

Rapid assessment of geo-hydrological hazards in Antananarivo (Madagascar) historical centre for damage prevention

Andrea Ciampalini, William Frodella, Claudio Margottini & Nicola Casagli

To cite this article: Andrea Ciampalini, William Frodella, Claudio Margottini & Nicola Casagli (2019) Rapid assessment of geo-hydrological hazards in Antananarivo (Madagascar) historical centre for damage prevention, *Geomatics, Natural Hazards and Risk*, 10:1, 1102-1124, DOI: [10.1080/19475705.2018.1564375](https://doi.org/10.1080/19475705.2018.1564375)

To link to this article: <https://doi.org/10.1080/19475705.2018.1564375>



© 2019 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



Published online: 17 Feb 2019.



Submit your article to this journal [↗](#)





Article views: 348



View Crossmark data [↗](#)



Rapid assessment of geo-hydrological hazards in Antananarivo (Madagascar) historical centre for damage prevention

Andrea Ciampalini^a, William Frodella^b, Claudio Margottini^c  and Nicola Casagli^b 

^aEarth Sciences Department, University of Pisa, Pisa, Italy; ^bEarth Sciences Department, University of Firenze, Florence, Italy; ^cISPRA, Geological Survey of Italy, Roma, Italy

ABSTRACT

The historical centre of Antananarivo represents one of the most important cultural heritage sites in Madagascar. During 2015, the whole city area was severely affected by geo-hydrological hazards due to cyclonic rain, resulting in severe flooding, and in widespread shallow landslides along the hillslopes. This event proved the vulnerability to geo-hydrological risk of the Upper town's historical buildings. In October 2017, a geo-hydrological hazard mapping was performed in the Upper Town by combining field surveys, remote sensing and geomatic data analysis in a GIS environment. This provided detailed products such as a geological-geomorphological map, a map of the hydrographic network and of the creek basins, and a geodatabase to be used for detecting areas prone to erosion and geo-hydrological hazards. The final aim was to understand the geological, geomorphological and hydrographic features of the Upper Town, in order locate the more critical areas and to recommend priority works to be carried out, as a first step toward a risk management strategy and a conservation/valorization plan for building the resilience of the site. The results highlighted that a Cultural Heritage site protection strategy can be planned also in case of limited data, which is a frequent condition in developing countries.

ARTICLE HISTORY

Received 5 September 2018
Accepted 7 December 2018

KEYWORDS

Soil erosion; cultural heritage; geo-hydrological hazard; field survey; Antananarivo

1. Introduction

In developing countries Cultural Heritage is often at risk due to natural disasters (fires, earthquakes, landslides, flooding, tropical storms) (Taboroff 2000; Margottini et al. 2015). Damages can also arise from the fragility of the structures or materials, destructive sabotage, war and incorrect urban planning (UNESCO 2010; Wang 2015). Furthermore, the infrastructures needed for the accessibility of Cultural Heritage site are of fundamental importance for a safe and fruitful use from the local population

CONTACT Andrea Ciampalini  andrea.ciampalini@unipi.it William Frodella  william.frodella@unifi.it

© 2019 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

and tourists (Margottini 2018). Due to strategic and spiritual purposes, several Cultural Heritage sites in the world are built on rock hilltops bounded by steep cliffs, which elevate above the surrounding hillside and plains (Egglezos et al. 2008; Ciampalini et al. 2012; Margottini and Di Buduo 2017). This geological-geomorphological setting can be particularly prone to slope instability, due to the presence of intensively fractured rock masses often overlapping on a soft erodible bedrock, and to the different response of the materials to weathering, erosion, seismic shocks or man-made excavations (Gigli et al. 2012; Frodella et al. 2016). The protection of Cultural Heritage sites from instability phenomena requires a specific inter-disciplinary approach, which should be planned considering the site geological and geomorphological characteristics, as well as the typology of the related hazard (Bianchini et al. 2015; Nolesini et al. 2016). Earth Observation (EO) data combined with detailed field surveys in a Geographic Information System (GIS) can provide the basic tools for geomorphological mapping (Guzzetti et al. 2012; Ciampalini et al. 2016; Bardi et al. 2017; Lombardi et al. 2017), especially in developing countries with limited data (Ciampalini et al. 2015; Margottini and Spizzichino 2017; Boldini et al. 2018).

1.1. Problems affecting the Rova of Antananarivo

Madagascar central highlands host the most important built Cultural Heritage sites: the royal fortifications of Ambohimanga (UNESCO World Heritage site since 2001), and the Antananarivo Upper Town, encompassing the Rova royal palace complex. The area is severely affected by geo-hydrological hazards, especially during the rainy season, when heavy rains from tropical storms and cyclones cause the flooding of the river plain areas and trigger landslides along the hillsides and mountain range slopes (Rakotobe et al. 2016). Deforestation (for agricultural and illegal logging) and intense quarrying activities are exacerbating soil erosion and landslide occurrence (Ramasiarinoro et al. 2012). The Rova was destroyed almost completely by a fire in 1995, shortly before it was due to be inscribed on the list of UNESCO World Heritage Sites (<http://whc.Unesco.org/en/list>). Building restorations ended in 2009 and the external of the palace is nowadays fully restored. Since 2005 the local administration has increasingly carried out protection and conservation activities for the city's architectural and cultural heritage. Currently the Rova and the whole Upper Town of Antananarivo are in the list of the UNESCO tentative sites (<http://whc.Unesco.org/en/tentativelists>). In this context, the Antananarivo urban area was severely affected by geo-hydrological hazard during in the first months of 2015, when a sequence of severe tropical storms hit Madagascar causing several deaths and thousands of evacuees across the country. In particular on 5 March, heavy cyclonic rain triggered diffuse flooding in the Lower Town and landslides in the Upper and Middle Town, causing damages to buildings and infrastructures including an estimated 36,000 evacuees and 20 casualties (Figure 1). This event focussed the attention on the vulnerability of the town's built Cultural Heritage (with special regards to the Rova royal palace) and the connected infrastructures (local roads, stairways, pedestrian pathways) with respect to geo-hydrological hazards.

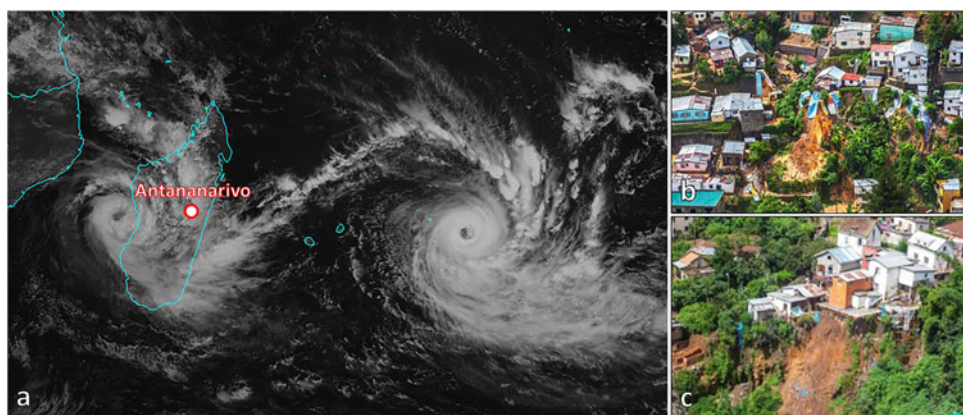


Figure 1. Twin cyclones Bansi and Chedza hitting Madagascar East coast on 16 January 2015 (a) (modified after European meteorological satellite EUMESAT image; available at: www.eumetsat.int); aerial pictures of the triggered shallow landslides within the city on March 5th event (b, c) (BNGRC - Bureau National de Gestion des Risques et des Catastrophes; <http://www.bngrc.mg>).

1.2. The adopted methodological approach for geo-hydrological hazard assessment

In this paper, a methodological procedure for geo-hydrological hazard assessment of the Antananarivo city centre was adopted. A geo-hydrological mapping was carried out by combining geological and geomorphological field surveys with remote sensing data, with GPS surveys and pre-existing topographic data. All data were homogenized in a GIS environment in order to combine analogue/vector data, and process and geo-rectify all the collected data in a geographic coordinate system, in order to create a dedicated geodatabase. This provided detailed products such as a geological-geomorphological map, a map of the hydrographic network and of the creek basins, also representing a fundamental tool to be used for detecting areas prone to erosion and geo-hydrological hazards in the Antananarivo hill area, with particular attention to the Upper Town historical buildings and related structures (roads, pathways, stairways), where limited data on local geology, geomorphology and hydrographic data were available. The final aim was to understand the geological, geomorphological and hydrographic features of the Upper Town and to recommend priority works to be carried out, as a first step towards a risk management strategy of the site, a safe use and touristic valorization of the site.

2. Study area geological-geomorphological setting

Madagascar is an island country located between the canal of Mozambique and the south-western Indian Ocean, spanning 1500 km in length and around 500 km in width (Figure 2(a)). Madagascar has a narrow coastal plain with a hot tropical climate, a range of temperate mountains and plateaus in the centre of the country and a strip of rainforest on the eastern flank (Green and Sussman 1990). From a geological point of view, the study area is characterized by the Antananarivo Craton, an Archaean crustal block recording ages of 2.5 Ga forming the basement of much of



Figure 2. Location of Antananarivo on Madagascar Google Earth image (a); detail of the Antananarivo area on optical satellite image (b) (the red polygon represents the Unesco buffer zone). Source: Author

Central Madagascar (Tucker et al. 2007), characterized by quartz-feldspathic biotite orthogneisses and migmatites (Nédélec et al. 1994; Kroener et al. 2000; Goncalves et al. 2004). In the region of Antananarivo, the granites stand out as hill domes up to over 200 m above the surrounding wide alluvial valleys and inter-mountainous plains, or, when the stratoid structure allows, as great ridges stretching over many miles, strongly characterizing the area geomorphological features (Dixey 1960; Nédélec et al. 2000). The central highlands are mantled by lateritic soils (essentially clayey laterites) from 10 up to 80 m in thickness, formed since Pliocene by the chemical weathering of the hard-crystalline bedrock (Cox et al. 2010). Covered with a sparse vegetation of grasses, these thick lateritic soils are exposed to the accelerated weathering and erosion called ‘Lavakas’, a marked gully erosion erosional feature common in Madagascar (Wells et al. 1991; Ramifehiarivo et al. 2017). Although human activities such as deforestation, overgrazing and road cutting can contribute to lavakas formation, these latter are caused by natural processes (Raveloson et al. 2015). From a geomorphological point of view, Antananarivo (18.55° S; 47.32° E) is located in the central highlands region of Madagascar, at approximately 1200 m a.s.l. above sea level, about 160 km from the east coast and 330 km from the west coast (Figure 2(a)). The capital Antananarivo in particular has a peculiar topographic setting, being its historical centre (Upper Town) located at the summit of Analamanga hill, the city’s highest peak. The urban area gradually developed from the Upper Town, down the the Analamanga hillslopes (Middle Town), to reach its current configuration by further expanding in the Ikopa river plain (Lower town). The urban area is characterized by the Ikopa River plain, which bounds the city to the south and west, alternating with several low rocky hill domes and ridges, the highest one being represented by the Analamanga hill, a long, narrow, granite ridge extending from north and south for

about 3 km (Figure 2(b)). The hilltop is represented by a flat area (1430 m a.s.l. at its highest point) from which the town developed.

3. Antananarivo historical urban background

Antananarivo was called Analamanga (the ‘blue forest’) until 1610, when the Merina King Andrianjaka built the first settlement around the Rova palace on the highest hill of the city (Analamanga), which privileged position assured an ideal defence and observation post (Kottak 1980). The first settlement was basically a fortified village hosting a garrison of 1000 man, therefore it took the name of ‘Antananarivo’ (the city of the thousand) (Figure 3(a,b)). King Andrianjaka also designated within the kingdom the twelve sacred hills of the Merina people (including the Ambohimanga and Analamanga hill), which were often ancient capital and spiritual-political sites, nowadays representing sites of great historical and cultural significance to the Merina people. At the end of the eighteenth century King Andrianampoinimerina unified the people of the Highlands making Antananarivo the capital of its kingdom, leaving Ambohimanga permanently (Larson 2000). The Rova palace complex (Figure 3), encompassing the chapel and royal tombs, served as the home of the sovereigns of the Kingdom of Imerina during the seventeenth and eighteenth centuries, and of the rulers of the Kingdom of Madagascar during the nineteenth century. The Rova original structure was made of wood (Figure 3(a,b)) but took its present form in 1870, when Queen Ranavalona II commissioned the Scottish missionary and architect James Cameron to encase the palace in stone bricks (Figure 3(c,d)). The architecture of the Rova complex has strongly influenced the Upper Town, with special regards to the Andafiavaratra palace (Figure 3(f)), which represents the second most important historical building of Antananarivo. The city of Antananarivo developed from the site of the first Rova, becoming the current historical core of the so called ‘Upper town’,

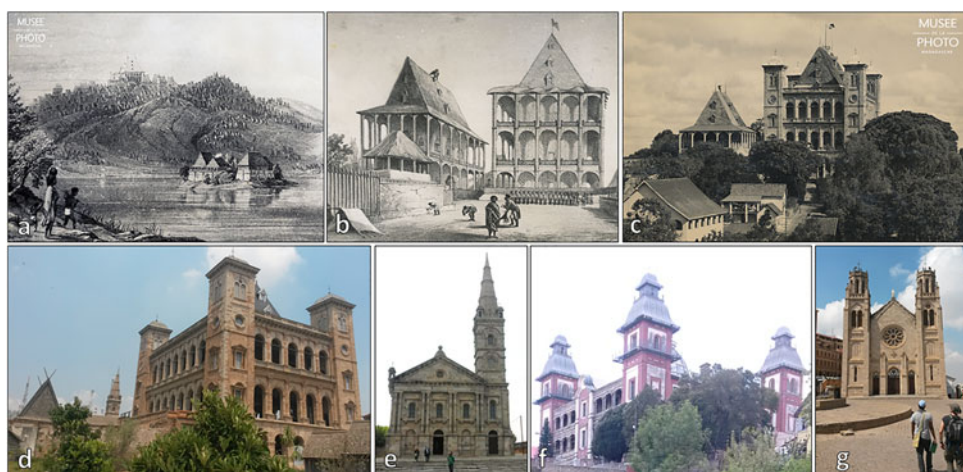


Figure 3. The Antananarivo Upper Town Cultural Heritage buildings: Rova palace complex lithographs and historical pictures (a–c; Courtesy of IMV-Institut des Métiers de la Ville-Tana City Lab; <https://www.imvtana.org>); current picture of the rebuilt structure following the 1995 fire; Rova palace (d), royal chapel (e). Andafiavaratra palace (f); Andohalo Cathedral (g). Source: Author

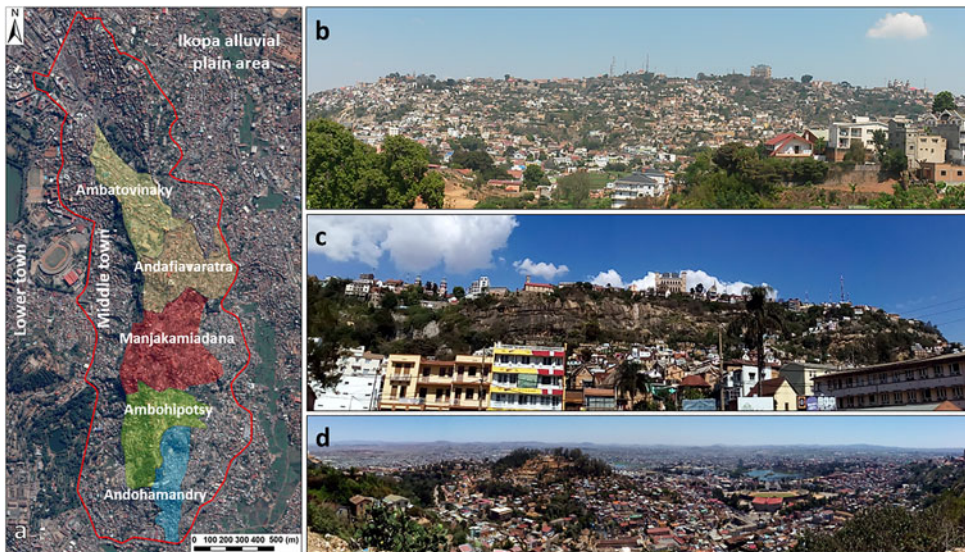


Figure 4. Spaceborne orthophoto (Pleiades satellite) of the town sectors showing the Upeer Town quarters (a) (in red the boundary of the Unesco Buffer zone). Panoramic views of the Upper-Middle town and Analamanga hill eastern (b) and western slopes (c). View of the Lower Town area (d). Source: IMV-Institut des Metiers de la Ville-Tana City Lab by its manager Tamara Teissedre-Philip (tamarateissedrephilip@prxmadagascar.org).

and gradually spreading down the Analamanga hill slopes (Middle Town) (Figure 4(a–c)). The hill western slopes, being best protected from cyclones originating over the Indian Ocean, were settled before those to the east. By the late nineteenth century (during the colonial period) the city had expanded to the Ikopa river flat terrain (Lower Town) (Figure 4(d)). During the last decades, the city has continued to evolve to nearly 1.7 million inhabitants today, covering an urban area of approximately 86.4 km² (Figures 2(b) and 4(d)). Nowadays the Upper Town hosts the town’s administrative quarter, still representing the most important built Cultural Heritage site of Madagascar.

4. Methodology

4.1. Ancillary data

All the available ancillary data were collected to implement a complete geodatabase of the study area. For this aim, three different work phases have been conducted: (i) data collection; (ii) database design and (iii) products generation (Figure 5). The collected data can be divided into two categories: (i) analogue data and (ii) digital georeferenced data. The first category includes available geognostic, bibliographic data and historical pictures. These data have been georeferenced to populate the geodatabase. Digital georeferenced data are represented by GIS vector shapefiles (topographic contour lines, lakes and ponds, springs, buildings, road system, etc.), VHR multispectral image (Pleiades, 0.5 m of spatial resolution, acquired on 22 May 2015) and two VHR DEM (one with 2 m of spatial resolution, acquired on February 2015, the second one with 1 m of spatial resolution acquired on October 2016) (both courtesy of IMV).

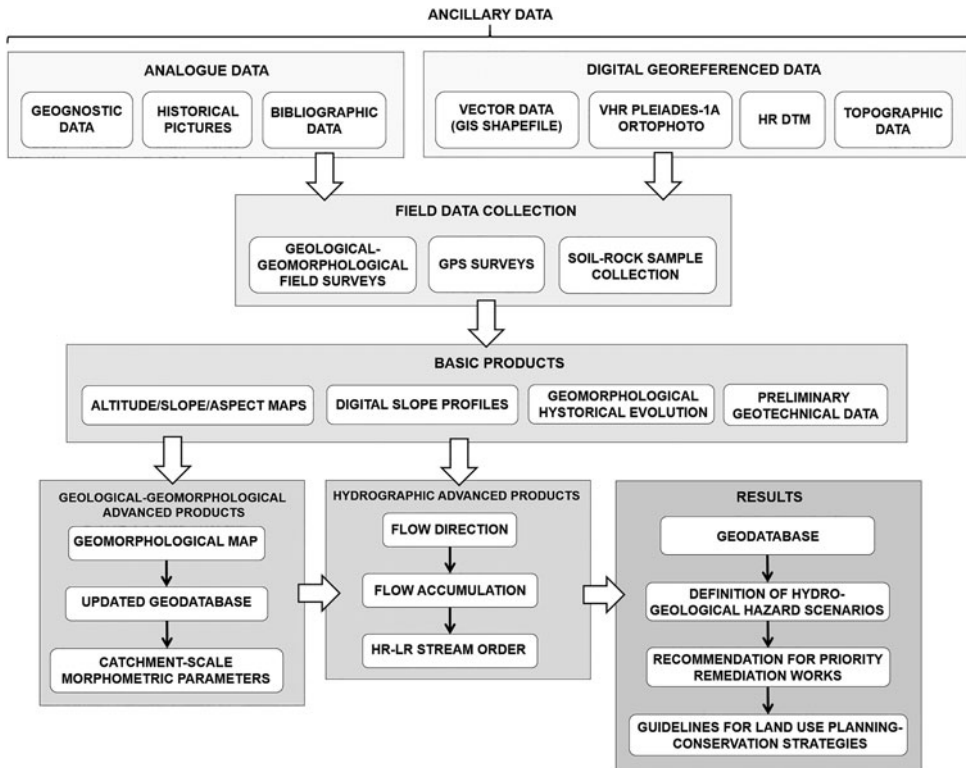


Figure 5. Workflow of the applied methodology.

4.2. Field data

During October 2017, field activities were performed to survey the main geological and geomorphological features of the Analamanga hill, with the aim of creating a geomorphological map of the study area and highlight the areas subject to instability and erosion. To this aim the survey was performed through the combination of a traditional field approach, topographic differential GPS survey of selected areas, analysis of the available orthophotos and high resolution DEMs. The GPS device (working in Real Time Kinematics mode) allowed the acquisition, in few seconds, of the position (LAT, LONG) and height of the surveyed point in WGS84 coordinates. The field survey was also performed to validate the observation deduced from EO data.

4.3. Hydrological analysis

The Analamanga hill shows a peculiar hydrographic setting characterized by two distinct networks: (i) the ‘natural’ hydrographic network, made of those creeks formed as a consequence of water erosion; (ii) the ‘anthropic’ hydrographic network formed by all the flow-paths represented by small streets and small artificial channels. The ‘natural’ hydrographic network was mapped during the field survey performed in October 2017. When possible, each identified creek was described in detail considering the presence of man-made structures, vegetation cover, presence/absence of

running water, presence of soils or cover in the related watershed. Field surveys were carried out along the entire accessible hydrographic network of the study area. The area was systematically inspected along all drainage lines up to the catchment divide. The goal of the field survey is the identification of the main water courses where rainfall usually accumulates. The complexity of the urbanization of the slopes of the study area did not allow to accurately map all the flow-paths. In this case, the 'anthropic' hydrographic network was automatically mapped using the DEM and the LIDAR products in GIS environment. The use of a DEM aims at identifying all the possible flow-paths from every point to the main water courses (Tarboton et al. 1991). This step is very important in hilly areas like Antananarivo where the shallow drainage network and the sewer system are completely lacking. The procedure followed to extract the hydrographic network from both the DEMs was the following: anomalous DEM sinks and peaks, representing discontinuities in the DEM surface have been filled (Planchon and Darboux 2002). Once that the imperfection has been removed we applied the Flow Direction algorithm. This step takes the filled DEM as input and measures the direction of flow out of each cell of the raster (Greenlee 1987; Jenson and Domingue 1988). The Flow Direction raster was used to obtain the Flow Accumulation, a raster allowing for the calculation of the accumulated flow (Tarboton et al. 1991; Jenson and Domingue 1988). A conditional tool was applied to control the output value for each cell, based on whether the cell value is evaluated as true or false in a specified conditional statement. This tool has been used to extract the stream network avoiding mapping very small lines produced by the noise of the LiDAR following the Strahler (1957) method (Tarboton et al. 1991). The raster represented by the Stream ordering can be transformed into a vector layer in order to be easily used in GIS environment. The transformation from a raster to a feature allowed to efficiently manage the stream network extracted from a LiDAR or a DEM. The last step concerns the identification of the hydrographic basins. Basins were identified by recognizing ridge lines between basins (divides) on the input flow direction raster, which is analyzed to find all sets of connected cells that belong to the same basin. The results are a raster of drainage basins that can be transformed into a shape file.

5. Results

5.1. Geomorphological characterization

The Analamanga hilltop is represented by a flat area (1436 m a.s.l. at its highest point, in correspondence of the Rova) rising gradually from north and alternating southward with three saddles (Figure 6). The hill is bounded on the south sector by slopes with angles from 30° to 50°, where the crystalline granite bedrock widely crops out in correspondence of quarry cuts (Figures 6–8). The western hillside is characterized by high slope angles from 50° to 80°, due to the presence of a continuous sub-vertical rock wall (bedrock) and several scarps, mainly N-S oriented (Figures 4(c), 7(a,b) and 8). The western slope foot is characterized by low energy surfaces formed by lateritic soils with a thickness up to tens of metres, gently linking with the Ikopa river plain alluvial deposits (Figures 6–8). On the contrary, the eastern hillside (more exposed to the cyclones coming from the Indian Ocean) has a minor slope angle (between 20

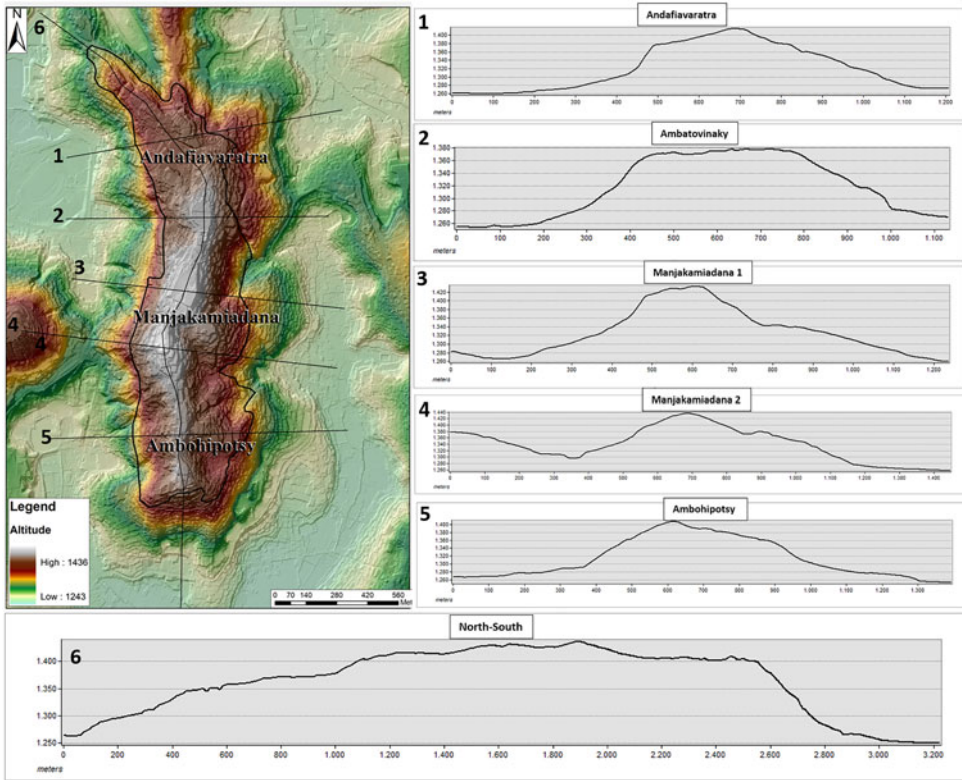


Figure 6. Analamanga hill DEM altitude map (the black boundary represents the UNESCO buffer zone), including with E-W (1–5) and N-S (6) profiles. Source: Author

and 40°) (Figures 4(b), 5 and 6(a)). The granite bedrock herein rarely crops out and is covered by widespread eluvial-colluvial deposits (Figures 7(a,e,f) and 8), formed by the weathering and erosion of the bedrock. These deposits, which maximum thickness in correspondence of the hilltop is about 30 m, as estimated both directly on the field and considering the available ancillary data (Hyvert 1994), alternatively overly directly on the bedrock or on the regolith, at times with the interposition of a few metres thick lateritic soil (Figures 5, 6(e,f) and 8). This slope cover hosts the aquifer that feeds the springs in the Upper Town area, which develop a complex dendritic-like hydrographic network (Figure 8). The contact between the slope cover and the granitic substratum gently dips toward East, for this reason most of the springs are located along the eastern slope. On the contrary the loamy laterite soils are affected by a simpler hydrographic network characterized by a low order stream network (Figure 8).

5.2. Hydrological analysis

Through the field survey 11 basins were mapped along the western slope, 4 basins along the southern slope and 15 basins along the eastern slope (Figure 9). The Analamanga hill is characterized by a radial-like pattern, which creeks deeply erode

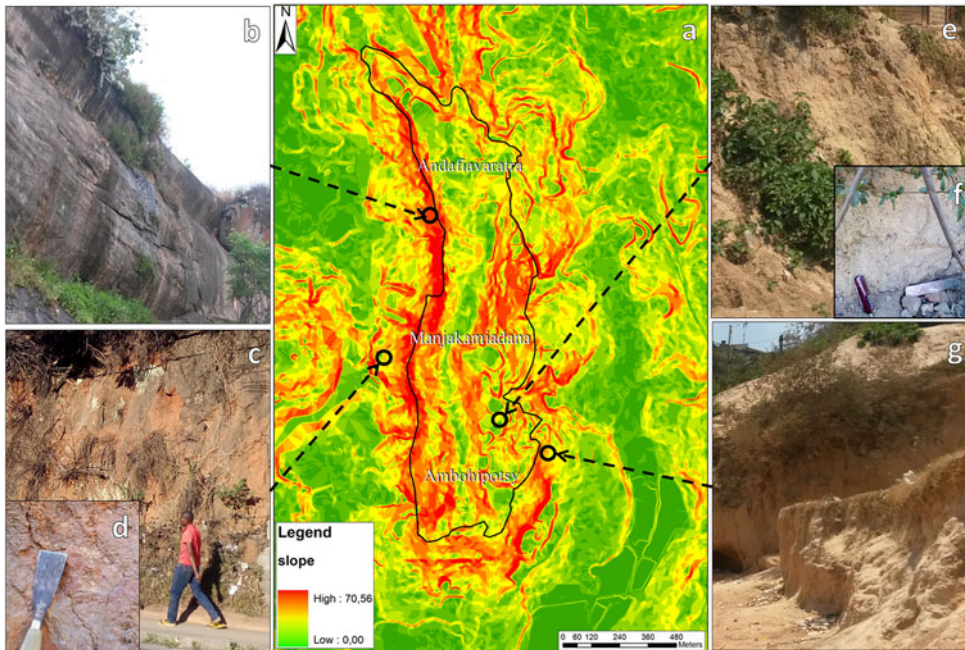


Figure 7. Analamanga hill DEM slope map (a), and the related geology (arrows show the outcrops): (b) granite western slope rock wall; (c) laterite soils (d: detail); (e) slope eluvial-colluvial deposits (f: detail); (g) alluvial deposits. Source: Author

both the hill slopes. The western slope is characterized by low order creeks (second order at maximum) forming deep and narrow valleys, trending WNW-ESE oriented, within the lateritic soils (forming gully erosional, 'Lavaka-like', features). A change in the slope degree of the western creeks can be observed in correspondence with the contact between the granites and the lateritic soils. At this point, creeks tend to engrave the lateritic soils forming the lavakas. The eastern slope is characterized by a more developed hydrographic network (sub-dendritic pattern-like), with wider basins trending NE-SW and characterized by a higher stream hierarchy (up to the third order) (Table 1). On the eastern slope the morphology is slightly different: the cliff is not present and the slope is more gentle. This morphology probably indicates the presence of a fluvial terrace, related to the past Ikopa river activity today located eastward. Along this slope, soils developed by the weathering of ancient alluvial deposits have been recognized. These soils are softer with respect to the laterite aiming at the development of a more complicated hydrographic network. The different geology led to the development of different erosive slope morphology. Lavaka-like erosional forms are present along the foot of the western slope, whereas widespread surface sheet erosion characterizes the eastern slope in correspondence with weathered alluvial deposits. Within the hydrographic network of the Analamanga hill, holy springs and cress fields were also mapped. Both represent important source of water during the dry season, but they are not sufficient to a complete water supply of the population. These springs are feed by a groundwater layer located on the top of the hill where a thick granular soil (up to 30 m) is bounded by the rocky substratum (observed in an

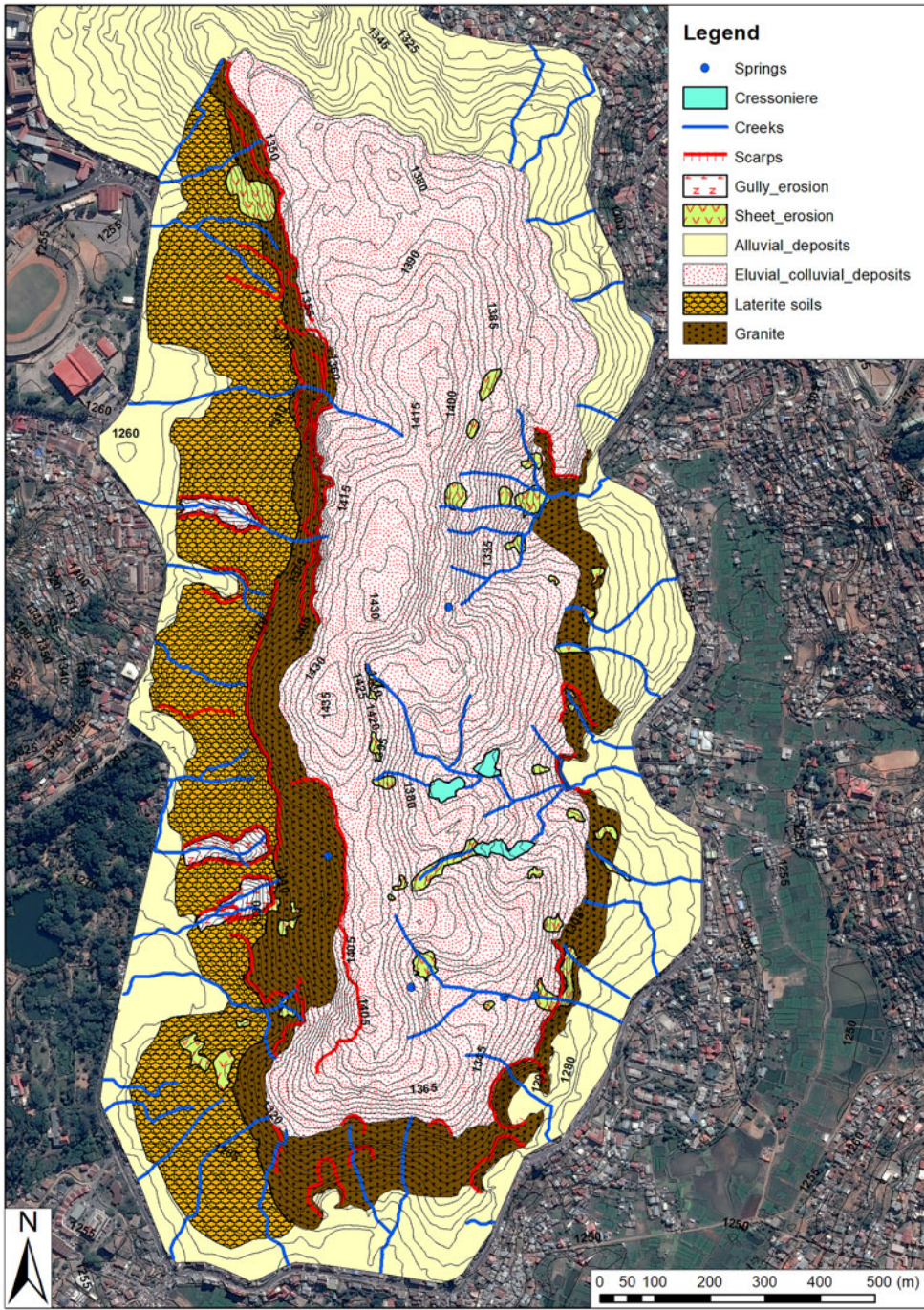


Figure 8. Geological-geomorphological map of Analamanga hill. Source: Author

excavation near the Rova and confirmed by the presence of a small natural water pool nearby the Immaculate Conception Cathedral). This groundwater allows cultivating cress fields in the middle part of the eastern slope.

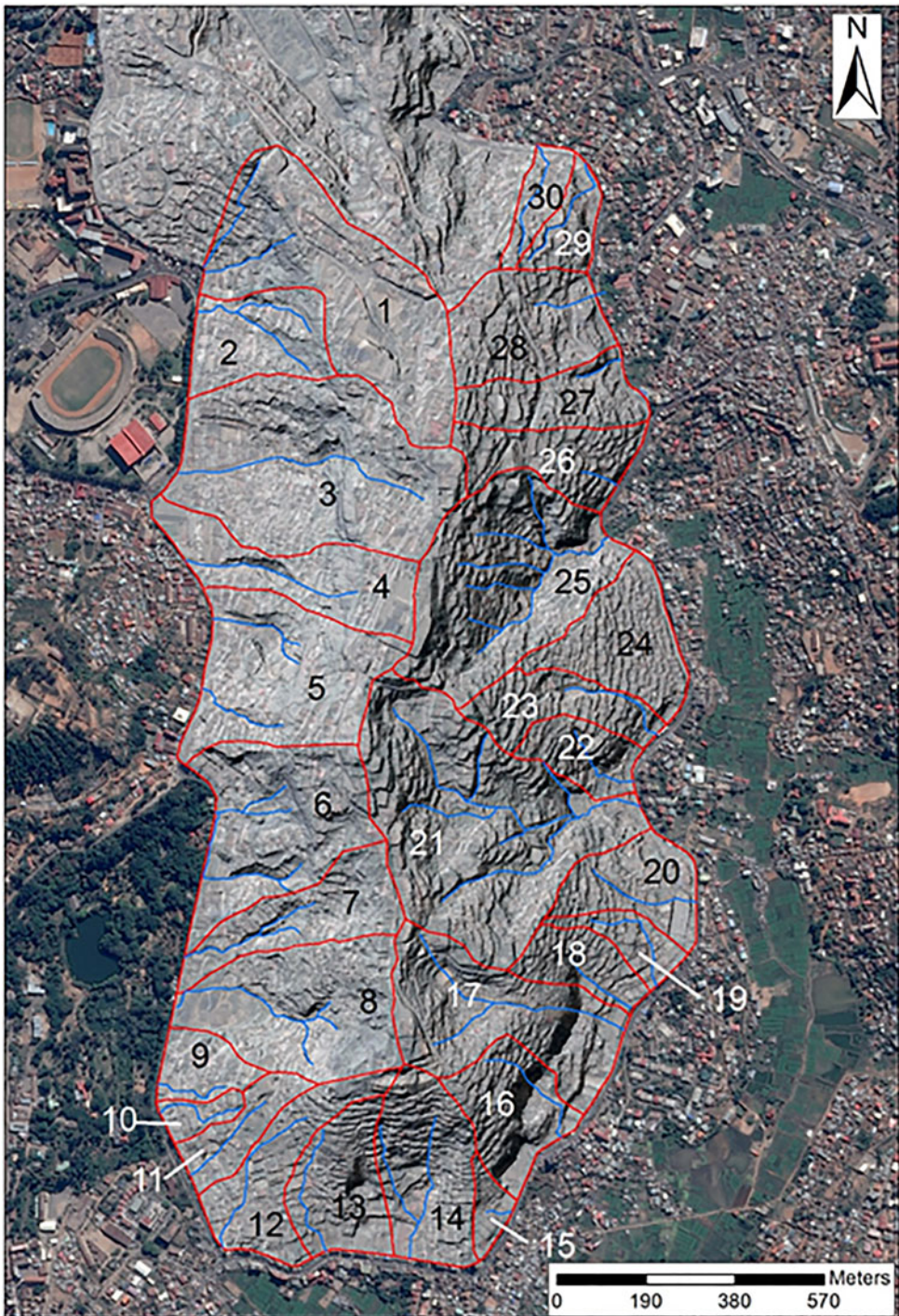


Figure 9. Hydrographic network (in blue) and hydrographic basins (in red) of the Analamanga hill. Source: Author

5.2.1. Hydrographic network automatic extraction

The flow direction map was useful to determine the main direction of the shallow water downhill, which is strongly correlated to the slope orientation. Within the study area the complexity of the hydrographic network is represented by the strong urbanization which modifies the natural runoff of the shallow water. The flow accumulation map was useful to detect areas where shallow water accumulates and to extract the related hydrographic network, by identifying all the possible water runoff paths (including small streets where water can flow outside the natural hydrographic network). This product is very useful in areas like Antananarivo where the artificial network for the rainfall collection totally or partially lacks. The hydrographic network identified by using a DEM is more complicated with respect to the natural hydrographic network and on turn, those identified by the LiDAR is more accurate with respect to those detected by using the 2 m resolution DEM. The automatic extraction allowed identifying two different hydrographic networks. The first one was obtained by using the 2 m resolution DEM. In this case the maximum stream order identified is the fourth. A more complicated and complete hydrographic network was obtained by using the LiDAR (the maximum stream order is the sixth). The complete result is summarized in [Table 2](#). Despite the very high accuracy of the hydrographic network extracted by using the LiDAR, the amount of detected flow paths makes very difficult the management of this product. The highest stream orders correspond with the most developed hydrographic networks that, usually, collect most of the rainfall. Both the stream order maps (derived by the 2 m resolution DEM and by the LiDAR) show that the most developed hydrographic network is located in the northern sector (Ambatovinaky), in the northwestern sector (between the southern part of Ambatovinaky and the northern part of Manjakamiadana), in the southeastern sector (Ambohipotsy and Andohamandry) and in the southwestern sector (Ambohipotsy).

5.3. Detection of areas at risk

On the basis of the performed field mapping and the hydraulic analysis, the following most critical creek basins were identified:

5.3.1. Basins 3–4

These two basins are located along the hill western slope, and their profile, from ridge to toe slope is characterized by an upper moderately low energy surface, passing downslope to a steep scarp and subsequently to low energy mid-slope-colluvial foot-slope surfaces ([Figures 7–9](#)). Their cover consists of eluvial-colluvial deposits in their upper sectors, while granite outcrops along the scarp. Thick laterite soils form the downslope sector, which links with the river plain alluvial deposits in the toe-slope sector ([Table 1](#); [Figure 11](#)). Both the basins natural hydrographic networks are characterized by a single straight channel (first order), on the contrary, the anthropic hydrographic network is well-developed due to the intense urbanization of the area ([Figures 10](#)). Creek no 3 develops from a small hanging-like valley, located over the scarp between the Rova complex and the Andafiavaratra Palace ([Figures 11](#) and [12\(a\)](#)). This valley is intensely urbanized and characterized by waterlogging areas (partially buried under the road paving); structural damages (cracks and fissures) affect the buildings located along its southern flank, while

Table 1. Characteristics of the mapped creeks.

Basin n°	Area (m ²)	Perimeter (m)	Mean slope (°)	Order	Geology	Running water	Notes	Accessible
1	139125	1857,18	16,56	1	Granite/latecite/eluvial-colluvial deposits	yes	Sheet erosion/scarps/ spring (buried Cathedral)	yes
2	47866,9	964,09	23,87	2	Granite/latecite/eluvial-colluvial deposits	yes	Sheet erosion/scarps	yes
3	165786	1703,47	19,57	1	Granite/latecite/eluvial-colluvial deposits	yes	Small pond (buried in parking lot)	yes
4	64636,5	1434,28	20,07	1	Granite/latecite/eluvial-colluvial deposits	no	Gully erosion/scarps	yes
5	101241	1438,05	24,08	2	Granite/latecite/eluvial-colluvial deposits	no	Scarps	No
6	99482,6	1482,91	23,91	2	Granite/latecite/eluvial-colluvial deposits	no	Gully erosion/scarps	yes
7	53325,5	1243,46	21,37	2	Granite/latecite/eluvial-colluvial deposits	no	Gully erosion/scarps/springs	yes
8	98294	1326,33	22,05	2	Granite/latecite/eluvial-colluvial deposits	no	Sheet erosion/scarps	yes
9	22258,6	647,52	14,64	1	Granite/latecite/eluvial-colluvial deposits	no	Sheet erosion	yes
10	10520,9	475,80	14,37	1	Granite/latecite/eluvial-colluvial deposits	no	Sheet erosion	yes
11	24774,6	833,48	14,96	1	Granite/latecite/eluvial-colluvial deposits	no	Scarps	No
12	51645	1360,18	14,96	1	Granite/latecite/eluvial-colluvial deposits	no	Scarps/granite quarries	yes
13	48935,8	956,02	18,27	1	Granite/latecite/eluvial-colluvial deposits	no	Scarps/granite quarries	yes
14	65393,1	1061,97	20,64	2	Granite/eluvial-colluvial deposits	no	Scarps/granite quarries	yes
15	10482,5	522,48	14,15	1	Granite/eluvial-colluvial deposits	no	Scarps/granite quarries	yes
16	47066,4	954,37	22,34	1	Granite/eluvial-colluvial deposits	no	Scarps/granite quarries	yes
17	95740,8	1536,01	18,61	2	Granite/eluvial-colluvial deposits	yes	Sheet erosion/scarps/3 springs	yes
18	27212,3	741,14	20,17	1	Granite/eluvial-colluvial deposits	no	Sheet erosion/scarps	yes
19	18295,5	740,29	12,20	1	Granite/eluvial-colluvial deposits	no	Sheet erosion	yes
20	40918,1	929,09	14,50	1	Granite/eluvial-colluvial deposits	no	Sheet erosion	yes
21	185145	1898,63	20,67	3	Granite/eluvial-colluvial deposits	yes	Sheet erosion/Cress field	yes
22	26741,2	711,35	22,68	1	Granite/eluvial-colluvial deposits	no	Scarps/sheet erosion	No
23	37678,4	1036,99	21,51	1	Granite/eluvial-colluvial deposits	no	Sheet erosion	No
24	54191,6	1152,39	15,92	1	Granite/eluvial-colluvial deposits	no	Sheet erosion	yes
25	130970	1502,19	25,41	3	Granite/eluvial-colluvial deposits	yes	Sheet erosion/spring	yes
26	42463,4	1120,8	21,63	1	Eluvial-colluvial deposits	no	Sheet erosion	yes
27	41279,7	1004,04	19,65	1	Eluvial-colluvial deposits	no	Sheet erosion	yes
28	62282,7	989,65	17,95	1	Eluvial-colluvial deposits	no	Sheet erosion	No
29	20529,7	699,64	17,97	1	Eluvial-colluvial deposits	no	Sheet erosion	yes
30	17136,2	659,97	17,65	1	Eluvial-colluvial deposits	no	Sheet erosion	yes

Table 2. Stream orders data.

Stream order	No. of streams (DEM)	No. of streams (LiDAR)
1	2161	7048
2	1033	3453
3	523	1764
4	204	886
5	–	28
6	–	7

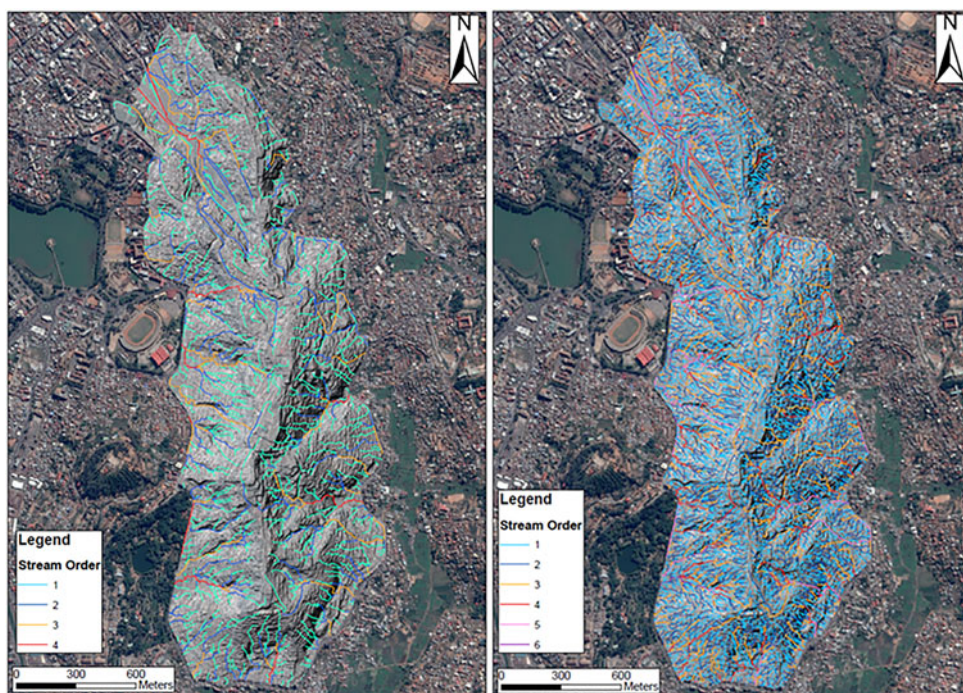


Figure 10. Analamanga hill hydrographic map by using the 2 m resolution DEM (on the left) and the LiDAR (on the right). Source: Author

retaining sand bags placed at the foot of the roadway indicate that the whole valley is affected by instability problems. The basin area, downslope of the scarp, is characterized by narrowing of the creek channel (Figure 12(b,c)), and by the partial burial of the water course beneath the street level. Furthermore, the obstruction provoked by illegal garbage dumping leads the water flow out from the sewer cover or from holes in the road pavement. The creek basin no 4 presents a critical situation in the lower part of the slope: here the creek deeply cuts the laterites forming a gully lavaka-like feature (Figures 11 and 12(d,e)). This erosional morphology, led to the instability of the valley flanks and the intense damaging of the surrounding pathways. The final part of the creek becomes very narrow and it is buried beneath the street level (Figure 12(e)). The geo-hydrological problems of this creek are exacerbated by the burning of the vegetation along the slopes, by several hovels and some concrete building located inside the creek course, and by the presence of abundant garbage obstructing the sewer system.

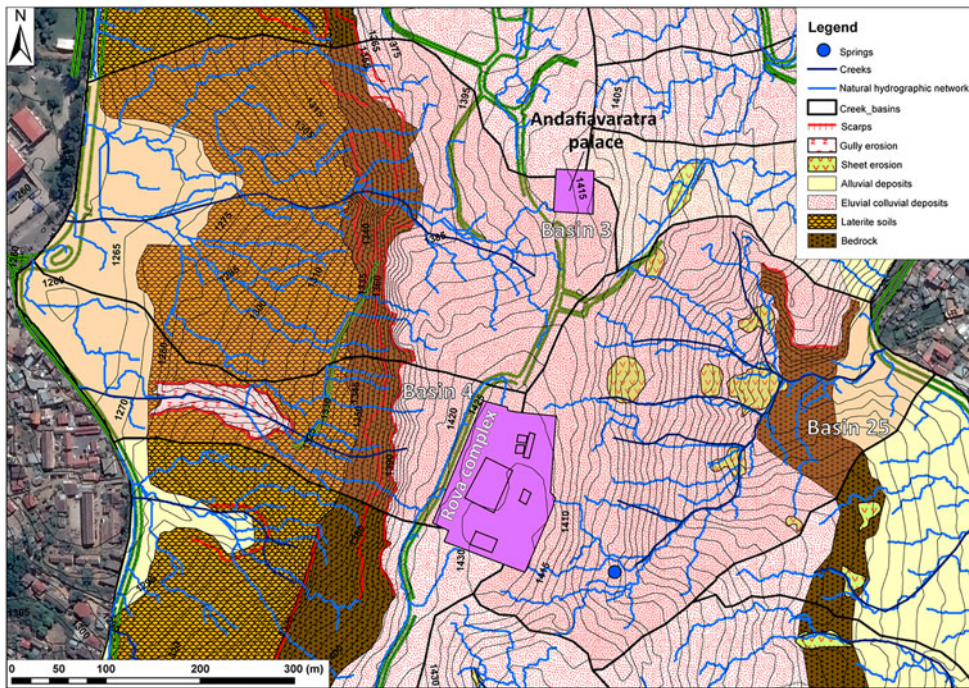


Figure 11. Maps of Basins 3–4 and 25. Green lines mark the roadways and paths. Source: Author

5.3.2. Basin 25

Basin no 25 is located in the Analamanga hill eastern slope and is characterized by a more gentle and regular morphology with respect to basins 3–4, except for a scarp located in the north lower sector (Figures 6, 8 and 10). In its upper sector, the basin cover is mainly formed by eluvial-colluvial deposits (up to a few metres of thickness) overlapping the intensively weathered bedrock, while alluvial deposits characterize the toe slope (Figure 12(f)). Sheet erosion phenomena are common and widespread within the eluvial-colluvial deposits (Figure 8). The basin hydrographic network is the most complex of the area, showing a dendritic-like pattern with a high drainage density (Figure 10). Despite the road system within the basin area is well developed, the artificial drainage network for the collection of rain water is totally or partially lacking, thus rain water flows mainly along the roads, and the sewer system, when present, is often obstructed by garbage. This area corresponds with one of the most prone to landslide zone due to the drainage network density, and to the presence of both granular eluvial-colluvial deposits and intensively weathered granite lacking vegetation cover. The basin is also characterized by the presence of running water within the hydrographic network and by springs (Figure 8). The reduction of the vegetation cover due to the increase of the population represents a real threat for this basin; furthermore, in order to create spaces for the construction of new hovels, the slope gentle morphology has been strongly modified by undercuts artificial terraces (Figure 12(f)). In fact, as a consequence of the 2015 cyclone event, part of the main road passing through this basin collapsed due to a small landslide (Figure 12(g)).



Figure 12. Geomorphological-erosional problems in basins 3–4. Hanging-like valley (a); damaged buildings (red square 1), retained roadway slope (red square 2). Creek 3 hydraulic narrowing (b). Creek 4 lavaka-like gully erosion (c) and hovels built within the creek bed (d). Basin 25 urbanization (e). Source: Author

6. Discussion

The Analamanga hill slopes, once in equilibrium with the surrounding environment, in the last decades have been intensively affected by several uncontrolled anthropic activities, such as: deforestation, illegal quarrying and urbanization (often represented by hovels lacking proper drainage and sewer systems) which are modifying the natural slope conditions, causing the increasing of soil erosion and slope instability processes. Being Madagascar a developing country, the infrastructures that could mitigate the geo-hydrological risks (such as dykes, levees and drainage systems) are few, not always well constructed and not properly maintained. Political and governance issues have also prevented Madagascar from having enough mitigation strategies and qualified personnel to assess the geo-hydrological risks and to design effective landscape

and urban planning (i.e. preventing Malagasy people from building homes in areas prone to landslides).

6.1. Problems

Rainfall induced flash flooding and landslides are a common threat to the communities living on hill-slopes in Antananarivo. Extreme population pressure, burning of the vegetation cover, indiscriminate hill slope cutting, increased precipitation events due to global warming and associated unplanned urbanization in the hills are exacerbating soil erosion and landslide events. The study area is affected by all these problems: the recent growing of the population associated to the unplanned urbanization led to the construction of several unauthorized hovels along the slopes. In order to build these hovels, slopes are continuously modified (slopes cutting and terracing, deforestation, littering). Today the concentration of hovels is very high along all the sectors of the middle town area, especially in the southern sector. This phenomenon is not associated to the construction of facilities, especially the sewer system, the canalization of rainfall water and the garbage collection. In this framework the detection of the flow-path of the rainfall is of primary importance considering the high amount of rainfall during the wet season. The presence of a diffuse urbanization, mainly represented by concrete buildings (some of them of historic interests) and a very huge number of hovels, has a relevant impact on the natural hydrographic network. Furthermore, the uncontrolled development of the urbanization without the related facilities (roads, sewer system and rainfall collection system) strongly modified the shape of the slopes. All these modifications led to the development of the anthropic hydrographic network which act as rainfall collector and in many cases also as sewer system. Today, the very poor conservation of the vegetation cover on the Analamanga hill reduces the retention of shallow water circulation and facilitates the occurrence of landslides and floods. Furthermore, several hovels have been observed inside the natural rivers courses. Their presence represents an obstacle for a correct water runoff especially in case of heavy rainfall events. Another important problem is represented by the abundant presence of garbage (scattered trash all over the slopes and small dumps) which is 'eroded' by the rainfall and channelized into the stream courses blocking the water runoff. As consequence of the occasional plague epidemics the government suggests burning the trash on the slopes. Despite the advantages for the human health, this habit led to burn also the scarce vegetation cover located along the slopes reducing again the shallow water retention and the slope stability.

6.2. Cultural heritage protection from instability phenomena

Climate change and extreme events such as earthquakes, fires, floods and storms, that are posing serious threats to cultural heritage, both movable and immovable. The focus of this paper is on the collection of data which can help to develop predictive models, early-warning devices and novel materials and technologies for adaptation and mitigation strategies. This will also contribute to the issuing of new guidelines, standards and policies whose scope goes even beyond the field of cultural heritage.



Figure 13. Historical aerial (a–c) and terrestrial (d) pictures of the Rova complex (first half of the twentieth century) and the surrounding Analamanga hill slopes. The comparison with the current setting of the Analamanga hill (Figure 4) shows the evidence of the progressive deforestation and increase of urbanization of the Upper and Middle town. Source: Author

Despite that the most important buildings (the Rova complex and Andafiavaratra palace), forming the cultural heritage of Antananarivo, are concentrated in a small part of the Analamanga hill, the analysis of the hydrogeological risks has been performed in a wider area for the following reasons: (i) the upper town of Antananarivo is scattered of buildings of historical interest even if less important with respect to the Rova and Queen palace (Figure 13); (ii) in order to promote tourism the road network to visit the historical part of the city needs to be safe and easily accessible. For the preservation of cultural heritage, it is crucial to develop and validate innovative cost-effective methods and non-destructive diagnostic technologies to map and monitor the state of preservation of, and the impact of environmental changes on, movable and immovable cultural heritage. GIS and new data handling systems have the potential to meet these needs for a more sustainable approach to preserving archaeological and historic sites and buildings. A map of heritage sites and exposure to risk must be prepared. Existing heritages, even when reconstructed, may suffer for not proper conservation and maintenance. An evaluation of the state of conservation and appropriateness of existing strategies, to mitigate the effect of natural threats, should be provided. In general, traditional materials and techniques should be used for conservation work. New materials and techniques (including bio- and nano-technology) may offer additional and longer-lasting solutions, especially for consolidating, coating or cleaning to preserve cultural assets or improve their physical state. However, these advanced materials and technologies should be environmentally friendly and harmless for the user. Emphasis should be given in the involvement of local companies and local population.

6.3. Recommendation and future perspectives

After a careful analysis of the obtained results and the identification of the main problems affecting the study area, we suggest the following actions:

- a. Implementation and proper maintenance of the sewer system. There is the real necessity of a comprehensive plan guiding the local administration in the management of landslide and flash flood hazard. This will consider: (i) Development of a detail hazard and risk map, also taking in account multiple hazards (e.g. seismicity); (ii) Mitigation of landslide and flash flood hazards in a changing climate; (iii) Rainfall water collection and discharge. A project for managing the run-off of free water is necessary. This may include also the waste water from houses. The proper management of surficial water may help in reducing the shallow landslides that are affecting the Antananarivo hills.
- b. Mitigation of soil erosion areas which can potentially trigger shallow landslides in case of heavy rains. The use ecosystem-based technology will be the most appropriate solution, in order to recreate a more natural environment in the Analamanga hill area (biofilter fabric and grassing, viminates, wooden drainage channels). The most appropriate solution and type of vegetation must be investigated by a botanic/green engineering expert.
- c. Stabilization-aggradation of steep slopes affected by gully erosion. The use of granite stone gabions can be an effective solution, easily managed by local workers. A proper design is required in any site, to investigate the soil conditions and the most suitable foundation.
- d. Avoiding construction of new buildings, unless not affecting the occurrence of new landslides, as per the DRM plan of the UNESCO site.
- e. Management of waste materials and avoiding the fire of garbage along the hill-slopes. There is the need to avoid the production of cohesionless material on top of the soil that may flow down, with even small intensity of rainfall.
- f. Mapping and monitoring cultural heritage – scaling up and zooming in. It is crucial to develop and validate innovative cost-effective methods and non-destructive diagnostic technologies to map and monitor the state of preservation of, and the impact of landslide hazard on movable and immovable cultural heritage. A map of heritage sites and exposure to risk must be prepared. Some advanced monitoring technologies (e.g. ground based radar interferometry, wireless sensor networks, laser scanning, etc.) aimed at understanding processes before the conservation can be implemented in relevant or high risky sites.

7. Conclusion

An integrated approach including geomorphological, geological and hydrological analyses was carried out in the area of Antananarivo (Madagascar) surrounding the Analamanga hill slopes, with the aim of mapping the areas more subject to geo-hydrological risks and recommend the priority works to be carried out for the remediation of the site. The area is located in a developing country with limited geological and geomorphological data. The output of the performed activities consisted

of the creation of a detailed geodatabase which, by means of geomatics methods, was integrated with the available data (topographic data, high resolution digital elevation models, very high-resolution satellite images), and homogenized in a GIS environment. The integrated use of high resolution DEM, remote sensing data and filed survey allow the identification of the areas more subjected to geo-hydrological risk in the surrounding of the most important cultural heritage site of Antananarivo. The main result consists in the identification of the most dangerous hydrographic basin of the study area with respect to shallow landslides and floods phenomena. The produced geodatabase represents a fundamental tool for susceptibility, hazard and risk assessment/management activities to be performed in the next future in the Antananarivo hill area. According to the performed investigations, there is a lack of spatial planning and control. This will be necessary to be implemented in the UNESCO core zone as well as in the Buffer zone.

Acknowledgements

This work was carried out in the framework the activities of the UNESCO chair on prevention and sustainable management of geo-hydrological hazards (University of Florence, Italy). The authors would like to thank: IMV Tana City lab and in particular Tamara Teissèdre-Philip and Alexandrine Wadel for providing all of the available topographic data, orthophoto, historical pictures and especially kindness and support during our work; François Cristofoli (RC Heritage/RCh consultants) for the logistic support and precious suggestions; Helihanta Rajaonarison of Antananarivo University for her precious knowledge and guidance, Niandr and Zahara for their valuable assistance and enthusiasm.

Disclosure statement

No potential conflict of interest was reported by the authors.

Websites

<http://whc.Unesco.org/en/list>
<http://whc.Unesco.org/en/tentativelists>
www.eumetsat.int
<http://www.bngrc.mg>
<https://www.americangeosciences.org/>

ORCID

Claudio Margottini  <http://orcid.org/0000-0001-5045-9942>
Nicola Casagli  <http://orcid.org/0000-0002-8684-7848>

References

- Bardi F, Raspini F, Frodella W, Lombardi L, Nocentini M, Gigli G, Morelli S, Corsini A, Casagli N. 2017. Monitoring the rapid-moving reactivation of earth flows by means of GB-InSAR: the April 2013 Capriglio landslide (Northern Appennines, Italy). *Remote Sens.* 9(2): 165.

- Bianchini S, Ciampalini A, Raspini F, Bardi F, Di Traglia F, Moretti S, Casagli N. 2015. Multi-temporal evaluation of landslide movements and impacts on buildings in San Fratello (Italy) by means of C-band and X-band PSI data. *Pure Appl Geophys.* 172(11):3043–3065.
- Boldini D, Guido GL, Margottini C, Spizzichino D. 2018. Stability analysis of a large-volume block in the historical rock-cut city of Vardzia (Georgia). *Rock Mech Rock Eng.* 51(1): 341–349.
- Ciampalini A, Cigna F, Del Ventisette C, Moretti S, Liguori V, Casagli N. 2012. Integrated geomorphological mapping in the north-western sector of Agrigento (Italy). *J Maps.* 8(2): 136–145.
- Ciampalini A, Raspini F, Bianchini S, Frodella W, Bardi F, Lagomarsino D, Di Traglia F, Moretti S, Proietti C, Pagliara P, et al. 2015. Remote sensing as tool for development of landslide databases: the case of the Messina Province (Italy) geodatabase. *Geomorphology.* 249:103–118.
- Ciampalini A, Raspini F, Frodella W, Bardi F, Bianchini S, Moretti S. 2016. The effectiveness of high-resolution LiDAR data combined with PSInSAR data in landslide study. *Landslides.* 13(2):399–410.
- 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.
- Dixey F. 1960. The geology and geomorphology of Madagascar, and a comparison with eastern Africa. *Q J Geol Soc.* 116(1-4):255–268.
- Egglezos D, Moullou D, Mavromati D. 2008. Geostructural analysis of the Athenian Acropolis wall based on terrestrial laser scanning data. The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences - ISPRS Archives 37, B5: 1093-1099. 21st ISPRS International Congress for Photogrammetry and Remote Sensing; Beijing; China; 3 July 2008-11 July 2008.
- Frodella W, Ciampalini A, Gigli G, Lombardi L, Raspini F, Nocentini M, Scardigli C, Casagli N. 2016. Synergic use of satellite and ground based remote sensing methods for monitoring the San Leo rock cliff (Northern Italy). *Geomorphology.* 264:80–94.
- Gigli G, Frodella W, Mugnai F, Tapete D, Cigna F, Fanti R, Intrieri E, Lombardi L. 2012. Instability mechanisms affecting cultural heritage sites in the Maltese Archipelago. *Nat Hazards Earth Syst. Sci.* 12:1–21.
- Goncalves P, Nicollet C, Montel JM. 2004. Petrology and in situ U–Th–Pb monazite geochronology of ultrahigh-temperature metamorphism from the Andriamena mafic unit, north-central Madagascar. Significance of a petrographical P–T path in a polymetamorphic context. *J Petrol.* 45(10):1923–1957.
- Green GM, Sussman RW. 1990. Deforestation history of the eastern rain forests of Madagascar from satellite images. *Science.* 248(4952):212–215.
- Greenlee DD. 1987. Raster and vector processing for scanned linework. *Photogramm Eng Remote Sens.* 53:1383–1387.
- Guzzetti F, Mondini AC, Cardinali M, Fiorucci M, Santangelo M, Chang KT. 2012. Landslide inventory maps: new tools for an old problem. *Earth Sci Rev.* 112:1–25.
- Hyvert G. 1994. Rova d’Antananarivo – Rova d’Ambohimanga Preservation, restauration et mise en valeur. Unesco report, Paris.
- Jenson SK, Domingue JO. 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogramm Eng Remote Sens.* 54(11): 1593–1600.
- Kottak CP. 1980. The past in the present: history, ecology, and cultural variation in highland Madagascar. 1st ed. University of Michigan Press 399p. ISBN-10: 0472063235
- Kroener A, Hegner E, Collins AS, Windley BF, Brewer TS, Razakamanana T, Pidgeon RT. 2000. Age and magmatic history of the Antananarivo Block, central Madagascar, as derived from zircon geochronology and Nd isotopic systematics. *Am J Sci.* 300(4):251–288.
- Larson PM. 2000. *History and memory in the age of enslavement: becoming Merina in highland Madagascar, 1770-1822.* Oxford: James Currey Publishers.

- Lombardi L, Nocentini M, Frodella W, Nolesini T, Bardi F, Intrier I. E, Carlà T, Solari L, Dotta G, Ferrigno F, et al. 2017. The Calatabiano landslide (southern Italy): preliminary GB-InSAR monitoring data and remote 3D mapping. *Landslides*. 14(2):685–696.
- Margottini C, Spizzichino D, editors. 2017. *Historical accesses to UNESCO cultural heritages: engineering geology for the sustainable conservation of Petra Siq*. Vol. 2, Innovative Infrastructure Solutions. 25. doi:10.1007/s41062-017-0074-7.
- Margottini C. 2018. TXT-tool 4.039-2.1: on the protection of cultural heritages from landslides. In Sassa K, Tiwari B, Liu KF, McSaveney M, Strom A, Setiawan H, editors. *Landslide dynamics: ISDR-ICL landslide interactive teaching tools*. Cham (Switzerland): Springer; p.647–667. DOI https://doi.org/10.1007/978-3-319-57777-7_40.
- Margottini C, Di Buduo G. 2017. The geological and landslides museum of Civita di Bagnoregio (Central Italy). *Landslides*. 14(1):435–445.
- Margottini C, Fidolini F, Iadanza C, Trigila A, Ubelmann Y. 2015. The conservation of the Shar-e-Zohak archeological site (Central Afghanistan): geomorphological processes and ecosystem-based mitigation. *Geomorphology*. 239:73–90.
- Nédélec A, Paquette JL, Bouchez JL, Olivier P, Ralison B. 1994. Stratoid granites of Madagascar: structure and position in the Panafrican orogeny. *Geodinamica Acta*. 7(1):48–56.
- Nédélec A, Ralison B, Bouchez JL, Grégoire V. 2000. Structure and metamorphism of the granitic basement around Antananarivo: a key to the Pan-African history of central Madagascar and its Gondwana connections. *Tectonics*. 19(5):997–1020.
- Nolesini T, Frodella W, Bianchini S, Casagli N. 2016. Detecting slope and urban potential unstable areas by means of multi-platform remote sensing techniques: the Volterra (Italy) case study. *Remote Sens*. 8(9):746.
- Planchon O, Darboux F. 2002. A fast, simple and versatile algorithm to fill the depressions of digital elevation models. *Catena*. 46(2-3):159–176.
- Rakotobe ZL, Harvey CA, Rao NS, Dave R, Rakotondravelo JC, Randrianarisoa J, Ramanahadray S, Andriambolantsoa R, Razafimahatratra H, Rabarijohn RH, et al. 2016. Strategies of smallholder farmers for coping with the impacts of cyclones: a case study from Madagascar. *Int J Disaster Risk Reduct*. 17:114–122.
- Ramasiarinoro VJ, Andrianaivo L, Rasolomanana E. 2012. Landslides and associated mass movements events in the eastern part of Madagascar: risk assessment, land use planning, mitigation measures and further strategies. *Madamines*. 4:28–41.
- Ramifehiarivo N, Brossard M, Grinand C, Andriamananjara A, Razafimbelo T, Rasolohery A, Razafimahatratra H, Seyler F, Ranaivoson N, Rabenarivo M, et al. 2017. Mapping soil organic carbon on a national scale: towards an improved and updated map of Madagascar. *Geoderma Regional*. 9:29–38.
- Raveloson A, Szabó AI, Ludván B, Székely B. 2015. Lavaka, the unusual gullies of Madagascar: a review for improved data collection. EGU General Assembly Conference Abstracts (Vol. 17). EGU General Assembly 2015, Vien 12–17 April 2015.
- Strahler NA. 1957. Quantitative analysis of watershed geomorphology. *EOS Trans*. 38(6):913–920.
- Taboroff J. 2000. Cultural heritage and natural disasters: incentives for risk management and mitigation. Kreimer A., Arnold M., editors. *Managing Disaster Risk in Emerging Economies*, Vol. 2. New York: World Bank Publications. Disaster Management Risk; p.71–79.
- Tarboton DG, Bras RL, Rodriguez-Iturbe I. 1991. On the extraction of channel networks from digital elevation data. *Hydrol Process*. 5(1):81–100.
- Tucker RD, Kusky TM, Buchwaldt R, Handke MJ. 2007. Neoproterozoic nappes and superposed folding of the Itremo Group, west-central Madagascar. *Gondwana Res*. 12(4):356–379.
- UNESCO. 2010. *Managing disaster risks for world heritage 978-92-3-104165-5*. Paris: UNESCO.
- Wang JJ. 2015. Flood risk maps to cultural heritage: measures and process. *J Cult Herit*. 16(2): 210–220.
- Wells NA, Andriamihaja B, Rakotovololona HFS. 1991. Patterns of development of Lavaka, Madagascar's usual gullies. *Earth Surf Process Landforms*. 16(3):189–206.