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Co-producing and communicating landslide knowledge for risk-informed urban development in Quito

Coproducción y comunicación del conocimiento de deslizamientos para el desarrollo urbano en Quito basado en el riesgo

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ABSTRACT: Landslides are a significant problem in Quito, Ecuador. Over time, hundreds of landslides have been recorded, resulting in many fatalities and economic losses. A team of researchers from several universities in Ecuador and the UK conducted a study to analyse the past and present landslide hazard in Quito and then to assess the likely future hazard for different urbanisation and climate change scenarios. Working with professional engineers, government and civil sector organisations, and the wider public, a multidisciplinary approach was adopted to combine geotechnical, geological and historical data, and apply methods ranging from geotechnical testing to citizen science. The researchers built open-access databases and communicated the results of their study through conferences, lectures, community assemblies and a science outreach website. A new geotechnical database was built by collating data on the soils of Quito from published papers, government reports and dissertations. The geotechnical data was analysed for quality and consistency and statistical distributions of geotechnical parameter values and correlations linking more basic soil parameters to complex ones. These efforts supported probabilistic modelling of slope stability for selected study sites. The geotechnical database and user manual were made freely available on a research repository. The approach to knowledge co-production and communication of databases and research results to partners in the Municipality of Quito and to educational centres has been valuable for raising awareness and understanding of landslide problems in Quito. Building such partnerships was found to be a critical part of the process to ensure that research results are available and relevant for making informed decisions about landslide risk management.

KEYWORDS: Landslides, Quito, Communication, Knowledge co-production, Building partnerships

1 INTRODUCTION

Quito, Ecuador, has an active geo-dynamic environment characterised by rainfall-triggered landslides, debris flows, erosion, floods, seismic activity, and volcanic hazards (Municipality of Quito 2015b and Watson et al. 2022). When combined with ongoing urbanisation and land use change, this city region presents an important geohazard and disaster risk case study, and a challenge for scientists, engineers, planners and communities. From 2019 to 2024 a multidisciplinary and multinational team has taken up this challenge in Quito as one of eight city regions engaged in the Tomorrow's Cities (Urban Disaster Risk Hub) project, funded by the United Kingdom Research and Innovation (UKRI) Global Challenges Research Fund (GCRF) (https://tomorrowscities.org/). A stated aim was "to catalyse and support a transition from crisis management to pro-poor, multi-hazard risk-informed urban planning and people-centred decision-making in expanding cities worldwide" (Galasso et al. 2021, p.1). The Tomorrow's Cities project was implemented through collaborations between many universities, governance organisations, communities and disaster risk professionals in the UK and countries in the global south (cf. Pelling et al. 2023). In Quito, the project has involved three local universities: Escuela Politécnica Nacional, FLACSO and Universidad San Francisco de Quito (USFQ); as well as government sector and civil society partners (see Sevilla et al. 2023 for further details).

Conventional disaster risk reduction projects often to start by obtaining geospatial data about past hazards and their causal factors for empirical-statistical or physics-based spatially distributed modelling (van Westen 2013). In the case of quantitative landslide hazard and risk assessments, the core dataset typically includes a landslide inventory, topography, geology, soil properties, land cover and rainfall or seismic triggers (Corominas et al. 2014). For hillside-specific slope stability assessments, engineers require a detailed site investigation including a topographic survey and boreholes for determining ground conditions and taking samples for geotechnical testing (Anderson & Holcombe 2013). However, such data-intensive approaches are hampered where data is scarce, where study areas are extensive (city scale) and where resources for site investigations (community scale) are limited (van Westen et al. 2006 and Maes et al. 2017).

Furthermore, in the case of landslides hazards in rapidly urbanising cities such as Quito, the highly localised interactions between informally constructed communities and slope stability also need to be accounted for (Anderson et al. 2008, Holcombe et al. 2016 and Bozzolan et al. 2020). Such hillside communities are often characterised by vegetation removal, non-engineered slope cuttings and lack of drainage – all of which can reduce slope stability whilst exposing the most socio-economically vulnerable households to new landslide hazards (Froude & Petley 2018 and Ozturk et al. 2022). The cycle of urban landslide risk accumulation is therefore not just a geotechnical engineering issue but one in which the unsafe conditions on urban slopes are driven by socio-economic and policy-related root causes and dynamic pressures (Bull-Kamanga et al. 2003 and Wisner et al. 2003). Even if geotechnical engineers can acquire sufficient data to model urban landslide hazards, on its own this is unlikely to significantly affect development planning and support pro-poor resilient actions in rapidly urbanising cities (Galasso et al. 2021). A companion paper details a methodology to obtain data for slope stability modelling using drone surveys (Zapata et al. 2024a).

In this context, resilient and sustainable urban development requires an interdisciplinary approach in which: scientists, engineers, community residents and policymakers are part of the process by which risk data is coproduced and risk drivers are jointly understood; the capacities of all stakeholders are strengthened for envisaging and codeveloping scenarios that could reduce future risk; and communities are empowered (see Gomez-Zapata et al. 2021, Smith et al. 2022, Sevilla et al. 2023 and Pelling et al. 2024). This approach was central to the vision of Tomorrow's Cities which aims to include disaster risk stakeholders in equitable partnerships, not only as data providers but also as risk-informed decision-makers, to bring about changes in the disaster risk cycle (Galasso et al. 2021, Pelling et al. 2023). The exchange of local knowledge and scientific information is essential part of this process because it enables learning from the past and promotes a culture of risk-informed decision-making (Sevilla et al. 2023).

This paper reports on the flow of landslide risk knowledge and information between stakeholders as part of Quito's Tomorrow's Cities project. It focuses on: (i) the approach to exchanging and combining local knowledge and scientific information that facilitated slope stability modelling and coproduced new understanding of landslides in Quito; and (ii) the communication of this data and knowledge amongst the different actors, and initial signs of its application in risk-informed decision-making. The paper also aims to place the Quito landslide research in the wider Tomorrow's Cities Quito research context.

2 LANDSLIDE HAZARD AND RISK IN QUITO

Mass movements are a persistent concern in Quito, Ecuador, causing significant impacts in terms of loss of life, injuries, and damage to infrastructure, property and livelihoods (Municipality of Quito 2015a, Municipality of Quito 2015b). These events are tied to the geomorphological and geological conditions of the city region. Quito is situated in the central and semi-planar zone of the Quito tectonic basin (Alvarado et al. 2014), bordered to the west by a series of active volcanic complexes: Atacazo-Ninahuilca, Pichincha, Atacazo and Pululahua (Bernard & Andrade 2011). These stratovolcano complexes have steep slopes and feature a series of radially arranged ravines (e.g. Earle 2019). To the east, the basin is bounded by elongated hills associated with anticlinal folds of the Quito fault system (Alvarado et al. 2014). This neo-tectonic environment is prone to endogenous hazard phenomena, such as volcanism and seismicity, and exogenous phenomena, such as mass movements and floods (Municipality of Quito 2015b).

The soils derived from the Cangahua Formation cover most of the surface of the Metropolitan District of Quito (Municipality of Quito 2015a). The Cangahua Formation consists of altered tuffs, paleosoils, lapilli, ash deposits, mudflows and alluvium (Vera & Lopez 1992, Clapperton et al. 1997 and Villagómez Díaz 2003). Its genesis is associated with the late Pleistocene Northern Andes conditions, abundant effusive volcanic materials, glacial and peri-glacial environments, aeolian transport and proximal deposition (Vera & Lopez 1992). The Cangahua has the typical behaviour of a material with high cementation and low permeability (cf. Crespo 1987 and O'Rourke & Crespo 1988). However, it is prone to weathering which significantly decreases its effective cohesion (cf. Crespo 1987 and O'Rourke & Crespo 1988). Therefore, cut slopes excavated in the Cangahua for road or building construction roads may appear stable after initial excavation, but once exposed to weathering their stability will likely be reduced over time (Hen-Jones et al. 2022).

Additionally, the city of Quito is expanding rapidly – between 1986 and 2020 the urban area grew from 160 ± 50 km^2 to 352 ± 47 km^2, expanding from flat areas with average slope angles of 5° to encroach on the surrounding hillsides (Watson et al. 2022). It is estimated that the average slope angle of urban areas will increase to 7°–11° if the city area doubles again in the future, as predicted (Watson et al. 2022, using data from Bonilla-Bedoya et al. 2020). Informal communities are often located on slopes steeper than this average angle, necessitating slope cuttings to create flat locations for road and house construction (cf. Municipality of Quito 2015a). Urban expansion has also been accompanied by the loss of green spaces (Watson et al. 2022), in which the plant cover plays both an ecological and slope stabilisation role (Hen-Jones et al. 2024).

3 LANDSLIDE KNOWLEDGE CO-PRODUCTION AND COMMUNICATION METHODOLOGY

A disaster risk knowledge co-production approach was adopted by the Tomorrow's Cities team in Quito, in which communication played a vital role (Sevilla et al. 2023). The first stage involved the Tomorrow's Cities team and stakeholders collating data and co-producing knowledge of hazard and risk drivers from both conventional scientific sources (such as peer-reviewed papers, maps, laboratory and site reports) and from local knowledge (via citizen science, community meetings, discussion fora, interactive museum exhibitions, and reviews of newspaper reports and social media). Hazard and risk assessments were then undertaken by the Tomorrow's Cities team for discussion with non-academic stakeholders (Sevilla et al. 2023). This second round of communication involved feedback of the compiled knowledge, data, and the preliminary results of any scientific analysis, for discussion and the inclusion of emergent knowledge and strategies for disaster resilience (Sevilla et al. 2023). In the case of urban landslide hazard assessment and risk reduction, similar knowledge co-production approaches have previously been successfully applied to in other cities in South America (Smith et al. 2022) and the Caribbean (Holcombe et al. 2013).

In Quito, the flow of landslide knowledge co-production and communication is summarized in Figure 1. A review of the conventional slope stability data sources, indicated in step 1 of Figure 1, showed that previous city-wide studies by the universities and municipal government yielded good quality digital maps of the topography, geology and soil types, as well as micro-zonation of the seismic landslide hazard for the city region (Municipio de Quito 2015b). However, the information in the public domain regarding the geotechnical characteristics of the soils was not available as a structure database. Instead, individual records were found in a variety of reports, dissertations and academic publications. Records of landslides (as well as other hazard and risk events) were in also available in a variety of formats and media types. Therefore, the first step for the landslide team was to collate and review these data sources for quality and consistency, and to organise the information for inclusion in databases.

Additionally, the wider Tomorrow's Cities team created interactive museum exhibitions, art installations and workshops to collate, communicate and elicit information about past disasters – enabling people to express their memories, experiences, priorities, perceptions, and the cultural knowledge of multi-hazard disaster events including landslides (see also Sevilla et al. 2023).

3.1 *Developing the new morpho-climatic risk events database*

As indicated in step 2a of Figure 1, a new geo-referenced database of hydro-meteorological phenomena such as floods, mudslides, landslides and rockfalls was developed by collating information or data from newspapers and other reports (Zapata et al. 2024b). Information on the locations and impacts of events (fatalities, injuries or significant damage) was also included in the database. In addition to individual reports of events, a significant amount of data came from the recovery and systematisation of documentary archives initiated by Peltre (1989) in the publication: "Quebradas y riesgos naturales en Quito, periodo 1900-1988". This was digitized and updated to include data up to 2020 by the Tomorrow's Cities research team (Zapata et al. 2024b).

3.2 *Developing the new geotechnical database for Quito*

To assess urban slope stability drivers, the Tomorrow's Cities team required information on the geotechnical properties of the dominant soils in Quito – primarily cangahua. An extensive review was conducted of the site investigation and geotechnical laboratory testing data available from the literature (Hen-Jones et al. 2022 and Othman et al. 2023a). Site locations and geotechnical data were recorded in a spreadsheet, with sheets and field names based, in part, on the Association of Geotechnical and Geoenvironmental Engineering Specialists (AGS) data format (AGS 2017) (Othman et al. 2023a). Statistical analysis was then carried out to characterise the variability of key soil parameters and regression analysis was used to develop empirical equations linking more basic soil parameters to more complex ones (see Hen-Jones et al. 2022 and Othman et al. 2023b).

3.3 *Community-based case studies and citizen science*

Several community-scale case studies were selected by the wider Tomorrow's Cities team to represent different risk environments within the city. With respect to slope stability issues, these case study locations varied in terms of soil types (consolidated versus unconsolidated cangahua), urbanisation impacts on the slopes (informal housing versus mining versus natural vegetation), and hydro-climatology (higher rainfall in the south of the city versus north). In these case-study locations there was insufficient detail in the DEM to identify slope characteristics at sub-10m-scales such as slope cuts, surface drainage and land cover.

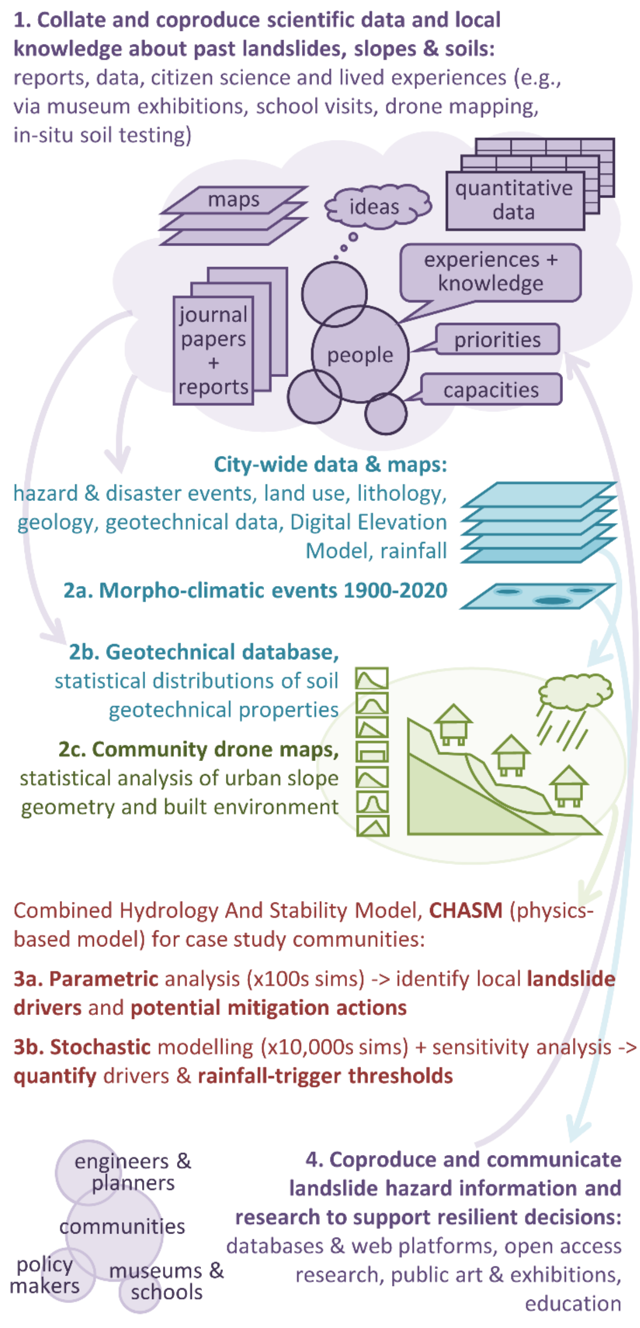

Figure 1. Knowledge co-production and communication of slope stability factors and landslide drivers in Quito to support risk-informed decision-making amongst engineers, policymakers and communities.

Drone mapping was used as one of the community engagement activities. This was also a useful approach during Covid-19 social distancing restrictions in lieu of conventional community walk-throughs and onsite fieldwork (see the companion paper Zapata et al. 2024a for more details). A variety of other knowledge co-production and communication modes were also used including open-air community meetings and citizen science (Zapata et al. 2024a, Santillán & Puga-Cevallos 2023) – soil sampling for geotechnical testing (Zapata et al. 2023a) and field double-ring infiltrometer experiments for measuring soil hydraulic conductivity (Zapata et al. 2023a) and rainfall monitoring. In this way action-learning was encouraged among communities and researchers (for similar approaches see e.g., Holcombe et al. 2013 and Smith et al. 2022).

3.4 *Modelling landslide drivers in case study communities*

The assembled datasets and databases were used by the landslide research team to define the statistical distributions of landslide preparatory and triggering factors – soil geotechnical parameter values, slope cross-section geometries including cut slope heights and angles, estimated groundwater levels, vegetation cover, loading from houses, and rainfall intensities and durations (steps 2b and 2c in Figure 1). These distributions were sampled and used as inputs for the physics-based Combined Hydrology And Stability Model, CHASM, developed at the University of Bristol.

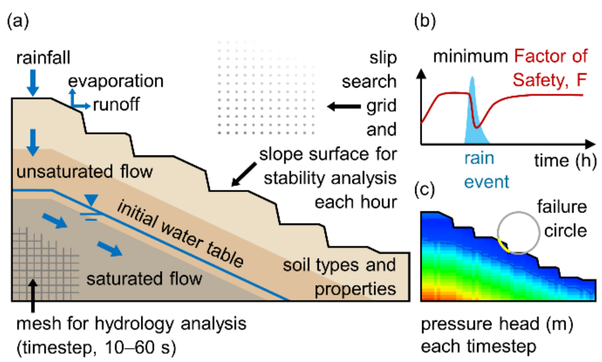

Figure 2. (a) schematic showing the main slope inputs for CHASM and model configuration for simulating dynamic hydrology and slope stability; (b) main CHASM output: minimum slope Factor of Safety (F) over time; (c) selected outputs for a simulation hour: pressure head and location of potential failure surface with minimum F.

CHASM simulates the dynamic hydrology of slope cross-sections over time using a forward explicit finite difference scheme to model rainfall infiltration, unsaturated and saturated seepage (using Richards' Equation – Richards 1931; and Darcy's Law – Darcy 1856) and the resulting negative and positive pore water pressures every 10-60 seconds. At the end of each simulation hour the pore water pressure field is used in a slope factor of safety calculation by implementing Bishop's circular method of slices (Bishop 1955) with an automated slip surface search. Descriptions of the model development, equations, applications, and verification can be found in Anderson & Howes (1985) and Wilkinson et al. (2002) and in the examples cited below. Figure 2 illustrates the configuration of slope cross-sections in CHASM and the main slope stability analysis outputs. Two methods of CHASM analysis were used in Quito, as indicated in Figure 1 by steps 3a and 3b:

- *Parametric modelling:* hundreds of combinations of landslide preparatory and triggering factors were selected from the statistical distributions that were representative of a specific case study community. This allowed well-known slope characteristics to be held constant whilst uncertain or unknown landslide factors were varied. The CHASM simulation results were tabulated in 'look-up tables' to allow landslide drivers (i.e., the most influential factors) to be visualised and uncertainties in the data to be accounted for. Details of the CHASM parametric modelling approach can be found in Holcombe et al. (2016), for example.
- *Stochastic modelling:* Monte Carlo sampling was used to generate tens-of-thousands of CHASM input files which were statistically representative the population of slopes in the chosen case study area. The simulations were carried out using the High Performance Computing facilities at the University of Bristol, UK. Analysis of the outputs was carried out using the Sensitivity Analysis For Everyone (SAFE) toolbox (Pianosi et al. 2015). This approach allowed the effects of different landslide drivers and data uncertainties to be quantified, and rainfall thresholds for triggering landslides to be identified. For details of this methodology see Bozzolan et al. (2020) for example.

3.4 *Strategies for effective dissemination of scientific data*

The translation and dissemination of complex scientific information in language accessible to non-specialist audiences plays a crucial role in Disaster Risk Reduction (DRR) (Musacchio et al. 2016). It enables citizens and decision-makers to better understand the hazards to which they are exposed and the potential risk reduction measures. Scientific data empowers communities to be involved in disaster risk management, from planning to response to recovery (Patterson et al. 2010). Active participation is also essential for building resilient communities. For example, citizen science has been shown to improve the response of communities to early warnings of hazards (Hicks et al. 2019).

The most effective methods for communicating science include using simple and direct language, avoiding the use of technical language, using audiovisual resources such graphics, images and videos, which are powerful tools for communicating complex information interactively and comprehensively (Burns et al. 2003). Two-way communication between scientists and communities is also important because it creates spaces for dialogue and participation (Koningstein & Azadegan 2021).

Given the importance of disaster risk data and knowledge, there is a global open data movement amongst risk reduction researchers, policymakers and professionals to ensure that data and derived scientific outputs such as maps are freely accessible. For example, the Open Data for Resilience Initiative (OpenDRI) supports DRR project teams and has developed principles, guidelines and training in how to collect, share and use data for co-producing disaster risk knowledge (GFDRR 2024).

In Quito, the new co-produced slope and landslide knowledge and research findings were communicated among the Tomorrow's Cities team, academic community and engineering professionals via meetings, online workshops, the new open access databases, and peer-reviewed publications. Communication with non-academic stakeholders and members of the public in Quito was facilitated by interactive museum exhibitions, interactive maps and websites, policy-briefings, murals and installations in public spaces, community meetings, workshops, and school outreach. The following section gives some examples of the wider uptake and impact of the datasets and project activities discussed in this paper.

4 LANDSLIDE KNOWEDGE & COMMUNICATION OUTPUTS

4.1 *Open access databases launched*

4.1.1 *Quito Morpho-climatic events Database 1900-2020*

The new morpho-climatic event database contains over 1300 records of landslides, debris flows, subsidence and floods and their impacts in Quito from 1900 to 2020 (Zapata et al. 2024b). For each event historic and contemporary narratives were translated into qualitative and quantitative data in 25 information fields including the location, type of hazard, date, and the resulting human and material losses (Zapata et al. 2024b). After the digitization and systematisation of data, the primary database was analysed and produced as a project on the USFQ DataHub research centre – a multidisciplinary collaborative space in which researchers, professors and students from the Universidad San Francisco de Quito create and publish databases on topics of national development interest. The database is available as under a Creative Commons License from Zapata et al. (2024b). Figure 3 shows the full dataset with respect to the urban extent of Quito. Database users can create their own maps under the terms of the licence. Finally, the morpho-climatic event database was also incorporated into a new interactive website which was co-created with middle-school students in Quito as a tool for learning about the physics of geological and hydrometeorological hazards and risk management measures to reduce their impacts – see section 4.2.2.

4.1.2 *Quito Geotechnical Database v1.1*

Geotechnical data for a total of 299 locations in the Quito city region were recorded in the new geotechnical database. For each site the locations, sample depths, ground conditions and multiple geotechnical parameters were included. The database was made available free of charge for download from the research data repository at the University of Bristol (Othman et al. 2023a). To facilitate the use of this database, the open data repository also includes a user manual which provides information on the data sources and the collation, formatting and field naming methodologies used (Othman et al. 2023a). Figure 4 illustrates some of the key features in the structure and usage of the database.

During the initial database development by Hen-Jones et al. (2022) probability density functions were derived for geotechnical parameters of interest for slope stability analysis including total and effective friction angle and cohesion (distinguished according to the type of soil strength test undertaken), particle size distributions, water content, unit weights, void ratio, Atterberg limits and plasticity index. The statistical analysis also indicated a difference in the parameter ranges in north Quito versus south Quito. Negative linear relationships were derived between effective friction angle and void ratio, and between effective friction angle water content (Hen-Jones et al. 2022). Othman et al. (2023a) formatted the database and added SPT and Vs_{30} data and data for additional sites and carried out further statistical analysis of the parameter distributions, correlations, and transformation functions.

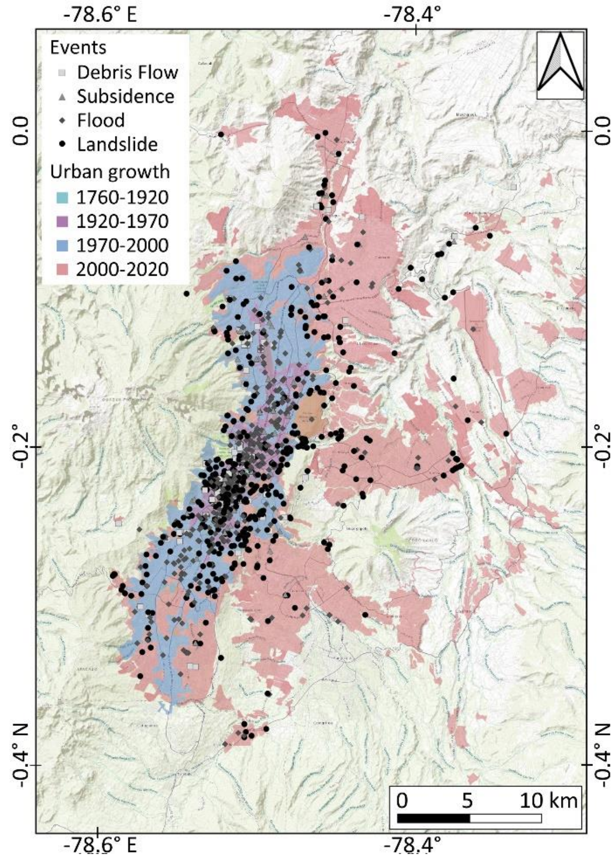

Figure 3. Morpho-climatic events in Quito 1900-2020 (Zapata et al. 2024b) plotted in relation to topography (Esri, 2024) and urban extent (data to 2015 from Gobierno Abierto, Secretaría General de Planificación https://gobiernoabierto.quito.gob.ec/smi/, last accessed 22 May 2024; with additional data from Zapata et al. 2024b)

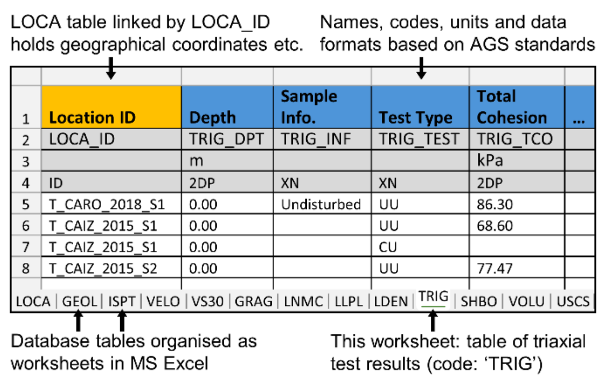

Figure 4. Schematic showing structure and usage of the Quito Geotechnical Database (Othman et al. 2023a) when accessed as an Microsoft Excel spreadsheet.

4.2 *New partnerships to co-produce and share risk knowledge*

4.2.1 *Citizen science and landslide assessment in communities*

As a result of community engagement and citizen science in the case study locations, drone surveys provided topographic information at the scale of 10cm allowing measurement slope cross-sections, including cut slope dimensions, and classification of land cover (Zapata et al. 2024a). Residents were also engaged in measuring soil hydraulic conductivity in the field (Zapata et al. 2023a). Data from these in-situ measurements and the new geotechnical database were used to configure parametric CHASM analysis of slopes in a typical informal community in south Quito. This indicated that reductions in effective cohesion (for example, as a result of weathering) were a leading driver of slope instability, and that this effect was particularly noticeable for slopes with high saturated hydraulic conductivities and a resultant sensitivity to rainfall (Zapata et al. 2023b). Further parametric analysis by Zapata et al. (2024a) indicated the how steep cut slope angles could lead to localised landslides. Stochastic CHASM modelling and sensitivity analysis carried out for a typical informal community in north Quito also indicated (and quantified) the dominant influence of modelled cohesion and saturated hydraulic conductivity, along with natural and cut slope angles, water table and rainfall duration (Hen-Jones et al. 2024).

4.2.2 *Multimedia educational resources for school students*

Multimedia education offers a combination of text, audio, images, video and animations that significantly improves communication quality and the user's understanding and retention. For this reason, the Tomorrow's Cities team developed the ‘Reduce Risks in Quito’ digital platform (reducirriesgosenquito.com) to disseminate knowledge of Disaster Risk Reduction (DRR) initially for a young secondary school audience (Sevilla et al. 2023). However, a more diverse audience was included during the creation process to include the general public. The development process of this website was co-produced by a multidisciplinary creative team of audiovisual artists, programmers, historians, and physical science researchers, among others. A group of secondary school students played a vital role as a pilot group who collaborated in several content feedback workshops – surveys indicated that more than half of them subsequently identified measures to reduce risk through workshops using this ‘Reduce Risks in Quito’ website (Sevilla et al. 2023).

4.2.3 *Ecuadorian College of Architects and disaster risk data*

The philosophy behind the Tomorrow's Cities project is to link actors related to disaster risk management in informed decision-making for risk reduction (Galasso et al. 2021). In this way, during the different stages of the Tomorrow's Cities Project in Quito, public entities, communities, and the civil sector of the population were invited to collaborate in research and knowledge dissemination activities. The College of Architects of Ecuador currently includes the data of the Morpho-climatic Database of Quito 1900-2020 in its urban information geoportal, https://ciuq.ec; thus showing a wider use of this valuable resource.

4.3 *Mural in memory of 2022 La Gasca disaster casualties*

In January 2022, a debris flow occurred in El Tejado ravine in La Gasca sector of Quito, leaving 28 dead and 52 injured (Secretaría Nacional de Gestión de Riesgos y Emergencias, 2022). In response to this event, the municipality of Quito allocated around 2 million dollars for post-event recovery tasks (Sanchez 2023).

Despite the inevitable fading of public attention, the city of Quito and its resilient citizens have taken significant strides to preserve the memory and lessons of this disaster. A project by the Urban Citizen Laboratory of Resilience is one such example of this proactive approach. This initiative aims to create a platform for the Commune of Santa Clara de Milán and La Gasca residents to fortify their social and community networks see: labciulacomuna.com, La Chaki Urbana (n.d.)). One of the outcomes was the collaborative design and construction of a memorial mural for La Gasca 2022 disaster (Figure 5). The mural features 28 ornamental plants in memory of the victims, and informative diagrams that help visitors understand the risk cycle including a timeline of the debris flows and floods that have occurred in the Quebrada El Tejado using information from the new morpho-climatic disaster events database for Quito 1900-2020 (Zapata et al. 2024b) (see: labciulacomuna.com, La Chaki Urbana (n.d.)).

Figure 5. Mural in memory of casualties in the Gasca disaster, January 2022. Part of the mural focuses on the historical memory of the debris flows and floods that have occurred in the area, with information extracted from the database of morpho-climatic events in Quito 1900-2020. (Photos: C. Zapata).

5 SUMMARY AND CONCLUSIONS

Landslides have significantly affected Quito over its history and are likely to increase as the city expands onto steeper slopes. Scientists, engineers, community residents and policymakers in the city face several challenges in tackling landslides as well as flood, seismic and volcanic hazards and risks. These include dynamic interactions between the natural and built environments; socio-economic drivers of disaster risk; and limited data and resources. In this context the Tomorrow's Cities team in Quito adopted a multidisciplinary approach that emphasized citizen science and involved the active participation of local government and public institutions, academia, non-governmental organisations, and communities. This was facilitated by an engagement and communication strategy that aimed to enable all actors to learn from the past and develop a culture of risk informed decision-making (Sevilla et al. 2023).

With respect to landslide risks knowledge in Quito – the focus of this paper – the initial outputs from this project were new datasets and maps at city-wide and community scales – the Morpho-climatic disaster events database 1900-2020, the Quito Geotechnical Database, drone maps of hillside communities (past landslides, natural and cut slope angles, building types, ground cover and vegetation etc.), and soil hydraulic conductivity measurements. These datasets facilitated a subsequent set of activities and outputs – physics-based slope stability modelling (parametric and stochastic) to identify natural and anthropogenic landslide drivers and potential mitigation measures in the case study communities; and the development of interactive maps of urbanisation and past landslides (and other disaster events) for the whole of Quito.

Practical examples of the impact and outcomes of this risk knowledge co-production and communication approach in Quito can be evidenced from the application of the two databases, their adoption by project partners, and feedback from users. The new Quito geotechnical database and the morpho-climatic events database have provided sources of technical information related to landslides and landslide hazard assessment for geotechnical engineers, scientists and planners. These databases have also been applied in the dissemination of knowledge for landslide risk management amongst public and civil sector users and the wider public. The source data for the morpho-climatic event database is freely available for use by anyone on the San Francisco de Quito data-hub; while a user-friendly web interface allows non-experts to display the data on a map for chosen timeframes. The interactive map is enhanced with narratives from historic reports and co-produced by participants in museum exhibitions and workshops.

The co-production and communication of landslide knowledge has been further extended to include middle school and secondary school children via the "Reducing Risks in Quito" interactive web platform described in section 4.2.2, which incorporates the morpho-climatic event database. The impact was evidenced by real testimonies from their users that these web platforms have raised their awareness about the territory where they live and personal actions they can take to reduce the future effects of these events (Sevilla et al. 2023). The morpho-climatic event information has also been used by the College of Architects of Ecuador in their planning portal (see section 4.2.3) and in a mural created by a citizen-led initiative in an area directly affected by mudflows where significant economic and human losses have been recorded in the past. The recovery of collective memory is a key part of the strategy for preventing future disasters in Quito (see section 4.3). The examples in this paper, together with those presented by the wider Tomorrow's cities team in Quito (Sevilla et al. 2023), show some initial evidence of how the co-production and communication of knowledge relating to landslides and disasters in general can potentially support a risk-informed culture of urban development in Quito.

6 ACKNOWLEDGEMENTS

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7 DATA AVAILABILITY

The work reported in this paper has not generated any new experimental data. Links to the open access databases, user manuals and online interfaces are contained within the main text and reference list.

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