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MARLI: a mobile application for regional landslide inventories in Ecuador

Abstract The regions of Central and South America most susceptible to the occurrence of landslides will become even more vulnerable in the context of climate change. *The Josefina disaster*, in 1993, demonstrated both the vulnerability of local infrastructures and communities in the Paute River basin (Ecuador). Since this natural phenomena, several landslide inventories and susceptibility studies were developed, revealing the vulnerability of the Paute River basin to unstable terrain and the need for further studies throughout the basin. Despite this, no studies have been done since then to update the information generated. This paper describes a Mobile Application for Regional Landslide Inventories (MARLI), a simple but efficient open-access platform to report landslide events using the Open Data Kit system. Its design makes reporting fast, simple and cost-effective with an added benefit, and a specialized knowledge is not required for its use. MARLI was tested for the collection of landslides in Cuenca (Ecuador). From the data taken in the field, it was possible to analyze the performance and suitability of collected data and compare the results with regional inventories in the same area. Additionally, these results can be used for the elaboration and update of large-scale inventories or the training of automatic identification systems of landslides and later evaluation of their precision in a small-medium scale. Likewise, this product constitutes a fundamental input for the formulation of mitigation strategies, to formulate the appropriate response and in time, also the elaboration of reconstruction plans before the increase in the occurrence of such phenomena.

Keywords Landslide inventory and mapping · Citizen science · Mobile tool · Open source · MARLI

Introduction

Landslides are the most common type of geo-hazard worldwide and play a major role in the evolution of landforms (Malamud et al. 2004). These complex natural phenomena can be characterized and classified in many types (Varnes 1978; Cruden and Varnes 1996; Reichenbach et al. 2018) and are controlled by several conditioning factors such as soil type, land use, slope or geology (van Westen et al. 2008; Reichenbach et al. 2018). Also, it is very well known that extreme climatic events, such as precipitation, snow melting or temperature changes, and its variations, affect the stability of natural and engineered slopes and have consequences on landslides (Gariano and Guzzetti 2016). Several studies have raised the impact of climate change on landslides (Petley 2010; Coe and Godt 2012). In this scenario, an increase in the temperature of the earth's surface is estimated, which influences the intensity and frequency of precipitation, increasing the occurrence of landslides and therefore the risk to properties and people. Latin America will be one of the regions most affected by this chain of phenomena (Gariano and Guzzetti 2016). Petley (2012) showed in his study that research can play an important role in reducing the impact of such phenomena, so that those countries with higher levels of research, present a lower number of fatalities. Although in the last decade there has been an increase in studies in this area, in South America, scientific production is still far from countries like Norway or Italy (Sepúlveda and Petley 2015).

Because of the magnitude of landslide impact from both a personal and economic standpoint, it is critical to strengthen the process for assessing landslide susceptibility, hazard, and risk; formulating prevention and mitigation strategies; and conducting appropriate and timely planning response to the occurrence of such phenomena (Tao et al. 2019). In this context, the role of Landslide Inventories (LI) is unquestionable. As defined by Malamud et al. (2004), an LI map is the representation of the spatial distribution of landslides at a given cartographic scale. Although there are different ways to classify the types of inventories (based on scale, based on the method used to obtain it, based on the purpose of the inventory…), one of the most popular classifications is the one proposed by Guzzetti et al. (2012). In this way, four types of geomorphological LI are differentiated: (1) historical, where the accumulated effects of many landslides over a long period of time (tens or hundreds of years) are shown; (2) event-driven, where the effects caused by a single trigger are shown; (3) seasonal, where slides occurring during one or several seasons are shown; and (4) multi-temporal inventories, where slides produced by multiple events over years are shown.

Gathering qualitative and quantitative data from landslide occurrences is a hard task. Starting from the location, the type, and the affectation of the phenomena, that poses a challenge in itself to correctly register data. It is evident that the accuracy, the correct description of the phenomena, and its magnitude are crucial data to be included in LI (Olyazadeh et al. 2016). Traditionally, this information was obtained from conventional methods, such as field surveys or aerial photograph interpretation; however, thanks to the increased availability and coverage of data from remote sensors, these methods have given way to semi-automatic methodologies based on digital terrain models (DTM), the analysis of high-resolution images or the combination of different types of data (Scaioni et al. 2014). Despite this, conventional methods are still mainly used to train the new methodologies and validate their results. We can appreciate a global trend toward increasing efforts in landslide risk assessment through the implementation of landslide databases. However, to this day, these efforts remain absent in most countries due to high cost, intense labor, and time-consuming. Therefore, the development of tools and processes that are accessible, that does not require advanced technical knowledge, and that are low cost, are fundamental tasks to respond to the growing demand for LI—in a framework of climate change—from regions with limited resources, where people and properties are threatened.

Personal smart devices provide the response to such demand. These tools are not only a communication tool but also a device combining several technologies: satellite-based GPS, which allows fast and accurate landslide location; high-quality cameras, allowing immediate graphical documentation of these phenomena; Wireless Fidelity (Wi-Fi); Bluetooth; quad-core processors, data collection and visualization applications, which based on the above technologies, facilitates the consultation of thematic information and geographic data while presenting the ability to store and transfer data over the network (Liu et al. 2014; Venkatasrinivasa Murthy 2017). In recent years, the number of such tools available has increased due to the rapid growth of cell phone usage, related infrastructure, and the increasing possibilities for free online education sources in developed and developing countries (Raja et al. 2014; Kocaman and Gokceoglu 2019), allowing the collection of field data in different fields linked to natural risk management (e.g., forest (Ferster et al. 2013), geomorphological maps (Mantovani et al. 2010), floods (Joy et al. 2019), earthquakes (Liang et al. 2017) or landslides (Olyazadeh et al. 2016)).

Despite the data collection and visualization tools boom (e.g., Open Data Kit, KoBoToolbox, Formhub or Geographical Open Data Kit), their ease-of-use and low-cost, there are not far too many examples of its application for the landslide field survey. ROOMA, developed by Olyazadeh et al. (2016), is one of the few mobile-map applications designed for the fast landslide data collection and to complement conventional remote sensing methods. This application was tested in Nepal in addition to recording landslide characteristics, risk elements were also collected. In many cases, the field survey with ROOMA allowed to improve the level of detail of the delineation of landslide areas; however, a considerable number of small landslides and active landslides in the gullies have not been identified. On the other hand, BEWARE is a platform for interactive landslide event reporting, analyzing and unifying landslide data and multimedia management (Vulović et al. 2017). This platform is made up of two mobile applications for data collection on the field, both on-line and in off-line modes under the android platform. Landslide Monitoring Application (LaMA) is another example of a simple and user-friendly mobile app to collect essential landslide data by non-expert users (Kocaman and Gokceoglu 2019). Since it is orientated to the collection of information by the civil society, these data are limited mainly to the geo-location, date and time of landslide, effects of the landslide on people, description of damages, photographs and videos of the landslide. Other studies, as the one done by Rosser et al. (2017), contemplates as a future task, the developing of an application for smartphones that enables research teams to report landslides and capture data in the field, but currently, there is no record of the stage of its development.

In addition, open citizen participatory data collection represents a starting point for field geologists engaged in the production of detailed event landslides inventories, allowing optimization in time and efforts. Volunteered geographic information (VGI) has also become a strong emerging field especially in large international initiatives (Goodchild 2007; Kocaman and Gokceoglu 2019). Some initiatives like Cooperative Open Online Landslide Repository (COOLR) or the USGS landslide Hazard Program have created a large interest in the scientific and educational world due to its potential for data acquisition, data analysis, and data modelling to represent hazard phenomena that affect territory and population (Baum et al. 2014). NASA's Global Landslide Hazard Assessment for Situational Awareness (LHASA) is a referent in this matter. This project intends to build a global inventory of landslides, where the COOLR is an open platform from which citizen scientists and technicians can report the occurrences that they are aware of (Kirschbaum and Stanley 2018). The International Consortium on Landslides (ICL) is other non-profit scientific organization for global promotion of understanding and reducing landslide disaster risk, supported, among others, by the United Nations Educational, UNESCO and FAO (Sassa 2015, 2019).

On the other hand, landslide assessment remains as a crucial task in land management and hazard/risk management, tasks that have been successfully and unsuccessfully undertaken this by all type of stakeholders (Government's, Non-governmental Organizations, Private Sector, and Research Institutes), studies done in a wide spectrum of locations and magnitudes. Even though almost a decade ago, Guzzetti et al. (2012) mentioned in his study the need to provide quality indicators of the inventory maps (completeness, geographical and thematic accuracy); however and despite the technological advances described, this practice remains anecdotal and is not free of problems (Tanyaş et al. 2017; Tanyaş and Lombardo 2020). Furthermore, despite the tools and methodologies developed for the elaboration, updating, and validation of LI at the regional or medium-large scale level using personal electronic devices, these initiatives are anecdotal in regions like Latin America.

Natural and anthropogenic landslides are common in the Andes of Ecuador, producing serious and continuous damage. Unfortunately, only a few studies have been conducted in the country (Basabe et al. 1996), and currently, there are neither databases registering these phenomena nor updated inventory maps. Thus, we have developed a mobile application to locate, characterize and typify landslides, using the Open Data Kit (ODK) system, and to undertake the task of gathering landslide data in a massive but controlled way, mainly with three purposes:

1. To increase the number of studies carried out with landslides as a tool to reduce the negative impact of these events in infrastructure, properties and people.
2. To make available to the scientific community, municipal technicians, and civilians a low-cost and easy-to-use tool for the mass collection of landslide data.
3. To obtain current and detailed information (high spatial and temporal resolution) to (1) elaborate and update inventory maps at regional level; (2) train and validate automatic methodologies to obtain these maps at smaller scales; and (3) enrich existing databases (at a regional, national and global level).

Methods

Design and development of the app system

In order to deliver on the increasing demand for spatial data, different organizations have gathered and displayed data on the web during the last decade. One of the major reasons for your success is the fact that recollecting and publishing the data has become a much easier task. The integration of remote sensing technology, high capacity computing, the evolution of the internet of things, and GPS location technology has greatly driven the idea of recollecting data through mobile devices, thereby widening the spectrum range of investigation possibilities. Taking into account the development in computer and communication technologies associated with advances in geo-information technologies, the LI development has been improved substantially. Using these advances, a Mobile Application for Regional Landslide Inventories (MARLI) was designed and developed under the Android platform to suit the need for updated and more detailed LI. In this regard, Open Data Kit is an effective tool for collecting data in the field (on-line/off-line) and it consists of three steps: design data collection form, collect data and export the collected data (Venkatasrinivasa Murthy 2017). More detailed description of these steps is given below.

System architecture

The architecture of the system is based under two basic blocks: collection of data (ODK Collect) and data display (ODK Aggregate). Traditional forms have been replaced by tools that, by means of electronic forms and intelligent mobile devices, allow the collection of data (text, numbers, geolocation, photographs, videos, audio…) (client side—ODK Collect). These data, even without an Internet connection at the time of data collection, are sent to an online server. This component, *ODK Aggregate*, allows managing the forms and administrating the collected data, and it is hosted on a own local server (server side—ODK Aggregate). Also, in the server side, we implemented a Spatial Data Infrastructure (SDI) to visualize, manage and analyze the data (data visualization—see "Data visualization" section) (Additional file 1: Fig. S1).

The advantage of ODK platform is that the tools are open source and are based on open standard XForms to build the forms. XForms is a model view controller based XML markup language. It was developed by the World Wide Web consortium (W3C) to enhance and overcome limitations of other traditional languages such as HTML (Botts et al. 2008). Considering that the expertise of the user is a prominent factor that plays an important role in deciding the functionalities of mobile devices (Venkatasrinivasa Murthy 2017), for this study, we have implemented two types of forms. The first one called *Citizen Form* and a second one called *Technical Form* aiming to target two profiles types for the landslide data collection. These profiles are as follows: One open to all the community with no regard of expertise on the subject of landslides and a second profile with a technical background on landslide identification, classification and characterization (for more details on the forms, see "Citizen and technical forms" section).

The data are first stored on the smartphone, and then, when the phone is connected to Internet via GSM (Global System for Mobile) or Wi-Fi, the data are uploaded on the server. Finally, the forms stored on the server, which include a unique automatic identifier, are exported to a spreadsheet (CSV format), and then, this file is transformed into a vector format of points from the latitude and longitude fields. In this way, the result of the field data collection can be loaded into a GIS for analysis, editing and processing (process described in "Cabinet work" section) for subsequent display ("Data visualization" section). Additionally, it is also possible to export the data to Keyhole Markup Language (KML) format, which is an XML-based markup language for representing geographic data in three dimensions; or export them to JavaScript Object Notation (JSON), which is based on a subset of the JavaScript Programming Language. This allows a wide possibility of data exchange formats, expanding the possibilities of processing the recorded data.

Citizen and technical forms

The design of the forms was based on the study by Kirschbaum et al. (2010), where a difference is made between primary and secondary elements, grouped into 5 categories (location, date-hour, event characteristics, impact information and information source). In addition, the study sought to meet four requirements: (1) it had to take into account an adequate number of fields that were simple enough to collect data quickly and accurately; (2) it could be covered by both technical specialists and civil society; (3) the information recorded could be integrated into existing databases; and (4) it took into consideration the requirements of the National Secretary for Risk Management (SNGR) as a tool to facilitate the making and updating of landslide inventories. Table 1 quotes and briefly describes the elements that were finally included in the MARLI forms grouped into the 5 categories cited by Kirschbaum et al. (2010). Additionally, the data collected will be loaded on the Cooperative Open Online Landslide Repository Platform (COOLR).

In addition to the requirements cited, MARLI has two target users. One is the common user with enough knowledge to correctly fulfill the data that the application requires aiming mainly on the location of landslides (citizen form). This form was included, because as other authors have previously stated, the volunteer contributions are considered fundamental to explain the occurrence, magnitude and intensity of landslides in mountainous and rural areas (Kocaman and Gokceoglu 2019). The other target is the technical operator which can identify, characterize and typify landslides in a more technical matter due to his/her experience and training which translates in high quality data (technical form). In addition, as conducted by Jäger et al. (2018) in his study, both the database and the application are currently upgraded into a bilingual design (Spanish and English). In this way, it is intended to facilitate the integration of MARLI data into regional, national, and continental databases.

The citizen form is destined to all the community (open participatory data collection). The citizen data can provide useful information for technicians, allowing a more efficient investment of resources. In this case, all users of the application can participate in the generation of a LI by providing information in 4 of the 5 categories of elements considered in this study (see Table 1). More detailed description of these elements was included in Additional file 1 (section 1.2). On the other hand, the technical form was designed under the premise of a technical user. This specialized user has the characteristic that they have a prior knowledge in engineering-geology and have a speciality in landslides hazard management. This technical form was distributed among a group of technicians that collaborated in the creation of the landslide inventory for the Canton Cuenca. These technicians were registered in the tool, and each one was assigned a username and password to access the technical form. More detailed description of these elements was included in Additional file 1 (section 1.2).

Table 1 MARLI: Primary (•) and secondary (∗) elements (based on Kirschbaum et al. (2010)) in citizen/technical forms. The description of these elements was included in Additional file 1 (section 1.2)

Group	Element	Form	SN	NS	Field type	References
Location	Relative Location•	CF / TF	1	CF:2/TF:2	Text field	Kirschbaum et al. (2015), Jäger et al. (2018)
	GPS Location•	CF / TF	2	CF:5/TF:3	Location field	Kirschbaum et al. (2015), Rosser et al. (2017)
	Distance to landslide∗	TF	3	CF: /TF:4	Numeric field	
	Direction of the landslide∗	TF	4	CF: /TF:5	Numeric field	
Date/Hour	Date/Hour of report•	CF / TF	5	CF:6/TF:6	Field Date/Hour	Kirschbaum et al. (2015), Olyazadeh et al. (2016), Jäger et al. (2018)
	Report in real time∗	CF / TF	6	CF:13/TF:7	Field Yes/No	Olyazadeh et al. (2016)
Event characteristics	Type of the event∗	TF	7	CF: /TF:8	List of options	Kirschbaum et al. (2015), Olyazadeh et al. (2016), Jäger et al. (2018)
	Status of the event∗	TF	8	CF: /TF:9	List of options	Jäger et al. (2018)
	Speed of the landslide∗	TF	9	CF: /TF:10	List of options	Glade and Crozier (1996)
	Landslide triggering event•	TF	10	CF: /TF:11	List of options	Kirschbaum et al. (2015), Olyazadeh et al. (2016), Jäger et al. (2018)
	Landslide category∗	TF	11	CF: /TF:12	List of options	Olyazadeh et al. (2016), Jäger et al. (2018)
	Estimated landslide volume∗	TF	12	CF: /TF:13	List of options	Rosser et al. (2017)
Impact information	Is there affected population∗	CF / TF	13	CF:14/TF:14	Field Yes/No	Kirschbaum et al. (2015), Jäger et al. (2018)
	Road infrastructure damage∗	CF / TF	14	CF:17/TF:15	List of options	Kirschbaum et al. (2015), Olyazadeh et al. (2016), Jäger et al. (2018)
	Other infrastructure affected∗	TF	15	CF: /TF:16	Field Yes/No	Kirschbaum et al. (2015), Olyazadeh et al. (2016), Jäger et al. (2018)
	Picture of infrastructure∗	TF	16	CF: /TF:17	Multimedia field	
	Hazard level∗	CF / TF	17	CF:19/TF:18	List of options	Olyazadeh et al. (2016)
	Number of fatalities∗	TF	18	CF: /TF:19	Numeric field	Kirschbaum et al. (2015), Jäger et al. (2018)
Information source	Picture landslide∗	CF / TF	19	CF: /TF:20	Multimedia field	
	Name of the event∗	TF	20	CF: /TF:21	Text field	
	Surface-water∗	TF	21	CF: /TF:22	List of options	Glade and Crozier (1996)
	Geology∗	TF	22	CF: /TF:23	Text field	Jäger et al. (2018)
	Land use∗	TF	23	CF: /TF:24	Text field	Olyazadeh et al. (2016), Jäger et al. (2018)
	Picture of land use∗	TF	24	CF: /TF:25	Multimedia field	
	Links to news∗	TF	25	CF: /TF:	Text field	Kirschbaum et al. (2015)

SN = Screen Number, NS = Next Screen, CF = Citizen Form, TF = Technical Form (see screens in Fig. 1)

Interface design and options

Figure 1 shows how the forms are presented to the users. When the application is opened, the first screen included in Fig. 1 appears. In this screen, the user must choose between the two forms developed in this study: citizen or technical. In the first case, it will be screen number 1 while in the case of the technical form, authorization verification will be requested. Each field technician will have an independent login. Logins will also be provided to interested municipal technicians. In order to keep track of each technician's work, a field will be added to each technician's record where the login user name will be recorded.

Regardless of the screen, they all have the same interface structure. First, on the left edge of each screen, the five categories proposed by Kirschbaum et al. (2010) are displayed by means of tabs. Inside, a set of circles that correspond to the number of screens included in the categories. So, the user will see "not-filled" those issues that remain to be covered. As soon as the user answer the question on each screen, he/she must save his/her answer (button *Save & Next*, first in the upper right corner) and it will automatically move on to the next screen. When the user reaches the last one, he/she will press the button *Save & Send* to end the registration and send it to the server. The data are uploaded on the server, register by register, when the phone is connected to Internet. It is also possible to go back in the screens in case it is necessary to edit the form, using the button *Preview* in the lower left corner of the MARLI interface. In that corner, it was also included the button for new landslide registration without the need for new logging. All the available buttons are indicated in the screen number 1 in Fig. 1.

Data visualization

First, a script is developed in the R environment (R Development Core Team 2010), using the R package *leaflet* (v. 2.0.3) via QGIS, in order to display the main landslide characteristics. Then, an interactive map is created using the previous code and the main results of the field survey and the subsequent cabinet analysis. The scheme of script is made up of three parts: (1) the creation of map interface; (2) selection of layers and the legend; and (3) map export for online view. This map is available through Spatial Data Infrastructure of the IERSE (Instituto de Estudios de Régimen Seccional del Ecuador).[1] As in previous researches (Rosser et al. 2017; Bragagnolo et al. 2020), open-source software is used to achieve two purposes: to make that results obtained within the framework of this study available to the public free of charge and to facilitate researches into assessment of natural disasters.

Cabinet work

In this study, a distinction is made between desk work prior to the field survey, i.e., data collection, planning work to analyze the operation of MARLI; subsequent work to identify, correct or eliminate and complete records, i.e., analysis work after the information has been recorded in the field. As for the tasks of the first group, first of all, the study area is divided into survey quadrants. Each quadrant will be assigned to a pair of field technicians. Then, the guide routes for each quadrant are drawn up based on the cartography and data available (administrative boundaries, orthophotos, topography, geology), and if available, the records captured by civil society using the citizen form.

The tasks of the second group (post-data collection work) start by loading and transforming the records into vector format in order to be able to visualize and edit them in a GIS. The identification and elimination, if any, of duplicate records is then carried out. Knowing that record duplication is one of the most common problems when different blocks of data are merged (citizen and technical data) (Jäger et al. 2018), special attention was paid to this point in the previous planning. Despite this, isolated cases of very close points were identified. Despite the difficulty of identifying them, they were analyzed and corrected. Additionally, geology and land use fields were revised and harmonized. On the other hand, the points recorded represent the foot of the slide, but if this is not the case, these points are rectified using satellite images (GeoEye) and the *distance and direction to the landslide* fields. The last steps consisted of setting the head of the landslide according to the contour lines, satellite images and the photographs of the landslide taken in the field. Then, the area affected by each slide is digitized.

Taking as a reference the studies developed by Van-Den-Eeckhaut and Hervás (2012) and Saleem et al. (2019) and also thanks to the geo-localization of each record, it was possible to assign additional information to each identified landslide. Specifically, data related to landslide dimension such as affected area, length, and width are completed by digitizing on orthoimage or height from top to toe using the DTM. Additionally, the information related to geo-environmental characteristics was also extended through the use of available thematic layers such as hydrogeology, slope gradient, slope aspect and drainage system. All these variables were obtained from the thematic layers calculated in the framework of the SIGTIERRAS program,[2] which depends on the Ministry of Agriculture and Livestock, and available for free download in the geoportal of that program.[3]

Field application, results and discussion

Study area

The Canton Cuenca is located in the province of Azuay, southern part of Ecuador (South America), and the population of this region is of 636.000 inhabitants. Cuenca covers a surface of about 3.100 km^2 within the occidental and oriental mountain ranges (Fig. 2). The Canton has a morphology characterized by a series of highlands and plains (approximately 2.580 m over sea level). The predominant lithologies are mainly represented by the sedimentary and clayey materials, adding to a changing climate, ranging from persistent droughts to extensive rainfall (precipitation averages in the order of 940 mm/year, where December to May are considered months of high precipitation and June to November are considered dry months), which encourages the occurrence of landslides.

These phenomena are frequent in Cuenca, they can create problems for the population and cause the destruction of infrastructure. One event that marked the region was the landslide of Tamuga Hill that occurred on the left bank of the Paute River in the southern Andes (see Fig. 2, *Josefina landslide*). This event, which occurred at the end of 1993, is known as *El desastre de la Josefina*

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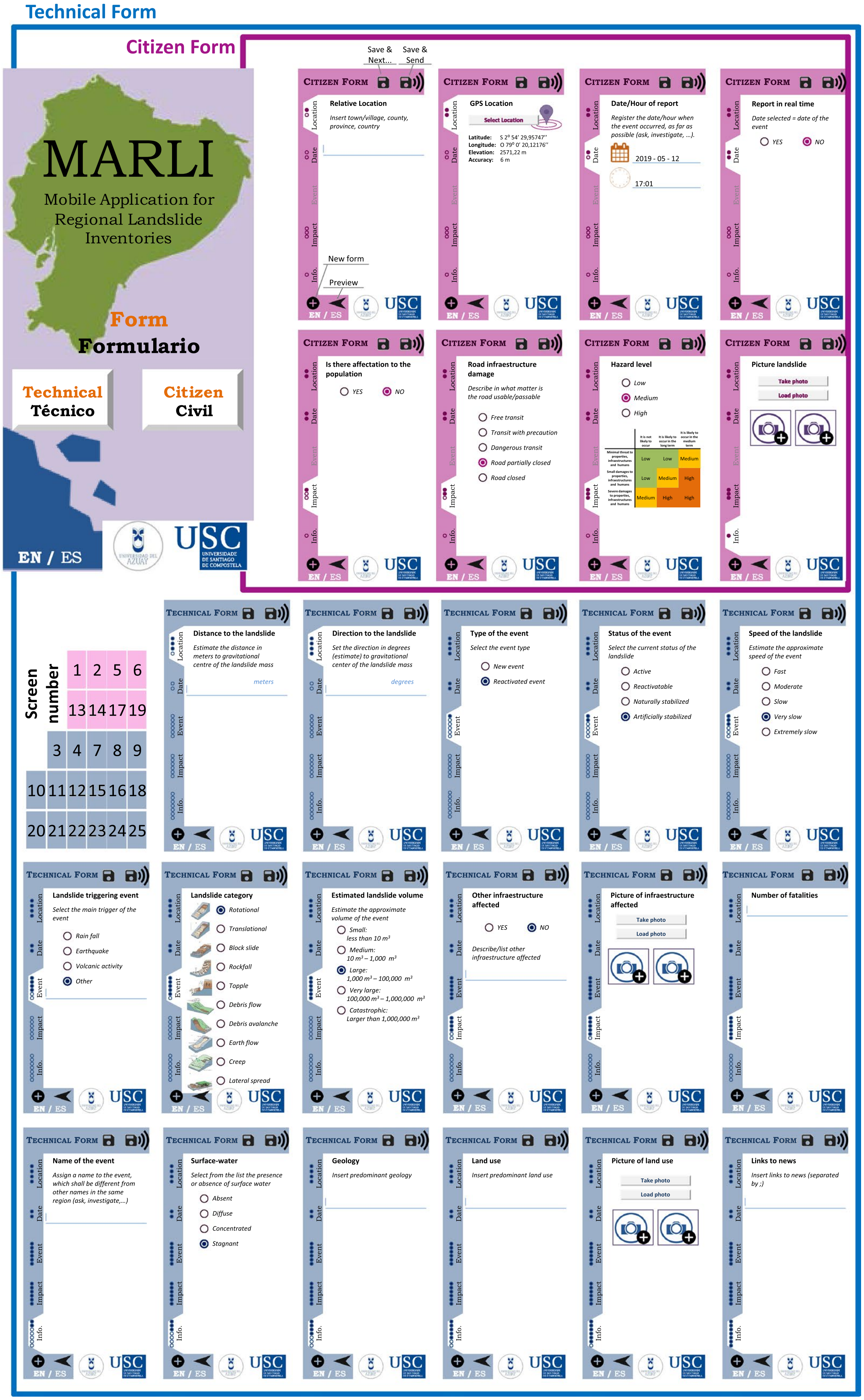
[1] http://gis.uazuay.edu.ec/proyectos/deslizamientos.

[2] http://www.sigtierras.gob.ec.

[3] http://geoportal.agricultura.gob.ec/index.php.



		1	2	5	6
		13	14	17	19
	3	4	7	8	9
10	11	12	15	16	18
20	21	22	23	24	25

Relative Location
Insert town/village, county, province, country

GPS Location
Select Location
Latitude: S 2° 54' 29,95747''
Longitude: O 79° 0' 20,12176''
Elevation: 2571,22 m
Accuracy: 6 m

Date/Hour of report
Register the date/hour when the event occurred, as far as possible (ask, investigate, …).
2019 - 05 - 12
17:01

Report in real time
Date selected = date of the event
○ YES ● NO

Is there affectation to the population
○ YES ● NO

Road infrastructure damage
Describe in what matter is the road usable/passable
○ Free transit
○ Transit with precaution
○ Dangerous transit
● Road partially closed
○ Road closed

Hazard level
○ Low
● Medium
○ High

	It is not likely to occur	It is likely to occur in the long term	It is likely to occur in the medium term
Minimal threat to properties, infrastructures and humans	Low	Low	Medium
Small damages to properties, infrastructures and humans	Low	Medium	High
Severe damages to properties, infrastructures and humans	Medium	High	High

Picture landslide
Take photo
Load photo

Distance to the landslide
Estimate the distance in meters to gravitational centre of the landslide mass
meters

Direction to the landslide
Set the direction in degrees (estimation) to gravitational center of the landslide mass
degrees

Type of the event
Select the event type
○ New event
● Reactivated event

Status of the event
Select the current status of the landslide
○ Active
○ Reactivatable
○ Naturally stabilized
● Artificially stabilized

Speed of the landslide
Estimate the approximate speed of the event
○ Fast
○ Moderate
○ Slow
● Very slow
○ Extremely slow

Landslide triggering event
Select the main trigger of the event
○ Rain fall
○ Earthquake
○ Volcanic activity
● Other

Landslide category
● Rotational
○ Translational
○ Block slide
○ Rockfall
○ Topple
○ Debris flow
○ Debris avalanche
○ Earth flow
○ Creep
○ Lateral spread

Estimated landslide volume
Estimate the approximate volume of the event
○ Small: less than 10 m^3
○ Medium: 10 m^3 – 1,000 m^3
● Large: 1,000 m^3 – 100,000 m^3
○ Very large: 100,000 m^3 – 1,000,000 m^3
○ Catastrophic: Larger than 1,000,000 m^3

Other infrastructure affected
○ YES ● NO
Describe/list other infrastructure affected

Picture of infrastructure affected
Take photo
Load photo

Number of fatalities

Name of the event
Assign a name to the event, which shall be different from other names in the same region (ask, investigate,…)

Surface-water
Select from the list the presence or absence of surface water
○ Absent
○ Diffuse
○ Concentrated
● Stagnant

Geology
Insert predominant geology

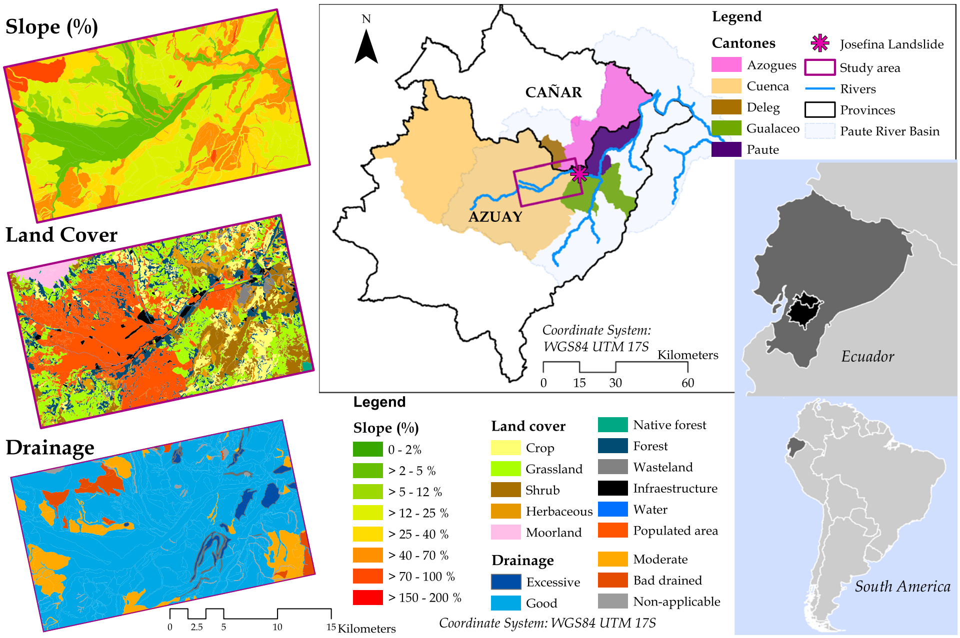
Land use
Insert predominant land use

Picture of land use
Take photo
Load photo

Links to news
Insert links to news (separated by ;)

Fig. 1 Interface of MARLI: citizen form (purple box) and technical form (blue box)

Fig. 2 Description of study area. The slope, land cover and drainage maps were obtained from SIGTIERRAS project



and highlighted the vulnerability of both the infrastructure and the population. Since that event, landslide susceptibility studies and inventories have been carried out in that region, the most relevant being the Prevention-Ecuador-Basin-Paute pilot project (PRECUPA project). This initiative was developed within the framework of international cooperation to support Ecuador in strengthening its capacity to prevent natural disasters (more details in Basabe et al. (1996)). The studies were carried out between 1994 and 1998, recognizing the vulnerability of the Paute Basin to unstable terrain and the need to carry out more studies throughout the basin. In spite of these results, since then no work has been done to update the information generated in this project.

Taking into account this background, the study presented here is developed within the area of greatest susceptibility to geological origin phenomena according to the study carried out by Basabe et al. (1996) within the framework of the PRECUPA project. The study area covers 380 km^2 (purple box in Fig. 2) and affects the cantons of Cuenca, Gualaceo and Paute in the province of Azuay, and the cantons of Azogues and Deleg in the province of Cañar (Fig. 2). This zone is located within the Paute River basin and includes the area affected by the Josefina disaster. The majority of the surface in the study area presents a slope between 25 and 100% (slope map in Fig. 2). On the other hand, the majority coverage in the study area is *populated area* (30%), followed by *grassland* (20%), *forest* (15%), *shrub* (12%) and *crops* (10%) (land cover map in Fig. 2). Finally, in terms of drainage capacity, 80% of the study area has the capacity to easily eliminate water from rainfall, although not quickly. The soils are of medium to fine texture and some horizons can remain saturated for several days, while the water table is found at depths greater than 120 cm (good drainage). In 10% of the surface of the study area, the elimination of water is slow in relation to the supply and the soils have a wide range of textures. The presence of a slow permeability layer, or a high water table (60–90 cm deep) (moderate drainage) (drainage map in Fig. 2).

Analysis of the results

Data collection yields

It is widely known that the main limitations in the elaboration of inventory maps are time and technical/human resources (Guzzetti et al. 2012). In this sense, the use of MARLI showed that it is possible to cover wide extensions of surface effectively, besides providing a standard in the information survey, parametrizing the data, and allowing a good characterization of the landslides. The area surveyed corresponds to a polygon of 380 km^2, which was divided into 36 quadrants of 13.5 km^2 each one (18 North Sector, 18 South Sector). Taking into account the number of landslides, the complexity and accessibility of the sector, an average of one quadrant every two days was established, and an average of 20 landslides per quadrant. Thus, the inventory undertaken using MARLI application shows a total of 668 landslides (considering duplicate records, 710 landslides) within the study area in a period of less than 2 months. It should be highlighted that this process included the planning, surveying and field, and the works in cabinet.

Table 2 compares the performance obtained in this study with other inventories. Based on the ratio of the average number of square kilometers covered per interpreter per month, it can be seen that the MARLI application allows for the management and collection of landslide data in an approximately equal or more efficient manner than most of the studies included in Table 2, which mostly use conventional methods. Taking into account these data, it is observed that the efficiency of the inventories is directly proportional to the extent of the area covered by the inventory, except for the inventory conducted by Olyazadeh et al. (2016). On the other hand, the values of the ratio landslides collected per interpreter per month do not vary as much as the previous ratio, and circumstance that coincides with the one identified by Guzzetti et al. (2012) and that depends, mainly, on the scale, the number of experienced

Table 2 Comparison of yields with studies that included field work

Research	Method	Area	Landslides	Density	Month	Rate		Attributes	Team
		km^2		Lands./km^2		Lands./month	km^2/month		
Cardinali et al. (2000)	PI/FSH	1500	4000	2.67	6	333.3	125	–	2
Guzzetti et al. (2004)	I/FS	500	1024	2.05	2	256	125	–	2
Ardizzone et al. (2007)	PI/FS	90	70	0.8	0.4	175	225	< 10	1
Galli et al. (2008)—1987	PI	8456	5270	0.6	9	292.8	469.8	< 10	2
Galli et al. (2008)—1999	PI	8456	47414	5.6	28	564.5	100.7	< 10	3
Galli et al. (2008)—2002	PI	78.89	2564	32.5	5	259.4	7.89	< 10	2
Mondini et al. (2011)	PI/FS	60	821	13.7	2	82.1	5.9	< 10	5
Fiorucci et al. (2011)	PI/FS	90	457	5.1	2	228.5	45	< 10	1
Olyazadeh et al. (2016)	MA	123	59	0.5	0.07	421.5	878.6	14	2
MARLI	MA	380	668	1.8	2	167	95	25	2

Method, methodology used to create the inventory (FS—field survey; FSH—field survey by helicopter; PI—photo-interpretation; MA—mobile application); Area, extent of the area covered by the inventory (km^2); Landslides, total number of mapped landslides; Density, landslide density (Lands./km^2); Month, time required to prepare the inventory (month); Rate, average number of landslides and square kilometers per technician per month (Lands./month and km^2/month), respectively; Attributes, total number of fields collected during a field trip; Team, total number of technicians

personnel, the adequate technology, the complexity of the terrain and the abundance of the landslides.

Qualitative and quantitative results

As already mentioned, in the study area (≈ 5% of Azuay), 668 landslides were recorded and outlined, representing 3.83% of the surface area of the study area with an average density per square kilometer of 45.8 and with an average size landslide of 2.2 ha. Figure 3 is prepared to show the types of landslides present in the study area. This figure shows, through a mosaic, the different types of slides in horizontal axis and the different levels of slope in vertical axis. Each block is colored in proportion to the presence of water on the surface. Although MARLI contemplates up to ten different types of landslides, only seven types are present in the study area. The area of each block is proportional to the number of landslides.

Most of the identified landslides are of a rotational type and are located in areas which slope varies between 12 and 40% (medium-high slope), where the presence of groundwater is mostly diffuse. The fall type slides have a significant weight in areas which slope is between 40 and 70% and in areas with a slope of less than 5%. As expected in high slopes, the propensity to fall material is strong and even more so if the lithology inherent to the sector corresponds to materials with little cohesion, that is, in such areas, the potential for falling rocks, conglomerates, and soil blocks increases greatly. As for the fall in low slopes, very rare in the area of study, they occur mainly on slopes where anthropogenic actions have occurred, such as roads, or in small cuts, of low height and gentle slopes, where the material has been removed giving rise to the fall in blocks of material.

On the other hand, tipping, flow, or lateral spread landslides are the ones that have less presence in the study area. This fact can be attributed to the lithology in the study area that, although the area is favorable to the occurrence mainly of creeping and rotational type movements, are not so favorable to flow type movements or tipping because of the cohesion of the clays that do not allow the materials to break down easily.

Figure 4 is developed to identify the characteristics of areas that are susceptible to landslide occurrence. For this purpose, the different levels of the lithology[4] and slope are represented in the y and x axes, respectively. Additionally, by means of a color legend, the soil cover present in the delimited zones as landslides is shown and its representativeness (surface in hectares) is reflected by means of

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[4] Lithology legend Fig. 4: 1. Sandy clays, often reddish and with presence of gypsum, and thick tuffaceous sandstones; 2. Clear laminated shales, with gypsum; locally, sandstones and basal conglomerates with levels of clays and siltstones; 3. Silts, clays, sands, gravels and blocks; 4. Heterogeneous mixture of fine materials and rocky angular fragments of very different sizes; 5. Tobaceous sandstones of medium to thick grain, levels of conglomerates and weak layers of clays, silts and shales; 6. Heterogeneous mixture of fine materials and rocky angular fragments, with absence of stratification and internal ordering structures; 7. Limonites, shales and fine-grained conglomerates; 8. Limonites, shales and fine-grained interstratified sandstones, shales with coal seams, coarse-grained and conglomerate sandstones; 9. Coarse and brecciated andesitic conglomerates, with intercalations of sandstones and tuffaceous siltstones, scarcely lithified and consolidated; 10. Silt and clay (predominant in the distal zone) and sand, gravel and blocks (predominant in the apical zone), in variable proportions and with marked changes of lateral and vertical facies; 12. Volcanic agglomerate with white glass matrix (Llacao) and well stratified volcanic-sedimentary sequence with predominance of tuff (Gualaceo); 13. Sands, silts, clays and conglomerates; 14. Silts, clays, sands, gravels and blocks in variable proportions; 15. Tuffs and agglomer-

the size of the points. All these variables were obtained from the thematic layers calculated in the framework of the SIGTIERRAS program.

Based on this figure, a large part of the area affected by landslides is concentrated in areas with slopes between 12 and 40% in populated areas, of pasture, crops or forestry plantations on type 1, 2, 4, 5, 9 and 15 soils (see lithology legend in footnote 4). In areas of a high slope, landslides can occur regardless of land use; however, in less steep terrain, changes in land use can affect the stability of the slope (Hearn and Hart 2019). In this regard, some researches have shown that anthropogenic intervention is the main agent of landslides in urban areas due to excavations in slope areas, water leakage, and the cultivation of certain species (De Brito et al. 2016). Also, the conclusions of the studies developed by Di Martire et al. (2012) or Sepúlveda and Petley (2015), showing that population density has a strong positive correlation with the density of landslides, increasing the possibilities of affecting people.

With respect to changes in land use, in the last few decades, Ecuador has experienced important processes of informality in the land occupation (Muñoz Sotomayor et al. 2018), with two different phenomena. On the one hand, the advance of the agrarian frontier due to population growth and the lack of suitable places for people inhabit, which entails the replacement of natural elements, such as native forests, by crops or pastures. This phenomenon causes erosion on the slopes due to agricultural activity, increasing the possibility of landslides. On the other hand, informal settlements on the outskirts of cities, mainly in areas at risk due to slopes, areas of flooding or instability, and on the banks of rivers and streams (De Brito et al. 2016; Rivera Torres and Serrano Fernández de Córdova 2019). Thus, there are circumstances, identified as critical by Alexander (2012) (location of dense populations in precarious, informal or poor urban settlements), which may lead to an increase in the number of deaths from landslides. All of this highlights the vulnerability of the population of these communities, their infrastructure, and the farm areas.

One of the main factors at the local level for the occurrence of landslides is geology/lithology (Karsli et al. 2009; Sepúlveda and Petley 2015). As discussed in Basabe et al. (1996) and Hungerbühler et al. (2002), in the Paute River basin, the greatest frequency of landslides occurs in areas of sedimentary formations made up of shales, incompetent lake limonite's, expansive clays altered with tuffaceous sandstones, and metamorphic formations made up of fractured phyllites. This information corresponds largely to the data collected in the field. Adding to these lithological factors, the presence of water or high precipitation makes the propensity for landslides greater (Sepúlveda and Petley 2015).

In addition to being conditioned by factors such as soil, slope, or geology, landslides are also affected by climatic phenomena. Like the results shown at the continental level by Sepúlveda and Petley (2015), the main trigger for these phenomena in the study area is

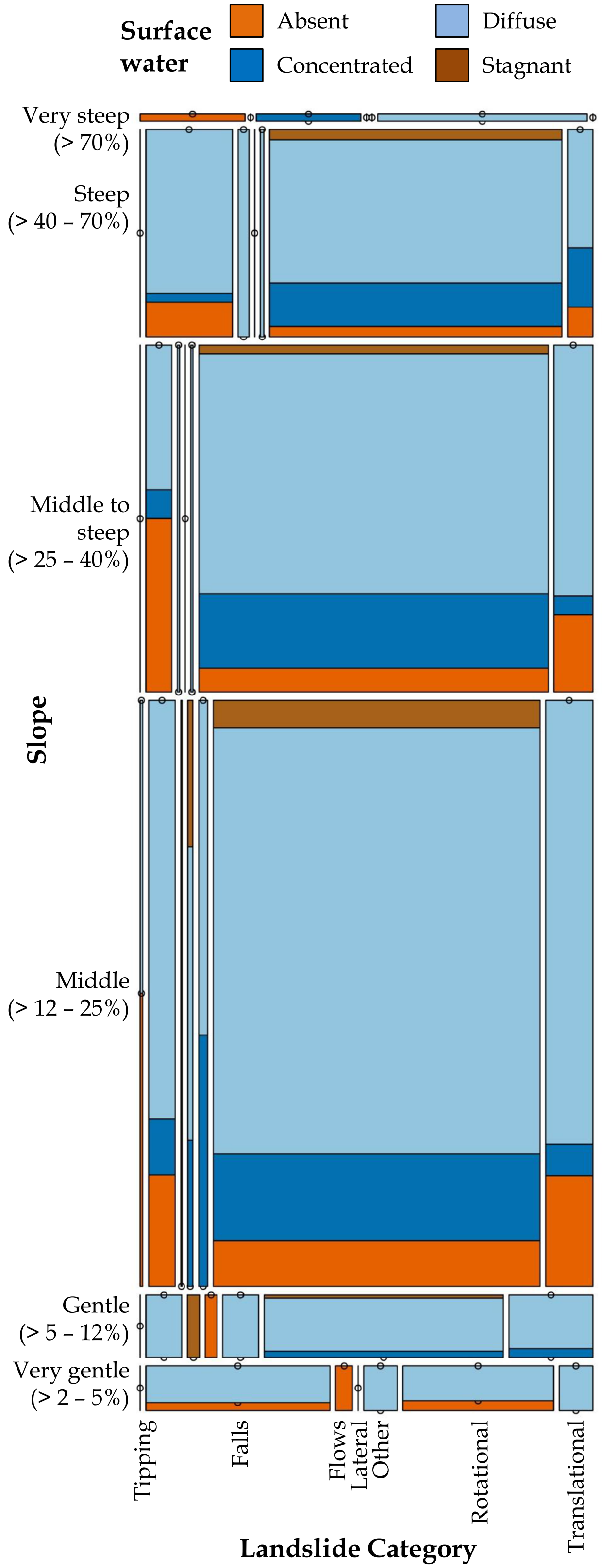
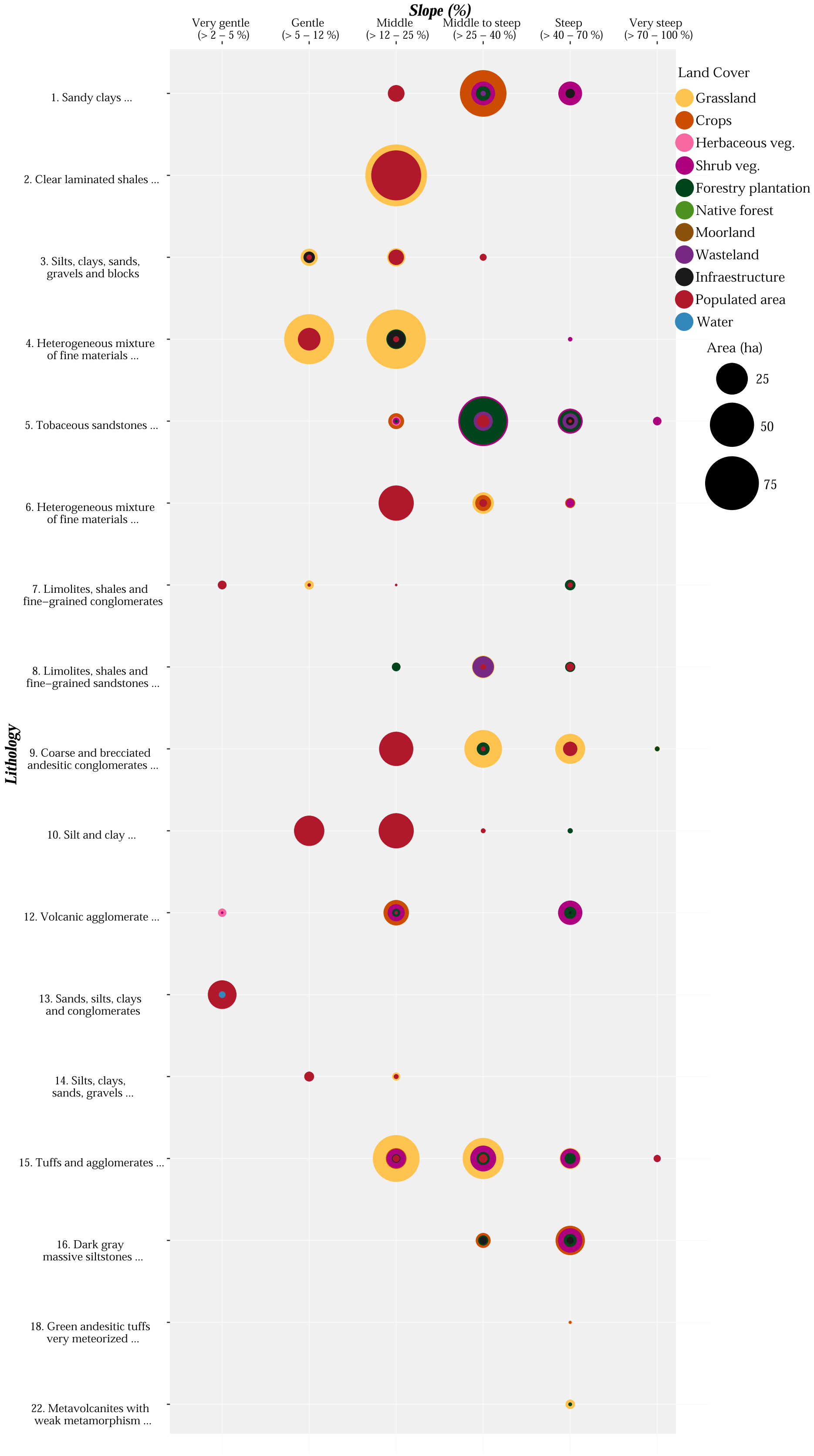


Fig. 3 Slope, surface water and landslide category

Footnote 4 (continued)

ates (dacite, rhyolithic and andesitic) kaolinized, with low percentage of lava; 16. Dark gray massive siltstones and quartz-feldspathic sandstones; limestone, gravel and tuffaceous sandstones; 18. Green andesitic tuffs very meteorized and andesitic to andesite-basaltic lavas; 22. Metavolcanites with weak metamorphism, massive lavas and green phyllites, green schist, quartzite and marbles.

Fig. 4 Where landslides occur in the study area



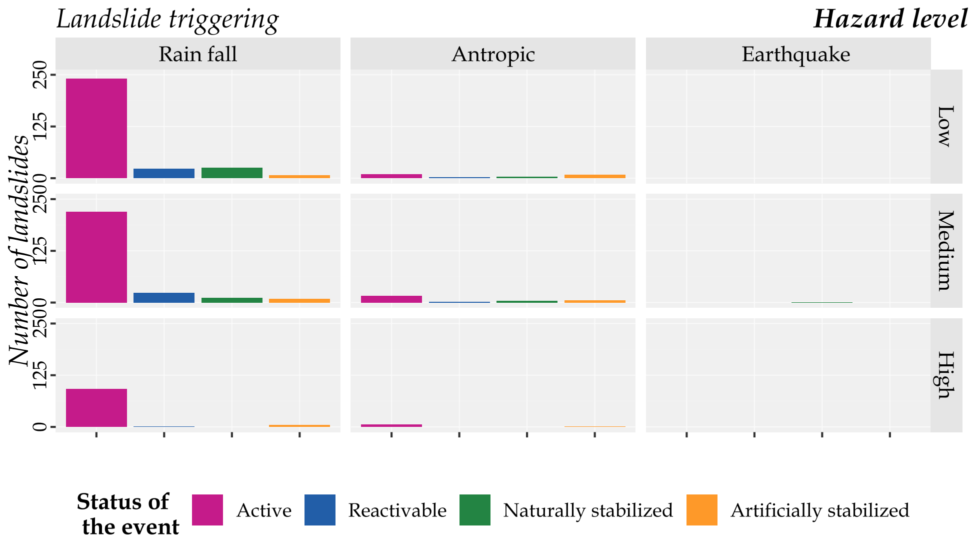


Fig. 5 Landslide triggering, hazard level and status of the event

the precipitation, and to a lesser extent, due to anthropic causes or earthquakes as shown in Fig. 5. Most of the registered landslides are active and present a low-medium level of danger according to the data collected in the field. Although MARLI contemplates up to four states of activity, it is observed that a significant number of landslides are active and present a high level of risk (Fig. 5). This sample of recent activity should be taken into consideration to carry out prevention tasks since changes in climatic conditions (e.g., increasing precipitation rates) can endanger adjacent areas (Jäger et al. 2018). These factors, along with those identified from the analysis in Fig. 4, and in the context of climate change in which we find ourselves, re-emphasize, as did Basabe et al. (1996) more than two decades ago, the need to carry out more studies of this nature in Ecuador.

Among the most commonly used variables to analyze the susceptibility to the occurrence of landslides is the distance to rivers and distance to roads (Hearn and Hart 2019). Figure 6 is created to test how close to roads and rivers the recorded landslides are. This was done by taking into account the courses of the main rivers and the first- and second-order roads. Additionally, populated areas were also considered. Different buffers were applied to each of these vectorial layers, and the percentage of surface affected by landslides that overlap with each layer independently was calculated. From the results of this spatial analysis, it is observed that approximately 25%, 15% and 2% of the surface affected by landslides is located less than 50 m from populated areas, roads, and rivers, respectively. These values amount to 50%, 35% y al 15%, respectively, if the distance is 300 m. These results show that a significant number of landslides threaten populations and infrastructure, exposing communities to material damage and, in the worst case, loss of human life.

Figure 7 shows the web map created from the main data collected in the field and subsequent work (blue, orange, and red polygons in Fig. 7), as well as the landslides recorded in the framework of the PRECUPA project (yellow polygons in Fig. 7) using the functions of the R *leaflet* package (map attached as auxiliary information). OpenStreetMap and a Sentinel-2 color composition were used as base maps. The polygons showing the slides recorded by MARLI are represented according to the risk levels recorded in the field (low, medium, and high). Additionally, by hovering the cursor over these polygons, the category, the trigger, the speed, and, again, the hazard can be consulted. This web map can be explored by clicking in Fig. 7, from "MarliLandslide.html" file (Additional file 1) or by accessing the Spatial Data Infrastructure of University of Azuay (http://gis.uazuay.edu.ec/proyectos/deslizamientos/MarliLandslide.html).

Figure 6 shows that a very small percentage of the surface affected by landslides was close to rivers. From the map in Fig. 7, it can be seen how this low percentage corresponds to the largest and most dangerous landslides (red polygons) and is located in urbanized areas near the course of the Paute River. All of them are located on the southern bank of the Paute River, where the slope and erosion effect is greater so that these active landslides can produce the Paute River dam again, as in the La Josefina landslide (Basabe et al. 1996).

On the other hand, there is also a particularly intense sliding activity, of small volume and mostly of medium or low risk, in the southeast of the study area. These records differ from the landslides recorded at PRECUPA, which are larger and located mainly in the western zone of the study area. This fact can be attributed to the fact that the results of the PRECUPA project were generalized based on existing cartography. However, in the case of MARLI,

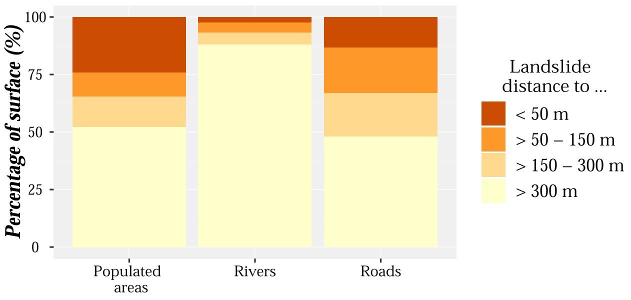


Fig. 6 Landslide distance to populated areas, rivers and roads

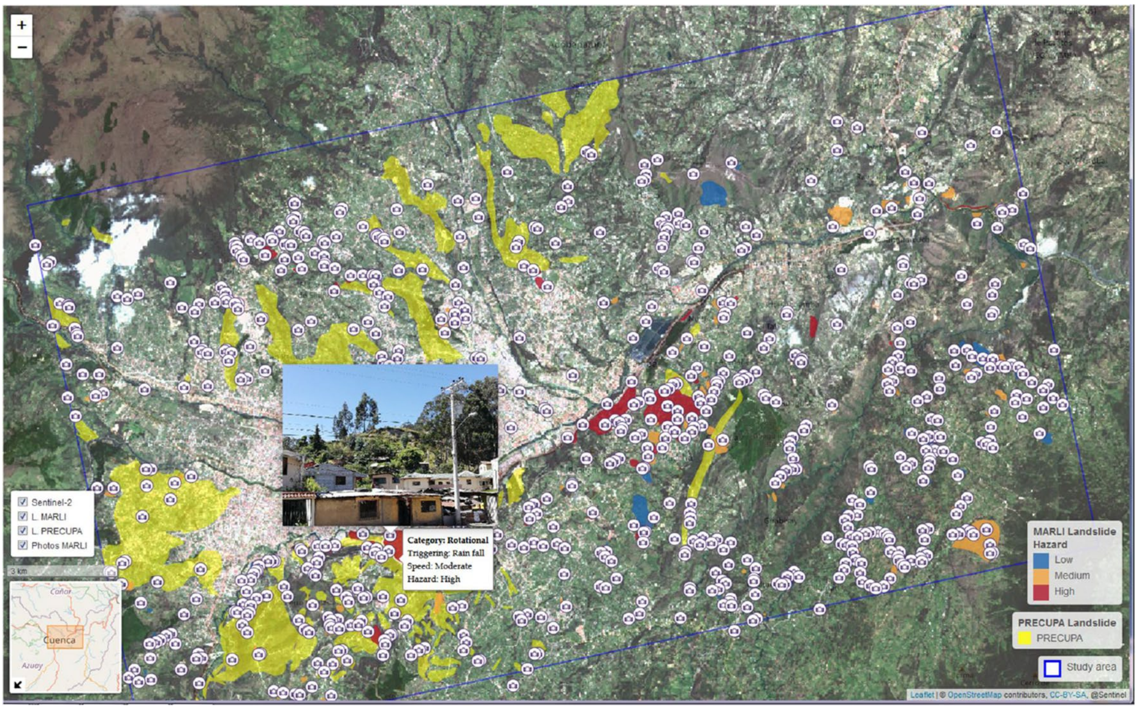


Fig. 7 Web map using Leaflet package and R software (Additional file 1)

the landslides and its in situ evidence were located, in addition to having higher resolution cartography and images. Additionally, another possible explanation can be related to the accessibility factor, which at the time of the PRECUPA project was much more reduced than it is today.

Comparison with existing databases

In this section, a comparison is made at the regional level between the inventory carried out in the framework of the PRECUPA project in 1996 and that obtained in this study. Additional file 1: Table S1 includes the statistics for PRECUPA and MARLI landslide inventory maps for the study area. The number of landslides recorded in PRECUPA (130) is multiplied by 5 in the inventory made from MARLI (668), which causes the density of landslides to increase from 3.6 to 45.8 landslides per km^2. However, in the inventory elaborated from MARLI, the surface occupied by landslides in the study area is three times smaller than that registered in the PRECUPA inventory (3.83% y 9.55%, respectively). This same trend is observed in the studies carried out by Galli et al. (2008) and Lupiano et al. (2019), where the surface occupied by landslides also decreases as the completeness of the inventories increase. The improvement of inventories may be due to the methods used, the increased resolution of the information layers employed, and the technological advances that have occurred in the last two decades.

Afterward, the degree of cartographic matching between the two maps, using the method proposed by Carrara (1993) and later used by Galli et al. (2008), is assessed. For that, the overall error index (Eq. 1) and the degree of matching (M) (Eq. 2) are calculated.

$$E = \frac{(\mathrm{LI}_1 \bigcup \mathrm{LI}_2) - (\mathrm{LI}_1 \bigcap \mathrm{LI}_2)}{(\mathrm{LI}_1 \bigcup \mathrm{LI}_2)} \times 100 \quad (1)$$

$$M = 100 - E \quad (2)$$

where $\mathrm{LI}_1 \bigcup \mathrm{LI}_2$ is the geographical union of the two landslide inventories and $\mathrm{LI}_1 \bigcap \mathrm{LI}_2$ is the geographical intersection of the two inventories. If the two inventories are about equal, the cartographic matching is perfect ($M = 1$) and the error is minimal ($E = 0$).

Table 3 shows the quantitative comparison of the PRECUPA and MARLI inventories. As in the research of Galli et al. (2008), the geographical unions and intersections with due regard to the buffers of 10 m, 50 m y 100 m around the landslides are calculated in order to mitigate the discrepancies associated with the production of the inventories. According to Table 3, if we combine the inventories PRECUPA and MARLI, the area affected by the landslide in the area

Table 3 Quantitative comparison of PRECUPA and MARLI inventories

	Buffer size (m)			
	0	10	50	100
PRECUPA $\bigcup$ MARLI (km^2)	48.33	53.26	64.81	101.71
PRECUPA $\bigcap$ MARLI (km^2)	1.47	1.89	3.32	9.50
E (Mapping error) (%)	97.0	96.5	94.9	90.7
M (Mapping match) (%)	3.0	3.5	5.1	9.3

of study amounts to 12.7%, while in 1996 (PRECUPA) it was 9.55% (Additional file 1: Table S1). These data can be taken as an indicator of the increase of instability in the region, caused, besides by the geological character of the area and the presence of water that saturates and alters the fine granular layers (Basabe et al. 1996), by the increase of the anthropic activity during the last two decades (its population increased 50% since 2001 according to data of the National Institute of Statistics and Censuses[5]).

Taking into account the value of the mapping match index with the null buffer size, it is concluded that both inventories present few similarities as they share only 3% of the surface that presents landslides. This value is close to 10% when a 100 m buffer is applied (Table 3). Recently, Jäger et al. (2018) showed in his study that a low overlap between slides from different inventories may indicate a low propensity for remobilization. Similar values to those obtained in this study were reported by Carrara (1993) (≈20%). These authors considered that these results were due to the fact that the inventories they compared represented different morphologic features. As Galli et al. (2008), we consider that this may be one of the reasons for the discrepancies obtained, but as recently reported by Lupiano et al. (2019), and due to the temporal distance between both inventories, it may also be due to the type and quality of the available data, methods used, mapping scale, type of landslides or their occurrence linked to certain triggers (rain, earthquakes, ...). Another aspect that may be related to this disparity between PRECUPA and MARLI is the "effect" generalization due to the characteristics of the data. In PRECUPA, much larger areas were delimited because the cartography and images available at the time presented a lower resolution and level of detail than those used in MARLI.

Conclusions

Several studies have shown that regions of Central and South America will become more vulnerable to landslides because of the increased frequency of extreme weather events. Despite the history of disastrous landslides in Ecuador, with the consequent loss of human lives, the prevention studies have been insufficient. This research is the first attempt to inventory landslides at the regional level two decades after the Josephine disaster. This study describes the development of MARLI, a simple but efficient open-access platform to report landslide events using ODK system. Its design makes reporting fast, simple and cost-effective with an added benefit, and a specialized knowledge is not required for its use. MARLI provides two types of forms: one open to all citizens (no prior knowledge), group can provide very useful and updated information, and a second form for specialized users. The user interface of MARLI, designed in accordance with the needs and capacities of different users, allows easy input of information into the database.

The results of this research show that the surface affected by landslides has increased during the last two decades. This circumstance may be a consequence of the processes of informality in land occupation that occur in Ecuador, either due to the advance of the agricultural frontier or the existence of informal settlements on the outskirts of cities. Additionally, the analyses carried out revealed a significant number of landslides registered with MARLI threaten populations and infrastructure, exposing the community to personal and material damage. This information can be taken as indicator of increased instability in the region, showing the need to monitor these phenomena in relation to territorial dynamics and factors derived from climate change.

The use of free tools, such as leaflet, R, and QGIS, together with spatial information, such as OpenStreetMap or Sentinel-2 images, made it possible to contextualize the data taken in the field, carry out spatial analysis and share research results in a simple, clear and low-cost way. This information is helpful to land use planners, policy-makers and network operators in their effort to manage landslide hazards. These tools are also crucial to increase the possibilities of research centers and institutions with limited resources to develop tools in order to mitigate the impact of landslides, improve interoperability by democratizing information and bring research results closer to both society and institutions. In addition, the existence of local landslide databases and making them available for the wide public can facilitate the application of landslide susceptibility mapping methods. Achieving this objective relies on the process of creating, maintaining, and updating landslide databases as a well-consolidated practice.

While the results and findings from this study are not sufficient as susceptibility analyses, they should not be ignored. Additionally, they can be used to carry out a comprehensive assessment of future landslides and, in turn, constitute a fundamental input for the formulation of mitigation strategies, appropriate and timely response, as well as the elaboration of reconstruction plans in the face of an increased occurrence of such phenomena.

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Authors' contributions

CS and SB conceived the presented the idea. CS and SB developed the theory and designed the forms for MARLI. CS developed the application. CS and SB performed all computations. CS, SB, DM verified de analytics and resulting data. All authors discussed the results and contributed to the final manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare that they have no competing interests.

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