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An integrated, replicable Landslide Early Warning System for informal settlements - case study in Medellín, Colombia

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Abstract. Due to climate change and growing urbanization, fatalities from landslides are rising worldwide, and thus solutions for people at risk are needed. This is especially the case for the Andean cities which are often expanding into the steep slopes surrounding them. In Medellín, Colombia, a combination of landslide-prone dunite rock and steep slopes in the east of the city creates a high-hazard scenario for about 87,000 residents, most of whom live in informal settlements. We developed a landslide early warning system (LEWS) which can be applied in such semi-urban situations. The LEWS consists mainly of a measurement system of horizontal and vertical sensor lines across the slope and autonomous point-sensors in between these lines. All parts of the LEWS, from hazard assessment to the monitoring system and the reaction capacity, are supported by extensive activities together with the local community to gain trust and create synergies. This also includes local authorities, agencies and NGO's. To test such a system, a prototype has been installed in a neighborhood in Medellín in 2020 - 2022. The experiences of this installation resulted in a framework for LEWS's of this kind which we have compiled on a wiki-page to facilitate replication by people in other parts of the world. Hopefully, this can stimulate a lively exchange between researchers and other stakeholders who want to use, modify and replicate our system.

1 Introduction

1.1 Landslide impact and losses in Colombia and the Aburrá Valley

Worldwide, a rise in the amount of deadly landslides can be observed in the last 50 years, and especially in the period between 1995-2014 (Cendrero et al., 2020; Haque et al., 2019). Rainfall therein is a major factor, especially in combination with densely populated areas. These endangered populated areas are often located in very steep terrain, and they consist of unplanned, informal settlements (Ozturk et al., 2022; Alexander, 2005; Sepúlveda and Petley, 2015; Santi et al., 2011). In these informal settlements, the vulnerability to landslides is naturally higher than in other urban areas, both physically (low construction standard of houses) and socially (reponse capability, hazard education and awareness) (Pollock and Wartman, 2020; Kennedy et al., 2016). Thus, in areas with low income and high inequality, landslides are a greater impeding factor (Aristizábal and Sánchez, 2020). This divide in landslide risk between rich and poor is expected to increase in the next decades, due to climate change and other factors, such as increased urbanization in mountainous environments, population growth and deforestation (Haque et al., 2019; Gariano and Guzzetti, 2016). With increasing precipitation and also precipitation variations, inhabited areas will be more at risk than ever (Johnston et al., 2021), while other hazards such as wildfires can act as a promoting factor

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for future landslides (Rengers et al., 2020).

In Latin America and Colombia, high relief, dense population and high seasonal precipitation are major factors promoting fatal landslides (Sepúlveda and Petley, 2015). Thus, fatalities occur mostly in populated mountainous regions, where mortality rates are significantly higher in less developed countries. Cases of deadly landslides have been rising in the last 20 years in Colombia and were triggered mostly by rainfall and anthropogenic factors (Garcia-Delgado et al., 2022). The most fatal landslides on the other hand were triggered by volcanic activity and earthquakes (Aristizábal and Sánchez, 2020). The department of Antioquia, which is located in the northwest of Colombia, has the highest total number of landslide events and the second most total fatalities (Garcia-Delgado et al., 2022; Gomez-Zapata et al., 2021). The area of Medellín and the Aburrà Valley are landslide hot spots, especially when looking only at anthropogenic triggers - one half of the landslides that were triggered by human activity in Colombia took place in the Medellín area (Aristizábal and Sánchez, 2020). Additionally, the third biggest landslide in Colombia occurred in Medellín in 1987 and caused 500 fatalities (Garcia-Londoño, 2005; Coupé et al., 2007). It was caused by human activity (water mismanagement) and is located in an area which is very similar to the area that is taken as an example site here (see section 1.3).

1.2 Local and multisectoral landslide early warning systems

In areas with high landslide hazard and dense urbanization, where constructive mitigation methods are not feasible, the only remaining option - resettlement - mostly is not possible because of the significant economic cost and other complex reasons (Dorner et al., 2019; Smith et al., 2020). Also, the community members usually have no interest in relocating, even if they are aware of the environmental risk they are exposed to (Nathan, 2008). Low-cost mitigation measures can and should be applied but they can only reduce the risk to a limited amount without being too costly. For these reasons, landslide early warning systems (LEWS) can be an effective measure to 'bridge' the gap for some years until other measures can be applied. It is important to note that in areas such as the example site of this project, LEWS should be seen as a mid-term, not a long-term solution.

Examples for such systems have been proposed before, but were limited to remote sensing or environmental monitoring (Mateos et al., 2022; Hart and Martinez, 2006; Segoni et al., 2009; Sirangelo and Versace, 1996). Other studies have shown that combining community measurement and warning systems with low-cost technical measurement systems can be effective (Bandara et al., 2013; Fathani et al., 2014), especially when the communities are involved in all parts of the risk management components (Baudoin et al., 2016). Because of their complex nature, urban landslide risk can only be reduced by interdisciplinary approaches, including e.g., geologists, engineers, social scientists and landscape architects (Alexander, 1989; Thapa and Adhikari, 2019). A LEWS resulting from this approach can be called an integrated LEWS (Fig. 1).

Notwithstanding the monitoring effort, which has to be adapted to the local circumstances, the other components of risk management also have to be addressed. For all of the parts of the system to work together effectively, it is especially important to increase the communication between the actors, to improve the risk education of the local population and to incorporate them into the process of developing and sustaining the warning system (Garcia and Fearnley, 2012; Fathani et al., 2017; Baudoin et al., 2016). Considering this, the social part of the LEWS is as important as the technical system, especially since local communities are the most involved party and often the first responders after an event (Karnawati et al., 2011). Still, their involvement in Early Warning Systems is often overlooked (Sharma, 2021).

1.3 Project overview and goals of the Inform@Risk project

To tackle the challenges posed by landslide risk in informal settlements, the Inform@Risk project came to life. It is a consortium of German universities, research institutes and small companies together with Colombian universities, agencies, NGOs and local communities. The project aims at a socially (1) and spatially (2) integrated, multi-scalar (3) and multi-sectoral (4) LEWS, which at the same time provides accurate measurements (5) using low-cost equipment (6), and whose technology and guidelines are replicable and transferrable (7) to other similar areas (Werthmann et al., 2023; Thuro et al., 2020; Singer et al., 2021). To achieve this, the LEWS is developed as a living lab (Hossain et al., 2019) in which the stakeholders collaborate by sharing ideas and knowledge, thus contributing to and improving the system.

To design and test such a system, an informal settlement with a high landslide hazard was selected in Medellín, Colombia. The neighborhood Bello Oriente is located in the north–east of the city in Comuna 3. It is an area of about 36.78 ha with approx. 4626 inhabitants living in 1285 buildings, 49% of which, around 2270 inhabitants, are located in a high hazard area (Werthmann et al., 2023). The site is located at the city border and is currently expanding into the not yet inhabited rural parts upslope to the east.

In Medellín, landslides are a prominent hazard since the city is surrounded by mountains and therefore has a very steep topography east and west of its center. The topographical difference between the valley floor and the surrounding highland is

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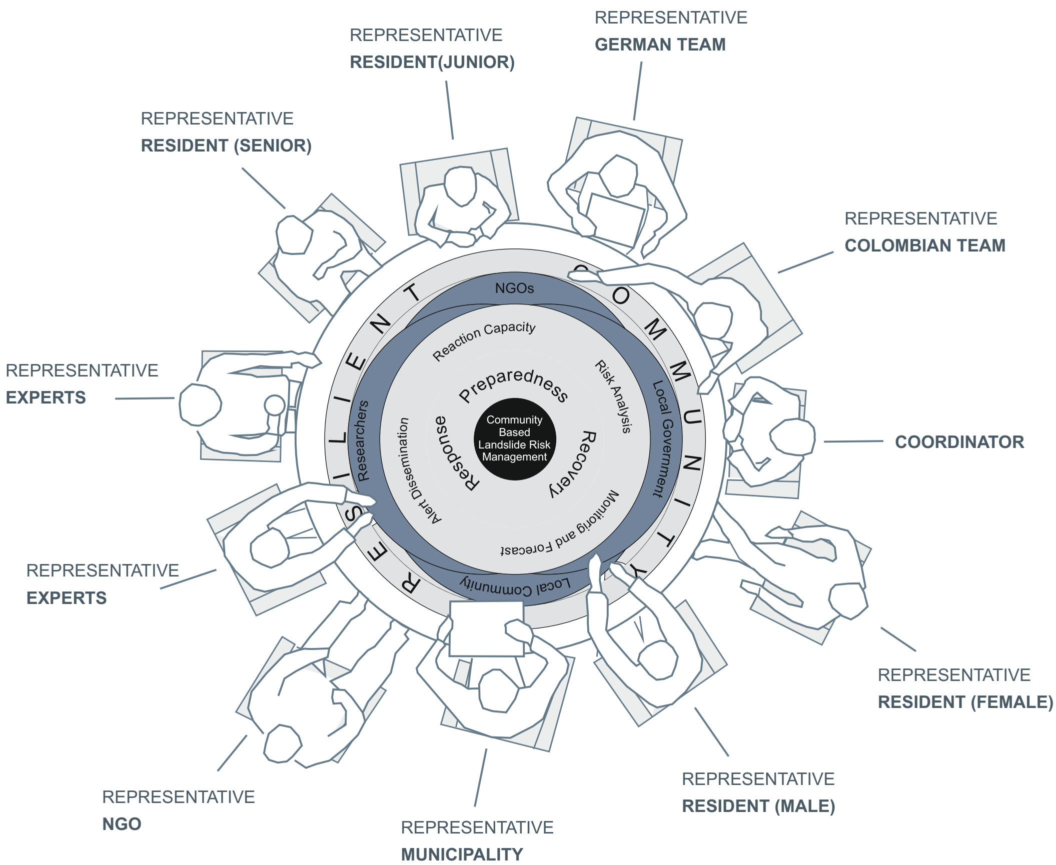

Figure 1. Example of a typical monthly stakeholder meeting for an integrated LEWS. This should Illustrate how the involvement of all stakeholders is deeply interlinked with the risk cycle and the four elements of the LEWS. Adapted from Sharma (2021) and Werthmann (2018).

about 1000 m (Ojeda and Donnelly, 2006). The steep hills in the east of Medellín mostly comprise dunite rock, an ultramafic rock which weathers easily and deeply (Aristizábal and Yokota, 2008). Therefore, these slopes are generally more susceptible to landslides (Ojeda and Donnelly, 2006; Breuninger et al., 2021b). This is especially striking when looking at the most devastating landslides in Aburrá Valley of the last 100 years that caused around 800 deaths: Most of them were located on the eastern slopes where the dunite crops out (Werthmann et al., 2012).

Based on the goals mentioned before, we have designed a monitoring system in a way so it can be applied to slopes in inhabited areas with high landslide hazard, but where the exact location of a future landslide is not known (Singer et al., 2021; Gamperl et al., 2021b). Therefore, the system needs to cover the high-hazard area with sufficient spatial and temporal density. This is of course dependent on the landslide size, thus also the economical cost is dependent on the expected landslide size.

The scope of this contribution is to expand the concepts for a monitoring system as published in Singer et al. (2021); Gamperl et al. (2021b) and show them in the larger picture of the whole LEWS, including also the social angle (section 2). To illustrate this, the progress of the installation of the Inform@Risk LEWS in Bello Oriente in 2021 and 2022 is shown in the subsequent section (section 3). The valuable experiences of this endeavor allowed us to refine the proposed LEWS significantly. In order to make these experiences publicly available to interested parties, we decided to publish all newly developed material using multiple channels, which are described in section 4.

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2 Methodology of LEWS

In the following, we give a short outline of the methology of our proposed LEWS, focusing mainly, but not only on the monitoring and forecasting parts. First, the requirements regarding risk assessment are shortly described. Subsequently, the monitoring and forecasting part of the LEWS is introduced, followed by the distribution of the system using the Inform@Risk wiki. Finally, the last two parts, community- as well as socio-spatial integration of the system, are described.

2.1 Risk assessment

Before installing any measurement system, a detailed hazard and risk analysis has to be carried out (Fathani et al., 2017). The goal of the risk assessment should be a risk map, which combines the hazard for events of different sizes which are to be expected in this area with the local vulnerability and elements at risk. To assess the hazard, a detailed investigation, including on-site geological, geomorphological and process mapping, direct and indirect geological studies like drillings, geophysical methods and numerical modeling should be performed. Which of these methods are applied in a specific scenario, needs to be decided after a preliminary (preferably on-site) analysis (Thuro et al., 2020).
For assessing the hazard from the geological findings, we decided to use an approach which combines the locally used hazard analysis defined in the POT 2014 (Alcaldía de Medellín, 2014) with the swiss methods for analyzing and assessing natural hazards. The latter is based on detailed geological investigation and delineation of hazard scenarios for different processes and return periods (Heinimann et al., 1998).

2.2 Combination of measurement systems for a low-cost system: CSM and LoRa® network

A measurement system has been designed based on the requirements of the project (section 1.3). The system has been described before (Singer et al., 2021; Gamperl et al., 2021b), thus we will only give an overview here and describe the changes that have taken place since.

The monitoring system is based on both point- and line measurements. The former comprise sensor nodes on the surface and in the subsurface in small drillings which are connected by a LoRa® (Long Range) Network, while the latter consist of horizontal and vertical CSM (Continuous Shear Monitor, Thuro et al. (2010)) lines in trenches and drillings. A schematic layout of such a system can be seen in figure 1 in Gamperl et al. (2021b).

The horizontal CSM lines provide continuous deformation measurements across the slope. If an event occurs and the landslide passes through the line, the exact location can be assessed. The vertical lines in deep drillings on the other hand give the exact depth of a landslide, if it occurs in the area of the drilling.

The point measurement instruments can perform various measurements on the surface and shallow subsurface. Measurement nodes have been designed in such a way that, depending on the situation, they can be attached on walls or other infrastructure to observe tilting or other movements ('Infrastructure Nodes' in Fig. 2). They also measure other factors such as temperature and barometric pressure (Gamperl et al., 2021b). These nodes can also be installed on top of shallow drillings, in which piezometers and tilt sensors are submerged ('Subsurface Measurement Nodes' in Fig. 2). These sensors are versatile and relatively cheap, so that in high hazard areas, a higher quantity can be installed easily. This way, beginning movements can be detected by multiple sensors, so that confidence of interpretation is increased and false positives are less likely.

All data is being retrieved by multiple central stations. The data is transmitted via wire for the CSM system and by LoRa® transmission for the sensor nodes. For the wireless system, at least two gateways are necessary to have a redundant system. It might not be necessary to install a new LoRa® gateway if there is already one in proximity of the site. With a reach of up to 15 km it is likely that a small number of gateways can receive data from multiple landslide prone slopes or neighborhoods.

2.3 Open source hardware and software on the Inform@Risk wiki

In order to make the monitoring part of the proposed LEWS as easily replicable as possible, we have compiled all necessary information on a wiki page under www.informatrisk.com (Fig. 3). For the technical parts of the measurement system described in the last section, we have created material lists, installation/construction manuals, as well as datasheets, when necessary. The necessary steps to construct the sensors and install them in the field are explained in detail using pictures from example installations, as well as graphical descriptions.

All software needed for the measurement nodes is published on a GitHub page. This makes it easily accessible and promotes interaction between coders who want to add or change parts of the code. The website is accessible under: https://github.com/moritzgamperl/informrisk-lora-node.

To provide flexibility as well as easy replicability, the designs rely heavily on 3-D printed parts. The 3-D designs are also available on the wiki and can be accessed and modified easily using open source software such as Blender or Ultimaker Cura.

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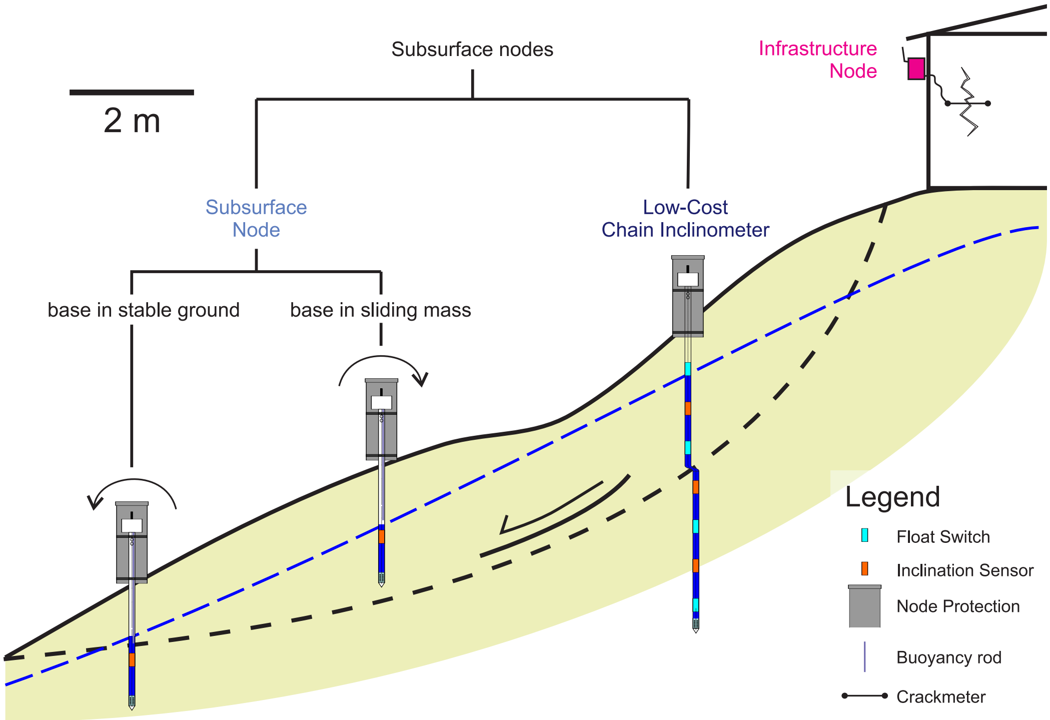

Figure 2. Different point measurements which are possible with the Inform@Risk Measurement Node. Adapted from Gamperl et al. (2021a).

For example, the 3-D printed parts of the subsurface nodes in small drillings have been designed for a casing diameter of 1 inch, but can easily be adapted to e.g. casings of 1.5 or 2 inches diameter. These general descriptions should allow anyone with basic knowledge on electronics and 3-D printing to replicate the sensors.

The basic measurement node, on which all sensors rely, consists of a printed circuit board (PCB) with about 100 components, the design of which is also available on the website, including the circuit schematics as PDF and fritzing files. This should allow easy future modification, if for example additional or updated sensors should be added. Nonetheless, the design can be taken and used as is.

The provided firmware for the nodes is as flexible as the nodes themselves and can be used for both the infrastructure nodes as well as subsurface measurements. The documentation for the firmware is hosted on the GitHub page, while the installation of the software on one's personal computer is described in an instruction manual which is hosted on the project wiki website. The necessary software to install the firmware on the nodes comprises the Arduino development environment (IDE) and various Arduino libraries, most of which can be downloaded directly in the IDE, while some of them have been written specifically or adapted for the measurement notes. The latter ones can be downloaded also from the project wiki website.

The measurement nodes can also be used for additional purposes: For example they can be used to measure ambient factors such as temperature and barometric pressure (which they already do with the basic code), but they can also be attached to e.g. pluviometers, rain gauges, wind measurements ect. Minor changes to the code have to be made, though. Because of the restrictions of the LoRa protocol, they cannot be used to transfer information which requires a high data rate. For example, when transmitting data from a pluviometer, the sum of rainfall in a specific time period, e.g. 20 minutes, would have to be transmitted.

Descriptions on how to perform low-cost extensometer measurements are also given in an additional document hosted in the wiki. The measurements themselves must be performed using a commercial wire potentiometer, but the wire suspension and guiding can be done using simple 3-D printed parts and some easily available basic construction parts. The laying of the wire itself in the horizontal measurement line is also delineated. The measurements can be made using the measurement nodes mentioned before and the required software is provided on the GitHub page. The CSM system on the other hand, which has

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Figure 3. Inform@Risk wiki page, accessible under www.informatrisk.com. The wiki is a central place for all information about the LEWS. Currently, the wiki is available in three languages, english, german and spanish (further content and languages can be added by anyone who feels inclined).

been installed for the Inform@Risk project, is more difficult to replicate because of the sophisticated software needed, the high amount of data which is produced, and the high cost of both cable and measurement instruments.

General descriptions are also given on how to install and operate a LoRa® gateway. In general any commercially available LoRa® gateway can be used. However, as their continuous, interruption-free operation is essential, many things need to be considered, when installing the gateways, including signal reception, power supply and storage, data storage, internet connection, redundancy and remote control of the main components and system protection. Consequently, gateways usually have a highly individualized design, adapted to the specific installation site. Furthermore it is advisable to integrate these essential systems socially into the public space, as we believe this will greatly increase the reliability of the system (see 2.5). Therefore it is difficult to give specific guidelines on this part of the system. Thus, only general system considerations and a general overview of what devices are needed and how they can be installed and operated can be given on the wiki.

2.4 Community integration into all parts of the LEWS

In the Inform@Risk LEWS, the local at-risk community is one of the main actors (Baudoin et al., 2016; Gumiran et al., 2019). For this reason, multiple participatory activities were developed to address the components of risk knowledge and analysis, monitoring and forecasting, alert dissemination and response capacity. Regarding the risk analysis component of the system, several workshops were developed to both explain the technical results of the geological analysis of the area, and to identify the historical landslide events and the risk factors of the area in order to reduce the latter (e.g., leaks in the water pipes, incorrect construction techniques, etc). Additionally, walking tours of the neighborhood were conducted with the participation of technical professionals and members of the community to identify risk factors, thus allowing for an exchange of knowledge regarding the risk perception of the neighborhood's inhabitants.

Regarding the monitoring and forecasting part, some manual monitoring elements were constructed with the community (Breuninger et al., 2021a) and the automatic sensors were explained in detail. There was also intensive work on identifying the

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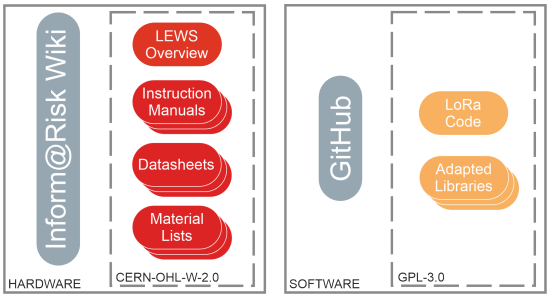

Figure 4. Overview of the open-source information about the monitoring system provided on the wiki- and GitHub pages. The licenses, CERN-OHL-W-2.0 for hardware and GPL-3.0 for software, allow open distribution, modification and publication of all material, as long as reference to the source is given.

Figure 5. Picture of one of the meetings with various stakeholders of the project. Picture: C. Garcia.

visual signs of a landslide (ex. cracks, tilted trees, water poles, etc) since community monitoring is one of the most important elements within the system.

About the alert dissemination part, multiple alert dissemination channels were implemented together with the community in order to increase redundancy. The channels comprise the use of WhatsApp groups, door-to-door alert notices between nearby neighbors, push up messages through the Inform@Risk App, messages through a large sounds system installed in the upper part of the area, and a siren system.

Finally, to address the response capacity, evacuation routes and the five meeting points, located in stable areas as defined by the hazard assessment, were identified and marked. Multiple exercises were carried out to define the actions to be taken at the different qualitative alert levels defined with the community. These exercises included theoretical risk scenarios and the development of two evacuation drills.

Since the EWS has been developed in an informal settlement, it has been relevant to identify the power relationships among the different actors, including those with a governmental, legal and illegal role. This implies constant and open communication in order to gain and maintain trust among the different actors. One of the key actors in the community trainings and the social power management were the local civil society organizations of the area (Lassa, 2018). Some of the civil society organizations that supported the development of the EWS have been working with the community for several years so they have a deep understanding of the social structures and needs.

2.5 Socio-spatial integration of LEWS

Commonly, the physical parts of a LEWS are located in remote areas that are not accessible for people at risk. In the case of an informal settlement like Bello Oriente where people live in high-hazard areas for landslides, the sensors are located inside the neighborhood's public space, near to and onto peoples' houses. A key factor for a successful integrated LEWS is the acceptance and support of residents at risk (Baudoin et al., 2016; Marchezini et al., 2018). At the same time, it is necessary to protect the

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Figure 6. Photos of the participation of the community in the four components of the EWS. Pictures: C. Garcia

vulnerable physical parts of the monitoring system from external influences. Therefore, an approach on how to spatially and socially integrate the monitoring system into the public open space and how to protect the physical parts was implemented.

Sensor protections built as benches and seats for daily use can function as a natural reminder of landslide risk. In combination with informative elements like short inscriptions and explanatory signs, these small meeting spaces seek to raise acceptance and decrease vandalism. The type and material of the public space elements should be site-specific and jointly developed with residents at risk and experts, including e.g. landscape architects, urban planners, or architects. The main material chosen for constructing the benches and seats in Bello Oriente was red brick, as it is resistant to tropical weather conditions and is a well-known constructing material in the neighborhood.

Depending on the number, type, and location of sensors to protect, an overall concept for public space interventions should be developed. As one project goal is to build a low-cost system, not all sensors were protected with a bench construction in order to save costs. Those sensors located on steep slopes in remote areas were protected with a low-cost version. In this pilot, a simple plastic pipe marks these remote sensor locations. Sensors near pathways and streets, where people walk by, have a medium intensive set up, in our case a small brick seat (Fig. 7, left). Together with residents, places for building benches were chosen at socially and spatially suitable places where people can meet and benefit from them. As a special part of the monitoring system, the LoRa Gateway B was designed as an informative meeting space. A big bench was paired with a steel construction holding the antennas, the solar panel, and a sign showing more detailed information about landslide risk and the LEWS (Fig. 8, left). To add environmental elements and also to increase residents' responsibility and awareness for these places, micro gardens and trees were planted next to the benches. To protect the horizontal CSM lines from external disturbances like future construction activities, simple point markers every 3 to 5 meters display their location (Fig. 9).

For all sensor types an overall communication strategy was developed. Easy-to-understand impersonations explain the landslide risk and how the slope is monitored. As an example, the short form "LoRa®" means "parrot" in Spanish. Through simple wall paintings of "Lora the parrot" paired with the technical LoRa® box, the infrastructure nodes are visibly spread in the upper part of the neighborhood and serve as an important recognition feature for the integrated LEWS (Fig.8, right).

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Figure 7. Sensor protections as small seats or benches out of bricks supplemented by short inscriptions and bright colors.

Figure 8. Left: Gateway B functions as a small public space with a big bench and an information sign. Right: LoRa® infrastructure node combined with a wall painting: "Lora the parrot" impersonates the sensor.

3 Installation of prototype in Medellín

3.1 Sensor system

The described sensor system has gone through some iterations, both in the laboratory and in the field. These helped to improve both the capabilities of the system as well as the ease of use and replicability. Since an installation in Colombia was not possible in 2021 due to the Covid crisis, a test installation was performed in southern Germany (Gamperl et al., 2021b). This allowed us to increase the flexibility and ease of installation of the system. After this, an installation in the test site in Colombia was put through. The experiences of this installation allowed us to further improve the sensors and the process of installation. For example, it became clear that considering the ground conditions in Bello Oriente (mainly clay rich soils) for the cheap and shallow subsurface measurements it is easier to directly hammer in a steel pipe than to pre-drill a hole and insert a PVC pipe as presented in Gamperl et al. (2021b). Also, a diameter of 1.25 to 1.5" proved to be ideal for these kinds of installations.

In total, 111 measurement nodes were installed at the test site Bello Oriente in Medellin, Colombia in the time between march and august 2022. Figure 11 shows the final installation plan with the point-and line measurements as well as the deep drillings (50 m) with vertical CSM, extensometer and classic inclinometers. Some pictures of the field installation are shown in Fig. 10.

3.2 Data management, data analysis

All data acquired in the geosensor network and the other measurement systems currently installed in Bello Oriente is immediately transferred to an off-site central server, where it is processed and analyzed in near real time. The data from the LoRa system first goes through an open-source LoRaWAN® Network Server ("Chirpstack"), which manages the LoRa® network

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Figure 9. Point markers indicate the location of the horizontal CSM lines.

Figure 10. Photos of the installation of the measurement system in Bello Oriente in 2022.

including all communication to and from all LoRa® gateways using the LoRaWAN® specifications (see www.chirpstack.io for details). Then the data is stored, analyzed and visualized by the AlpGeorisk ONLINE data management service developed and operated by AlpGeorisk (details on this will be shared in an additional publication). The data stored and visualized on this web platform is accessed by an open-source smartphone app which was also developed as part of the project by the Deggendorf Institute of Technology. This app is an essential part of the community integration of the LEWS.

The data analysis methods are not yet fully implemented, but it is planned to combine dynamic thresholds for trigger- and deformation observations with sensor fusion and pattern recognition methods. This is needed first because of the large amounts of data that are incoming in the system (At the time of writing, about 50000 datapoints are created by the system each day), and secondly because of accidental or intentional tampering with the sensors that has to be taken into account because of the densely populated area the system is installed in.

The sensor fusion methods are needed because the large amount of data makes it very difficult for a person to check all sensors at a glance. These methods filter the incoming data and separate the significant from the insignificant data. For example when a threshold is surpassed on a single inclination sensor, the system checks if any of the surrounding sensor nodes have also registered a deformation increase. It also checks if any of the sensors monitoring the triggering factors (i.e. rainfall, groundwater, seismic events, etc.) show an increased level. Depending on the severity and degree of confidence of the observation, either the event is temporarily ignored or appropriate action is taken, which ranges from marking the event for review through the system manager to issuing an alert. In any case, the system will instruct the relevant sensors to increase the measurement interval and as further data of the event is collected throughout time, the system will reevaluate the event utilizing pattern recognition methods on the time series of the relevant deformation and triggering datasets. This cycle is continued until the event is identified as an outside influence, or - if the situation remains uncertain - is reviewed and classified by the system

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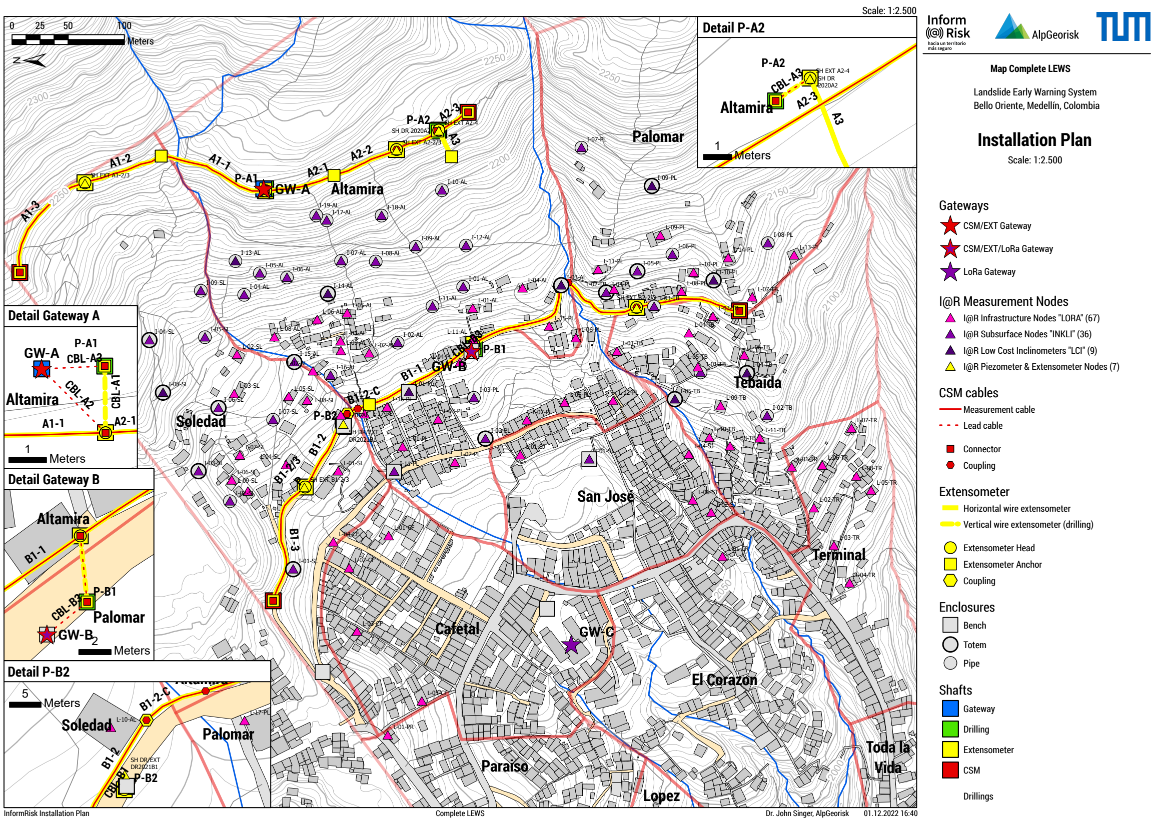

Figure 11. Final installation plan for the monitoring system in Bello Oriente.

manager. With time, the system will collect a database of classified events, which can be reviewed periodically and serve as training data for the pattern recognition algorithms.

The thresholds used for the different sensor types at the different locations are first determined based on sensitivity analyses performed using the geological/geomechanical models created during the hazard analysis and include absolute values as well as rates where applicable (e.g. deformation rate). Later with increasing length of observation the thresholds are adapted using the results from time series-analyses performed on the collected data.

Based on the analysis results, the short- to medium-term hazard level is assessed, and – if deformation is detected – early warnings and alarms are issued.

In order to assess the short- to medium-term hazard level, mainly the triggering factors rainfall and groundwater height are considered. On the one hand, time series analyses are 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 percent of the critical water table derived from the geological/geomechanical models created during the hazard analysis. The threshold values thereby are determined individually for different geological homogeneous zones throughout the project area and are applied to the according sensors in this area.

Warnings are issued publicly only if significant deformation has been detected. Depending on the amount of deformation observed, different early warning levels are structured to align to the qualitative warning levels developed together with the community. The number and value of thresholds used to define these levels are currently still being determined, but early warning will most probably cover the range from mm per year up to cm or dm per hour. Based on how many and which neighboring 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 (alert sound system).

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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 will be checked by an expert before they are sent to the inhabitants. Only when at least two neighboring sensor nodes show strong acceleration at the same time and the data has successfully been cross checked according to the above data analysis procedure, the warnings are issued without review. However, community members were trained in order to make an evacuation in case they consider it necessary, even if the sensor system fails to show a relevant movement.

4 Resources for reproducing the system

4.1 The Inform@Risk wiki

In order to facilitate one major goal of the project, the reproducibility (see section 1.3), we try to (1) make all newly developed open source parts as easily accessible as possible and (2) introduce feedback loops for the scientific and professional community to interact and improve the system.

Therefore, as stated earlier (2.3), we present a wiki webpage which hosts all documents needed to reproduce the hardware and software of the LoRa® and extensometer systems. It is linked to the GitHub page of the project, which hosts all firmware for the LoRa Nodes and the necessary libraries. Also hosted on the wiki are all 3D printing files that have been created for the project and several datasheets for the sensors. Finally, files for reproducing the PCB are also hosted on the wiki.

To facilitate feedback loops and community interaction, all instruction manuals are integrated and interlinked with the additional files mentioned before. There is a user management system which allows anyone to register to the wiki. This way, users can make changes, openly discuss the system and propose new and different hardware and software designs. Participants can also share their installation pictures and designs on the wiki.

4.2 Firmware for measurement nodes

To fit the newly developed PCB with its high flexibility and capability, we wrote fitting new firmware to reflect the hardware with code. This firmware uses various pre-existing open-source libraries in the arduino environment, some of which were adapted to fit the requirements. The main code has been written from scratch, rooted on the basic LoRaWAN codes from Arduino.

To make the code as easily accessible as possible, it is distributed via GitHub:
https://github.com/moritzgamperl/informrisk-lora-node/. This way, changes can be made by other contributors easily.
The firmware was written in a way so that it can mirror the flexibility of the nodes themselves: Additional sensors can be turned on or off, and the node can be used without any attached sensors (even without inclination sensor) as something similar to a 'smart home' sensor that measures temperature and barometric pressure. On the other hand, both analog (12 or 24 bit ADC) and digital (I2C, SPI and serial (TTL) ports) sensors can easily be attached. For example, we used the node not only in its intended functions, but also to control and monitor gateways (serial communication) and measure their voltage and current consumption, measure extensometers (linear potentiometer measurement) and piezometers (4-20 mA current loop measurement) in drillings of up to 50 m depth, and to control a siren system on site (relay).

The documentation for the firmware is split up in two parts. First, the documentation on GitHub, where the Code is hosted and can be accessed. This documentation covers the basic structure and layout of the code and what files are needed for what functionality. It does not provide instructions on how to install and configure the code.

Second, the instruction manual on the project website, which goes into detail about the installation of necessary software packages and libraries, and also about the steps required to connect the hardware to a computer. Also, the parts of the code which can be changed by advanced users (e.g. detailed configurations of sensors etc.) are explained.

5 Discussion

We have proposed and tested a landslide EWS which is specifically designed for informal settlements and socially and spatially integrated into the settlement. The first test installation in Medellín, Colombia showed that such a system can be financially feasible for authorities/decisionmakers, but substantial efforts have to be made with regard to the social part - a section where no shortcuts can be made.

In an effort to enable the replicability of the low-cost instrumental monitoring system, which is the basis of the EWS, a large quantity of information in form of documents, files and manuals have been made public on the Inform@Risk wiki page. The use of this wiki page allows for anyone anywhere to interact with us and voice criticism or propose changes to the system. We

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hope that this can be the start of a truly participative approach to landslide early warning for communities that are suffering the most from these hazards. The wiki also includes information about the other parts of the LEWS.

The designs of the sensors, accompanied by the illustrative elements used in this project, allowed a better understanding and identification of the instruments by the at-risk community. The interventions that were carried out to improve public spaces (i.e. benches and seats), which incorporated sensors inside them, lead to positive acceptance in general terms. People use the benches and seats to meet friends and family or watch their children play. Therefore, a LEWS supported by public space design can contribute to social interactions inside a neighborhood. It can be stated that the combination of benches or seats with informative elements like short inscriptions and additional signs work best. The meeting spaces became important means of communication since they promote that the people discuss the LEWS or landslide risk in general.

However, in individual terms, few people felt that the location of some of these benches would become spaces for drug use and territorial focus points for the local gangs. It is therefore essential that when replicating this project, joint planning is carried out with the community in terms of locating infrastructure for the improvement of public space and to increase knowledge transfer among the different actors and residents (e.g. through supplemental information campaigns).

At the time of writing, no technical instrument has been stolen or tampered with, which is a huge achievement. This might be the result of a constant social process that has lasted almost four years where the voices of all the actors have been heard and considered.

5.1 Efficiency of sensor system

Detailed investigations of the data produced by the system and their analysis and interpretation are out of scope for this publication and will be published in the future. Here, we will only briefly discuss some strengths and weaknesses of the system and the technical limitations which are present due to the concept of the monitoring system. To our knowledge, the proposed monitoring system is one of the first such systems where the costs are made completely transparent. Not only are detailed material lists available, but also a detailed cost estimation for transferring the system to other parts of Medellín is published (Sapena et al., 2023). This study shows that the system can be an efficient tool to raise the resilience of a settlement against landslides, while keeping the costs reasonable.

These costs however should only be invested if the limitations are clear: because the system is aimed at slopes with generally high landslide hazard, but an unknown exact future landslide area, it can only detect the initial movement of landslides in areas which are monitored. If initial movements occur in areas deemed very unlikely during the hazard analysis which are subsequently only monitored sparsely, the system might not detect these movements. In the same way, the system can only provide a certain density of point sensors (about one sensor every 20 m in average) without becoming economically infeasible. This means that smaller landslides can generally not be detected with certainty. Another uncertainty stated in Gamperl et al. (2021b), are the tilt sensors themselves: the short SMP can only detect tilting and will not give a clear signal for e.g. translational landslides. The measurement principle of the deeper LCI can also give misleading data if the slip surface is below the LCI itself (meaning slides deeper than 5 m).

The topic of data analysis is another essential point which we are still working on. Especially for the point measurements (LoRa Nodes), automatic warnings are essential because the amount of data from these sensors is too much to be monitored by experts every day. Currently, the system installed in Medellín sends about 50000 datapoints a day, including tilt data, temperature, and so on. Because of this amount of data, automatic analysis methods have to be employed, which both combine the sensor data of the same information in different areas (complementary sensor fusion) and of different sources to increase reliability (redundant sensor fusion). Cooperative sensor fusion on the other hand combines information from different sources in order to gain more complex, additional information (e.g. comparing trigger data from rain gauges with deformation data from inclinometers). These methods can help to exclude false positive warnings and increase early warning times.

5.2 Challenges of an integrated LEWS

Informal settlements, present in many cities of the world, are often built in unsafe areas without building code. Where they are located in high hazard areas, resettlement is often not an option due its high costs. An integrated LEWS can help increase the resilience of these communities in the short- to mid term. The system can only be developed by collaborating with local authorities, agencies & inhabitants and it has to be tailored for them. Considering this, we have provided a framework for the technical part, which is reflected by the social parts of the system and which both are adapted to the conditions on site. The latter is one of the most challenging parts as conditions in informal settlements can vary a lot (Perlman, 2010).

The Living Lab Model has already proved as the only appropriate approach for this (Hossain et al., 2019). Local people have to be involved during all steps of the development and implementation process (e.g. already with the site investigation works),

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this way a sustainable increase in landslide hazard awareness can be achieved and the training for the case of EWS alarms can be started early.

6 Conclusions

The previously mentioned experiences of implementing the EWS in Bello Oriente, Medellín, lead us to some conclusions regarding the installation of the system in other areas. Details about the economic calculations and efficiency of the transferability are published in Sapena et al. (2023). Regarding the technical and social restraints for implementing the system the following points have to be taken into account:

- Positive relations between the authorities, civil society organizations and community are essential. If relations are not good or nonexistent, efforts should be made to improve them.
- A building density of about 250 people per ha or more might render the proposed monitoring system ineffective. Here, focusing on social work is expected to be the more efficient approach, as trained inhabitants will be able to identify symptoms of early landslide movements (cracks, tilting, jammed doors) easily as opposed to a technical system which, in these areas, might produce comparably many false readings due to intentional or unintentional tampering; The technical monitoring system on the other hand is ideal in sparsely inhabited steep slopes above settlements with little population.
- If the operating risk management authority operates such a system in multiple areas of one metropolitan area, the effort for operation can be highly diminished since gateways and other infrastructure can be shared if circumstances (e.g. distance and line of sight) are opportune.
- The same is true for the data management system which is easily scalable.
- Installation efforts for the line measurements (CSM) system are a lot higher than for the point measurements; thus the cost can be reduced by not using as many line measurements - at the caveat of losing spatial resolution (continuous deformation observations along the line); on the other hand, costs can be reduced easily by installing the horizontal CSM/EXT lines during other construction activities (e.g. telephone/gas or water lines).

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References

Alcaldía de Medellín: Acuerdo 48 de 2014, Plan de Ordenamiento Territorial de Medellin., https://www.medellin.gov.co/es/wp-content/uploads/2022/10/POT-Medellin.pdf, 2014.

Alexander, D.: Urban landslides, Progress in Physical Geography: Earth and Environment, 13, 157–189, https://doi.org/10.1177/030913338901300201, 1989.

https://doi.org/10.5194/nhess-2023-20
Preprint. Discussion started: 20 February 2023

Natural Hazards and Earth System Sciences
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Discussions

Alexander, D.: Vulnerability to Landslides, in: Landslide Hazard and Risk, edited by Glade, T., Anderson, M., and Crozier, M. J., pp. 175–198, John Wiley & Sons, Ltd, Chichester, West Sussex, England, https://doi.org/10.1002/9780470012659.ch5, 2005.

Aristizábal, E. and Sánchez, O.: Spatial and temporal patterns and the socioeconomic impacts of landslides in the tropical and mountainous Colombian Andes, Disasters, 44, 596–618, https://doi.org/10.1111/disa.12391, 2020.

Aristizábal, E. and Yokota, S.: EVOLUCIÓN GEOMORFOLÓGICA DEL VALLE DE ABURRÁ Y SUS IMPLICACIONES EN LA OCURRENCIA DE MOVIMIENTOS EN MASA, BOLETÍN DE CIENCIAS DE LA TIERRA, p. 14, 2008.

Bandara, R. M. S., Bhasin, R. K., Kjekstad, O., and Arambepola, N. M. S. I.: Examples of Cost Effective Practices for Landslide Monitoring for Early Warning in Developing Countries of Asia, in: Landslide Science and Practice, edited by Margottini, C., Canuti, P., and Sassa, K., pp. 581–588, Springer Berlin Heidelberg, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-31445-2_76, 2013.

Baudoin, M.-A., Henly-Shepard, S., Fernando, N., Sitati, A., and Zommers, Z.: From Top-Down to "Community-Centric" Approaches to Early Warning Systems: Exploring Pathways to Improve Disaster Risk Reduction Through Community Participation, International Journal of Disaster Risk Science, 7, 163–174, https://doi.org/10.1007/s13753-016-0085-6, 2016.

Breuninger, T., Gamperl, M., Menschik, B., and Thuro, K.: First Field Findings and their Geological Interpretations at the Study Site Bello Oriente, Medellín, Colombia (Project Inform@Risk), in: Proceedings of the 13th International Symposium on Landslides, International Society for Soil Mechanics and Geotechnical Engineering, Cartagena, Colombia, 2021a.

Breuninger, T., Menschik, B., Demharter, A., Gamperl, M., and Thuro, K.: Investigation of Critical Geotechnical, Petrological and Mineralogical Parameters for Landslides in Deeply Weathered Dunite Rock (Medellín, Colombia), International Journal of Environmental Research and Public Health, 18, https://doi.org/10.3390/ijerph182111141, 2021b.

Cendrero, A., Forte, L. M., Remondo, J., and Cuesta-Albertos, J. A.: Anthropocene Geomorphic Change. Climate or Human Activities?, Earth's Future, 8, https://doi.org/10.1029/2019EF001305, 2020.

Coupé, F., Arboleda G., E., and Garcia L., C.: Villa tina: Algunas reflexiones 20 años después de la tragedia, Gestión y Ambiente, 10, 31–52, 2007.

Dorner, W., Ramirez Camargo, L., and Hofmann, P.: CAN GEOINFORMATION HELP TO BETTER PROTECT INFORMAL SETTLEMENTS? - A CONCEPT FOR THE CITY OF MEDELLIN, ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-3/W8, 115–120, https://doi.org/10.5194/isprs-archives-XLII-3-W8-115-2019, 2019.

Fathani, T. F., Karnawati, D., and Wilopo, W.: An Adaptive and Sustained Landslide Monitoring and Early Warning System, in: Landslide Science for a Safer Geoenvironment, edited by Sassa, K., Canuti, P., and Yin, Y., pp. 563–567, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-05050-8_87, 2014.

Fathani, T. F., Karnawati, D., and Wilopo, W.: Promoting a Global Standard for Community-Based Landslide Early Warning Systems (WCoE 2014–2017, IPL-158, IPL-165), in: Advancing Culture of Living with Landslides, edited by Sassa, K., Mikoš, M., and Yin, Y., pp. 355–361, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-59469-9_30, 2017.

Gamperl, M., Breuninger, T., Singer, J., García-Londoño, C., Menschik, B., and Thuro, K.: Development of a Landslide Early Warning System in informal settlements in Medellín, Colombia, in: Proceedings of the 13th International Symposium on Landslides, International Society for Soil Mechanics and Geotechnical Engineering, Cartagena, Colombia, 2021a.

Gamperl, M., Singer, J., and Thuro, K.: Internet of Things Geosensor Network for Cost-Effective Landslide Early Warning Systems, Sensors, 21, 2609, https://doi.org/10.3390/s21082609, 2021b.

Garcia, C. and Fearnley, C. J.: Evaluating critical links in early warning systems for natural hazards, Environmental Hazards, 11, 123–137, https://doi.org/10.1080/17477891.2011.609877, 2012.

Garcia-Delgado, H., Petley, D. N., Bermúdez, M. A., and Sepúlveda, S. A.: Fatal landslides in Colombia (from historical times to 2020) and their socio-economic impacts, Landslides, 19, 1689–1716, https://doi.org/10.1007/s10346-022-01870-2, 2022.

Garcia-Londoño, C.: El Deslizamiento de Villatina., in: Desastres de Origen Natural en Colombia 1979-2004., edited by Hermelin, M., pp. 55–64, Universidad EAFIT, Medellín, 2005.

Gariano, S. L. and Guzzetti, F.: Landslides in a changing climate, Earth-Science Reviews, 162, 227–252, https://doi.org/10.1016/j.earscirev.2016.08.011, 2016.

Gomez-Zapata, J., Parrado, C., Frimberger, T., Barragán-Ochoa, F., Brill, F., Büche, K., Krautblatter, M., Langbein, M., Pittore, M., Rosero-Velásquez, H., Schoepfer, E., Spahn, H., and Zapata-Tapia, C.: Community Perception and Communication of Volcanic Risk from the Cotopaxi Volcano in Latacunga, Ecuador, Sustainability, 13, 1714, https://doi.org/10.3390/su13041714, 2021.

Gumiran, B. A., Moncada, F. M., Gasmen, H. J., Boyles-Panting, N. R., and Solidum, R. U.: Participatory capacities and vulnerabilities assessment: Towards the realisation of community-based early warning system for deep-seated landslides, Jàmbá Journal of Disaster Risk Studies, 11, https://doi.org/10.4102/jamba.v11i1.555, 2019.

Haque, U., da Silva, P. F., Devoli, G., Pilz, J., Zhao, B., Khaloua, A., Wilopo, W., Andersen, P., Lu, P., Lee, J., Yamamoto, T., Keellings, D., Wu, J.-H., and Glass, G. E.: The human cost of global warming: Deadly landslides and their triggers (1995–2014), Science of The Total Environment, 682, 673–684, https://doi.org/10.1016/j.scitotenv.2019.03.415, 2019.

Hart, J. K. and Martinez, K.: Environmental Sensor Networks: A revolution in the earth system science?, Earth-Science Reviews, 78, 177–191, https://doi.org/10.1016/j.earscirev.2006.05.001, 2006.

Heinimann, H. R., Hollenstein, K., Kienholz, H., Krummenacher, B., and Mani, P.: Umwelt-Materialien Nr. 85 - Methiden zur Analyse und Bewertung von Naturgefahren, Tech. rep., 1998.

Hossain, M., Leminen, S., and Westerlund, M.: A systematic review of living lab literature, Journal of Cleaner Production, 213, 976–988, https://doi.org/10.1016/j.jclepro.2018.12.257, 2019.

https://doi.org/10.5194/nhess-2023-20
Preprint. Discussion started: 20 February 2023

Natural Hazards and Earth System Sciences Discussions

Johnston, E. C., Davenport, F. V., Wang, L., Caers, J. K., Muthukrishnan, S., Burke, M., and Diffenbaugh, N. S.: Quantifying the Effect of Precipitation on Landslide Hazard in Urbanized and Non-Urbanized Areas, Geophysical Research Letters, 48, https://doi.org/10.1029/2021GL094038, 2021.

Karnawati, D., Fathani, T. F., Wilopo, W., Setianto, A., and Andayani, B.: Promoting the hybrid socio-technical approach for effective disaster risk reduction in developing countries, pp. 175–182, Orlando, USA, https://doi.org/10.2495/DMAN110161, 2011.

Kennedy, I. T. R., Petley, D. N., and Murray, V.: Landslides, in: Koenig and Schultz's Disaster Medicine, edited by Koenig, K. L. and Schultz, C. H., pp. 716–723, Cambridge University Press, 2 edn., https://doi.org/10.1017/CBO9781139629317.045, 2016.

Lassa, J. A.: Roles of Non-Government Organizations in Disaster Risk Reduction, Oxford Research Encyclopedia of Natural Hazard Science, https://doi.org/10.1093/acrefore/9780199389407.013.45, 2018.

Marchezini, V., Horita, F. E. A., Matsuo, P. M., Trajber, R., Trejo-Rangel, M. A., and Olivato, D.: A Review of Studies on Participatory Early Warning Systems (P-EWS): Pathways to Support Citizen Science Initiatives, Frontiers in Earth Science, 6, 184, https://doi.org/10.3389/feart.2018.00184, 2018.

Mateos, R. M., López-Vinielles, J., Bru, G., Sarro, R., Béjar-Pizarro, M., and Herrera, G.: Landslides in Urban Environments, in: Treatise on Geomorphology, pp. 415–432, Elsevier, https://doi.org/10.1016/B978-0-12-818234-5.00142-5, 2022.

Nathan, F.: Risk perception, risk management and vulnerability to landslides in the hill slopes in the city of La Paz, Bolivia. A preliminary statement, Disasters, 32, 337–357, https://doi.org/10.1111/j.1467-7717.2008.01043.x, 2008.

Ojeda, J. and Donnelly, L.: Landslides in Colombia and their impact on towns and cities, in: 10th IAEG Congress, p. 112, 2006.

Ozturk, U., Bozzolan, E., Holcombe, E. A., Shukla, R., Pianosi, F., and Wagener, T.: How climate change and unplanned urban sprawl bring more landslides, Nature, 608, 262–265, https://doi.org/10.1038/d41586-022-02141-9, 2022.

Perlman, J. E.: Favela four decades of living on the edge in Rio de Janeiro, Oxford University Press, New York, oCLC: 1303480415, 2010.

Pollock, W. and Wartman, J.: Human Vulnerability to Landslides, GeoHealth, 4, https://doi.org/10.1029/2020GH000287, 2020.

Rengers, F. K., McGuire, L. A., Oakley, N. S., Kean, J. W., Staley, D. M., and Tang, H.: Landslides after wildfire: initiation, magnitude, and mobility, Landslides, pp. 2631–2641, https://doi.org/10.1007/s10346-020-01506-3, 2020.

Santi, P. M., Hewitt, K., VanDine, D. F., and Barillas Cruz, E.: Debris-flow impact, vulnerability, and response, Natural Hazards, 56, 371–402, https://doi.org/10.1007/s11069-010-9576-8, 2011.

Sapena, M., Gamperl, M., Kühnl, M., Singer, J., Garcia-Londoño, C., and Taubenbock, H.: Cost estimation for the instrumentalization of Early Warning Systems in landslide prone areas, Natural Hazards and Earth System Sciences, in prep., 2023.

Segoni, S., Leoni, L., Benedetti, A. I., Catani, F., Righini, G., Falorni, G., Gabellani, S., Rudari, R., Silvestro, F., and Rebora, N.: Towards a definition of a real-time forecasting network for rainfall induced shallow landslides, Natural Hazards and Earth System Sciences, 9, 2119–2133, 2009.

Sepúlveda, S. A. and Petley, D. N.: Regional trends and controlling factors of fatal landslides in Latin America and the Caribbean, Natural Hazards and Earth System Sciences, 15, 1821–1833, https://doi.org/10.5194/nhess-15-1821-2015, 2015.

Sharma, R.: Community Based Flood Risk Management: Local Knowledge and Actor's Involvement Approach from Lower Karnali River Basin of Nepal, Journal of Geoscience and Environment Protection, 09, 35–65, https://doi.org/10.4236/gep.2021.96003, 2021.

Singer, J., Thuro, K., Gamperl, M., Breuninger, T., and Menschik, B.: Technical Concepts for an Early Warning System for Rainfall Induced Landslides in Informal Settlements, in: Understanding and Reducing Landslide Disaster Risk: Volume 3 Monitoring and Early Warning, edited by Casagli, N., Tofani, V., Sassa, K., Bobrowsky, P. T., and Takara, K., pp. 209–215, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-030-60311-3_24, 2021.

Sirangelo, B. and Versace, P.: A real time forecasting model for landslides triggered by rainfall, Meccanica, 31, 73–85, https://doi.org/10.1007/BF00444156, 1996.

Smith, H., Coupé, F., Garcia-Ferrari, S., Rivera, H., and Castro Mera, W. E.: Toward negotiated mitigation of landslide risks in informal settlements: reflections from a pilot experience in Medellín, Colombia, Ecology and Society, 25, art19, https://doi.org/10.5751/ES-11337-250119, 2020.

Thapa, P. S. and Adhikari, B. R.: Development of community-based landslide early warning system in the earthquake-affected areas of Nepal Himalaya, Journal of Mountain Science, 16, 2701–2713, https://doi.org/10.1007/s11629-019-5586-5, 2019.

Thuro, K., Singer, J., Festl, J., Wunderlich, T., Wasmeier, P., Reith, C., Heunecke, O., Glabsch, J., and Schuhbäck, S.: New landslide monitoring techniques – developments and experiences of the alpEWAS project, Journal of Applied Geodesy, 4, 69–90, https://doi.org/10.1515/jag.2010.008, 2010.

Thuro, K., Singer, J., Menschik, B., Breuninger, T., and Gamperl, M.: Development of a Landslide Early Warning System in informal settlements in Medellín, Colombia, Geomechanics and Tunnelling, 13, 103–115, https://doi.org/10.1002/geot.201900071, 2020.

Werthmann, C.: Stärkung der Resilienz informeller Siedlungen gegen Hangbewegungen durch die Vernetzung von Frühwarnsystemen, Web-Technologien und Landschaftsplanung in partizipativen Prozessen - Fallstudie Medellín, Kolumbien, Funding proposal, Leibniz Universität Hannover, Hannover, 2018.

Werthmann, C., Echeverri, A., and Elvira Vélez, A.: Rehabitar La Ladera: Shifting Ground, Research Report, Universidad EAFIT, Medellín, 2012.

Werthmann, C., Schäfer, H., Garcia, C., Seiler, L., Thuro, K., Menschik, B., Taubenböck, H., and Schröck, S.: Inform@Risk. Interim Results of the Development of an Early Warning System against Landslides in an Informal Settlement: the Case of Bello Oriente in Medellín, Colombia, Natural Hazards and Earth System Sciences, in prep., 2023.