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A Real-time Monitoring and Early Warning System for Landslides in Southwest China

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Abstract: Landslides not only cause property losses, but also kill and injure large numbers of people every year in the mountainous areas. These losses and casualties may be avoided to some extent by early warning systems for landslides. In this paper, a real-time monitoring network and a computer-aided automatic early warning system (EWS) are presented with details of their design and an example of application in the Longjingwan landslide, Kaiyang County, Guizhou Province. Then, according to principle simple method of landslide prediction, the setting of alarm levels and the design of appropriate counter-measures are presented. A four-level early warning system (Zero, Outlook, Attention and Warning) has been adopted, and the velocity threshold was selected as the main warning threshold for the landslide occurrence, but expert judgment is included in the EWS to avoid false alarms. A case study shows the applicability and reliability for landslide risk management, and recommendations are presented for other similar projects.

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Introduction

Land sliding is a significant hazard for people and property in mountainous regions. Particularly in developing countries, the social, political and cultural problems may increase the vulnerability to natural hazards. On June 28, 2010, a large landslide occurred in Guanling County, Guizhou Province and killed 99 persons (Kong et al. 2010). Another large landslide occurred on January 11, 2013 in Zhenxiong County, Yunnan Province, and caused 46 deaths (Yin et al. 2013). Daunia region in Southern Italy, abundant mass movements cause a high level of potential risk to the urban centers and transportation systems (Pellicani et al. 2013b). Moreover, in the Southwest China, mega earthquakes, e.g. Wenchuan earthquake (May 12, 2008), Lushan earthquake (April 20, 2013) and Ludian earthquake (August 3, 2014), have further sensitized the public, the news media, and the government to the vulnerability of population, and signaled an urgent demand for an effective EWS in such regions.

Early warning is usually feasible for shallow landslides, triggered by rainfall (David et al. 1987; Glade 1997; Dai et al. 2004; Godt et al. 2006; Chleborad et al. 2008; Baum et al. 2010), but effective landslide warning systems are still far from reality. In general, an EWS is not only a simple monitoring system, but it includes expert knowledge on other aspects such as the geological situation, the identification of element at risk, an analysis of the mechanism of slope movement, and societal considerations. A rigorous adherence to the information chain is needed because any error will significantly disturb the result of early warning. A missing landslide event or a false alert may seriously affect the confidence in the system. After decades of study on geological and mechanical aspects of landslide initiation processes, definition of thresholds for landslide occurrence, it is now possible to implement real-time monitoring systems by sensor integration and use of a wireless sensor network, and to develop a basic EWS. Presently, several EWSs have already been established. Examples were reported by Yin et al. (2010), Intrieri et al. (2012) and Ramesh (2014). Other similar applications can also be found in the literatures (Terzis et al. 2006; Rosi et al. 2011 and Kotta et al. 2011).

In this paper, the detailed design and implementation of a real-time monitoring network and EWS are presented with an example of application. The WSN includes inclinometers, pore-water pressure meters and rainfall gauges. The EWS follows the research that delivered a complete landslide database (Huang et al. 2013).

1 Study Area

The Longjingwan landslide (E 106°48'38.6", N 27°05'45.6") located in Jinzhong Town, Kaiyang County, Guizhou Province (Figure 1), is an old landslide reactivated by heavy rainfall twenty years ago.

The topography of study area is composed of tablelands and mountains at an average elevation of 1100 m above sea level, as shown in Figure 1. The landslide is 570 m long and 330 m wide. The depth of the sliding surface is about 31~40 m, and the main sliding direction is to the SE. According to the report from field investigations, the landslide was reactivated by a heavy rainfall on June 24, 1995. Most of the buildings on the landslide were damaged. The velocity of displacement increased in every rainy season, causing a high potential risk to the local people and their properties.

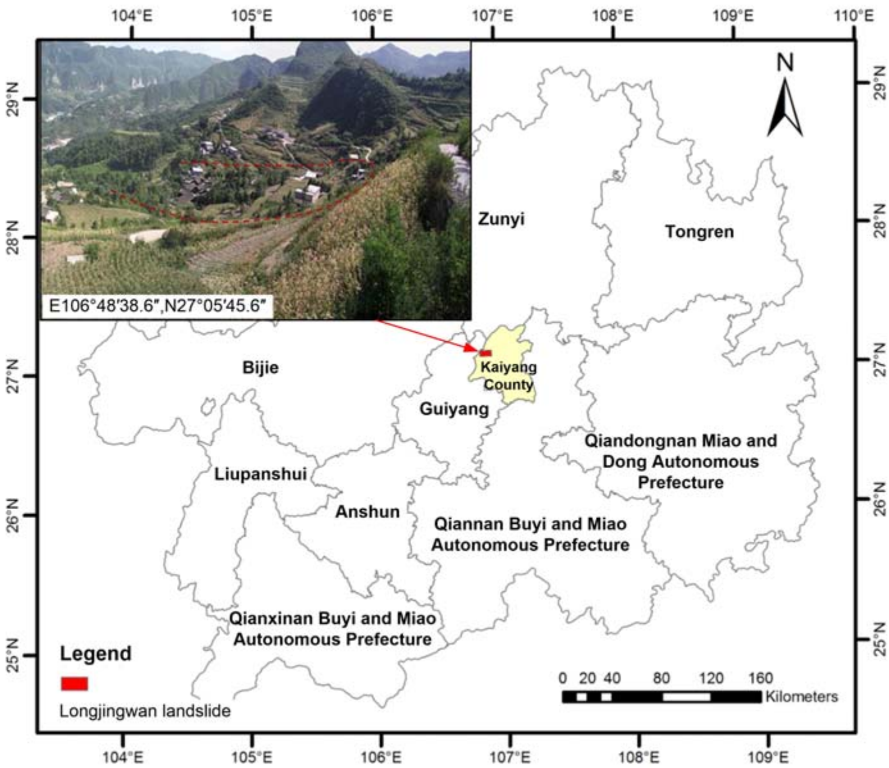

Figure 1 The study area is located in Jinzhong Town, Kaiyang County, Guizhou Province. The inset photograph upper left shows the general view of Longjingwan landslide.

2 Real-time Monitoring Network

Before, monitoring stations are usually composed of several systems, which are manipulated by human in site every time with low efficiency and prohibitively expense (Lee 2009). Wireless Sensor Networks (WSN) is an approach which can provide more stable monitoring data for an EWS in real time, and the possibility for an involved agencies to get information in an early state from a hierarchic information structure independently and automatically (Ramesh 2014).

2.1 Monitoring networks for landslides

A WSN for landslide early warning system is composed of various monitoring sensors (Figure 2), each of which is equipped with a wireless communication interface. These devices are called nodes, which can sense, transmit, receive and forward the monitoring data in a self-organizing network, but the nodes are usually limited in power and memory, so that only small amounts of data can be transmitted at each time.

Generally, an initial mass movement is detected with help of a traversing inclinometer by manually moving the probe along the length of borehole casing, to determine the depth and thickness of slip zones, and the magnitude, rate and direction of landslide movement (Machan 2008). Once the slip surface has been identified, a string of tilt sensors can be connected together and placed permanently in the borehole casing at the defined depths to measure the deformation by automatic monitoring. Extensometers are generally used to measure the aperture of the crack at the back scarp of a landslide.

Rain gauges are always used to measure rainfall, which is one of the main inducing factors of landslide (David et al. 1987; Yin et al. 2010). Hydraulic sensors are used to monitor pore pressure, moisture content, and other factors contributing to the potential instability of slopes.

2.2 Monitoring network for the Longjingwan landslide

Three kinds of sensors were selected for the wireless sensor network for the monitoring of the Longjingwan landslide (Figure 3 and Table 1). It is composed of a rain gauge (YL01), three in-place inclinometers to measure deep displacements (SQ01~03), and three piezometers for pore-water pressure (SY01~03). The sink node, which has a higher power than the other nodes, collects and forwards data from the scattered nodes through Zigbee technology, a kind of network communication protocol with high data rate and low energy consumption (Lee 2009). Then, different kinds of monitoring data can be transmitted through a remote data transmission by general packet radio service (GPRS).

Even in bad weather conditions, like rain, mist or fog, and also at night, the monitoring sensors work well, but, the power supply needs consideration. Solar power or alternating current is used as often as possible, but there must be a backup power supply (storage battery) for the monitoring devices. Secondly, the precision and accuracy of monitoring sensor are not easy to determine. During deep displacement measurement, there may be a case that the casing become bent or sheared, then continuous measurement has to be accomplished by

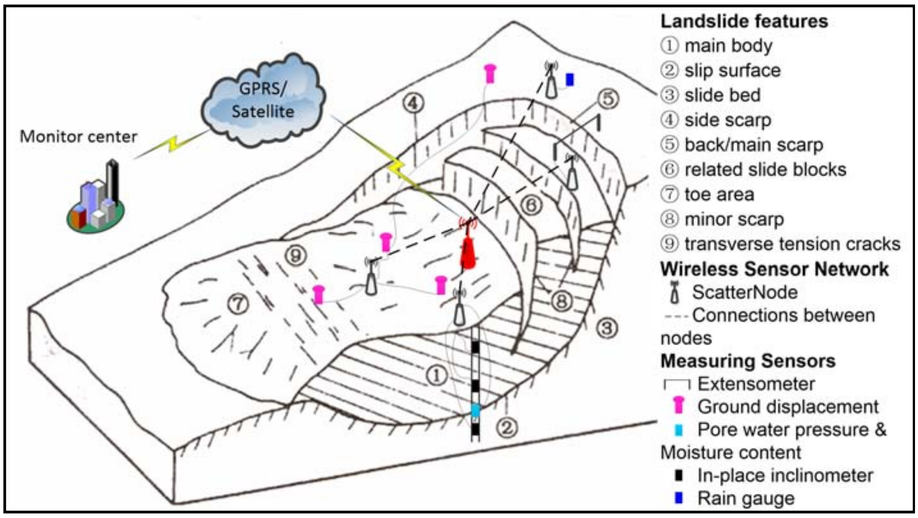

Figure 2 A typical real-time monitoring network for landslide.

Table 1 Monitoring devices for the Longjingwan landslide

No. of device	Accuracy	Position	Monitoring type
YL01	0.50 mm	Surface	Rainfall amount (mm)
SQ01	0.1% full scale (F.S)	Underground {10.8, 20.5, 30.2, 40.6} (m)	Deep displacement (mm)
SQ02	0.1% full scale (F.S)	Underground {8.75, 16.43, 24.21, 34.53} (m)	Deep displacement (mm)
SQ03	0.1% full scale (F.S)	Underground {7.75, 15.43, 22.04, 29.42} (m)	Deep displacement (mm)
SY01	0.025% full scale (F.S)	Underground {43} (m)	Pore water pressure (water head: m)
SY02	0.025% full scale (F.S)	Underground {36} (m)	Pore water pressure (water head: m)
SY03	0.025% full scale (F.S)	Underground {32} (m)	Pore water pressure (water head: m)

extensometers on the ground. Moreover, the devices contain kinds of options and field procedures, and a specific software for both pre- and post- processing of monitoring data. Therefore, a short training needs to make the operator capable of using the equipment properly for specific tasks.

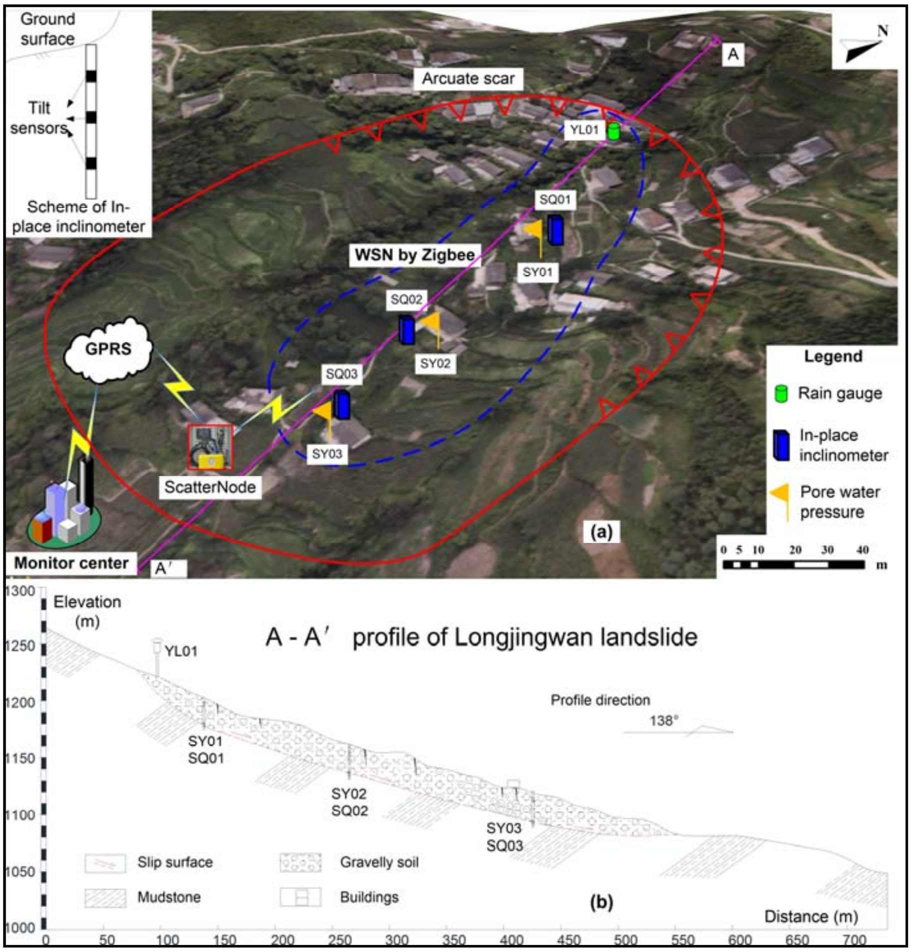

Figure 3 The real-time monitoring network for Longjingwan landslide (a) schematic view; (b) cross section.

3 Landslides Early Warning System (EWS)

An early warning system for landslides via Internet, has been developed on the basis of the platform WIMS (WebGIS-based Information Management System) in a previous study (Huang et al. 2013), but new functionalities, such as monitoring data analysis and early warning have been developed.

3.1 System design

The EWS, presented in Figure 4, has been specifically designed and implemented with a case explanation of Longjingwan landslide for the local population, but it provides useful suggestions for other similar cases. As shown in Figure 4, the structure of the EWS is mainly composed of four parts, as follows.

Devices of monitoring: The selected devices for a particular landslide have been used to establish a real-time monitoring system for predicting landslide occurrences.

Remote transmission: In such a real-time monitoring system, wireless data remote transmission plays a significant role in linking the sites to the control center. Wired networks, GPRS/ GSM and satellites are used for the remote transmission, but GPRS is the most popular for its low cost and high efficiency (Zhang et al. 2011).

Data processing and analysis: The key functionalities of EWS are monitoring data processing, analyzing and communicating. All monitoring data must be converted, and integrated into the data server. Then, all the monitoring data can be shown in the form of graphs and tables on the Website to end users.

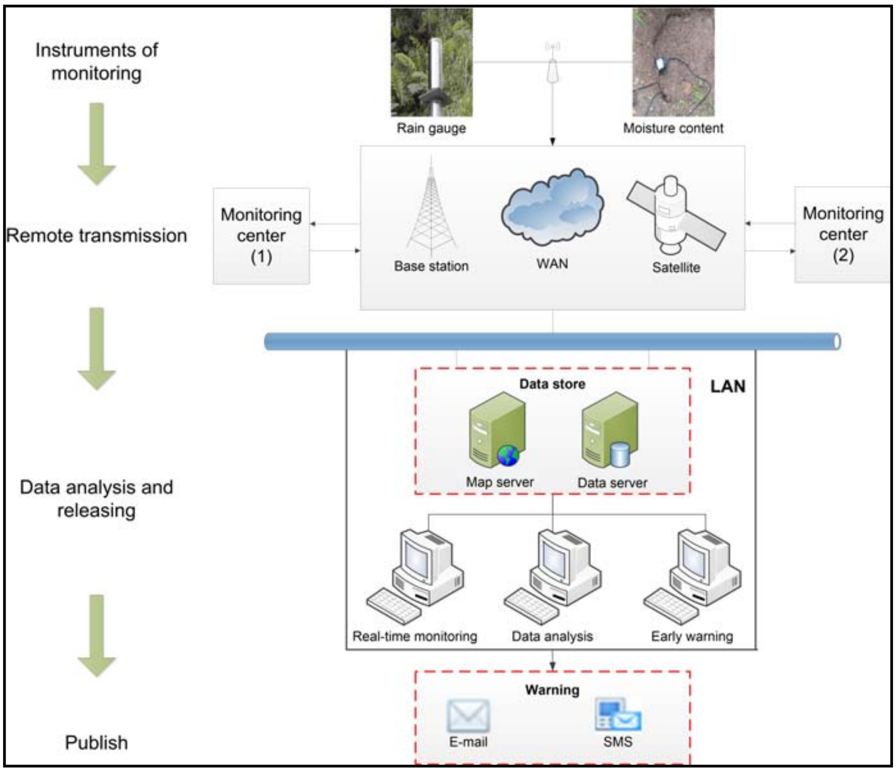

Figure 4 Architecture of the early warning system for landslide.

Publish: Before sending alert, some sociological aspects must be considered. E.g. the public may be unfamiliar with landslides, agency roles and missions, rapid communication in remote areas, the mean of warnings and the correct actions to take. Therefore, a clear warning language and instructions need to be determined for the local people, and an educational program necessary to ensure them to understand the hazards and appropriate actions following a warning message.

3.2 Applying criteria to warning system

There is no EWS valid for all cases. Every EWS must be designed for a specific site, and may be largely different from the landslide types (Lacasse et al. 2009). The prediction of landslide occurrence and emergency response are so complicated that some simplifications must be done. Therefore, a four-level early warning criteria system to give alert for the onset landslides has been adopted, as shown in Table 2.

As stated by Intrieri et al. 2012, in emergency conditions everything must be simple and straight-forward, the action to be taken must be clear and fast, and misunderstandings or human errors are not tolerable. For such reasons, only the velocity threshold is considered as the main forecast criterion. Pore-water pressure and other factors are regarded to be of secondary importance. In order to avoid false alarms by an automatic EWS, therefore, expert judgments are included in the final decision. The recommended responses to the four - levels of EWS are illustrated as follows.

Zero: A blue signal in the website indicates that there is no likelihood of landslide occurrence. No warning will be given to the local authorities and population. However, general inspection and monitoring are still continued, and the monitoring data must be checked daily and a monthly monitoring bulletin is needed.

Outlook: When the deformation of an inclinometer exceeds its own velocity threshold, a warning is given through a beeping sound at the monitoring center and a yellow signal shown in the website, which indicates that there is a chance of landslide occurrence in the near future. During this period, the monitoring values must be checked daily and a weekly monitoring bulletin is released. Continuous communication with the local

Table 2 Recommended warning levels and activities adopted for the EWS (after Intrieri et al. 2012)

Levels	Trigger	Definition	Response
I	Default level.	Normal safe situation.	Zero: but data are checked daily. Monthly monitoring bulletin.
II	When the deformation of one displacement exceeds its own velocity threshold.	Must be more than seasonal variations or caused by human activity.	Outlook: Data are checked daily. Weekly monitoring bulletin.
III	When the deformation of two or more displacement exceed their own velocity thresholds.	Increased landslide activity due to prolonged rainfalls. Potentially dangerous.	Attention: Data are checked more frequently. Daily monitoring bulletin. Authorities and experts are alerted. Preparing for alarm.
IV	A comprehensive analysis of displacement, pore water pressure etc. as well as including expert judgments.	Accelerating trend far beyond any seasonal fluctuation. Collapse is expected.	Warning: Data are checked even more frequently. Two monitoring bulletins per day. Local people are alerted.

authorities and daily weather forecasting are included in the activities as well at this level of early warning.

Attention: When the deformation at two or more inclinometers exceed their own velocity thresholds, a warning is given through an alerting sound at the monitoring center and an orange signal in the website, indicating that there is a certain likelihood of landslide occurrence in the near future. At this warning level, the monitoring data are checked more frequently, a daily bulletin is released, and an alert SMS is sent to the concerned authorities and experts to call them for a discussion on the counter-measures based on the monitoring data and the weather forecast. The local authorities must prepare itself for a possible alarm, but no public communication is necessary yet.

Warning: The accelerating trend of deformation data is beyond the normal seasonal fluctuation, according to a comprehensive analysis by experts. A warning is given through a highly alerting sound at the monitoring center and a red signal in the website, which indicates that there is a great likelihood of landslide occurrence in the near future. At this warning level, the population will be alerted through loud speakers or sirens, and alert SMS will be sent to the authorities emergency services. The population will be asked to leave the threatened location and will be told where to go to.

3.3 Data analysis and release

In order to increase the reliability of the alerts, the EWS was designed as a computer-aided automated operation process. Therefore, the registered users must be divided into two categories. The first category can only view the data, but experts can edit the velocity thresholds and make a final decision, controlled by a procedure illustrated in Figure 5.

Each warning level shows a different colored signal, indicating the corresponding probability of landslide occurrence or risk level. For example, when the signal turns into yellow or orange, SMSs and emails will be sent to the first category of concerned users and experts, informing them that one or more of the pre-defined warning threshold values have been exceeded. The experts are requested to check whether it is likely that the landslide will be triggered, or that it is a false alert by software mistake or other reasons. A decision must be taken whether to change the early warning signal back to blue, or upgrade it to red. Meanwhile, the issue which must be ensured firstly is that the landslide is expected to show an accelerating trend in a few days before collapse, and which must leave enough time for the emergency procedures. Thus, expert judgments or discussion must be given in a very short time for the short period of forewarning time.

3.4 Case study

Part 1 in Figure 6 is a tree menu for a landslide information query, for navigation and for checking the real-time monitoring data and warning level. Part 2 is a 3D WebGIS interface to show the landslide topography and other information, e.g. the limits of Longjingwan landslide and the

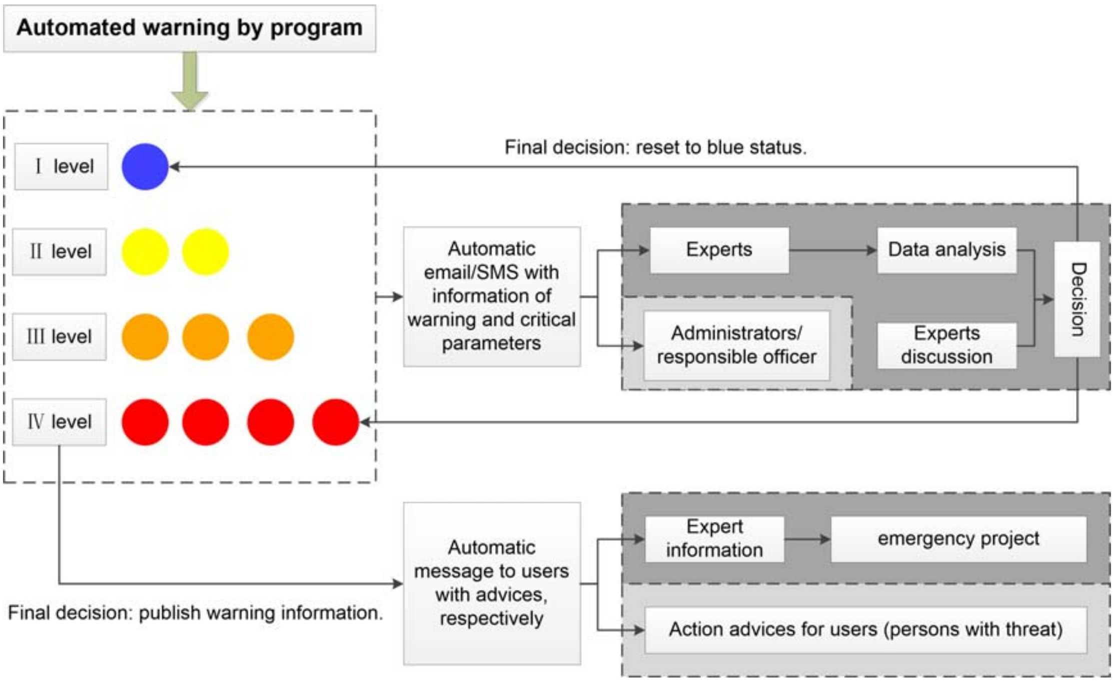

Figure 5 Flow diagram for an early warning system for landslides (after Thiebes 2012).

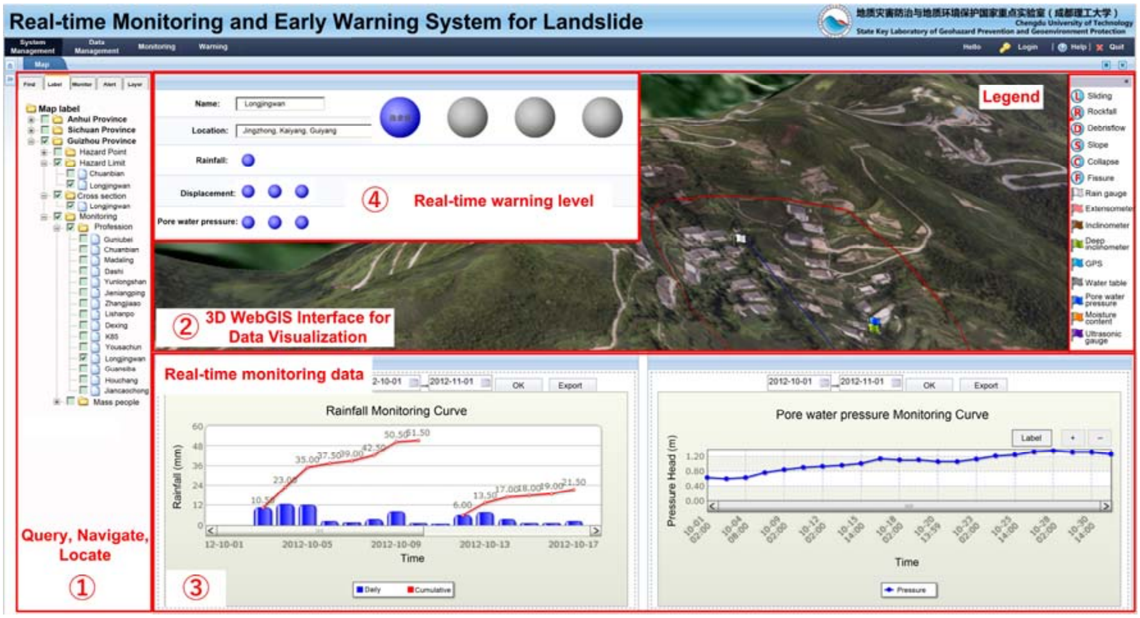

Figure 6 Main interface of the EWS for the Longjingwan landslide.

location of the monitoring sensors. Part 3 is a display interface for real-time monitoring data, e.g. the rainfall and pore- water pressure curve of Longjingwan landslide. Part 4 is a linkage interface to show the real-time warning level calculated by an automatic way.

In order to demonstrate how the EWS gives a warning for Longjingwan landslide, a detail analysis about the effects of rainfall to the landslide movement is illustrated from May to September in 2012 (which is the biggest movement during the recent 3 years), as shown in Figure 7. It can be seen, the movement velocity is quite small even in rainy season. Based on expert's suggestions, therefore, a preliminary velocity threshold of displacement is set to be 5, 15, 50 mm/month for yellow, orange and red respectively. At the beginning of May 2012, several heavy rainfalls occurred on May 8 (14 mm),

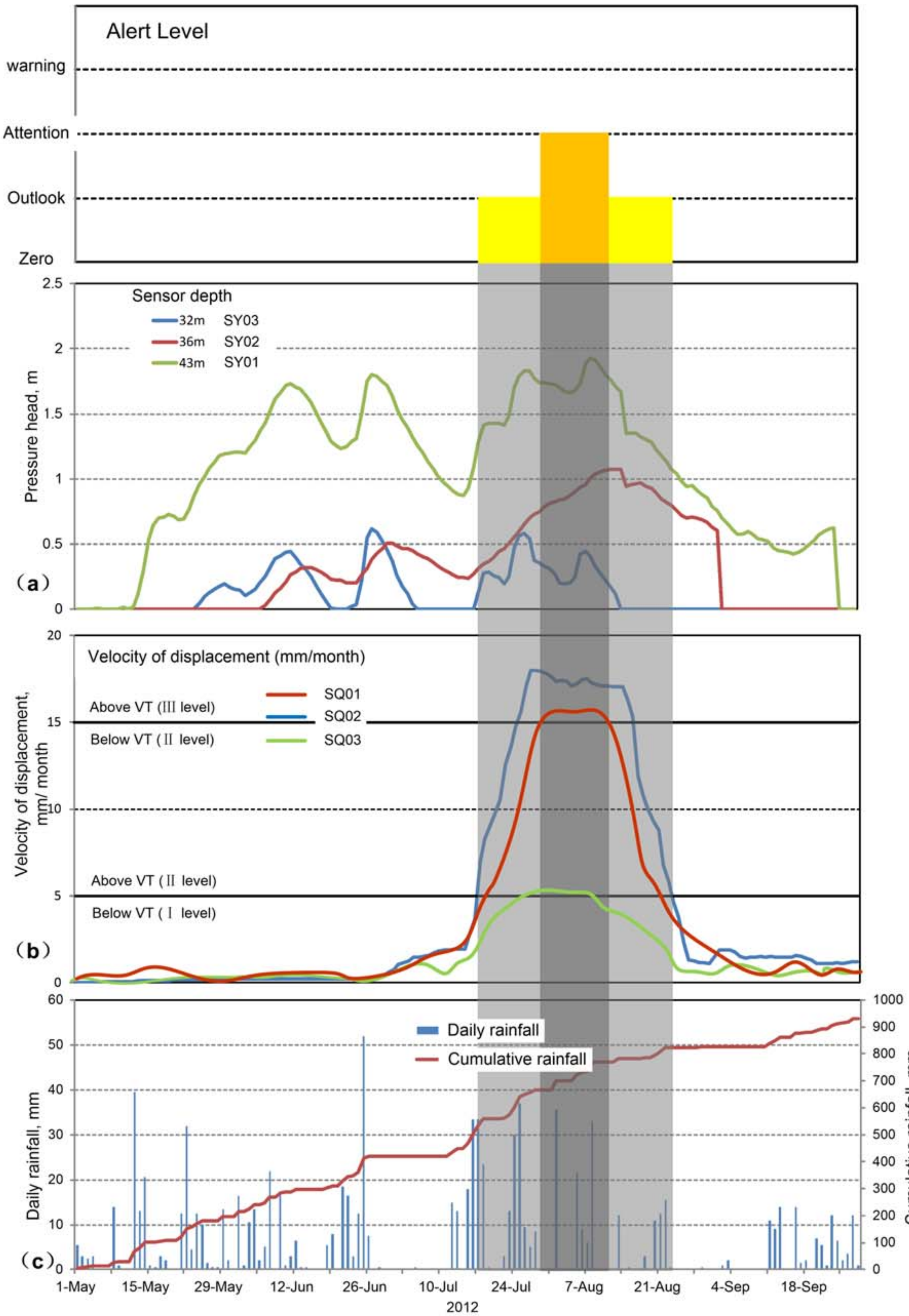

Figure 7 Real-time early warning for the Longjingwan landslide (a. Pore-water pressure, b. velocity of displacement, c. rainfall at the Longjingwan landslide, May – September, 2012.)

May 12 (39.5 mm), May 14 (20.5 mm) and May 21 (32 mm), leading to increase of the pore water pressure and displacement at deep - level. However, the increase of pore pressure and the velocity of displacement did not exceed the set threshold levels. Due to continuous rainfall until June 7 (22 mm), the water pressure became a bit high for the first time and lasted for about 8 days. Then, a second period of rainfall started on June 24 lasting for 7 days, but the velocity of displacement didn't exceed the threshold value during this period. On July 18, the velocity of displacement increased sharply, and after one day later which exceeded the threshold value (level 1 and the alert was raised to the yellow level 2). Due to the continuing heavy rainfall, after the Yellow status lasting for one week, the velocity of displacement exceeded the level 2 and the alert level 3 (orange) was reached on July 26. Fortunately the velocity did not increase further, it has decreased when the rainy storm ended. Therefore, the early warning signal has been turned back into blue status on August 26.

4 Discussion and Conclusion

The development of sensor technology, and WSN offers a useful way to monitor the landslide movement real time and continuously. This paper presents a real-time monitoring network and the design of a computer-aided EWS for landslide early warning. A four-level warning criteria system has been integrated into the automatic operation process, and a phase of expert judgment is also included to avoid false alarm. The Longjingwan landslide had been selected as a case application for the provided methodology.

It should be noted that some restrictions need to be taken into account in practical use. Firstly, the velocity threshold inevitably represents a simplification of the relationship between monitoring data and landslide occurrence. Always, when landslide happened, there might be more than one factor (Nadim and Intrieri 2011). Therefore, the system was designed to be a flexible one so that, if necessary, thresholds can be changed according to the practical situation. The second issue is to choose the suitable sensors for the real-time monitoring network, which are usually determined by the accuracy, lifetime and distance of transmission. Finally, but the most complex problem is the alert to the public. For an EWS, warning message is just regarded as a potential danger, not an imminent hazard. Then, whether any actions need to be done at once, or after a period of time, and how long it is. These questions make the final determination become much more difficult in practical operation.

In spite of these limitations, the study has reached the goal of finding a better way to design the real-time monitoring network and EWS according to the modern wireless sensor network. Even though there are still some of outstanding issues encountered during the practical use, the system has been proved that it can do a great favor in landslide prevention and mitigation. Consequently, the presented EWS works in a computer-aided automatic way, false alarms, usually introduced by some uncertain factors, may, to some extent, be controlled by expert judgments and discussions. Finally, the subsequent study needs to be carried out to research deeply into the regularity of mass movement, to improve the system's applicability and reliability in the future.

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