# Development of a Landslide Early Warning System in informal settlements in Medellín, Colombia

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## Abstract

*In the last years and the years to come, the South American Andes face numerous challenges, old and new, both manmade and natural. Climate change as a catalysator for increasingly heavy storms and precipitation, deforestation and forest fires weakening the soil structure as well as a rapid growth in informal settlements in steep areas all lead to an increasing exposure to risk, especially for the most vulnerable people. The project "Inform@Risk" tries to increase the resilience of informal settlements against mass movements in the Andes. The project area is located in Medellín, the capital of the region of Antioquia in Colombia. There, the hazard of landslides is especially high due to steep slopes and highly weathered dunite rock. Many of Medellín's informal settlements are located at the urban/rural border in the east and west of the city, where the slopes are steepest.*

*The goal of the project is to develop a low cost, easily reproducible Landslide Early Warning System (LEWS) with a high degree of community integration. To achieve this, a multi-disciplinary and multi-actors approach was chosen, including scientists both in Colombia and Germany in the fields of landscape architecture, remote sensing, engineering geology, risk management and geoinformatics, as well as NGOs working closely with the local government and the communities at risk.*

*Here, the concept for the technical part of the EWS is presented. It consists of an innovative sensor system with a combination of linear measurements using Continuous Shear Monitor profiles and extensometers horizontally in the ground, as well as a number of sensor nodes distributed in the project area to perform point measurements where needed. The sensor nodes are low cost and use the Long Range (LoRa) communication protocol to save energy and service time. Additionally, manual sensors will be installed by the community for preliminary measurements, and also to increase the risk awareness of the inhabitants. All data of the EWS is collected in the Inform@Risk Cloud and displayed via an app which will be developed in the course of the project. Before the installation of the EWS sensors, in-depth geological and geotechnical investigations are performed, the first part of which is also presented in this issue (Breuninger et al., 2020).*

## 1 PROJECT OVERVIEW

Due to climate change and its effects on draught, rainfall intensity and frequency, the probability of landslides, especially in the tropical areas of the world, has increased heavily over the past years and decades. One of the most endangered regions, due to its latitude and steep slopes, are the Andes in South America. Recent events such as the forest fires in many areas in South America further increase the hazard of mass movements (Angarita 2019). More than 10 million people in the Andes are exposed to natural hazards (Peduzzi et al. 2009). Those numbers are expected to increase, as informal settlements in and around cities are rapidly growing due to rural depopulation (Davis 2006; Glade et al. 2006). A resettlement of millions of people is not feasible. Therefore, other solutions must be found to reduce natural hazards and risk.

To decrease the devastating impacts of landslides in the region, the project "Inform@Risk" is developing an economically and regionally adapted Early Warning System (EWS) for informal settlements. A key goal is to strengthen the resilience of residents against the risk of landslides.

The Department Antioquia and especially its capital Medellín located in the Aburrá Valley (VA) have suffered the most casualties by landslides in Colombia (Corporacíon OSSO 2016). Currently, more than 200,000 people are living in informal settlements in Medellín. Here, an EWS is a sustainable alternative to an almost impossible resettlement of all people at risk.

EWS for landslides are already common in the alpine region (e.g. Zangerl et al. 2010) and have also been applied in the Aburrá Valley (e.g. Aristizábal et al. 2010; "SIATA", www.siata.gov.co). However, the focus of the existing projects in the Aburrá Valley has been mostly on monitoring and warning on a regional scale, whereas site-specific warning systems with community involvement and evacuation alarms are still rare in urban regions.

Therefore, the goal of this project is to develop a replicable warning system for one neighbourhood, that can serve as a prototype for the whole region. The project has an urban-lab approach, meaning that all the partners, German and Colombian, work closely together with the people at risk. The project is put through in an area of high landslide hazard, but with no active landslides. The focus therefore is on detecting newly occurring landslides and strengthening the resilience of the people at risk, rather than monitoring already active landslides.

The barrio Bello Oriente at the eastern slope of the city of Medellín was chosen as a test site for the Inform@Risk project (Fig. 1). It is an informal settlement located at the city border in an area of high landslide hazard. The slope is up to 60° steep and consists of a thick layer (up to 40 metres) of residual soil covering the dunite bedrock (Echeverri et al. 2012).

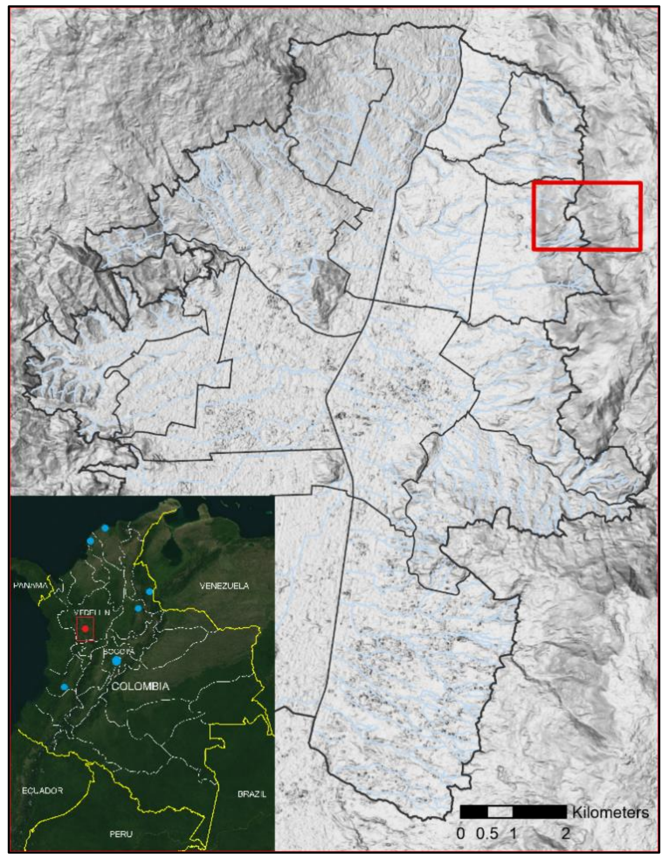


Figure 1: Urban area of Medellín in the Cordillera Central of Colombia. The Project area Bello Oriente is highlighted in red.

The instrumental backbone of the EWS will be a geotechnical monitoring system, which will consist of geotechnical, hydrological and deformation measurement systems linked together in a geosensor network, mainly based on LoRa wireless technology.

The project "Inform@Risk" is a collaboration of three German universities (Leibnitz-University of Hanover, Technical University of Munich and

Deggendorf Institute of Technology), the German Aerospace Center (DLR), two small-sized German enterprises and several partners of the City of Medellín, including the University EAFIT (URBAM Institute), the Municipal Disaster Management Agency of Medellín (DAGRD), the municipal Planning Department, two community based organizations (Convivamos & Tejearañas), the Geological Society of Colombia and the Early Warning System of Medellín (SIATA).

## 2 LANDSLIDE PROCESSES IN MEDELLÍN

### 2.1 Landslide history in Medellín

In the last 50 years, more than half a million families were affected by landslides in Colombia (Servicio Geológico Colombiano 2017). This is particularly relevant in Medellín. Here, more than 1300 people have died by landslides since 1920 (Corporacíon OSSO 2016). This is partially due to the increased informal urbanization of steep areas in the last century and especially in the last decades. Figure 2 shows the landslides where more than 10 people were reported as missing, wounded or dead since 1920 in Medellín (Corporacíon OSSO 2016).

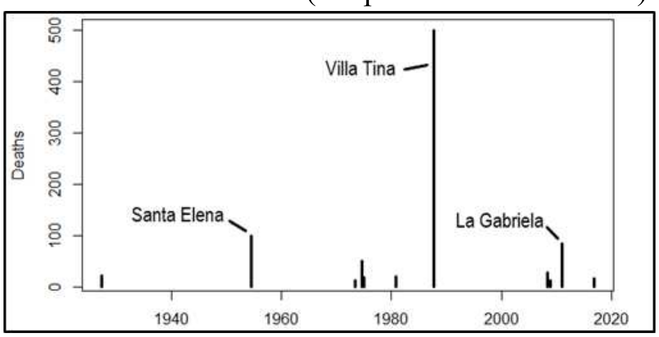


Figure 2. Landslides with more than 10 casualties reported in Medellín from 1920 to 2019 (Corporacíon OSSO 2016).

Landslide risk and casualties are expected to increase over the next years, as, on the one hand, the population density on the slopes will rise further, and, on the other hand, the effects of climate change will lead to more extreme weather events, especially in terms of high precipitation.

### 2.2 North-Eastern slopes of Medellin

The slopes in the northeast of the city are especially prone to landslides (Fig. 3). Two of the most devastating landslides in terms of human loss occurred in this area: "Villa Tina" on Sep. 27, 1987 causing more than 500 deaths with a moving mass of 40,000 cubic metres (Ojeda & Donnelly 2006); and "La Gabriela" on Dec. 05, 2010, causing 85 deaths (Echeverri et al. 2012). This higher risk in the east is caused mostly by three factors:

1. The steep slopes in this part of the valley
2. Deeply weathered ultramafic rocks (dunites) which appear in the east of the city (see also Breuninger et al., 2020)
3. High density of informal settlements

Figure 3 shows an overview of the landslide risk in the whole city, as evaluated by the municipality in the course of the "Masterplan" (POT Decreto No. 1626, Alcaldía de Medellín 2014). The high-risk areas in the northeast of the city are highlighted in red.

### 2.3 Previous Risk Assessment Studies

Landslide hazard evaluations and risk estimations have been conducted in Colombia and in Medellín. The scale has been mostly city scale or even larger (e.g. Aburrá Valley) or the whole of Colombia (e.g. Hidalgo & Vega 2014, Vega et al 2017, Van Westen and Terlien 1996). A general hazard map for landslides in Colombia in the scale of 1:100,000 has been produced by Servicio Geológico Colombiano (2017). Also, the previously mentioned "Masterplan" includes hazard maps with scales of 1:5,000 to 1:10,000. For risk estimation and early warning, mostly GIS-based approaches have been used so far, as presented by Huggel et al. (2010).

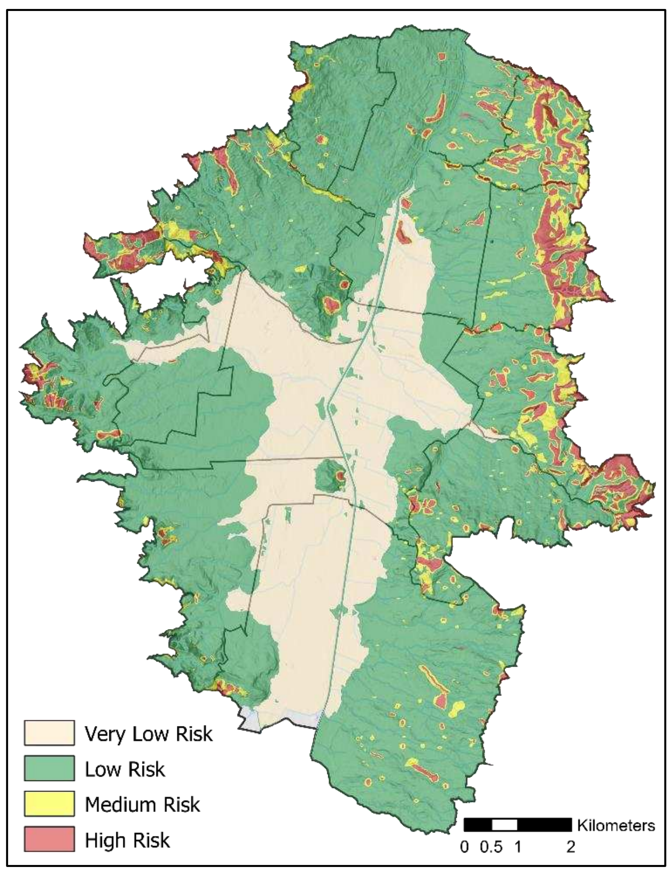


Figure 3. Overview of the landslide risk in the city of Medellín. After Alcaldía de Medellín (2014).

At local level, after the Master Plan of 2014, the municipality started developing "detail risk studies" at scale 1:2.000 in several high-risk polygons of the city of Medellín. Additionally, several universities have developed local hazard studies.

In 2010, the local municipality and the Environmental Agency of the Metropolitan Area (AMVA) created an EWS for Medellin and the Aburrá Valley called "SIATA" (Sistema de Alerta Temprana de Medellín y el Valle de Aburrá, www.siata.gov.co). This system consists of different monitoring datasets including weather and precipitation, air quality and seismic data.

Most of the above approaches are based on data with a regional scale and therefore only allow a general probabilistic hazard assessment, which is not sufficient for a site-specific alarm or early warning (Thiebes and Glade 2016).

### 2.4 Expected types of landslides

The majority of landslides in the northeast of Medellín are rotational slides in the deeply weathered soils on top of the dunite. On the upper parts of the valley, translational slides and sometimes rockfalls are more prominent because the rock surface is generally shallower there. Also, flash floods occur, which usually follow the predefined morphology of the creeks or ravines.

Based on the existing geological information, shallow to medium depth (2–20 m) rotational slides with 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 landslides usually are triggered either by rainfall or seismic events. One main trigger is also 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 and complete detachment. Based on probabilistic models, the most probable locations for landslide events can be determined, however, the exact location of a future event remains unknown.

## 3 CONCEPTUAL APPROACH FOR THE EWS

For the development of the Inform@Risk landside EWS, a people centered approach was chosen, involving the four EWS components: (1) risk knowledge, (2) monitoring and warning, (3) warning dissemination and communication and (4) response capability (UNISDR, 2006). This demands that the affected residents, community-based organizations, local authorities and scientists are actively involved in the development process, including their participation in monthly round table meetings and participatory workshops, as well as the notable integration of the early warning and evacuation elements in the public space of the settlement. This approach increases the landslide hazard awareness of the residents and hopefully the acceptance of the EWS, thereby increasing the possibility of a long-term operation of the system – long after the research project has ended.

The technical element of the EWS will be based on an integrative approach, including detailed geological investigations and analysis techniques, manual as well as state of the art automatic geotechnical monitoring technology, advanced data analysis methods and modern data dissemination, public participation and crowdsourcing via smartphone app.

In this article, the focus will be on the geological/geotechnical element of the EWS: how can a reliable, spatially and temporally precise early warning be issued, which will allow people to get out of harm's way in case of a landslide event?

The general idea is to be able to predict the future behavior of the observed landslide prone area, based on detailed geological models, which have been calibrated by observational data from geotechnical laboratory tests and a dense geosensor network. By including the triggering process in the consideration (e.g. intense precipitation leading to high ground water levels), 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 evacuation-alarms can be issued probably hours to minutes prior the event. Note that landslides triggered by earthquakes can naturally not be predicted by this system due to their quick initiation after an event.

The first essential step in the development of the proposed landslide EWS is therefore a detailed geological investigation, including landslide phenomena mapping, electric resistivity tomography measurements, geotechnical characterization of the different geological units and numerical landslide modelling (see Breuninger et al. 2020, this issue). The goal of these investigations is to develop a detailed understanding of the landslide processes to be expected in the project area, especially concerning their dimension (magnitude), spatial distribution, probability of occurrence and trigger mechanisms.

Based on the geologic investigations the required observation targets and exact system characteristics (e.g. spatial and temporal resolution) of the geosensor network will be defined. The geosensor network then should reliably detect any potentially developing landslide in the project area. Based on the current understanding of the landslide processes (see point 3.3) following preliminary observation targets have been defined:

1. Surface deformation measurements (relative or absolute, e.g. inclination, crack-opening, extension) with a spatial density of ideally one measurement per 100 to 1600 m² (10 x 10 to 40 x 40 m) and mm accuracy. This will allow an area wide detection of slow slope movements which are expected to precede a major failure.
2. Subsurface deformation measurements at the most probable landslide occurrence locations for the assessment of the landslide depth.
3. Hydrogeological observations (groundwater levels) within the most relevant hydrogeological units for the characterization of the groundwater flow regime.
4. Local and regional, ideally spatially distributed meteorological observations (e.g. precipitation from rainfall radar) for the determination of the rainfall in the catchment area of the site.
5. Where reasonable, additional geotechnical observations, which might indicate the onset of a landslide (e.g. earth pressure behind retention walls and other structures) should be included.

Additional requirements of the system include a high cost-effectiveness, easy handling and low maintenance work and cost. Ideally the system can be maintained by the residents themselves with occasional support of the local authorities.

## 4 GEOSENSOR NETWORK

A first draft of the layout of a geosensor network that would fulfill most of the requirements listed above is shown in Figure 5. The main components are Continuous Shear Monitor (CSM), wire extensometers and other state of the art deformation and geotechnical sensors, which are linked together in a geosensor network using LoRa low power communication infrastructure.

### 4.1 Continuous Shear Monitor - CSM

The CSM is a specialized development of the Time Domain Reflectometry (TDR) technology for geotechnical applications. 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. Therefore, the method is particularly suitable for deformation monitoring in landslides and embankment failures.

The TDR measuring device examines the characteristic impedance (wave impedance) of a coaxial cable. For this purpose, short voltage pulses of a few milliseconds duration are fed into the coaxial measuring cable with an ultra-sharp signal edge. These signals then propagate through the cable until they are partially or totally reflected at the cable end or at a fault in the cable. The reflections are recorded by the TDR device and compared to the output signal.

If a reflection occurs, the distance to the measuring device can be determined over its transit time (time between emission of the measuring signal and reception of the reflection), since the measuring signals propagate within a coaxial cable at a constant speed. By analyzing the signals caused by cable deformation, information about the amount and type of deformation can be obtained.

### 4.2 LoRa Sensor Nodes

The nodes provide point measurements in the areas between the horizontal CSM measurements. The sensor nodes are being built on basis of an Arduino system (Arduino MKR WAN 1310) as an open source hardware solution, the circuitry of which will be published and open for reproduction. The node firmware is written on the Arduino programming environment, which is based on the C programming language, which also will be distributed as open source. The nodes communicate to central stations using the standardized LoRaWAN communication protocol (LoRa Alliance 2018). Thus there are no retrictions in which LoRa gateway and server software solution is used. There are open source server software solutions (e.g. The Things Network (www.thethingsnetwork.org) or ChirpStack (www.chirpstack.io)) available. In total the costs to implement such a LoRa Sensor Network are very low.

Depending on the type of sensors needed, there will be different types of sensor nodes, which for example will include a 16 or 24 bit A/D converter to connect high precision sensors like piezometers or crack meters. Each node is equipped with an accelerometer, magnetometer and a gyroscope to perform tilt and acceleration measurements (e.g. on walls or other structures that will move if a landslide occurs).

After building the geosensor network within this project, the objective is to publish the hardware and software of the sensors, so that local risk management agencies in afflicted areas can easily build their own sensor network, provided there is a LoRa gateway nearby.

### 4.3 Manual Sensors set up by the community

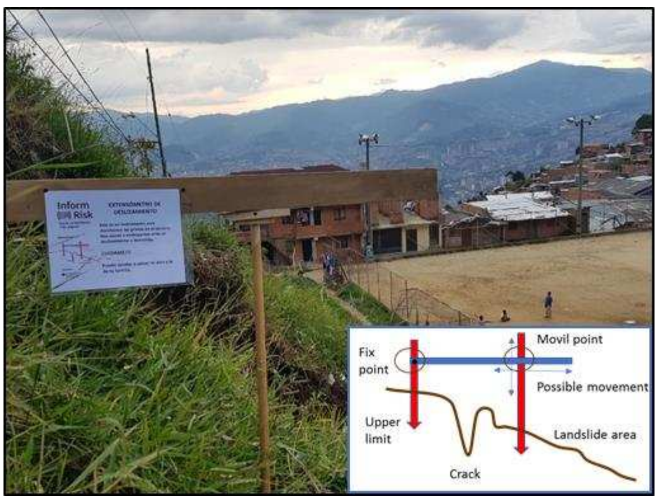


Figure 4. Example of manual monitoring instruments, as implemented in Bello Oriente.

Before the installation of the automatic instruments described before, several manual monitoring instruments are installed in different parts of the project area by the Colombian partners including the local community. These sensors have two main objectives: first, to train people into landslide monitoring using simple instruments built by themselves; second, to raise landslide risk awareness in the general community while they get used to seeing and working with landslide monitoring instruments.

The instruments consist of handmade extensometers and crack monitors. The first ones are installed in several parts of the project area that presents superficial cracks and the seconds are installed inside houses along the area (Fig. 4).

## 5 DATA ANALYSIS & EARLY WARNING

All data collected from the LoRa geosensor network and the CSM lines will be immediately transferred to an off-site central server (Inform@Risk Cloud), where it is processed and analyzed in near real time.

First the raw data is checked for its plausibility by applying valid data ranges and comparing the data to typical data patters (timeseries) expected according to the observed landslide process. The latter has to be defined individually for each sensor and sensor location. Based on this each dataset is categorized as “valid, natural behavior”, “unusual behavior” (e.g. tampering) and “invalid behavior” (e.g. sensor failure). Only valid data is passed on to further processing.

The goal then is to 1. evaluate the short to medium term hazard level based on current rainfall and groundwater data, which indicates how probable a slope failure in the near future is, 2. issue precise and localized early warnings if an onset of movement is detected and 3. issue alarms and evacuation orders if certain deformation rates are surpassed.

The thresholds for the short to medium term hazard level for instance will be based on the groundwater sensitivity determined in limit equilibrium analyses. This allows to assess a critical groundwater level which potentially will trigger a landslide. Depending on the medium to long-term rainfall, different assumptions concerning the current state of the soil water content, consistency and consequently the strength parameters of the analyzed soil will be applied, resulting in different thresholds for critical groundwater levels depending on the preceding amount of medium to long-term rainfall. As soon as the sensor network detects an onset of movement, a leveled early warning is issued. Depending on the rate of deformation and the affected area different actors (experts, trained community members, first responders, complete community) are informed.

If a critical acceleration is detected in several neighboring sensor nodes, then an evacuation alert is issued to the community members located downslope of the landslide via a smartphone app and, as eminent threat to life is assumed, via acoustic warnings (siren).

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.

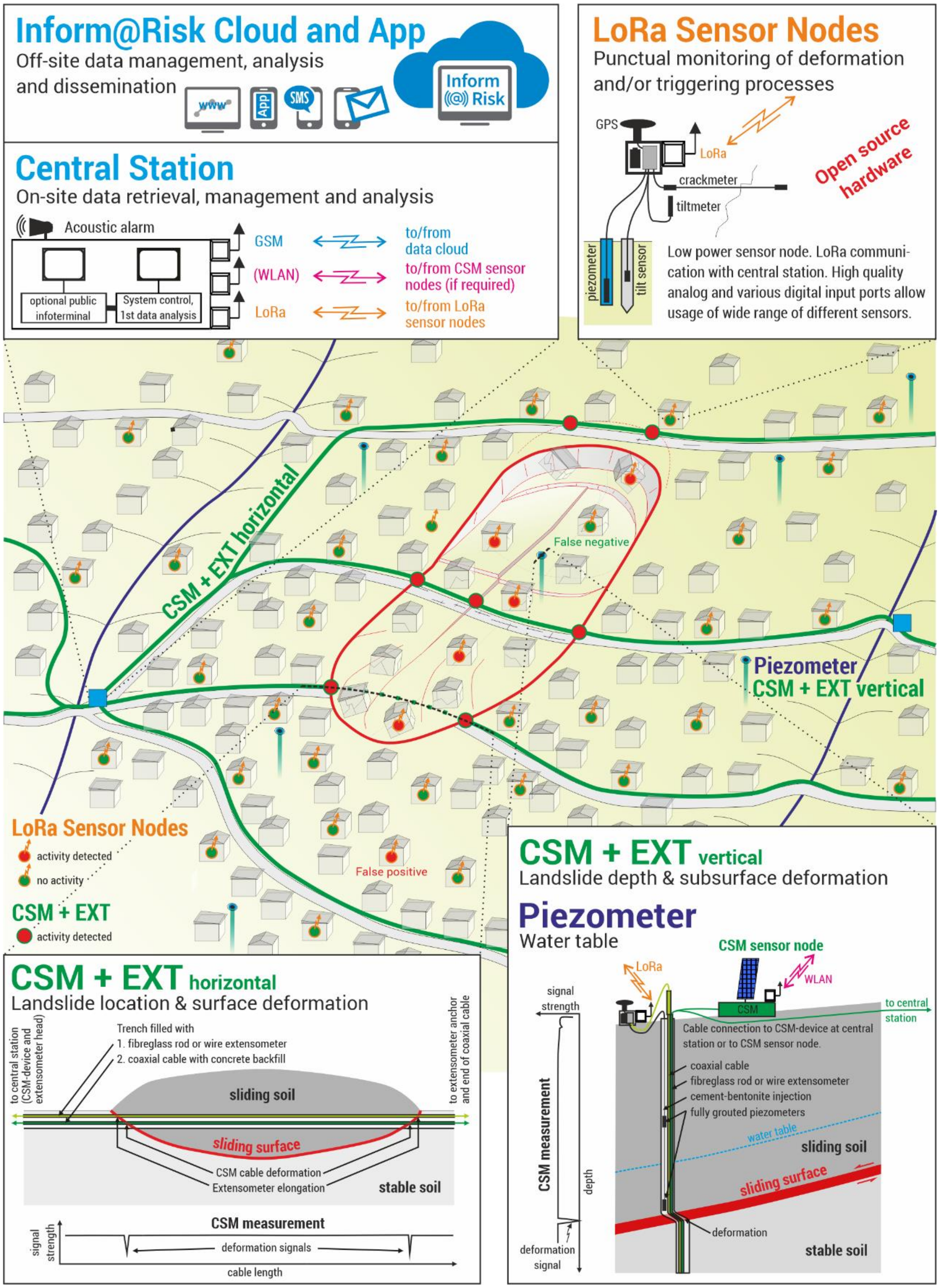


Figure 5: Schematic layout of the proposed landslide early warning system for informal settlements. The system mainly relies on Continuous Shear Monitor (CSM) measurements and state of the art geotechnical and deformation sensors, which are distributed throughout the project area. The CSM system can locate and assess the deformation amount of shear deformation along coaxial cables, which are buried into trenches. In order to be able to measure large deformation amounts up to over 1 m, wire extensometers are installed parallel to the CSM measurements. The communication within the geosensor network is facilitated by LoRa technology – a comparably new low power, long range communication technology. Subsurface deformations and groundwater levels are monitored using CSM and piezometers respectively, which therefore need to be installed into boreholes. All data is transferred to the onsite central station and into the Inform@Risk Cloud, where the data is analyzed.

## 6 CURRENT STATE OF PROJECT

The “Inform@Risk” project started in March 2019 and is expected to finish in March 2022. The first months have been focused on selecting the site, developing geologic and geoelectric campaigns, organize and develop several monthly meetings and workshops with the local community and all the partners of the project in order to plan the activities and build trust.

The year 2020 will focus on doing more workshops in order to define the monitoring sites and design the public spaces, developing geologic and drilling campaigns, and the installation of the monitoring instrumentation.

## 7 ACKNOWLEDGEMENTS

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## 8 REFERENCES

Alcaldía de Medellín (2014). *“Plan de Ordenamiento Terretorial (POT)”*. Medellín. – Alcaldía de Medellín.

Angarita, J. R. (2019) *“Alerta en 87 municipios de Boyacá por deslizamientos e incendios forestales”* RCN Radio. Retrieved from: https://www.rcnradio.com/colombia/region-central/alerta-en-87-municipios-de-boyaca-por-deslizamientos-e-incendios-forestales

Aristizábal, E., Gamboa, M. F., Leoz, F. J. (2010). *“Sistema de alterta temprana por movimientos en masa inducidos por lluvia para el Valle de Aburrá, Colombia”*. Revista EIA. 13: 1155-169.

Corporacíon OSSO (2019). *“Sistema de inventario de efectos de desastres – Medellin – Área metropolitana”*. Retrieved from: https://www.desinventar.org/en/database (24.07.2019).

Davis, M. (2006). *“Planet of Slums”*. London & New York, Verso.

Echeverri, A, Vélez Villa, A. E., Ward-Karet, M., Orbea Cevallos, S, Werthmann, C., O`Carroll, A., O’Shea, Conor (2012). *“Re Habitar La Ladera”*. Medellín, Lulu.

Glade, T., Anderson, M. G., Crozier, M. J. (2006). *“Landslide hazard and risk”.* John Wiley & Sons: 255-256.

Hidalgo, C. A. and Vega, J. A. (2014). *“Hazard Estimation for Landslides Triggered by Earthquakes and Rainfall (Aburrá Valley-Colombia)“*. Revista EIA 22: 93-109.

Huggel, C., Khabarov, N., Obersteiner, M., Ramírez, J. M. (2010). *„Implementation and integrated numerical modeling of a landslide early warning system: a pilot study in Colombia”*. Natural Hazards 52: 501-518.

LoRa Alliance (2018). *“LoRaWAN™ 1.0.3 Specification”*. Retrieved from https://lora-alliance.org/lorawan-for-developers (10.10.2019).

Ojeda, J. and Donnelly, L. (2006). *“Landslides in Colombia and their impact on towns and cities”*. IAEG Proceedings 2006. London, The Geological Society of London.

Peduzzi, P., Deichmann, U., Dao, Q.-H., Herold, C., Chatenoux, B., De Bono, A. (2009). *“Global assessment report on disaster risk reduction: patterns, trends and drivers”.* Retrieved from http://archive-ouverte.unige.ch/unige:32362 (22.07.2019).

Servicio Geológico Colombiano (2017). *“Las amenazas por movimientos en masa de Colombia”*. Bogota, Servicio Geológico Colombiano.

Thiebes, B. and Glade, T. (2016). *“Landslide Early Warning Systems—fundamental concepts and innovative applications”*, in: Landslides and Engineered Slopes. Experience, Theory and Practice, Proceedings of the 12th International Symposium on Landslides, June 12–19, 2016, Napoli, Italy.

UNISDR (2006). Global Survey of Early Warning Systems. UN/ISDR, http://goo.gl/qrJWWq.

Van Westen, C. J. and Terlien, M. T. J. (1996). *“An approach towards deterministic landslide hazard analysis in GIS. A case study from Manizales (Colombia)”*. Earth Surface Processes and Landforms 21: 853-868.

Vega, J. A., Hidalgo, C. A., Marín, N. J. (2017). *“Landslide Risk: Economic Valuation in The North-Eastern Zone of Medellin City”*. Materials Science and Engineering 245: 1-11.

Zangerl, C., Eberhardt, E., Perzlmaier, S. (2010). *“Kinematic behaviour and velocity characteristics of a complex deep-seated crystalline rockslide in relation to its interaction with a dam reservoir”*. Engineering Geology 112: 53-67.