Technical Concepts for an Early Warning System for Rainfall Induced Landslides in Informal Settlements

John Singer, Kurosch Thuro, Moritz Gamperl, Tamara Breuninger, and Bettina Menschik

Abstract

In developing and emerging countries informal settlements often develop uncontrollably around major cities. In mountainous regions these low-income settlements frequently are situated in areas subject to high landslide risk. An intermediate solution to reduce landslide risk for the inhabitants is the installation of a landslide early warning system. The Infom@Risk project is developing a socially integrated cost-effective landslide early warning system, that specifically addresses the complex spatial and social conditions of informal settlements. This paper discusses some of the technical concepts implemented in the planned early warning system, such as a low-cost LoRa wireless geosensor network, the measuring system "Continuous Shear Monitor" and the methods to be used in data analysis.

Keywords

Landslide early warning system • Geosensor network • Continuous shear monitor • Informal settlement

Introduction

Although great advances in the recognition, prediction and mitigation of landslides have been made in the last decades, landslide events still claim a high social and economic tribute worldwide. For example, Froude and Petley (2018) have collected and analyzed records of 4862 fatal landslide events around the globe in the years 2004–2016 in which in total nearly 56,000 people were killed. Of these events the majority (79%) were triggered by rainfall. At the same time fatal landslide events cluster around cities and occur most frequently in countries with lower gross national income—usually developing and emerging countries.

This is often linked to the existence of informal settlements around cities in low income countries. These unauthorized, uncontrollably growing settlements often develop due to rural depopulation and migration towards urban centers e.g. in the expectation of better economic opportunities, public services and higher incomes (Hallegatte et al. 2016). In mountainous terrain informal settlements often are built on previously unpopulated steep slopes surrounding the city center and thus are frequently subject to substantial landslide risk. Examples for such a development can be found in Asia, Africa, South and Central America (e.g. Smyth and Royle 2000).

Due to their unclear legal status and the magnitude and extent of landslide hazard present in many informal settlements, municipalities and administrations with limited financial resources are overwhelmed by the task of implementing necessary mitigation measures or by the controlled resettlement of the population to safer areas. Several projects throughout the world have shown that simple to follow construction and development guidelines as well as low cost mitigation measures, e.g. based on bioengineering, can significantly reduce landslide risk, especially if they are conducted in a socially integrated way (e.g. Holcombe et al. 2016). However, even after implementing such measures, the remaining landslide risk often is still far above an acceptable level and the population is still exposed to potentially deadly landslide hazards.

Early warning systems (EWS) can be an effective measure to reduce the landslide risk in these areas until final long-term risk reduction solutions are found. Until now the use of early warning systems in developing countries has been limited due to the high costs and complex operation of such systems. However, with the technological advance and increasing affordability of monitoring devices, for example

J. Singer (✉)
AlpGeorisk, Einsteinstr. 10, 85716 Unterschleissheim, Germany
e-mail: singer@alpgeorisk.de

K. Thuro · M. Gamperl · T. Breuninger · B. Menschik
Chair of Engineering Geology, Technical University of Munich, Arcisstr. 21, 80333 Munich, Germany
e-mail: thuro@tum.de

N. Casagli et al. (eds.), *Understanding and Reducing Landslide Disaster Risk*, ICL Contribution to Landslide Disaster Risk Reduction,
https://doi.org/10.1007/978-3-030-60311-3_24

MEMS (Micro-Electro-Mechanical Systems) sensors and long-range wireless radio transmission techniques, the implementation of landslide early warning systems in informal settlements nowadays is conceivable.

The Inform@Risk research project (2019–2022), which is funded by the German Federal Ministry of Education and Research, plans to develop and implement a socially integrated cost-effective landslide early warning system, that specifically addresses the complex spatial and social conditions of informal settlements. The multidisciplinary project involves landscape architects (Leibniz University Hannover, LUH), geologists (Technical University of Munich, TUM), geotechnical instrumentation experts (AlpGeorisk, AGR), remote sensing experts (German Aerospace Center Oberpfaffenhofen, DLR and Expert Office for Aerial Image Evaluation and Environmental Issues, SLU), and software developers (Technical University Deggendorf, THD).

In the following, after shortly introducing the study area, the technical (monitoring and warning) concepts of the early warning system, which have been jointly developed by TUM and AGR, are presented. The other essential elements of the EWS (UN/ISDR 2006) as e.g. the risk knowledge, warning dissemination and communication and response capability are only covered superficially and will be published in detail elsewhere. A list of publications related to the Inform@Risk research project can be found at https://www.bmbf-client.de/projekte/informrisk.

Study Area: Bello Oriente, Medellin, Colombia

The city of Medellin, Colombia has been chosen as a test site for the proposed EWS, where according to the municipality currently 200,000 people live in informal settlements at risk of landslides. In an extensive qualitative decisioning process mainly conducted by the municipality of Medellin and local advisors from universities, associations and non-governmental organizations (NGO) the informal settlement above the city district Bello Oriente was chosen as a project site for the implementation of the early warning system.

Bello Oriente is situated on the northeastern slopes above the city of Medellin (Fig. 1). Based on preexisting work from the municipality and especially Werthmann et al. (2012) and Werthmann and Echeverri (2013) as well as findings of a first field campaign conducted in mid-2019, a first assessment of the geology, landslide hazard and landslide exposure are given below.

Geology

In the study area, slopes of $25° \pm 5°$ predominate. The deeper underground consists of dunite, a magmatic rock

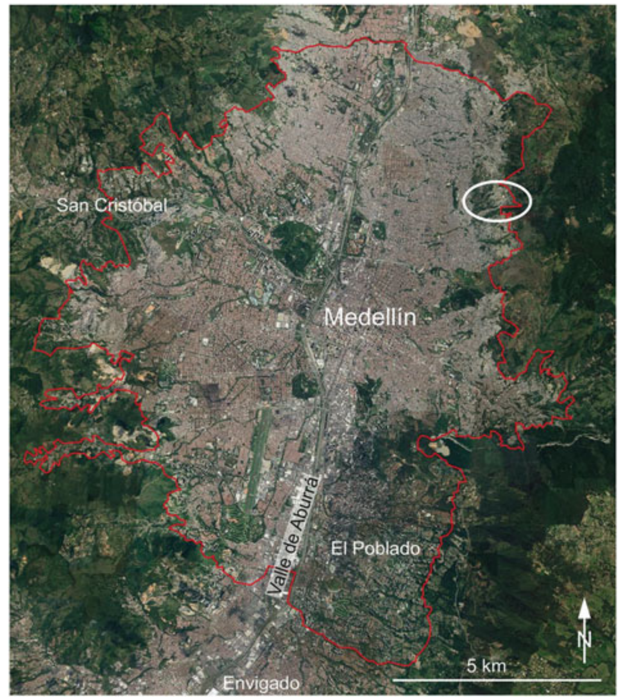

Fig. 1 Location (white oval) of the project area in the informal settlements above Bello Oriente, Medellin. Base map: Google maps; from Thuro et al. (2020)

which is extremely susceptible to weathering due to its high iron content (Fig. 2). Accordingly, as a result of the tropical conditions in the project area, the dunite is mostly covered with saprolite, a clay rich in situ product of weathering, which often still shows the original dunite structure. Depending on the exposure, the saprolite cover has a thickness between zero and several tens of meters. Especially in and below steeper segments of the slope, the dunite and saprolite have already been strongly moved by landslide processes and are therefore present as colluvium with a chaotic block-in-matrix structure. (Thuro et al. 2020).

Landslide Hazard

Most landslides observed in the northeast of Medellín are rotational slides in the deeply weathered soils and colluvium covering the dunite. On the upper parts of the valley, translational slides and sometimes rockfalls are more prominent because the bedrock surface is generally shallower there. Also, flash floods and debris flows occur, which usually follow the predefined morphology of the creeks. Due to its position about halfway up the slope, shallow to medium depth (1–20 m) rotational slides of medium to big size (10–100 m in width) are expected to be the most probable type of landslide to occur in the project area. The area affected by rockfall and flow type landslides is comparably small.

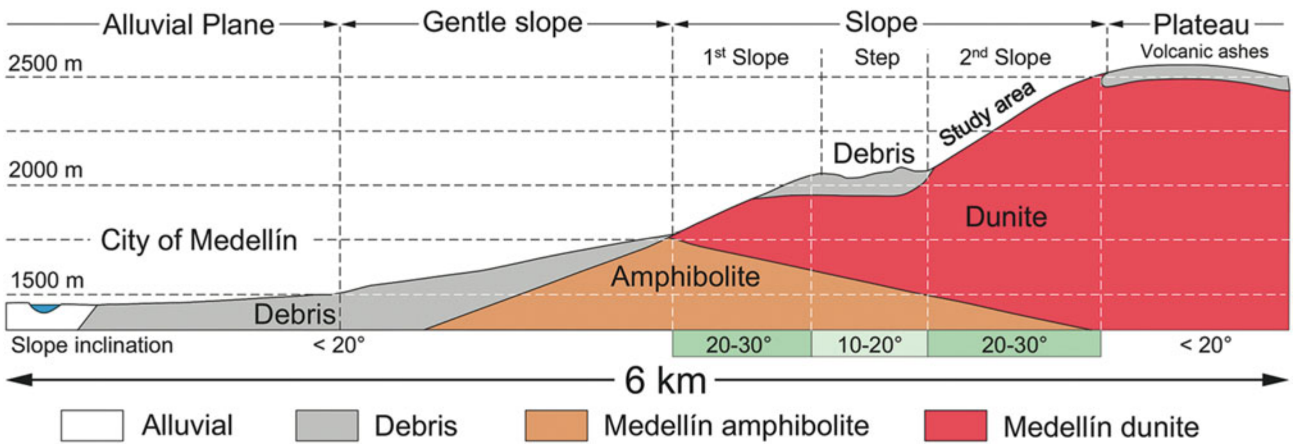

Fig. 2 Geological overview section through the northeastern slope above Medellin; the study area is situated on the upper slope where deeply weathered dunites predominate. Adapted from Werthmann et al. (2012)

The landslides are mostly triggered by rainfall or seismic events. Another frequent landslide trigger is anthropogenic activity like construction or leaky water pipes and septic tanks. When initialized, the slides are expected to have a wide range of possible velocity profiles, from continuously slow creeping movements, to slides with rapid acceleration, complete detachment and depending on the water content possibly liquefaction and very long runouts.

After conducting a geological exploration campaign, which includes exploratory drillings and an extensive laboratory testing program in May/November 2020, a more detailed assessment and differentiation of the landslide hazard will be possible.

Landslide Exposure

Preliminary results show that the project area is characterized by informal settlements built up by simple wooden or low strength masonry (mostly without reinforced concrete frames), one- to two story buildings. In a first analysis DLR counted 836 buildings in the project area, which are populated by estimated 1663 persons.

Most of the project area is endangered by the landslide processes characterized above. As soon as the hazard and exposure have been evaluated in detail, thematic risk maps for population, buildings and infrastructure will be compiled and serve as basis for the detailed planning of the EWS following the concepts described below.

Technical Concepts for a Landslide Early Warning System

To date most EWS for rainfall induced landslides either operate on a regional scale or are developed for a specific, already known landslide (Pecoraro et al. 2019).

Regional landslide EWS are usually based on statistical analyses of historic events or process models developed for geographical information systems (e.g. Marin & Velásquez 2019; Piciullo et al. 2018). These systems can provide a general indication of the current hazard level and can highlight the areas with the highest probability for the development of landslides. While these systems can raise awareness to affected areas, they cannot deliver site specific spatially and temporally precise warnings that allow to move people and assets out of harm's way, which is the goal of the Inform@Risk EWS.

In order to achieve this goal, the planned EWS operates at local scale and incorporates deformation and other geotechnical monitoring techniques comparable to those used in site specific EWS. However, as the exact locations of future developing landslides are unknown and spatially highly resolved area wide observations with conventional monitoring techniques would be very costly, new methodological and technical concepts are needed to implement such an EWS.

General Concept

The general idea is to be able to predict the future behavior of the observed landslide prone area, based on detailed hydrogeological and geotechnical models, which have been calibrated by observational data from hydrogeological field tests, geotechnical laboratory tests and a dense low-cost geosensor network. By including the triggering process in the models (e.g. intense precipitation leading to high ground water levels which trigger landslides), it is feasible to issue first general notifications, several days to hours in advance of a critical phase concerning the stability of the slope. When the onset of slow, but increasing movements is detected, spatially precise early warnings can be issued. In case of further or sudden strong acceleration of the slope, (evacuation-) alarms can be issued hopefully at least hours to minutes prior a catastrophic event, allowing people to leave the endangered area in time.

In order to reliably detect the initiation of landslides—especially in the small order of magnitude described above (rotational slides 10–100 m in width)—spatially highly resolved and accurate deformation observations are required. To achieve this high measurement density, the application of a geosensor network consisting of a combination of horizontally installed Continuous Shear Monitor (CSM) and wire-extensometer measurement systems combined with low cost wireless sensor nodes is planned (Fig. 3). While the CSM and wire-extensometer systems provide continuous, spatially highly resolved deformation observations along measurement profiles, the wireless sensor nodes add punctual observations based on the integrated MEMS sensors and other external geotechnical and hydrological sensors.

In order to achieve an optimal effectiveness of the system in terms of risk reduction, the density of the observations is varied throughout the project area based on the results of the risk assessment. In less risk prone areas, the sensor density is significantly reduced.

While this approach ensures an optimal cost–benefit ratio of the entire system, it must be emphasized, that especially small low intensity and very unlikely events might not be detected.

Geosensor Network

The monitoring system planned for the project site at Bello Oriente will cover about 20 hectares and consist of approximately 1.2 km combined CSM- and wire-extensometer lines and about 75–100 wireless sensor nodes. These communicate with 2–3 data gateways, which are distributed throughout the project area.

Combined CSM and Wire-Extensometer Lines

The Continuous Shear Monitor (CSM) is a specialized advancement of the Time Domain Reflectometry (TDR) technology for geotechnical applications (Singer et al. 2009). TDR is an electrical engineering measuring technique developed in the 1960s for locating cable faults and breaks in coaxial cables (in German-speaking countries often referred to as “cable radar”). With the CSM method, that in addition to the measurement technology itself includes procedures for the cable installation and signal processing, shear deformations (deformations perpendicular to the measuring or cable-axis) along a measuring cable can be monitored.

The CSM can seamlessly monitor measurement lines up to several hundreds of meters in length. While the system can localize and quantify localized shear with high accuracy, the maximum measurement range of shear deformation is limited to about 10 cm, when at this point the measurement cable is severed. In order to accomplish a larger measurement range (1 m and more) and at the same time add the possibility to detect axial extension along the measurement line, wire-extensometers are installed parallel to the CSM cables. These are segmented into elements of maximum 100 m length in order to allow a rough spatial allocation of the detected deformation. This is sufficient, as the location of the deformation usually will be provided by the CSM system.

However, the effort to install these systems is quite high, as they need to be placed in a trench with concrete backfill. Ideally the installation can be carried out in the context of other construction (e.g. streets, sewerage).

LoRa Wireless Sensor Network

The comparably new LoRa (Long Range) wireless technology allows the transmission of small data packets across large distances of several kilometers while only requiring very little power. This makes the development of sensor networks possible, which can be distributed in a wide area with little additional infrastructure required. The nodes can be operated with a few standard AA batteries for a very long period (up to about 2 years) and using small solar panels continuous operation for several years is conceivable. As the required hardware is affordable, the cost of the complete system is low.

For the Inform@Risk EWS new low cost LoRa sensor nodes are developed, which are based on the Arduino MKR WAN 1310 microcontroller. The nodes will include a 24-bit A/D converter allowing to connect precision analog sensors. Each node additionally is equipped with a high-quality MEMS tilt sensor, thermometer and barometer. The developed circuitry and firmware will be made available and distributed as open source.

The LoRa nodes transmit their data to LoRa gateways, of which for redundancy at least 2 are placed in the project area. These require power and internet access. Any data received from the LoRa nodes is directly forwarded to the data server and stored in the project database. The nodes can also receive commands e.g. to change the measurement frequency.

Sensor Placement

While the density of observations is determined by the risk analysis results as described above, the selection and placement of each individual sensor still must be executed with extreme care. The target area should be systematically checked for locations where a sensor most likely will detect changes in the measured value when a landslide develops. The resolution and range of the sensor as well as possible

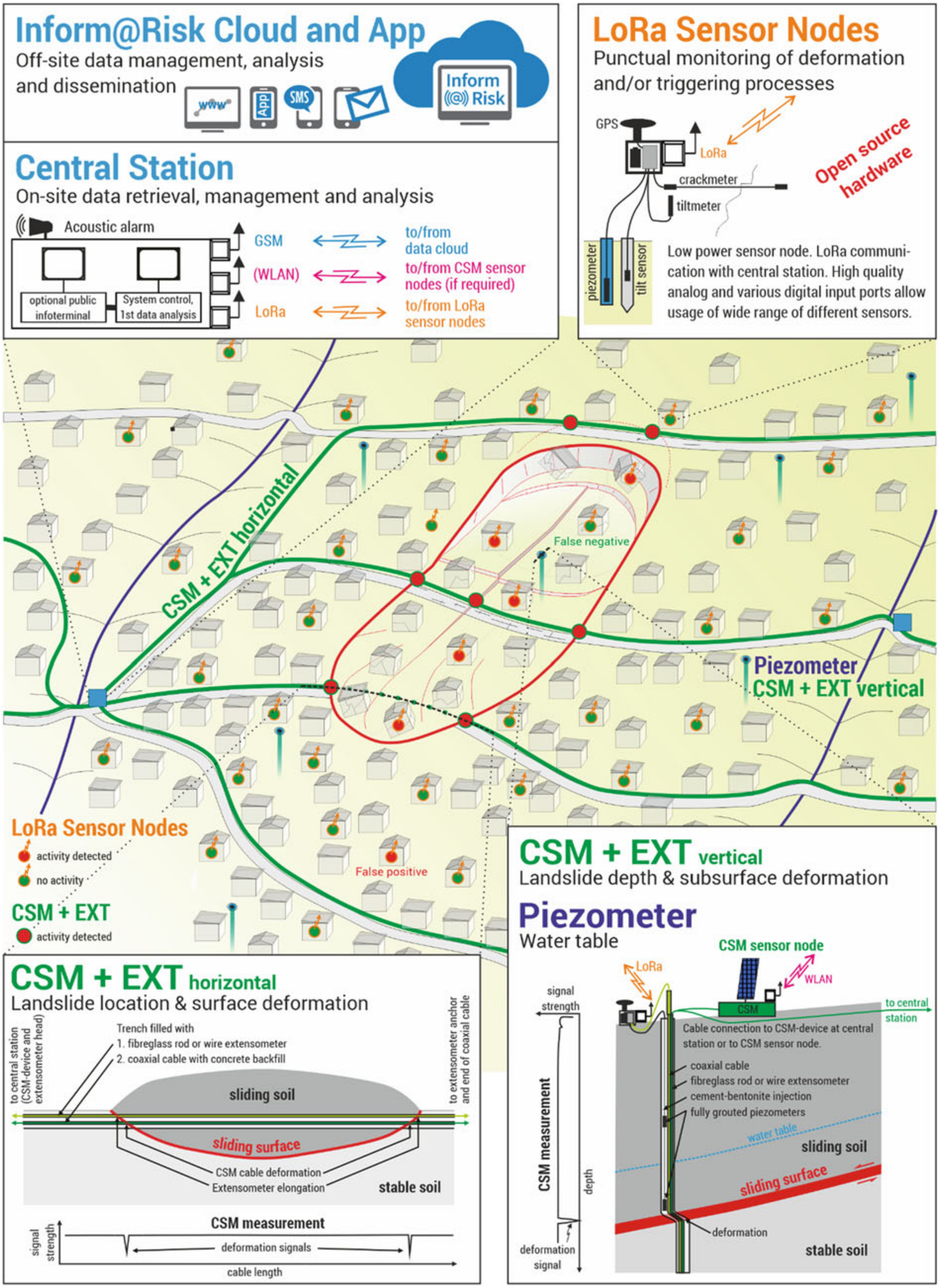

Fig. 3 Schematic layout of the proposed landslide early warning system (Thuro et al. 2020)

outside influences on the measurement should also be considered when placing a sensor. In any case the placement of each sensor needs to be documented in detail, as this will allow a better interpretation of the acquired data. In order to facilitate this process, it is planned to add an interactive sensor installation guide into the Inform@Risk app.

For the predominating rotational slides expected in the project area, MEMS inclination sensors seem to be an appropriate and simple observation method. These will be attached to buildings and infrastructure which are thought to tilt, when the slope starts to move. Additionally, small subsurface inclination probes will be used, which are driven 1–2 m into the ground (see Fig. 3, LoRa Sensor Node inset).

Data Analysis

All data collected from the geosensor network will be immediately transferred to an off-site central server (Inform@Risk Cloud), where it is processed and analyzed in near real time. The data analysis is based on threshold checks for various datasets, time series analyses and sensor fusion methods. Based on the analysis results the short- to medium term hazard level (or probability of failure) is assessed, and—if deformation is detected—early warnings and alarms are issued. The main information dissemination tool will be a newly developed mobile app.

Short- to Medium Term Hazard Level

In order to assess the short- to medium-term hazard level, the triggering factors rainfall and groundwater height are considered. On the one hand time series analyses will be performed to identify causal and temporal relationships between short-, medium- and long-term rainfall and groundwater levels. On the other hand, the hazard level is determined using groundwater level thresholds at e.g. 50, 75 and 90% of the critical water table derived from sensitivity analyses performed using the geological/geotechnical models created during the hazard analysis.

Early Warning and Alarms

Early warnings are issued as soon as significant deformation has been detected. Depending on the amount of deformation observed, different early waring levels are issued. The number and value of the static thresholds used to define these levels will be determined in course of the detailed hazard analysis, but early warning will most probably cover the range from mm per year up to cm to dm per hour. Based on how many/which neighbouring sensor nodes show deformation, the affected area and landslide mass are estimated and reported. If a further or sudden strong acceleration is detected, the system can issue an immediate (evacuation)-alarm using acoustic signals.

Depending on the hazard state, deformation rate and the affected area different actors (experts, trained community members, first responders, whole population) are informed.

Usually warnings are checked by an expert before they are sent to the inhabitants. Only in case at least two neighboring sensor nodes show very strong acceleration at the same time, the warnings are issued without review. The exact definition of the warning levels, warning content and the information dissemination paths will be developed in a participatory process, ensuring that, if possible, each actor gets the required information at the right point in time.

Outlook and Conclusion

It is planned to conduct a first test installation of the Inform@Risk EWS in November/December 2020. Based on these experiences the implementation of the entire system is planned for mid 2021. After a testing and evaluation phase of about 1 year the hopefully fully operational system is going to be handed off to the municipal early warning authority SIATA in 2022.

Although the technical concepts for the Inform-@Risk EWS were designed specifically for the study area of Bello Oriente, the approach can easily be adopted to many other areas in the Andes and worldwide.

Acknowledgements The project is funded by the German Federal Ministry of Education and Research in its program “Client II” (www.bmbf-client.de).

References

Froude MJ, Petley DN (2018) Global fatal landslide occurrence from 2004 to 2016. Nat Hazards Earth Syst Sci 18:2161–2181

Hallegatte S, Vogt-Schilb A, Rozenberg J, Bangalore M (2016) Unbreakable: building the resilience of the poor in the face of natural disasters. World Bank Publications, Washington, p 201

Holcombe EA, Beesley MEW, Vardanega, (2016) Urbanisation and landslides: hazard drivers and better practices. Proc Inst Civ Eng Geotech Eng 169:137–144

Marin RJ, Velásquez MF (2019) Influence of hydraulic properties on physically modelling slope stability and the definition of rainfall thresholds for shallow landslides. Geomorphology 351

Pecoraro G, Calvello M, Piciullo L (2019) Monitoring strategies for local landslide early warning systems. Landslides 16:213–231

Piciullo L, Cavello M, Cepeda JM (2018) Territorial early warning systems for rainfall-induced landslides. Earth Sci Rev 179:228–247

Singer J, Schuhbäck S, Wasmeier P, Thuro K, Heunecke O, Wunderlich Th, Glabsch J, Festl J (2009) Monitoring the Aggenalm landslide using economic deformation measurement techniques. Austrian J Earth Sci 102(2):20–34

Smyth CG, Royle SA (2000) Urban landslide hazards: incidence and causative factors in Niterói, Rio de Janeiro State. Brazil Appl Geogr 20:95–118

Thuro K, Singer J, Menschik B, Breuninger T, Gamperl M (2020) Entwicklung eines Frühwarnsystems für Rutschungen in den tropischen Anden (Medellín, Kolumbien). In press, Geomechanik und Tunnelbau

UN/ISDR (2006) Developing Early Warning Systems: A Checklist. EWC III - Third International Conference on Early Warning. 10 p., Bonn, Germany, March 27-29, 2006, UN Secretariat of the International Strategy for Disaster Reduction, Bonn

Werthmann C, Echeverri A, Vélez AE (2012) Rehabitar La Ladera: shifting ground. Universidad EAFIT Medellín

Werthmann C, Echeverri A (2013) Rehabitar La Montaña: Estrategias y procesos para un hábitat sostenible en las laderas de Medellín. Universidad EAFIT Medellín