Assessing Landslide Hazard in the High City of Antananarivo, Madagascar (UNESCO Tentative Site)

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Abstract

Built on the hilltop of a granite ridge rising above the Ikopa River valley (the Analamanga Hill), the High City of Antananarivo (Madagascar) is renowned for its baroque-style palaces the Rova royal complex and gothic cathedrals dating back to the nineteenth Century, and therefore is part of the UNESCO Tentative List. Due to the frequent cyclonic heavy cyclonic rain, geological and geomorphological conditions, and a general lack of urban planning the study area is particularly prone to landslides (as shown by events of the winter of 2015, 2018 and 2019). As a first step towards understanding quantitative landslide risk, the geological, geomorphological, geotechnical features, as well as landslide phenomena were defined in an integrated landslide hazard assessment. Results show that the main factors affecting landslides are slope, lithology, creek-gully erosion and anthropogenic activities, while most of the landslide events are clearly triggered by heavy rainfall events. Thematic maps produced by this study are fundamental land-use management tools to be applied as a first step towards a geo-hydrological risk reduction strategy by the institutions and actors involved in the protection and conservation of the High City.

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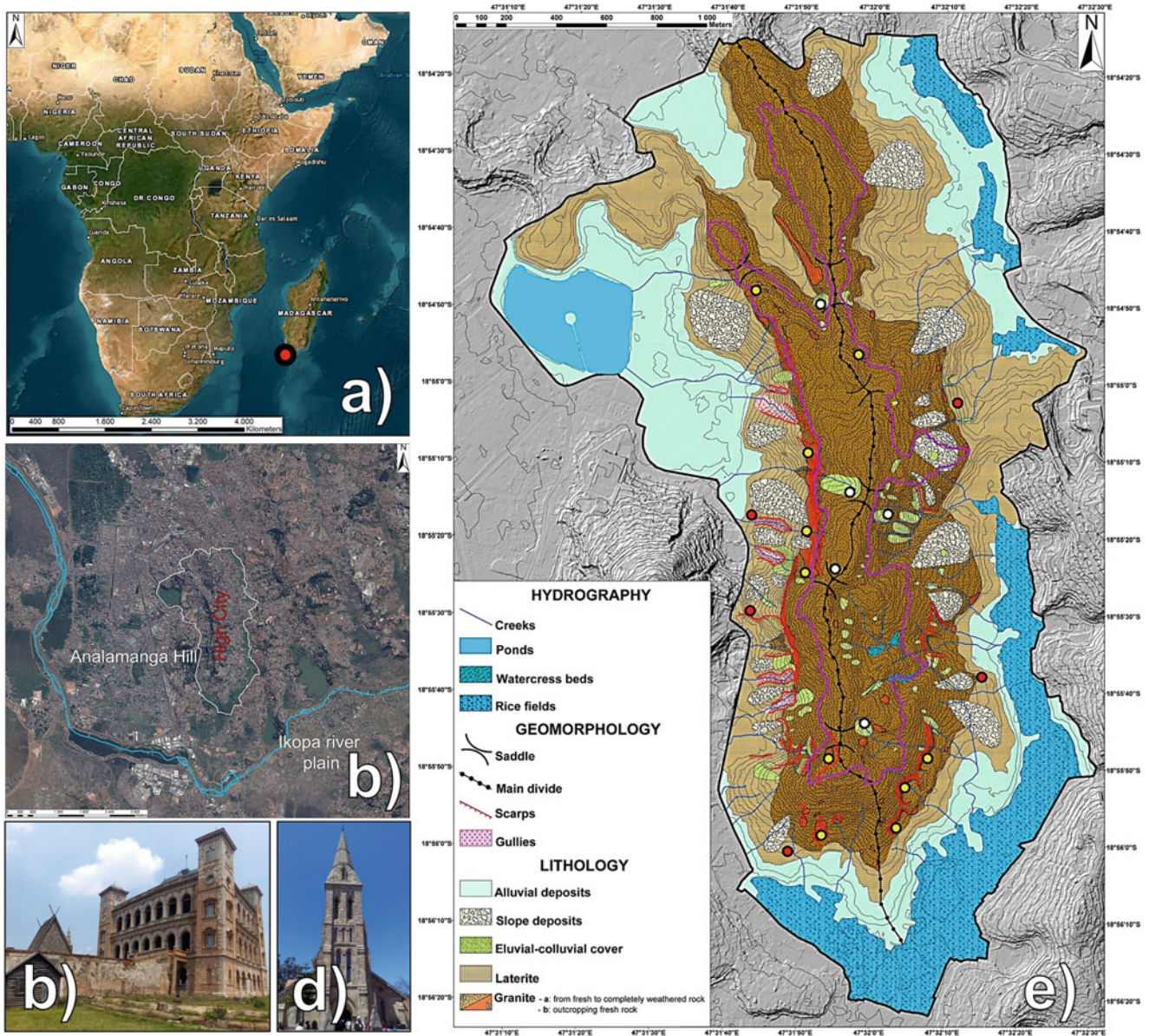
1 Introduction

The risk of natural disasters is often much higher in developing countries, such as Madagascar, where phenomena such as landslides, erosion and floods can lead to catastrophic consequences (Andriamamonjisoa and Hubert-Ferrari 2019). The reason for this lies in the relation between the geographical/climatic setting and the peculiar geological–geomorphological characteristics: heavy rainfall (three to four cyclones affecting the country every year) and a thick lateritic soil cover, resulting from a deep chemical weathering of the crystalline bedrock (Cox et al. 2010). Assessing landslide hazard in Madagascar is both a challenge because of the lack of data and local landslide-knowledge and a fundamental task to provide local authorities and stakeholders with important tools for risk management, building community resilience, protection of the cultural heritage assets, and for increasing the risk perception (especially amongst the poor and less educated citizen, who are the most exposed to landslides). Since 2017, the UNESCO Chair on Prevention and Sustainable Management of Geo-Hydrological Hazards of the University of Florence on behalf of Paris PRX Madagascar, RC-Heritage, and the municipality of Antananarivo, has been carrying out landslide risk research with the aim of enlisting the High City of Antananarivo into the UNESCO World Heritage (ICL 2022). The objective of this work is to describe the research activities to determine the landslide hazard for the Analamanga hill (Fig. 1): to understand the triggering factors and to investigate the impacts on both the historical buildings and the houses of the poorer neighborhoods, contributing towards a quantitative risk analysis. During the field surveys, capacity building was also carried out with local MSc students in geology and engineering from the Polytechnic of Antananarivo. This

Fig. 1 Geographical location of the study area at a continental (**a**) and local scale (**b**) (modified after Ciampalini et al. 2019). Examples of the High City cultural heritage: the Rova (**c**) and Ambohipotsy Curch (**d**).

Geological setting of the Analamanga Hill: red dots highlight the soil samples while yellow dots locate the rock samples (**e**) (modified after Frodella et al. 2021a, b)

study represents an important contribution that improves the knowledge on landslide processes in an area with limited landslide data such as Madagascar and can be reproduced in cultural heritage sites characterized by similar geomorphological and urban scenarios.

2 Materials and Methods

As a first step, a multitemporal landslide inventory was compiled involving: (i) geological/geomorphological field surveys (Frodella et al. 2021a); (ii) geotechnical laboratory analyses on collected soil and rock samples (Frodella et al.

2022); (iii) interpretation of remote sensing data, including very high resolution (VHR) multispectral Pleiades images, and two VHR DTMs (Ciampalini et al. 2019); (iv) homogenization in a GIS environment and interpretation to obtain a landslide inventory (Ciampalini et al. 2019); (v) interviews with the local population (Frodella et al. 2022). A rockmass 3D landslide kinematic global analysis (Frodella et al. 2021b) was performed on the rock cliffs to identify the areas more prone to instability. The data obtained were used as input for the landslide hazard assessment (Fell et al. 2008; Reichenbach et al. 2018). Being quite complex, and depending on the geology, erosional features and slope, a shallow landslide susceptibility with the Random Forest

Model (Breiman 2001; Catani et al. 2013) was performed for shallow phenomena (roto-translational slides involving the lateritic soil or the soil cover). For earth-debris flows acting within the large gullies (developed within the lateritic soils on the western footslope) runout simulations were carried out using the GPP code (Wichmann 2017). The trajectories of rockfall phenomena, occurring along the steep granite rock slopes on the top of the western slope and the hill southeastern sector, were modeled using the software ISGeomassi (CDM 2019). Finally, global rainfall data from 2015 to 2019 (Climate Engine 2021) and the available landslide temporal occurrence were analysed to identify the rainfall condition associated with the landslide triggering (Abraham et al. 2021).

3 Results

3.1 Multitemporal Landslide Inventory

A multitemporal landslide inventory map (LIM) spanning from 2015 to 2020 (Fig. 2) was compiled in a GIS environment using the outcomes of field surveys, satellite image and DTM interpretation. In particular, two inventories were combined: (i) 78 shapefile points and polygons involving shallow landslide events during the winter 2015 (BNGRC 2015; Ciampalini et al. 2019) and rockfall sources during events in the winters of 2018 and 2019 (BNGRC 2019); (ii) 35 point-type shapefile of rockfalls/slides and debris flow sources mapped in 2020 by integrating field surveys, GPS-RTK, and interviews with local population (Frodella et al. 2022). Four main groups of instability phenomena (Cruden and Varnes 1996) were identified (Frodella et al. 2021a; Fig. 2): (1) unchanneled shallow earth-debris rotational/translational slides (the most diffused phenomena); (2) channeled earth-debris rotational/translational slides; (3) rock falls and slides (planar and wedge); (4) complex rotational/translational slides.

3.2 Shallow Landslide Susceptibility

Once the susceptibility model was successfully trained and tested (AUC = 0.9), it was applied to the whole study area. According to the results, the most important parameters to identify landslide susceptible areas were the NDVI, slope aspect and curvature (both planar and profile curvature), while the less important were the flow accumulation and, as expected, the control parameter made of random values.

The final output is a raster with a 2 × 2 m cell size, where each pixel has a percentage value expressing the shallow landslide spatial probability of occurrence (Fig. 3). The map shows that most of the Analamanga Hill is affected by moderate to very high landslide susceptibility. These shallow landslide-prone areas are located along the Middle Town quarters, particularly at the foot of the central sector of the western hillslope (from north to south: Mahamasina, Ankadilalana, Tzimbazaza quarters; Fig. 3).

Here, shallow debris rotational/translational slides involve the eluvial-colluvial and the lateritic deposits, while linear creek erosion of the soft lateritic soils creates large gullies, which are rapidly expanding. Retreating scarps damage the road pavement, while diffuse slope instabilities occur at the headcut of their apex. The eastern slope is less prone to shallow landslides, except for the middle-southern sector, especially in two creek basins: the first is located east of the Rova in the Manjakamiadana quarter, while the second is located east of the Ambohipotsy quarter (Fig. 3). The north hill sector shows a general slope stability due to the widespread urban cover and the lower slope angles. An exception is the area around the tunnel, in the Ambohijatovo quarter. The southern sector shows some potentially unstable areas at the top of the abandoned quarried slope cuts in the Anjahana quarter.

3.3 Earth-Debris Flow Assessment

Following intense rainfall events, shallow earth-debris rotational/translational slides developing from the gully slopes and head-cut apexes can evolve into earth-debris flows that are channel within the hydrographic network (Frodella et al. 2022). These phenomena are more likely to occur in the gullies of the central and southern hill sector, for example the Mahamasina, Ankadilalana and Tzimbazaza quarters (Fig. 4). The earth-debris flow impact probability map shows how these phenomena involve the lateritic soils and anthropogenic waste deposits (since gullies are often used as dumps) that enhances the gully head-cut erosion and the scarp retreat (Fig. 4).

3.4 Preliminary Landslide Frequency Assessment

A preliminary landslide frequency analysis was performed by comparing the landslide frequency obtained by the surveys with the local population and web news, together with rainfall data from 2015 to 2020 (Fig. 5a). The comparison shows clearly that the main landslide events occur after major cyclones, during periods of intense precipitations. In addition, the total rainfall associated with each landslide over different time intervals was analyzed. The total rainfall associated with landslides increases constantly from days 1 to 7, while the rainfall increase from 15 to 30 days is lower than the one from 7 to 15 days, even if it is referred

Fig. 2 LIM of the Analamanga Hill (modified after Frodella et al. 2022)
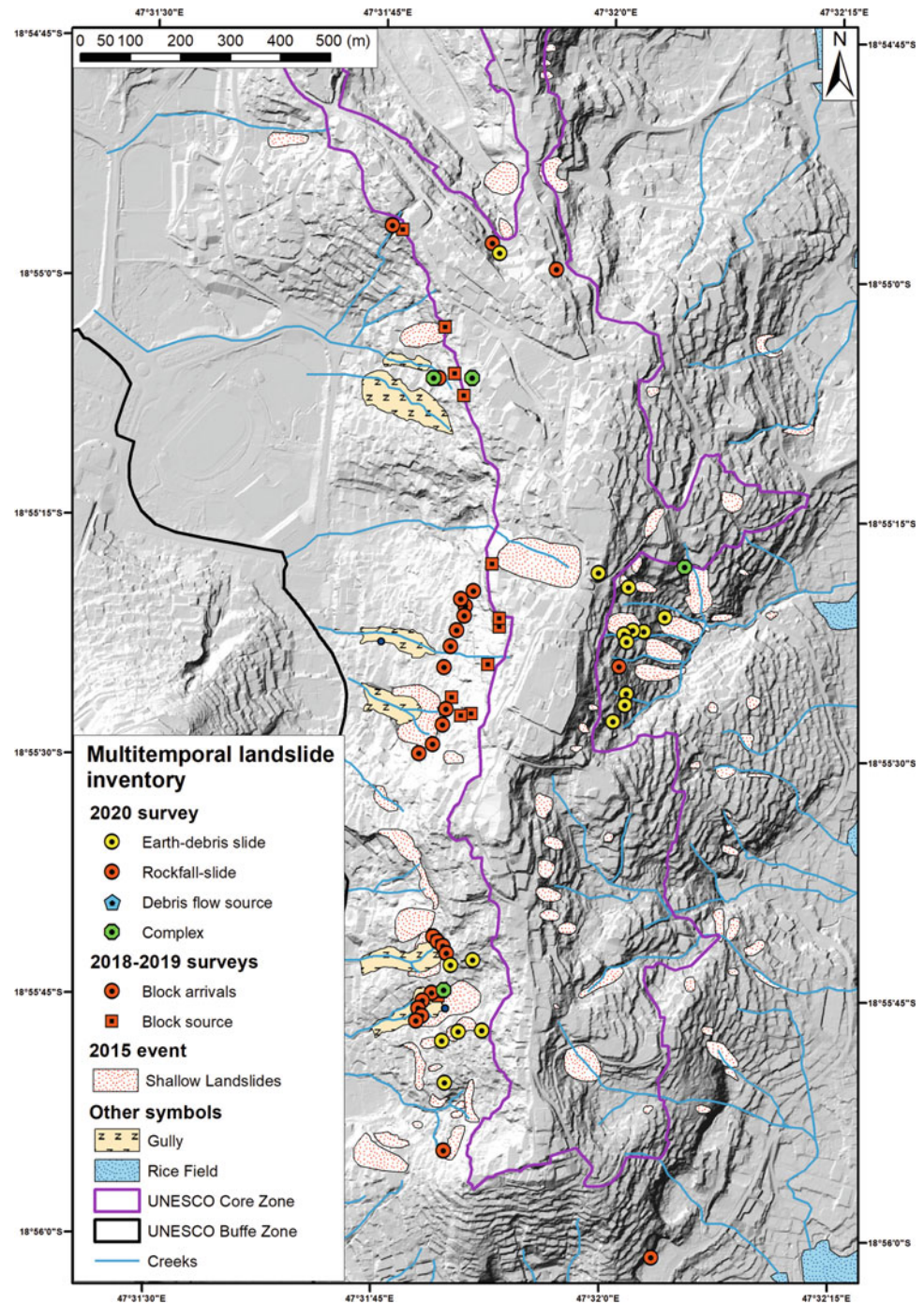

to a longer time interval (Frodella et al. 2022). This suggests that longer rain events have a lesser influence on triggering landslides. A further analysis of mean rainfall intensity helps to highlight that: (i) the intensity referred to 1-day duration shows quite spread values, while the distribution of intensities for longer durations is more constant; (ii) the rainfall intensity of events with 15- or 30-days duration is sensibly lower than that of shorter events (Frodella et al. 2022). On this basis it is possible to hypothesize that the rain events ranging from 2 to 7 days are probably most to be responsible

for the triggering of landslides. The definition of I-D (intensity duration) rainfall thresholds is usually based on hourly rainfall data, but Abraham et al. (2021) explored the possibility of using daily data.

To identify the threshold, the intensity (mm/d) of events with a duration between 2 and 7 days has been considered, based on the outcomes of the previous analyses. For each landslide event, the maximum intensity was extracted, along with its duration and the I-D couples have been plotted as shown in Fig. 5b. Notice in this figure, that some events

Fig. 3 Shallow landslide susceptibility map of the Analamanga Hill (modified after Frodella et al. 2022)
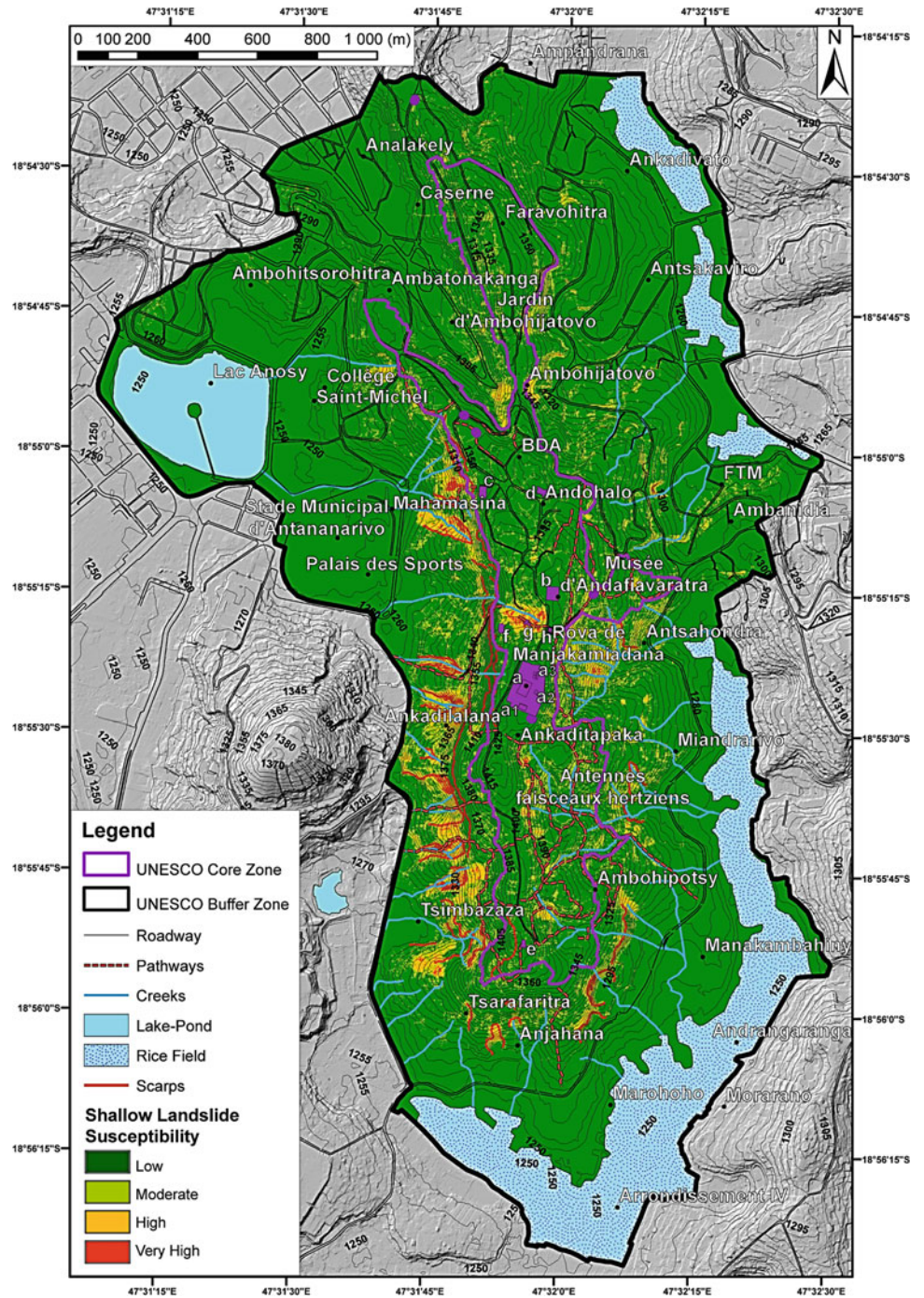
follow a common trend, while other events with a lower intensity, don't show any trend. Due to the paucity of data, a robust statistical analysis was not possible, so the threshold was defined as the lower bound of the most trending events and it is characterized by the equation:

$$I = 121.06D^{-0.3}$$

3.5 Rockmass Instability and Rock Fall Analysis

The 3D kinematic analysis was performed in correspondence of the largest rock outcrops in the study area: the quarry front in the hill south-eastern sector (Manakambahiny-Ankerakely quarter; "Sector 1"), and the rock cliffs along the western slope (from north to south: Mahamasina, Tsimialonjafy, Ambanin'Ampamarinana, Ankadilalana and Tzimbazaza
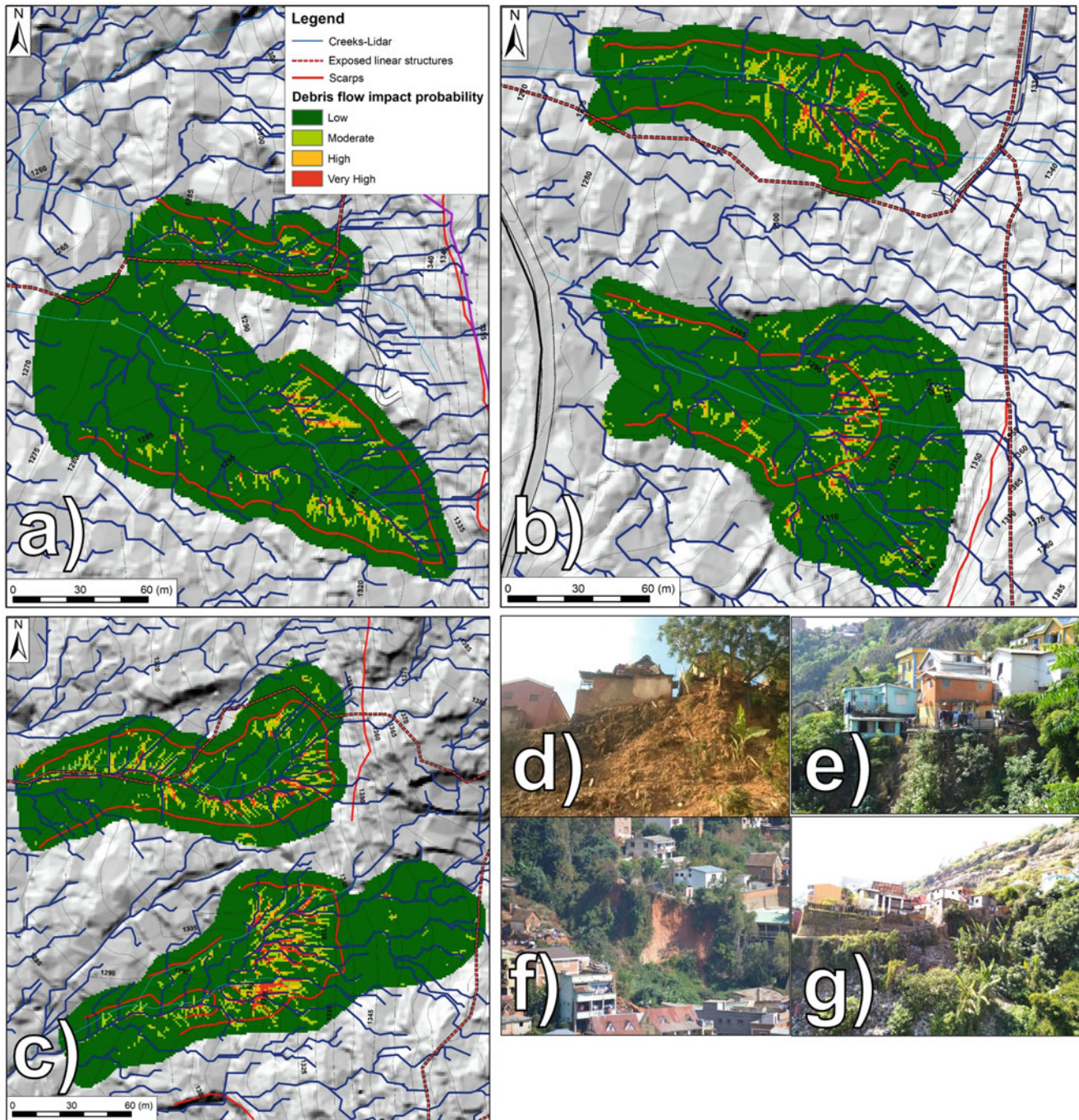
Fig. 4 Debris flow impact assessment map: gullies of Tsimialonjafy (**a**), Ambanin'Ampamarinana-Ankadilalana (**b**) and Tsimbazaza (**c**) quarters. Earth-debris rotational/translational slides involving lateritic soils and waste-dump deposits causing scarp retreat (**a**–**d**) (**f**), which, pose at high risk the housings (modified after Frodella et al. 2022)

quarters; "Sector 2") (Fig. 6). The maps in Fig. 6a, b show the 3D spatial probability of occurrence (expressed in GKI %; Frodella et al. 2021a, b) for the combined abovementioned instability mechanisms, with colors ranging from green representing stable areas to yellow (low GKI) and red (GKI 26%). The 2D kinematic analysis shows that topples are the most relevant detected instability mechanisms in the field are

(Fig. 6c, d), followed by wedge (Fig. 6e, f) and plane failures (Fig. 6g–h). Quarry fronts in the central-southern area are the most unstable sectors, while in western slope rock cliffs the most unstable sectors are homogeneously distributed (Fig. 5). These unstable areas (selected considering a value of GKI over the 95th percentile of its distribution curve) are used as sources for the rock fall trajectories together with the source
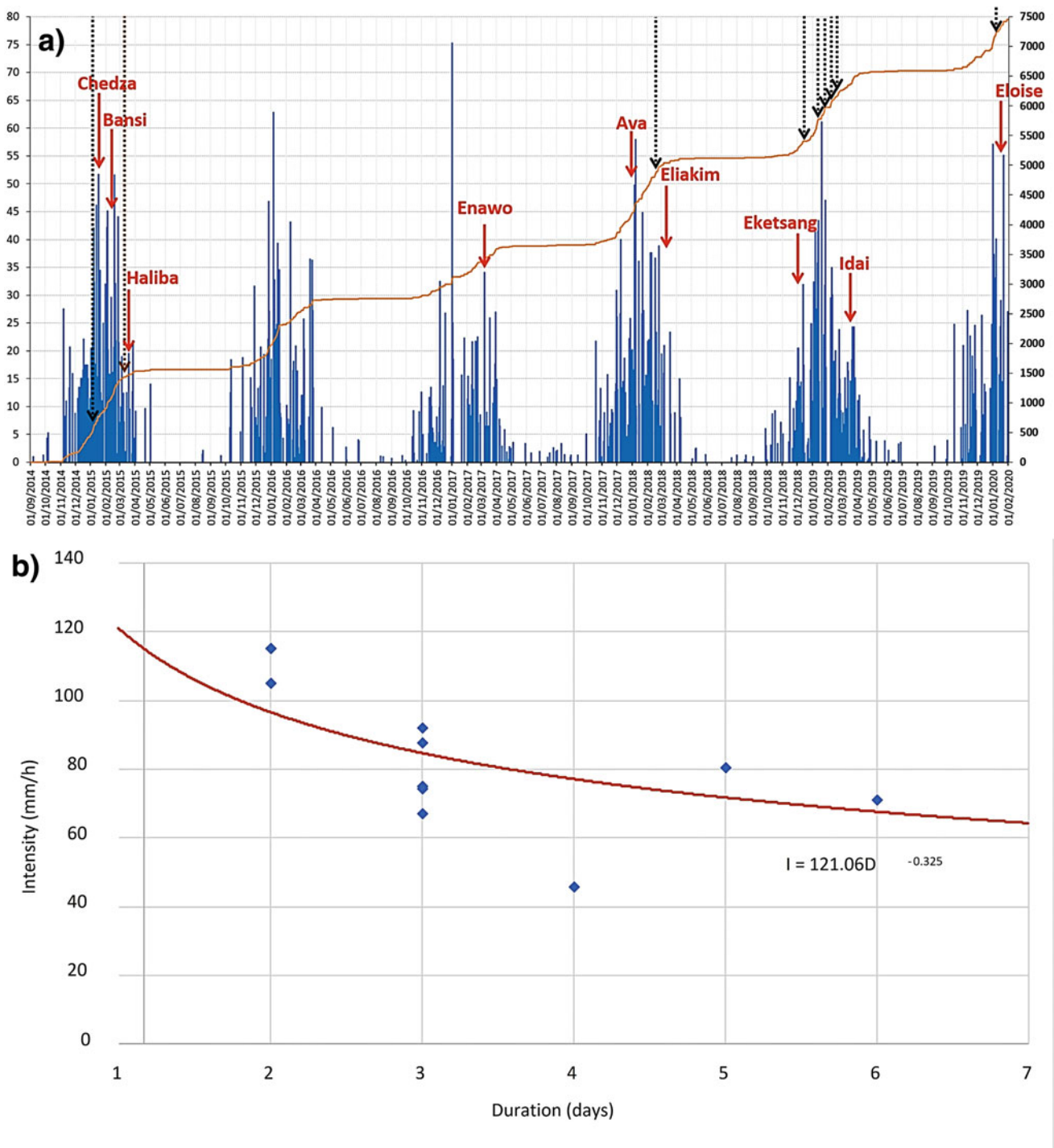
Fig. 5 Comparison between Rainfall data from September 2014 to January 2020 (Daily and cumulated data from Climate Engine, 2015), the recorded landslide events (dashed black arrows), and the recorded Cyclones (red arrows), reported in Frodella et al. 2021a, b (**a**) (the Dashed brown arrow represents the Winter 2015 landslide event). Intensity—Duration threshold for the study area

areas reported by BNGRC (2015, 2019) and slopes exceeding a steepness of 70°. A new methodology was implemented in a cloud compare (GDM 2015) environment by interpolating on these areas source contour lines at a selected distance based the operator's judgement; the code selected

the potential block sources along these lines. The trajectories of blocks show that large part of both Sectors 1 and 2 are affected by run-out of rock blocks (Fig. 7a, c, e). The rock fall analysis was calibrated using the outcomes of the field surveys, which allowed the recognition of how the rock cliffs
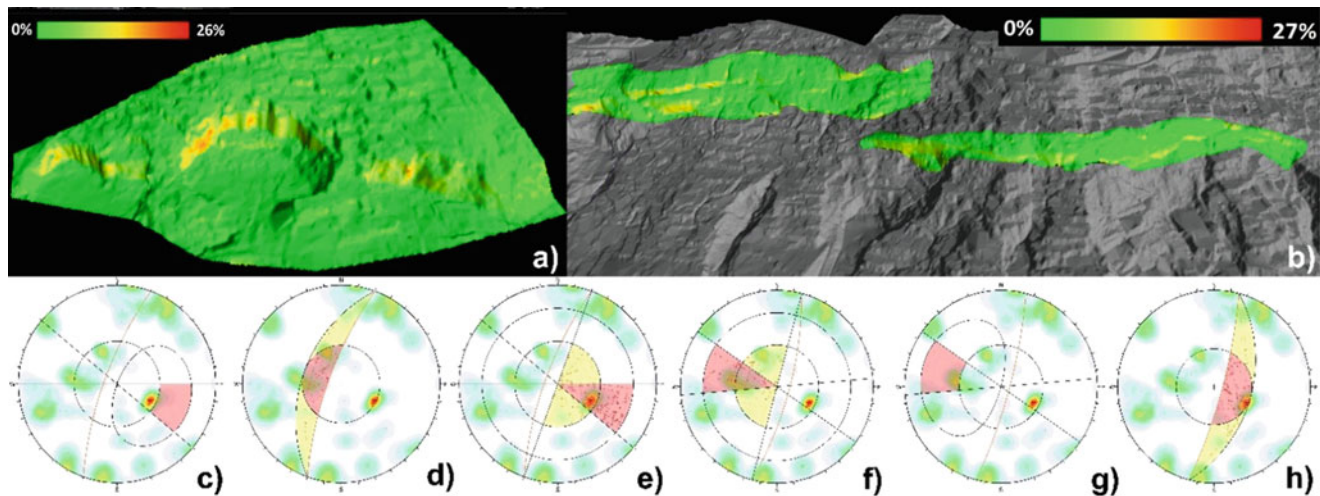
Fig. 6 3D GKI maps of sector 1 (**a**) and sector 2 (**b**). 2D kinematic analysis for toppling: sector 1 (**c**), sector 2 (**d**); wedge failure: sector 1 (**e**), sector 2 (**f**); planar sliding: sector 1 (**g**); sector 2 (**h**) (modified after Frodella et al. 2021b)

are frequently affected by blocks of various size, from decametric to plurimetric (Fig. 7d–g).

4 Discussion

Rainfall-induced landslides are a common threat to the communities living on hillslopes in Antananarivo.

The rapid urban development and the lack of a proper urban planning has caused several environmental problems such as intense slash and burn deforestation, illegal quarrying, unauthorized slope cutting and terracing for the construction of hovels, garbage dumping, lacking a proper sewer and drainage systems, narrowing, culverting and the swamping of the creeks (Ciampalini et al. 2019). This anthropogenic pressure does not consider the fragile geological and geomorphological context of the Analamanga Hill. Consequently, the urban area, in particular the slopes and footslopes are prone to landslide phenomena. This instability is especially evident during the frequent heavy cyclonic rainfall, as testified by the winter 2015 and the 2018–2019 landslide events (Frodella et al. 2021a, b). In this framework, the expected future increase of extreme meteorological events can only exacerbate landslide susceptibility.

The shallow landsides connected with the 2015 event slightly affected the UNESCO Core Zone (except for its southern area) along the pathway connecting the Rova palace with Ambohipotsy Cathedral (Figs. 3, 4, and 7). The cultural heritage buildings are not in landslide-prone areas, except for the Trano-Gasy Houses, which are built in an unstable area on the top of the western slope, between the Rova and Andafiavaratra Palace. The most exposed linear structures are the tracks running on both mid-slopes in the central southern sector of the Analamanga Hill. Within the UNESCO Buffer zone, the most exposed areas are the crude dwellings/hovels of the Middle City area and the mid-slope pathways, particularly the foot of the western hillslope (Tsimialonjafy-Ambanin'Ampamarinana-Ankadilalana-Tzimbazaza quarters) where shallow debris rotational/translational slides develop. Here, earth-debris rotational/translational slides involving residual soil were identified along the slopes of the main creek channels that deeply undercut the slope toe at the foot of the western hillside (Fig. 4). In this area, intense linear creek erosion of the soft lateritic soil cover creates large gullies that are rapidly expanding, damaging road pavement and buildings. The middle southern eastern slope is less prone to shallow landslides, except for an area located in the creek basin east of the Rova. The slope north hill sector shows a general stability due to the widespread urban cover and the low steepness of the gentle slope, while the southern sector shows some prone areas at the top of the abandoned quarry niches. Rock falls severely affect Sector 1 (the western footslope) and Sector 2 (southeastern slope) (Fig. 6). The slope north hill sector shows a general stability due to the widespread urban cover and the lower slope angles, except for the area around the tunnel, in the Ambohijatovo quarter.

Following intense rainfall events, shallow earth-debris rotational/translational slides develop from the slope of gullies and headcut apexes and can evolve into earth debris flows confined to channels within the hydrographic network. These phenomena involve the lateritic soils, as well as the anthropogenic waste deposits (often the gullies are used as dumps), enhancing gully headcut erosion and scarps retreat. Slope instability is more likely to occur in the gullies of the central and southern hill sector (Ankadilalana-Tzimbazaza quarters), and not in the High City's cultural heritage areas. Structures most impacted are the hovels built along the scarps and the pathways connecting with the Low City. An
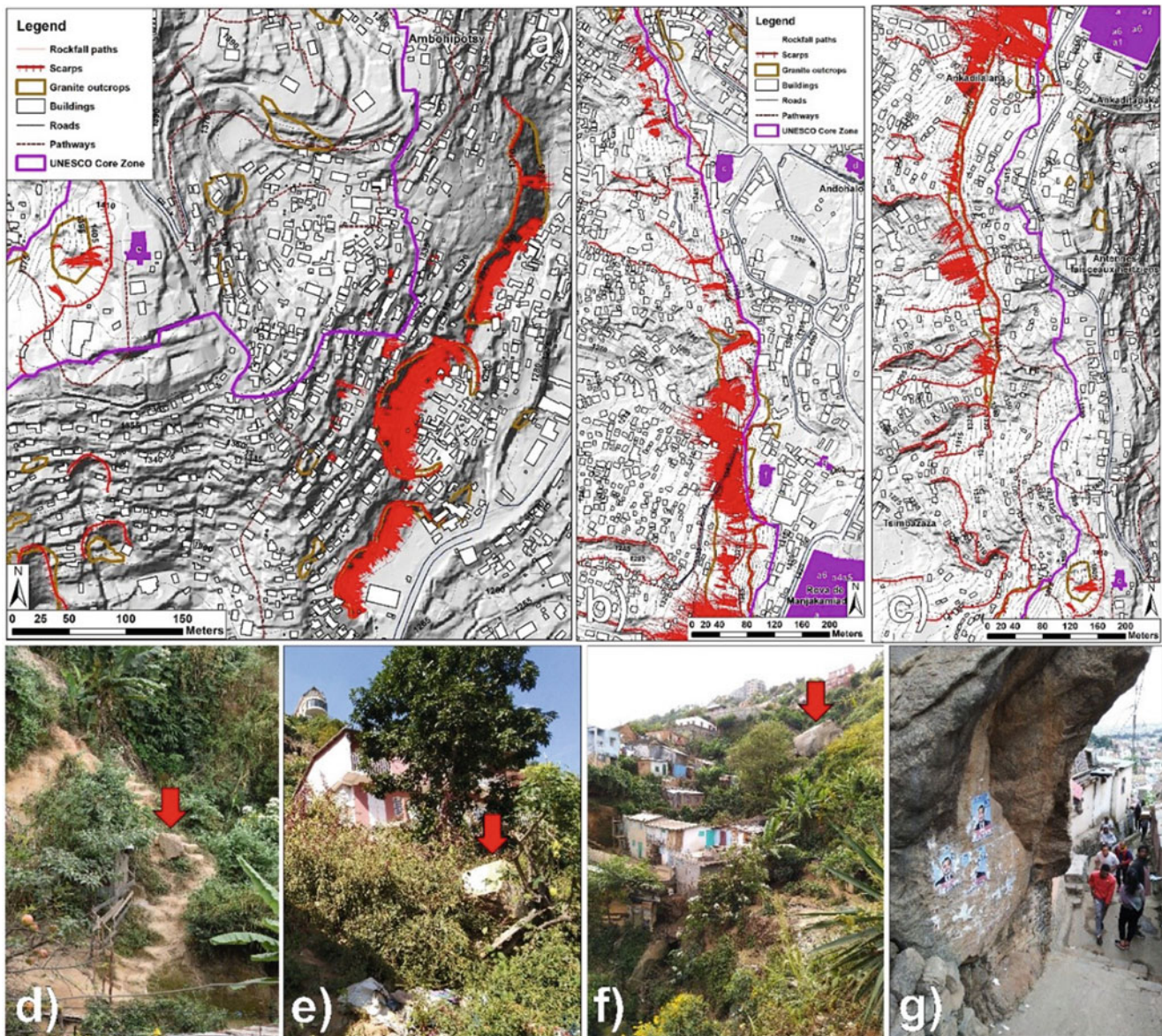
Fig. 7 Rock fall runout simulations. Sector 1: rock blocks trajectories in the analysed area (**a**); rock fall probability of occurrence (black lines represent the rockfall paths **b**). Sector 2: rock blocks trajectories in the North (**c**) and South sectors (**e**) and corresponding maps of rock fall probability of occurrence (black lines represent the rockfall paths: North sector (**d**), South sector (**f**). Recent and ancient rock block deposits on the western footslopes of decametric (**d**), metric (**e**) and plurimetric sizes (**f**, **g**)

assessment of rockmass instability associated with the fractured granite cliff corresponding to the abandoned quarries on the western slope and in the south-eastern hill sector. Simulations show that these areas can be sources of rockfall hazardous that may impact on the populated area of the Middle town with poor housings standards.

The landslide maps obtained can be used not only for hazard zoning but also for prioritizing landslide mitigation. Such measures include slope reprofiling, bioengineering methods using local material, wood barriers and check dams, bio-mats and grids to enhance vegetation regrowth in correspondence of the soi bare sectors, creek filtering dams,

nets, and fences for the rockfall/slides. Even if some results are based on very simple approaches and with a certain degree of uncertainty, this work can represent a starting point to create a structured activity aimed to the risk reduction of the area. This activity should start with the creation of a completer and more detailed landslide inventory, where the triggering day, characteristics, dimension of the landslides is defined. The landslide inventory can be used to produce a more accurate and detailed landslide hazard assessment, which, in turn, will result in more precise intervention for landslide risk reduction. For the near future, the Disaster Risk Management activities in Antananarivo should also focus on

the installation of an automated weather station and sensor network to collect accurate rainfall data and implement an Early Warning System. Risk assessment and spatial planning activities should be performed by the municipality of Antananarivo, BNGRDC and technical experts to prevent construction of new buildings in hazardous areas, manage waste materials and avoid the burning of garbage on the hillslopes. To reduce the social vulnerability, these activities should be harmonized with existing on-going projects, while public awareness must be raised to understand the hydrogeological risks. The next phase of activities will focus on sustainable management of the High City within the UNESCO world heritage framework. To this end, our study represents an important contribution for improving the knowledge of landslide processes in Antananarivo, Madagascar, and for other areas with limited data.

5   Conclusions

In this work an integrated landslide hazard assessment was carried out in the High City of Antananarivo, one of the most important cultural heritage sites of Madagascar. As a first step a multitemporal slope scale landslide inventory spanning from 2015 to 2020 was collected by combining field surveys campaigns, interviews with local people and analysing remote sensing data (High-resolution DTM and satellite orthophotos). To assess the hazard of the different identified instability phenomena a shallow landslide susceptibility was carried out using the Random Forest model, while the GPP and IS GeoMassi codes were adopted to perform debris flow-rock fall simulations.

The analysis undertaken shows that most of the mapped areas are affected by moderate to very high landslide susceptibility. Areas characterized by the higher susceptibility are in the Middle Town quarters, particularly at the foot of the central sector of the western hillslope (from north to south: Mahamasina, Ankadilalana, Tzimbazaza quarters). Here shallow debris rotational/translational slides mainly involve eluvial-colluvial and lateritic deposits, while rockfalls originate from the granite cliffs. The densely packed shacks and hovels of the Middle City are particularly prone to rockfalls at the base of steep rocky cliffs. At the western footslope, intense linear creek erosion of the soft lateritic soil cover creates large gullies, which are rapidly expanding. The eastern slope is less prone to shallow landslides, except for the middle-southern sector, especially in two creek basins. The first is located east of the Rova in the Manjakamiadana quarter, while the second is located east of the Ambohipotsy quarter. The southern sector shows unstable areas in proximity to abandoned quarry slope cuts in the Anjahana-Ambohipotsy quarters. Fortunately for the cultural heritage assets of the High City, most of them are not located in

shallow landslide-prone areas. Exceptions are the Trano-Gasy Houses, located on an unstable area at the top of the western slope between the Rova and Andafiavaratra Palace. The most exposed linear structures are tracks running on both mid-slopes in the central-southern sector of the Analamanga Hill.

A preliminary analysis on the rainfall-induced landslide frequency shows that the main landslide events occurr after major Cyclones during periods of intense precipitations. Rain events ranging in duration from 2 to 7 days are most probably responsible for the triggering of landslides. Furthermore, we define an intensity (I)-duration (D) rainfall threshold for landslide triggers. Thematic-hazard maps produced as part of our study represent a first step for land-use planning by institutions and actors involved in developing a robust geo-hydrological risk reduction strategy for protection and conservation in the High City.

References

Abraham MT, Satyam N, Rosi A, Pradhan B, Segoni S (2021) Usage of antecedent soil moisture for improving the performance of rainfall thresholds for landslide early warning. Catena 200:105147

Andriamamonjisoa SN, Hubert-Ferrari A (2019) Combining geology, geomorphology and geotechnical data for a safer urban extension: application to the Antananarivo capital city (Madagascar). J Afr Earth Sci 151:417–437

BNGRC - Bureau National de Gestion des Risques et des Catastrophes (2015) Point de situation zone a de glissements de terrains a Antananarivo. February 2015, Technical report

BNGRC - Bureau National de Gestion des Risques et des Catastrophes (2019) Point de situation zone a risque de glissements de terrains de Manjakamiadana et ses environs. January 2019, Technical Report

Breiman L (2001) Random forests. Machine learning 45(1):5–32

Catani F, Lagomarsino D, Segoni S, Tofani V (2013) Landslide susceptibility estimation by random forests technique: sensitivity and scaling issues. Nat Hazards Earth Syst Sci 13(11):2815–2831

Ciampalini A, Frodella W, Margottini C, Casagli N (2019) Rapid assessment of geo-hydrological hazards in Antananarivo (Madagascar) historical Centre for damage prevention. Geomat Nat Haz Risk 10(1):1102–1124

Climate Engine (2021). Available online: https://clim-engine-development.appspot.com. Accessed 20 Jan 2021

Cox R, Zentner DB, Rakotondrazafy AFM, Rasoazanamparany CF (2010) Shakedown in Madagascar: occurrence of lavakas (erosional gullies) associated with seismic activity. Geology 38(2):179–182

Cruden DM, Varnes DJ (1996) Landslides: investigation and mitigation. Chapter 3-Landslide types and processes. Transportation research board special report, vol 247, pp 36–75. Transportation Research Board, ISSN: 0360-859X

Fell R, Corominas J, Bonnard C, Cascini L, Leroi E, Savage WZ (2008) Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. Eng Geol 102(3–4):99–111

Frodella W, Spizzichino D, Ciampalini A, Margottini C, Casagli N (2021a) Hydrography and geomorphology of Antananarivo High City (Madagascar). J Maps 17(4):215–226

Frodella W, Elashvili M, Spizzichino D, Gigli G, Nadaraia A, Kirkitadze G, Adikashvili L, Margottini C, Antidze N, Casagli N (2021b) Applying close range non-destructive techniques for the detection of conservation problems in rock-carved cultural heritage sites. Remote Sens 13:1040

Frodella W, Rosi A, Spizzichino D, Nocentini M, Lombardi L, Ciampalini A, Vannocci P, Ramboason N, Claudio MC, Tofani V, Casagli N (2022) Integrated approach for landslide hazard assessment in the High City of Antananarivo, Madagascar (UNESCO tentative site). Landslides 19(11):2685–2709

ICL (2022) IPL-ICL Project n°260: Landslide Risk assessment in the High City of Antananarivo (https://www.landslides.org/projects/ipl-projects/)

Reichenbach P, Rossi M, Malamud BD, Mihir M, Guzzetti F (2018) A review of statistically-based landslide susceptibility models. Earth-Sci Rev 180:60–91

Wichmann V (2017) The gravitational process path (GPP) model (v1.0)–a GIS-based simulation framework for gravitational processes. Geosci Model Dev 10(9):3309–3327