{aligned} &V_i = \sum_{t=t_{i-1}}^{t_i} v_t, i = 1,2,\dots,n \\ &V = \{V_1, V_2, \dots, V_n\} \end{aligned} \tag{2}$$

The original data (Table 3) processed by Eqs. 1 and 2 are shown in Table 4.

Table 4. Processed rainfall data (Δt=5 minutes)

ID	Monitor equipment code	Time	Rainfall (*mm*)
1	520121030001YL0201	2017-3-22 09:30	0.0
2	520121030001YL0201	2017-3-22 09:35	0.5
3	520121030001YL0201	2017-3-22 09:40	0.0
4	520121030001YL0201	2017-3-22 09:45	0.5
5	520121030001YL0201	2017-3-22 09:50	1.0
6	520121030001YL0201	2017-3-22 10:55	0.0
7	520121030001YL0201	2017-3-22 10:00	0.5
8	520121030001YL0201	2017-3-22 10:05	1.5

4.2 Automatic Identification the Rain Events

The start time of a rain event is very important and not only affects the cumulative rainfall of the rain event but also affects the early warning results. Many scholars in this field have addressed the division of rain events [27-30], which is a critical step in the early warning model to achieve the automatic identification of rain events. Based on the analysis of historical data combined with real-time monitoring data of rainfall and precipitation characteristics, the following dividing criterion for a rain event proposed by Jan and Lee [27] was used in this paper:

A continuous rain event: the time at which rainfall intensity is greater than or equal to 4 mm/h is defined as the effective start time of a rain event, and the end of the rain event is the time at which the rainfall intensity is less than 4 mm/h and has persisted at this level for more than 6 hours.

In the real-time early warning process, the current time (i.e., the time to start the warning calculation, which can also be defined as the end of rainfall time) is usually included in the rain event. Therefore, the start time of this rain event will be one of the most crucial pieces of information at the beginning of each warning. If no rain is observed, then the warning process will exit. Otherwise, the rainfall data will be traversed so that the start time of the rain event can be obtained, and this process assumes a time t_s as follows:

(1) at time t_s, the rainfall intensity is greater than or equal to 4 *mm/h*, and

(2) from t_s to 6 hours ago, the rainfall intensity is less than 4 *mm/h* per hour.

If the above two conditions are satisfied at the same time, then t_s could be considered the start time of a rain event. As shown in Fig. 5, t_w is the current time (warning time). Traversing the monitoring data from t_w forward, when t_s=15:00, the *RI* (Rainfall Intensity) will satisfy conditions 1) and 2) at the same time as shown in Equation (3).

$$\begin{cases} RI(t) = 5.0mm/h \geq 4.0mm/h, t = t_s \\ RI(t) < 4.0mm/h, t \in [t_s - 6h, t_s) \end{cases} \tag{3}$$

This rain event started at 15:00 (t_s, as shown in Fig. 5).

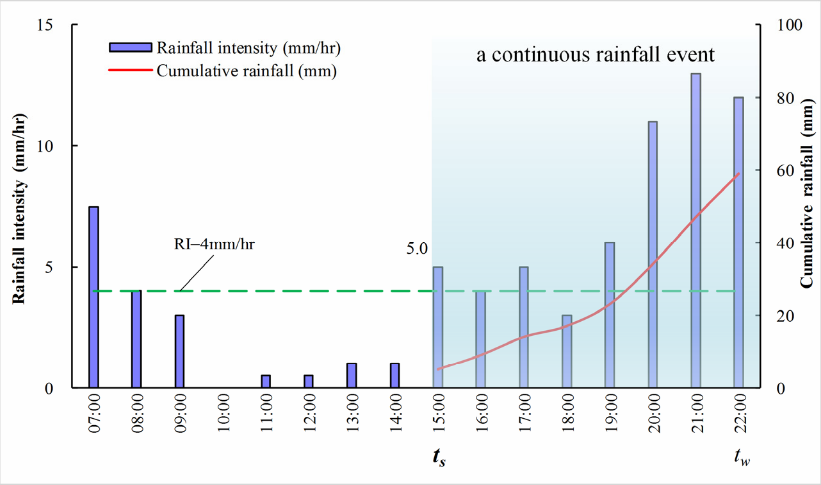


Fig. 5. Continuous rain event; RI - Rainfall Intensity

As vital information, the start time of the rain event should be determined as soon as possible to reduce the time required to calculate the early warning and generate a timely warning result. At the beginning of each warning process in the automatic EWS, the start time of the rain event can be quickly captured by analyzing the monitoring data collected by the rain gauge. The process is shown in Fig. 6.

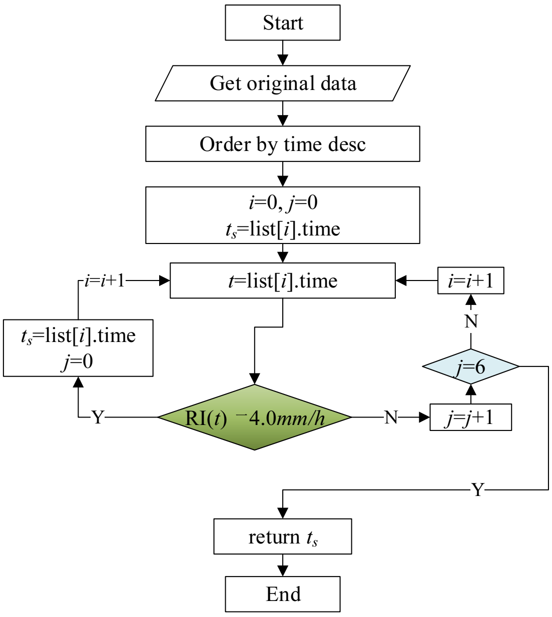


Fig. 6. Flow chart of finding the start time (t_s) of a continuous rain event

As shown in the flow chart, *j*=6 means that the rainfall intensity is less than 4 mm/h and lasted for 6 hours. When the rainfall intensity is greater than or equal to 4 mm/h, j is re-counted (j=0). When the program loop is over, the return value is the start time of the rain event, whereas under conditions with no rain, the return value is the current time. Because the program is compiled into a stored procedure and directly executed in the database, it is highly efficient and fully guarantees the real-time performance of the warning results.

Statistics of the rain events in recent years based on the analysis of the original rainfall data collected by the No. 2 rain gauge in the Zoumaling gully are shown in Table 5.

Table 5. Rain events in the Zoumaling gully (Data from rain gauge #2)

#	Start Time	End Time	Cumulative Rainfall (mm)	Max Rainfall Intensity (mm/hr)	Duration (hr)
1	2012-07-02 01:40	2012-07-02 13:50	25.5	6.0	12.2
2	2012-07-14 12:15	2012-07-14 22:20	23.5	11.0	10.1
3	2012-07-17 06:05	2012-07-18 00:20	21.6	5.5	18.3
4	2012-07-21 04:40	2012-07-22 01:30	56.0	27.5	20.8
5	2012-08-14 13:10	2012-08-15 01:20	50.5	17.0	12.2
6	2012-09-24 04:35	2012-09-25 17:35	37.0	4.0	37.0
7	2012-10-29 16:15	2012-10-30 01:40	22.0	15.0	9.4
8	2013-04-04 15:25	2013-04-05 12:10	23.5	4.0	20.8
9	2013-06-19 06:40	2013-06-19 15:40	40.5	16.5	9.0
10	2013-06-30 06:15	2013-06-30 20:20	35.5	14.0	14.1
11	2013-07-03 17:45	2013-07-04 18:10	98.5	13.5	24.4
12	2013-07-08 12:10	2013-07-09 05:30	303.5	58.0	17.3
13	2013-07-15 14:35	2013-07-16 02:00	29.0	9.5	11.4
14	2013-07-22 01:10	2013-07-22 04:35	19.0	7.0	3.4
15	2013-07-25 02:45	2013-07-25 05:00	18.5	15.5	2.3
16	2013-07-25 16:10	2013-07-26 02:55	17.5	6.5	10.8
17	2013-08-06 22:15	2013-08-08 02:55	84.5	13.0	28.7
18	2013-09-19 00:25	2013-09-19 15:00	45.5	23.0	14.6
19	2014-04-13 23:10	2014-04-14 19:40	30.5	7.0	20.5
20	2014-04-24 16:20	2014-04-25 11:30	21.5	3.5	19.2
21	2014-07-31 06:55	2014-07-31 17:50	27.5	10.0	10.9
22	2014-10-03 14:00	2014-10-04 02:20	38.5	14.5	12.3
23	2014-10-11 08:20	2014-10-12 01:00	27.5	5.5	16.7
24	2015-06-22 00:42	2015-06-23 02:20	52.0	6.5	25.6
25	2015-06-28 17:24	2015-06-29 05:00	22.5	20.5	11.6
26	2015-08-17 03:19	2015-08-17 22:10	49.5	15.0	18.8
27	2015-09-08 05:37	2015-09-09 11:00	30.5	8.5	29.4
28	2015-09-22 00:24	2015-09-22 17:10	26.5	6.5	16.8

5 Field Testing

5.1 Study Area

Zoumaling gully is located in Qingping Township, Mianzhu City, Sichuan Province, China approximately 80 km from the northeast of the epicenter of the M8.0 Wenchuan earthquake. The Yingxiu-Beichuan Fault runs through the left bank of the gully. The entire basin area of this debris flow is 5.76 Km^2. The catchment area of this main gully is 3.98 Km^2, and the length of this main gully is 3.93 *Km.* The longitudinal gradient from the gully mouth to gully source and gully bed ranges from 85‰ to 361‰, the local gradient at the gully source reaches 620‰, and the angle of the side slope ranges from 30° to 45°. The highest elevation in the gully catchment is 2,044 m, and the lowest elevation is 904 m at the estuary of Mianyuan River, thus representing a relative height difference of 1,140 m [31-32].

5.2 Early Warning Model

In this paper, the research results of Yu [33] are applied to develop the monitoring and warning system of debris flow in Zoumaling gully. The threshold value of rainfall is R^* (mm).

$$R^* = 12.5I + P \tag{4}$$

where I represents to the rainfall intensity (*mm/h*), i.e., the cumulative rainfall from the warning time to one hour ago, and P represent the cumulative rainfall (*mm*), i.e., the cumulative rainfall in the rainfall process.

The R^* of the debris flow early warning in Zoumaling gully is shown in Table 6. The value is adjusted according to the actual situation of the annual monitoring. R^* divides the entire warning area into four parts as shown in Fig. 7:

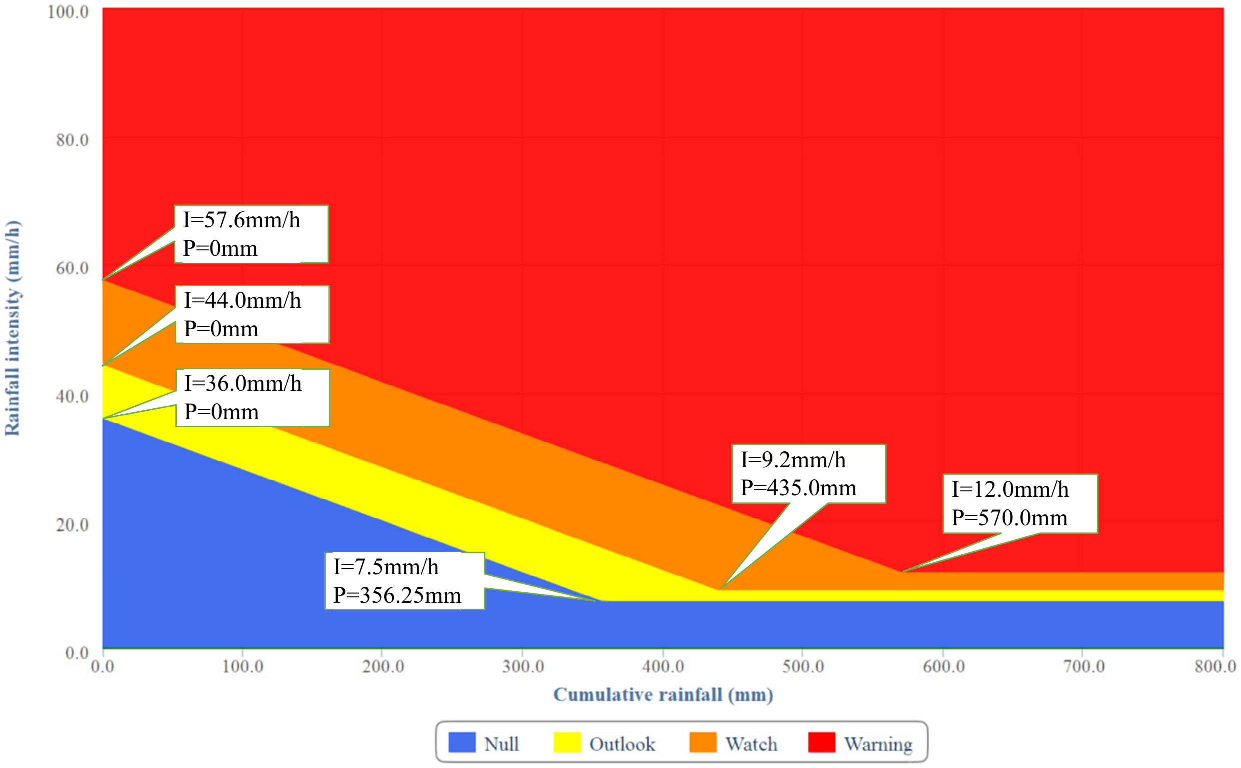


Fig. 7. Screenshot of the debris flow warning model chart in Zoumaling gully

(i) Null (Blue area, $R^* <$ Outlook level threshold);
(ii) Outlook (Yellow area, Outlook level threshold $\leq R^* <$ Watch level threshold);
(iii) Watch (Orange area, Watch level threshold $\leq R^* <$ Warning level threshold);
(iv) Warning (Red area, $R^* \geq$ warning level threshold).

Table 6. Monitoring thresholds for debris flow early warning in Zoumaling gully

Debris Flow	Outlook R^* (*mm*)	Watch R^* (*mm*)	Warning R^* (*mm*)
Zoumaling gully	450.0 (7.5)	550.0 (9.2)	720.0 (12.0)

The values in parentheses are the minimum critical rainfall intensity values (I_{min}). The EWS starts the early warning process only when the rainfall intensity (I) is greater than I_{min}.

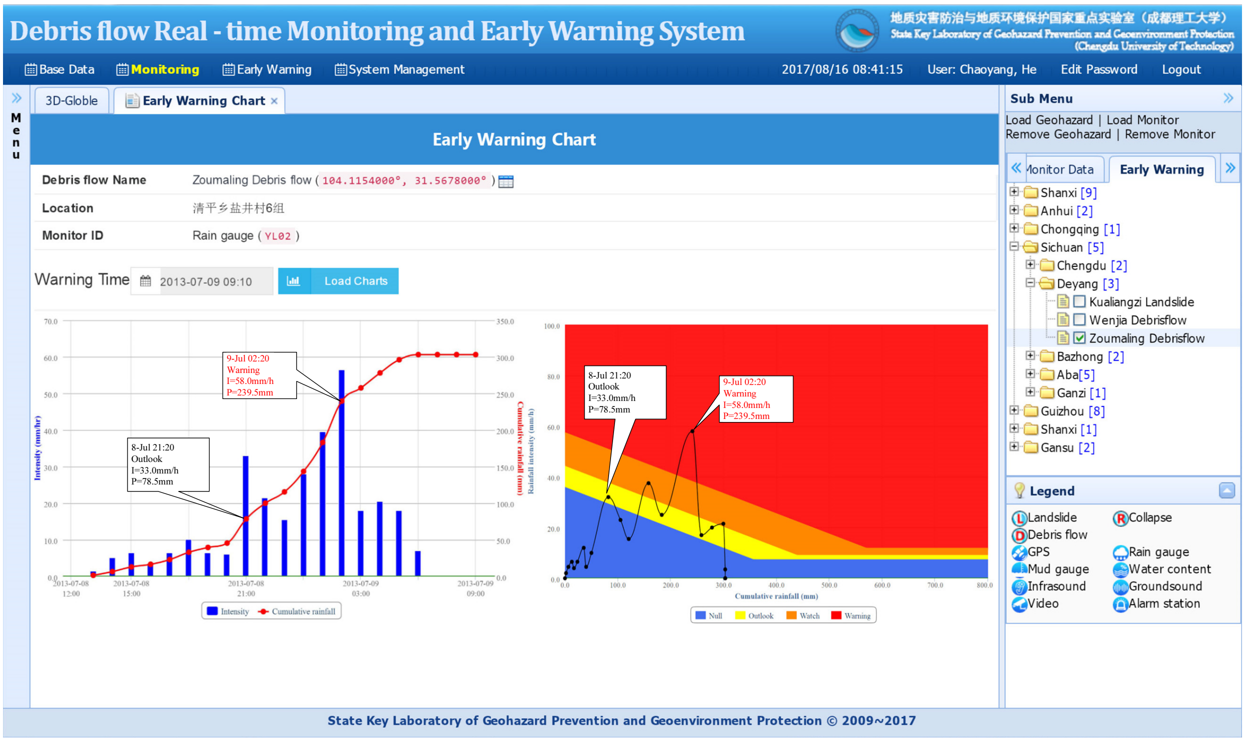
5.3 Application Test

From 8 to 9 of July 2013, heavy rainfall occurred in the Wenchuan earthquake disaster area of Sichuan Province, China. The heavy rain triggered the simultaneous occurrence of multiple debris flows in

Qingping Township in Mianzhu City, which resulted in heavy property loss. The debris flows occurred in the Zoumaling gully [34] at approximately 21:30-22:00 on July 8, 2013, and the volume of the alluvial fan was approximately 35.32×10^4 m^3 (Yin 2014). A photograph of the debris flow disaster in the Zoumaling gully is shown in Fig. 8.

Fig. 8. Photograph of the debris flow disaster in Zoumaling gully (Photo by Yin [34], August 24, 2013)

Users of the debris flow REWS can focus on the dynamics of the rain event in real time. As shown in Fig. 9, the bar chart is the real-time monitoring data chart and the area chart is the warning chart. The rain event starts at 12:20 on July 8, 2013 and stops at 06:20 on July 9, 2013, and the duration is 18 *h*. In this rain event, the maximum rainfall intensity is 58.0 *mm/h* and the cumulative rainfall is 303.0 *mm*.



Debris flow Real - time Monitoring and Early Warning System

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2017/08/16 08:41:15

User: Chaoyang, He

Early Warning Chart

Debris flow Name	Zoumaling Debris flow (104.1154000°, 31.5678000°)
Location	清平乡盐井村6组
Monitor ID	Rain gauge (YL02)

Warning Time 2013-07-09 09:10

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Fig. 9. Debris flow real-time monitoring and early warning system (REWS)

According to Yin [34] (2014), the debris flow occurred at approximately 21:30 - 22:00 on 8 July 2013. As shown in Fig. 9, the rainfall intensity was 6.0 *mm/h* at 20:20 pm, quickly reached 33.0 *mm/h* at 21:20, and triggered a warning mechanism. The debris flow REWS issued the first warning message (Outlook, Yellow signal) at 21:20 on 8 July, and the corresponding parameters were I=33.0 *mm/h* and P=78.5 *mm*. This finding is consistent with the actual situation, and the REWS gave a successful early warning of the Zoumaling debris flow. The warning messages issued by the REWS are listed in Table 7.

Table 7. Warning results for the debris flow event in Zoumaling gully on July 8-9, 2013

#	Time	Alert levels	Alert signal	I(*mm/h*)	P(*mm*)	R(*mm*)
1	8-Jul 21:20	Outlook	Yellow	33.0	78.5	491.00
2	9-Jul 00:30	Watch	Orange	37.5	158.0	626.75
3	9-Jul 01:10	Outlook	Yellow	25.0	183.0	495.50
4	9-Jul 02:20	Warning	Red	58.0	239.5	964.50
5	9-Jul 03:20	Outlook	Yellow	17.0	257.5	470.00
6	9-Jul 04:20	Outlook	Yellow	20.0	278.0	528.00
7	9-Jul 05:40	Watch	Orange	21.5	299.5	568.25

According to the testing results, the system automatically sent an Outlook warning message (yellow signal) to successfully alert the user to the Zoumaling debris flow before it occurred. Moreover, as the rainfall intensity changed, the system was able to process the monitoring data in time and quickly respond with the alert level. As shown in Table 7, throughout this early warning process, the DEWS automatically sent 7 warning messages to the relevant personnel, including four outlook messages, two watch messages, and one warning message. Therefore, the system can conduct real-time and stable processing of monitoring data and can provide real-time warnings according to the corresponding early warning model.

6 Conclusions

This paper summarizes the practical problems that are encountered in the monitoring and early warning process for debris flows, and proposes a set of debris flow automatic early warning technologies that respond to the actual demand. The core technology underlying the debris flow early warning is the rapid and accurate identification of a rain event. In this paper, a set of automatic identification methods for a rain event is proposed and implemented based on the division of a rain event proposed by other scholars. System service technology is also used to resolve occasional crashes of the early warning program. The implementation of system service technology guarantees a more stable operation of the entire early warning process and realizes its automation. The research results have achieved good results in the monitoring and early warning of Zoumaling gully debris flow.

The DEWS can be easily used in other similar projects focused on the real-time monitoring and early warning of debris flow. Our ongoing research will focus on identifying methods of improving the accuracy of EWSs.

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