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Constraining landslide timing in a data-scarce context: from recent to very old processes in the tropical environment of the North Tanganyika-Kivu Rift region

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Abstract

Understanding when landslides occur and how they evolve is fundamental to grasp the dynamics of the landscapes and anticipate the dangers they can offer up. However, knowledge on the timing of the landslides remains overlooked in large parts of the world. This is particularly the case in low-capacity regions, where infrastructures are weak or absent and data scarcity is the norm. The tropics stand out as such regions, despite being affected by high and increasing landslide impacts. There, persistent cloud cover, rapid natural vegetation regeneration, cultivation practices and high weathering rates further challenge the harvest of timing information. Based on a synthesis of our recent work we present new findings on the characterisation of the timing of the landslides in the North Tanganyika-Kivu Rift region, a tropical environment with very low capacity and high population density. Our aim is also to highlight the methodological approaches and research strategies that we adopt to investigate such slope processes in a large region lacking baseline studies. From an inventory of more than 9000 landslides with various timing accuracy (from daily to thousands of years), we identify causes and triggers of the slope instabilities in a context of important human-induced landscape changes. This is achieved through a holistic approach that combines field work, satellite remote sensing, historical photograph processing and geomorphic marker understanding. The role of the needs of the local stakeholders in the setting-up of the research strategy is also highlighted and research perspectives discussed.

Keywords

Landslide inventory . Causes and triggers . Environmental change . Hazard assessment . Remote sensing . Africa

Introduction

Understanding when landslides occur and how they evolve is crucial for e.g. landscape evolution modelling, environmental change assessment, hazard prediction and early warning system development (Tucker and Hancock, 2010; Corominas et al., 2014; Tarolli et al., 2014; Gariano and Guzzetti, 2016; Sidle and Bogaard, 2016; Pánek, 2019; Guzzetti et al., 2020). Early warning systems often require information on the timing of landslide occurrence at a (sub-) daily level (Guzzetti et al., 2020) while, at the other side of the spectrum, numerical models of landscape evolution can deal with data constrained within a timeframe of thousands of years (Tucker and Hancock, 2010; Burbank and Anderson, 2012).

Despite the recent advances in e.g. landslide mapping, due to the increased availability of high-resolution high-quality satellite imagery (Fisher et al., 2012; Guzzetti et al., 2012; Belward and Skøien, 2015; Williams et al., 2018), knowledge on the timing of slope instabilities remains rare or is even absent in large parts of the world (Maes et al., 2017, Pánek, 2019; Guzzetti et al. 2020). Characterising the timing is even more complex in low-capacity regions where infrastructures are weak or absent and data scarcity is the norm (Maes et al., 2017).

The tropics, defined here as regions characterised by a tropical climate (Beck, et al., 2018), are environments where research on landslide process understanding is still generally neglected (Gardiano and Guzzetti, 2016; Maes et al., 2017; Reichenbach et al., 2018; Guzzetti et al., 2020). Many landslide-prone areas in the tropics are of very low capacity. In parallel, high population densities are often found, frequently on the rise and combined with high societal vulnerability. It is therefore no surprise that landslides disproportionately impact these regions (Petley, 2012; Kirschbaum et al., 2015; Froude and Petley, 2018; Haque et al., 2019). In addition, landslide frequency and/or impacts in the tropics are expected to increase in the future in response to increasing demographic pressure, deforestation and other land use/cover changes and changing climatic conditions (Sidle et al., 2006; DeFries et al., 2010; Lewis et al., 2015; Gariano and Guzzetti, 2016; Souverijns et al., 2016; Froude and Petley, 2018; Haque et al., 2019).

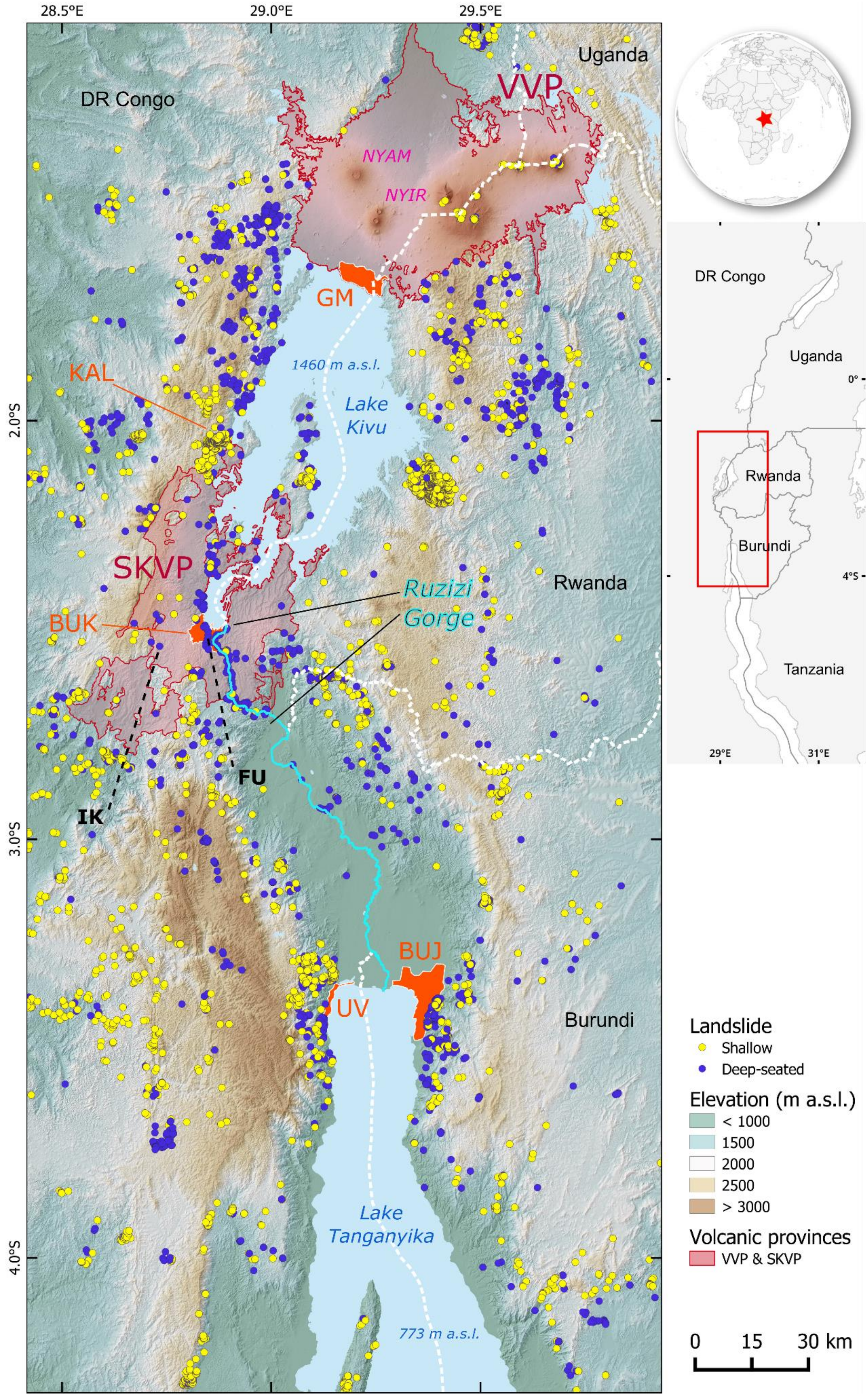
The tropics also present environmental conditions that challenge the harvest of information on the timing of landslides: (1) the frequency of optical satellite image acquisition is impeded by cloud persistence conditions (Wilson and Jetz, 2016; Robinson and al., 2019), (2) natural vegetation regeneration after a disturbance can be very rapid and conceal landslide scars (Sidle et al., 2006; Chazdon, 2014), (3) slash-and-burn practices and shifting cultivation leave complex heterogeneous patterns across the landscape that challenge landslide scar delineation (Baker and Bunyavejchewin, 2009; Rabby and Li, 2019), and (4) soil/rock weathering is high (Thomas, 1994), the latter also making absolute dating more challenging (Burbank and Anderson, 2012). In addition, in high population density regions, anthropic influences such as land reclamation and levelling are expected to smoothen or even obliterate landslide morphological signatures (Van den Eeckhaut et al., 2007; Dewitte et al., 2009).

The objective of this contribution is two-fold. First, based on an overview of the progresses achieved over the last years we present new findings on the characterisation of the timing of the landslides in the North Tanganyika-Kivu Rift region, a tropical environment with very low capacity and high population density. Second, we highlight through this process-oriented synthesis the methodological approaches and research strategies that we adopt to investigate this large region lacking baseline studies. The paper follows a timeline structure where three categories of timing are analysed; from (1) the (sub-) daily information, to (2) the monthly to the multi-decade and historical perspective, and (3) the geomorphic landscape evolution markers. A last (4) section is dedicated to site-specific in-depth characterisations.

2. The North Tanganyika-Kivu Rift region: a populated environment where local stakeholder expectations must be met

The mountainous environments of the western branch of the East African Rift stand out as a landslide hotspot in the tropics (Stanley and Kirschbaum, 2017; Broeckx et al., 2018). The region is a system where natural predisposing and triggering factors, such as high rainfall intensities and high annual rainfall totals, moderate to high seismicity, high weathering and steep landscapes promote the occurrence of landslides (Jacobs et al., 2016; Monsieurs et al., 2018a; Nsengiyumva et al., 2019). More specifically we focus on a 50000 km² area that extents from the North Tanganyika Rift zone in the south to the Virunga Volcanic Province (VVP) in the north (Fig. 1), hereafter called North Tanganyika-Kivu Rift region (and abbreviated NTK Rift). The NTK Rift, that initiated about 11 Ma, opens up at a current rate of 2 mm/yr (Kampunzu et al., 1998; Saria et al., 2014) and is associated with active volcanism, seismic activity and fault structures (Smets et al., 2016; Delvaux et al., 2017; Oth et al., 2017). Its lithology is diverse and of various ages, leading to a wide range of weathering processes (Kampunzu et al., 1998; Pouclet et al., 2016; Smets et al., 2016; Delvaux et al., 2017; Laghmouch et al., 2018). Numerous knickpoints attest the occurrence of recent relief erosion waves. The region has a bimodal rainfall regime with annual precipitation ranging from ~0.8 m in the region of Bujumbura to > 2,5 m in the north-west mountains (Monsieurs, 2020). Most of the NTK Rift was covered with forests; large-scale deforestation having started to take place at the beginning of the 20th century (Ellis et al., 2010). This deforestation accompanied with land conversion to agriculture and the setting up of road and trail networks brought changes to the hillslope hydrology and the connected river patterns. It is indeed observed that recent incision is frequent in the steepest part of river reaches while the lowest sections seem to be more affected by lateral widening and braided patterns (Moeyersons, 2000; Moeyersons and Trefois, 2008).

The area has one of the highest population densities of Africa (frequently > 300 inhab/km^2), urban expansion is very fast, anthropogenic pressure high, accessibility low and population vulnerability high (Linard et al., 2012; Michellier et al., 2016). Bujumbura, Bukavu and Goma are cities with population of ~800000 inhabitants each (a few thousands in the 1950s; Michellier et al., 2018, 2020). At the global level, this region is one of the most exposed places to landslide hazard (Emberson et al., 2020). The livelihood of a large majority of the population depends on agriculture and a significant part of the population is directly or indirectly involved in the often illegal mining/quarrying sector, both contributing to changes in the landscape (Trefon, 2016). The area is at the border between four countries, with different – often weak- governance policies, socioeconomic characteristics and security levels; the latter issue limiting field accessibility. The lack of governance and poor political stability plays also a role in the deficiency of data recording (Trefon, 2016; Maes et al., 2018).



28.5°E
29.0°E
29.5°E
Uganda
DR Congo
VVP
NYAM
NYIR
GM
1460 m a.s.l.
KAL
Lake
Kivu
2.0°S
SKVP
BUK
Ruzizi
Gorge
Rwanda
FU
IK
3.0°S
BUJ
UV
Burundi
Lake
Tanganyika
773 m a.s.l.
4.0°S
DR Congo
Uganda
0°
Rwanda
Burundi
4°S
Tanzania
29°E
31°E
Landslide
Shallow
Deep-seated
Elevation (m a.s.l.)
< 1000
1500
2000
2500
> 3000
Volcanic provinces
VVP & SKVP
0 15 30 km

Fig. 1 Location of the NTK Rift and the main study sites. The landslide inventory is an updated version of the dataset from Depicker et al. (2020) and contains more than 8000 occurrences. VPP: Virunga Volcanic Province. SKVP: South Kivu Volcanic Province. NYAM: Nyamulagira volcano. NYIR: Nyiragongo volcano. BUJ: Bujumbura. BUK: Bukavu. GM: Goma. KAL: Kalehe. UV: Uvira. IK: Ikoma landslide. FU: Funu landslide

We adopt a holistic research strategy to characterise the landslide processes in the NTK Rift based on various datasets, methods and techniques (Table 1). The strategy was set up in 2014. At that moment little was known in the region, except from local-scale studies that reported on the occurrence of a few landslide events, mostly in cities (Moeyersons et al, 2004; 2010). Since landslides present an important constraint to the local population, a priority focus is given on hazard assessment and the consideration of human-induced environmental changes. In addition to a regional-scale investigation, priority attention is also paid to the cities of Bujumbura and Bukavu as well as the populated mountainous flanks west of Lake Kivu. In the region of Bukavu, two specific landslides (hereafter called Ikoma and Funu) are investigated more intensively (Fig. 1). The research is also designed with the long-term goal of setting-up early-warning systems (though not reached yet). The rationale for this is to meet the expectations and constraints of local stakeholders and research partners (Michellier et al., 2017). We can therefore build up long-term collaborations through, among others, support to local PhD researches who know the environments of their research, the local authorities and other resource people. This is a fundamental ingredient to warrant a strong field-based pillar in the characterisation of the slope processes, i.e. a unique set of information for such a low-capacity environment with limited field accessibility (Trefon and Cogels, 2006; Monsieurs et al., 2017).

		Target area						Importance					
		Regional				Local							
		NTK Rift	West of Lake Kivu	Bukavu/Ruzizi Gorge	Bujumbura	Funu landslide	Ikoma landslide	(Sub-) daily	Days to months/years	Decades	Geormophic markers	In depth	
Data/method/technique	**Time range**												**References****
Report	2002-present	X	X	X	X	X	X	C	H	L	-	L	Monsieurs et al., 2018a; Monsieurs et al., 2019a, 2019b
Very-high spatial resolution optical satellite images													
Google Earth imagery (VA)	2004-present	X	X	X	X	X	X	-	C	-	C	H	Maki Mateso and Dewitte, 2014; Depicker et al., 2020
DSM (1 m resolution) from (tri-) stereo Pléiades* (VA)	2013 - 2019			X	X			-	M	-	L	H	
Radar satellite images													
DInSAR (COSMO-SkyMed, Sentinel-1) time series	2015 - present			X		X		-	C	-	-	C	Nobile et al., 2018; Samsonov et al., 2020
DSM (5 m) from TanDEM-X images* (VA)	2014		X	X				-	M	-	H	L	Albino et al., 2015; Jacobs et al., 2018
Remotely-sensed rainfall products													
TMPA, IMERG	1998-present	X				X	X	C	C	-	-	H	
DSM (1 arc second) from SRTM (VA)		X	X										
Orthomosaics of historical aerial photos* (VA)	1950s; 1970s		X	X	X	X	X	-	-	C	M	C	Dewitte et al., 2018; Smets et al., n.d.
Field observation of recent events	2014-present	X	X	X	X	X	X	H	C	-	-	C	Balagamire et al., 2017; Kalikone Buzera et al., 2017; Kulimushi matabaro et al., 2017; Mugaruka Bibentyo et al., 2017
Field observation of older landslides	2014-present	X	X	X	X	X	X		H	H	C	H	Balagamire et al., 2017; Kalikone Buzera et al., 2017; Kulimushi matabaro et al., 2017; Mugaruka Bibentyo et al., 2017
Field observation of the landscape	2014-present	X	X	X	X	X	X	-	L	M	H	H	Dille et al., 2019; Depicker et al., 2020
UAV*	2017 - 2019					X	X	-	-	-	-	H	Dille et al., 2019
dGNSS*	2015 - 2019					X		-	-	-	-	H	Nobile et al., 2018; Samsonov et al., 2020
Rain gauge network*	2015-present	X	X			X	X	C	H	-	-	H	Monsieurs et al., 2018b

X = used for the target area
C = critical data set, H = highly important, M = moderately important, L = Less important, – = Not relevant
* = data produced within this study ** = references that concern this study area
VA = visual analysis (elevation, countour line, hillshading)
DSM = Digital Surface Model
DInSAR = Differential Interferometric Synthetic Aperture Radar
TMPA = Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA)
IMERG = Integrated Multisatellite Retrievals for Global Precipitation Measurement

Table 1. Data, methods and techniques used for acquiring information on the timing of the landslides in the NTK Rift. The ranking of their importance (after van Westen et al., 2008) is provided for four categories of time and the in-depth characterisations. The ranking is specific to the region.

3. Landslide characterised at a (sub-) daily accuracy

Although the NTK Rift is known for being of very low capacity, its population density is high, and local reporting of landslide events cannot be ignored (Monsieurs et al., 2018a). Using information from different sources (Internet, grey literature, etc.), we developed a regional-scale methodological workflow to search for landslide events with at least a daily accuracy and a known location (Monsieurs et al., 2018a). A landslide event being here defined as either a single landslide or a group of landslides with a common trigger over the same area (Kirschbaum et al., 2010). For the NTK Rift, we now have information on the timing and location for 152 landslide events spanning the 2002-2019 period; i.e. a figure much larger than the few entries that were initially available in international catalogues (Petley, 2012; Kirschbaum et al. 2015). This catalogue of dated landslide events was validated with field observation (e.g., Fig. 2e and Fig. 3c) as well as Google Earth imagery visual interpretation. It does not contain the occurrences linked to mining and quarrying activities (Fig. 4d).

According to Keefer (2002), earthquakes of moment magnitude M_w ~4 can already cause slope failures such as rock falls and rock slides. To further explore the triggering conditions of the dated landslide events, we confront them to the seismic catalogues from USGS (compiled and validated by Delvaux et al., 2017 + additional recent updates) and most recent (2016-2019) records from the local KivuSNet, the very dense seismic network implemented in the region (Oth et al., 2017). In the NTK Rift, 173 earthquakes with M_w between 4.1 and 6.3 occurred during the 1956-2019 period. Considering the empirical correlation proposed by Keefer (2002) that link earthquake-induced landslide distribution areas with $M_w > 5$, we found that 30 % of the landslide events are located in areas where seismicity could have played a role in the triggering of slope failures (Fig. 3a). However, we found that the time lag between earthquakes and landslide events is of at least a few years with an average of 29 years. For earthquakes of magnitude higher than that recorded in the last 60 years in the NTK Rift, Hovius et al. (2011) and Marc et al. (2015) show that the delayed effects of earthquakes on slope stability is of a few years maximum. In our analysis, even though the earthquake impact zonation is simple (Marc et al., 2017), we can argue that the dated landslide events are not triggered by earthquakes.

On the other hand, the link between rainfall seasonality and the triggering of landslides can be demonstrated at the regional level when plotting the dated events against the monthly rainfall based on ~20 years (2000–2019) of IMERG-F daily data (Huffman et al., 2019) averaged over the study area (Fig. 3b). This regional assessment of the triggering conditions must however not ignore that some landslides may actually have occurred without any apparent trigger (Dille et al., 2019; Section 6), and that human activities can sometimes be their only cause (Kalikone Buzera et al., 2017). For the former, Monsieurs (2020) evidences that few landslides seem to have occurred during dry periods. Using part of the event catalogue, Monsieurs et al. (2019a, 2019b) developed a new transferable rainfall threshold approach that is adapted also for a data-scarce context such as the NTK Rift. With this approach, they underscore that rainfall amounts required to trigger landslides decrease for increasing landslide susceptibility (Monsieurs et al., 2019a, 2019b). This analysis also shows that at the regional level, most landslides respond to antecedent rainfall conditions of several weeks. Note that this rainfall analysis benefited highly from the use of validated satellite precipitation products; the validation being done through rain gauge data in provenance of existing networks in Rwanda, but also from our own networks that have been deployed for more than three years in DR Congo and Uganda where such monitoring systems were absent (Monsieurs et al., 2018b; Camberlin et al., 2019; Monsieurs, 2020).

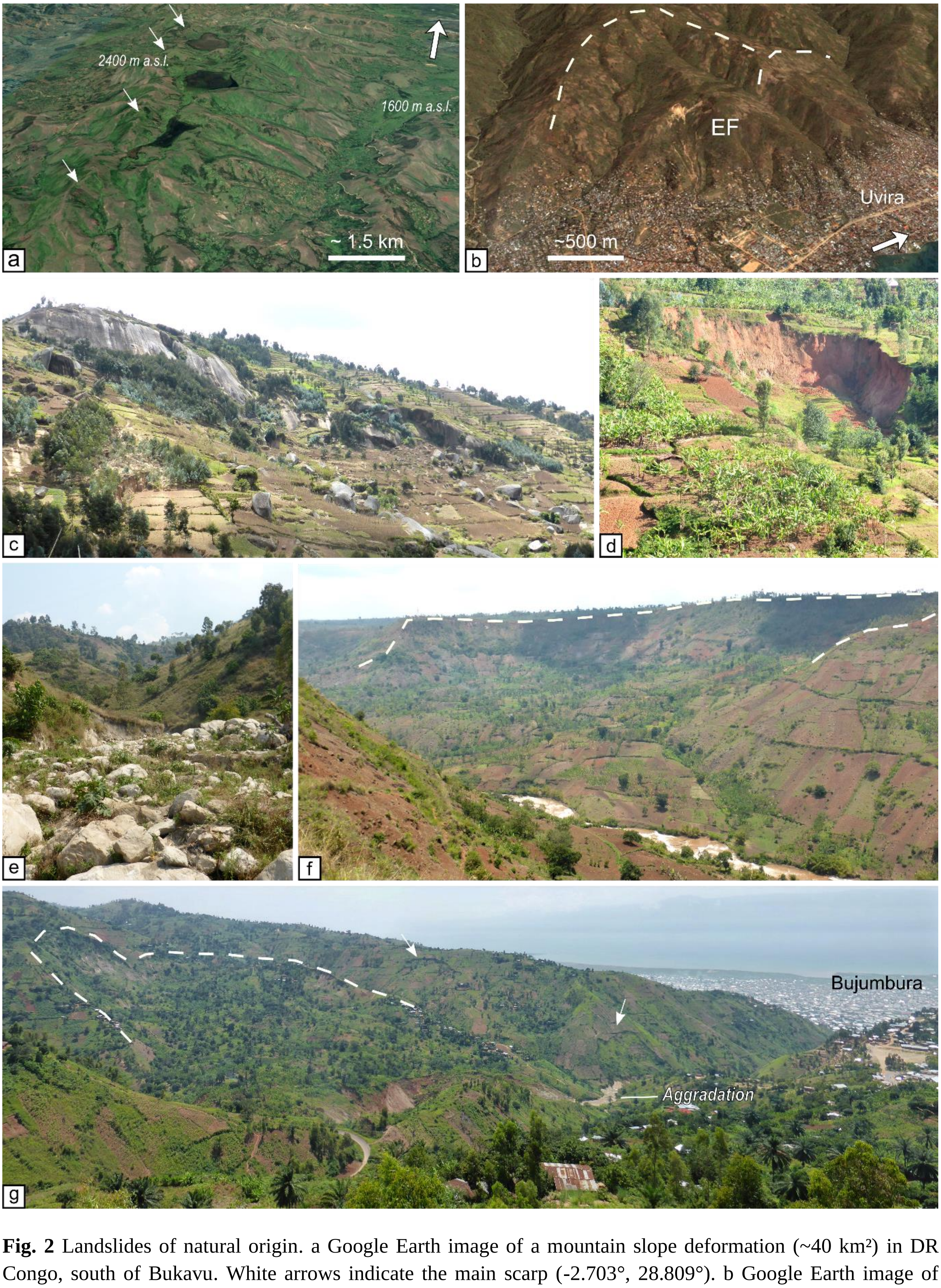


Fig. 2 Landslides of natural origin. a Google Earth image of a mountain slope deformation (~40 km²) in DR Congo, south of Bukavu. White arrows indicate the main scarp (-2.703°, 28.809°). b Google Earth image of slides along a fault system in Uvira (DR Congo). EF denotes an active earthflow on a displaced block (-3.391°, 29.127°). c Rock fall/avalanche in a granite outcrop in Rwanda, Sept. 2018 (-1.666°, 28.561°). d Recent rotational slide developed in thick regolith in Rwanda, Sept. 2018 (-1.804°, 29.606°). e Debris flow triggered by an intense thunderstorm on 25 Oct. 2014 in Kalehe (DR Congo). Photo taken in July 2015 attests the quick vegetation regeneration (-2.044°, 28.899°). f Rotational slide along the Ruzizi Gorge. Photo taken from DR

Congo (Oct. 2017), Rwanda is in the background (-2.637°, 28.909°). g Active slide – earthflow (Bujumbura, February 2015). White arrows indicate the main scarp of smaller landslides (-3.431°, 29.387°)

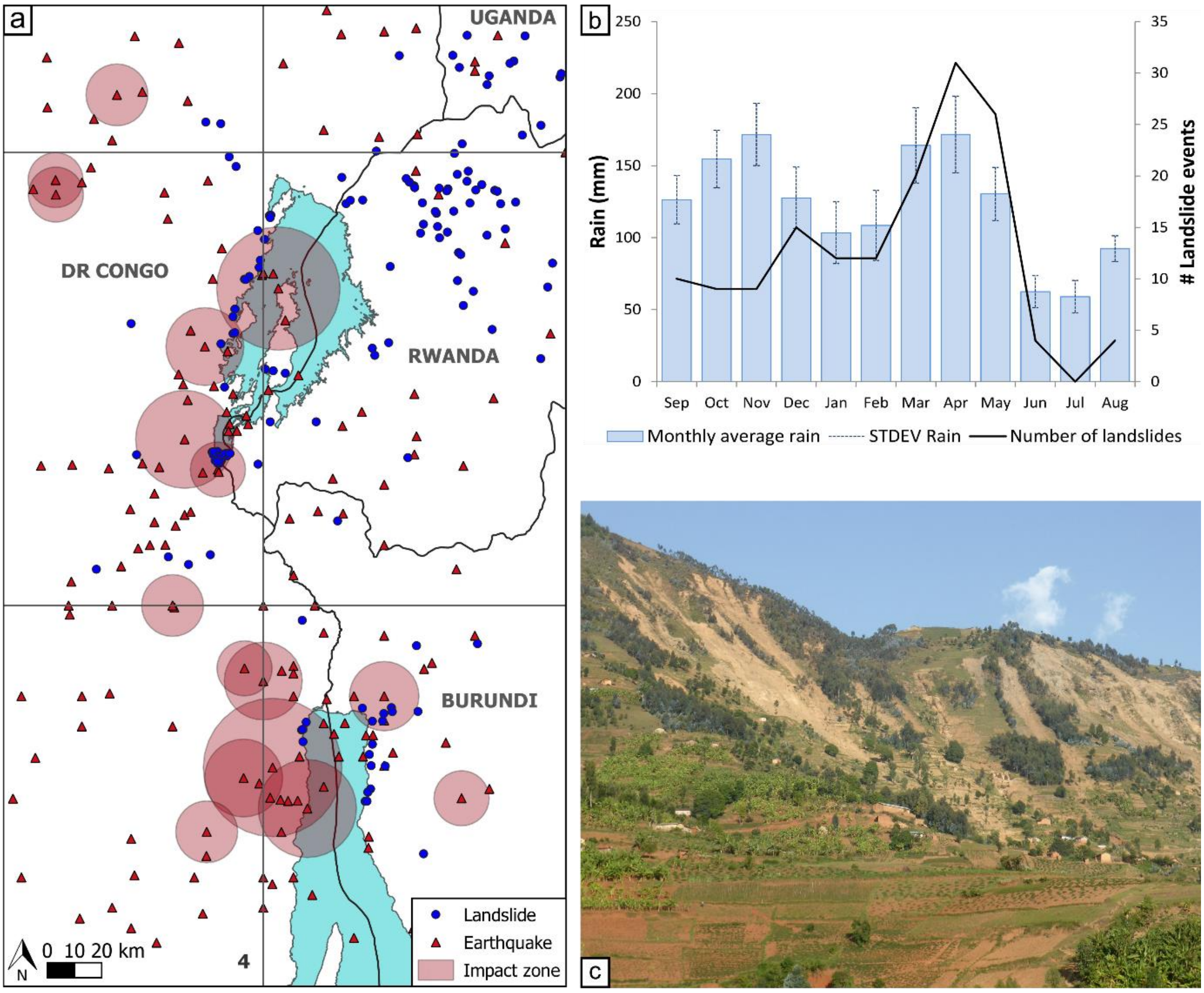


Fig. 3 Landslide events and triggering factors. a Location of the 152 dated landslide events and the 173 earthquakes with M_w between 4.1 and 6.3. For earthquakes with $M_w > 5.5$, the impact zone as proposed by Keefer (2002) are depicted in red. b Rainfall seasonality and distribution of the 152 dated landslide events. c Example of a landslide event in Rwanda (photo taken in Sept. 2018). About 1000 debris slides and debris avalanches were triggered by an intense rainfall on 6 May 2018. This event caused fatalities and was highly reported in the news (-2.151°, 29.368°)

4. Monthly, multi-decadal and historical landslides

Google Earth imagery is highly relevant to identify landslides in many different contexts, especially in remote terrains across large spatial extents (e.g., Fisher et al., 2012; Broeckx et al., 2018; Williams et al., 2018). In the NTK Rift, it offers at least one, but very often several very-high resolution images for most of the area (spatial resolution 30 to 60 cm), with higher density of acquisition over the large cities and areas of mining activities. In some places, the image cover spans more than 10 years.

Using Google Earth, we mapped more than 9000 landslides at the regional level (Maki Mateso and Dewitte, 2014; Maki Mateso et al., 2018; Depicker et al., 2020). The mapping (with 3D view activated and elevation exaggeration of 1) was done manually for all landslides and both source and deposit (runout) areas were delineated as polygons. For the old landslides that are covered with vegetation, this was the only option since automatic detection approaches would not work. For the recent and active ones, this was done to avoid amalgamation (Marc and Hovius, 2015). Also, a distinction is made between shallow and deep-seated landslides with the latter being > 5 m deep. This parameter of depth is important to consider in our research since the occurrence of shallow movements is much more sensitive to varying surficial landscape environments (e.g., land use/land cover and its changes) and rainfall conditions (Sidle and Bogaard, 2016). In addition, shallow landslide signatures disappear more quickly from the landscape (Dewitte et al., 2009; Sidle and Bogaard, 2016).

Landslides are diverse in size (from a few tens of m² to 40 km² - Fig. 2a), shape and process (categorized according to Hungr et al., 2014). They appear in various environments (urban areas, rural areas, pristine forests). In terms of time of occurrence, we identified three populations of landslides (Fig. 1):

- Recent landslides with a well constrained time of occurrence. These landslides occur between two subsequent satellite images in Google Earth (Fig. 2d,e, Fig. 3c). We often observe populations of rather shallow landslides (slide, flow) that can concentrate in clusters that correspond to events triggered by intense rainfall (Fig. 3c; Monsieurs et al., 2018a; Depicker et al., 2020). Larger and deeper landsides can also be present in these events. In addition to the clusters, landslides can occur individually (various shallow and deep processes of different sizes). For the shallow landslides, we observed that their scar can disappear quickly, sometimes in less than two years, because of land reclamation and/or quick vegetation regeneration (Fig. 2e; Maki Mateso et al., 2018). For the larger and deeper landslides, they remain visible easily over several years, attesting the activity that characterise the first years of a slope failure (Dewitte et al., 2008; Dille et al., 2019).
- Recent landslides whose time of occurrence cannot be constrained between two images. These landslides look active/recent in the oldest satellite images. All types of landslide processes identified in the former group are also in this category, except for the earthflows (Fig. 2g). The latter are known for sometimes being active during several decades (e.g., Mackey and Roering, 2011).
- Historical landslides are either landslides that do not appear active in the oldest images or active earthflows that cannot be constrained between two images. This population includes landslides whose period of origin is unknown and their age can only be given, when possible, in relative terms (Guzzetti et al., 2012). They can have occurred over periods of easily up to thousands of years (see Section 5). In this category falls only larger deep-seated landslides (Fig. 2a,b,c,f,g). Indeed, the morphological signature of smaller landslides is removed due to erosion and weathering processes, subsequent landslides, vegetation growth and anthropic influences. In addition, at the same time, landslide boundaries become increasingly indistinct (Malamud et al., 2004).

Google Earth is used here in a conservative way to delineate the landslides, especially the historical ones. It is only when feature observation is judged reliable that a new entry is added to the inventory. In natural landscapes, dense evergreen forests that characterise this tropical environment tend to mask scars of non-active landslides. As stressed in the introduction, this can be further exacerbated by high weathering. And in the human-dominated landscapes, agricultural patterns challenge feature delineation.

We validated more than 1000 landslides in the field (surveys carried out in the regions of Bukavu, Bujumbura, the Ruzizi Gorge, Kalehe and western Rwanda) and could attest the very high reliability of feature identification from Google Earth. With Google Earth, examining the shape and the size of both the landslide scar and deposit areas, distinction between shallow and deep-seated processes was not always straightforward due to the low topographic resolution of the 3D terrain display. Yet, observation in the field enabled us to confirm that this depth estimation is quite fair. It was further confirmed by analysing the topographic signature of landslides predating the acquisition of the 1- and 5-m resolution digital surface models (DSM) (Table 1); only deep-seated processes leaving an apparent scar. Despite Google Earth general good abilities, we also observe that we still miss many, often small, landslides; stressing the need of field-based observations for intensive local investigation.

Field investigations also allowed us to better grasp the role of human disturbances in the dynamics of the hillslopes (Fig. 4). Alongside actively quarried river reaches, we observe for instance the presence of many, rather small, recent and active landslides (Fig. 4e). We suggest that a lack of bedload is at the origin of local river incision, hillslope/riverbank over-steepening and subsequent collapse. Bujumbura, as well as regions in NW Rwanda, are particularly affected by this process. Oppositely to river incision, the presence of large erosion features such as gullies on the hillslopes (sometimes linked to mining/quarrying activities) can supply sediment to the river, modify their channel morphology and add variability to their erosion and aggradation patterns. A common observation in river morphology is the shift towards more braided systems with increase lateral mobility and subsequent hillslope/riverbank over-steepening (Fig. 4c). This shift in river morphology is in agreement with observations made by Moeyersons (2000) and Moeyersons and Trefois (2008) in the region. Note that increase lateral mobility and braided patterns are also due to active earthflows that supply sediment to channels (e.g. Fig. 2g). Land management such as terracing is known to change water drainage networks, which could lead to the occurrence of landslides (Sidle et al., 2006; Tarolli et al., 2014). Though this process still requires further investigation in the NTK Rift, some examples of recent landslides occurring in terraced landscapes were observed (Fig. 4b). Similarly to what is observed in other mountainous regions (e.g., Sidle et al., 2006; Brenning et al., 2015), the frequency of landslide occurrence is highly increased along the roads where inadequate drainage systems, hillslope undercutting (Fig. 4f), overloading and landfills are common. Most of these landslides along the roads are usually too small to be identified in Google Earth. Note that these landslides were not included in the regional landslide susceptibility assessment (Depicker et al., 2020) as they are linked to engineered slope controls that cannot be constrained from regional topographic products such as the 1 arc-second SRTM (Farr et al., 2007).

The city of Bukavu was further analysed thanks to the combined use of historical aerial photographs, recent satellite images, 1 and 5 m resolution DSMs and careful fieldwork (Table 1). We built a multi-temporal historical inventory for a period of 60 years and identified more than 130 landslides (Balegamire et al., 2017; Kalikone Buzera et al., 2017; Kulimushi Matabaro et al., 2017; Mugaruka Bibentyo et al., 2017). In total, they affect ~30% of the urban territory. Differentiation was made between rotational and planar slides as well as between shallow and deep-seated processes. Gully systems that are developed in large landslides and that in turn often trigger mass movement processes were also inventoried. Based on the empirical visual approach developed by Cardinali et al. (2002), we can propose a landslide chronology where relative ages are estimated for three categories (Fig. 5). A category with recent landslides (1) that includes landslides that look morphologically fresh on the historical aerial photographs, and new landslides or reactivations that occurred after the acquisition of historical photographs and that can be identified in the more recent photos or images, or checked by field mapping and archive analysis. Old landslides (2) that show a clear morphology without erosion features on the historical aerial photographs. Very old landslides (3) that show a morphology that is at least partly dismantled by erosion, sometimes heavily. Most large deep-seated landslides display old or very old features. Shallow landslides are all recent as it is assumed that older features are no longer identifiable. Gully systems are all considered as recent. As stressed by Guzzetti et al. (2012), the distinction of such timing requires the ability to visually recognize landslides that leave faint, subtle topographical or land cover changes.

Not all landslides in Bukavu are of natural origin. Small slope instabilities are often linked to slope cutting and over-steepening due to the construction of roads or terracing of the landscape for building, often illegally, houses on the steep slopes. Gully systems are often connected to poor and/or unmaintained drainage systems. For the reactivation in 1997 of a rather large deep-seated slide developed in more than 60 m thick regolith, we were able to reconstruct a careful history of the hillslope dynamics over the last 60 years, showing that complex interactions between natural and human processes played an important role in this failure (Mugaruka Bibentyo et al., 2017). We also identified the role of local runoff concentration and water pipe leaking on the local increased activity of parts of some other large landslides (Kalikone Buzera et al., 2017). At the scale of the city, changes in natural and human-induced distribution and patterns of landslides allows then to infer the possible evolution of the slopes, the most probable type of failures, and their expected frequency of occurrence and intensity. Based on the inventory we are then able to propose hazard scenarios that coincide with today's changing environment (Michellier et al., n.d.).

Bujumbura is currently investigated in a similar way as Bukavu (Table 1). The landslide patterns are however different between the two places. In Bukavu, landslides are present in the urban and populated areas, leading to disturbance and impacts immediately on site. In Bujumbura, besides the recent and active landslides that affect the banks of the rivers that run through it, landslides extent mostly on the steeper slopes at the outskirt of a rather-flat city centre (Kubwimana et al., 2018). Similarly as in Bukavu, some of these landslides are old to very old and rather large (up to a few km²) and the recent and small instability processes are also often influenced by anthropogenic disturbance. One specificity of Bujumbura lies in the presence of km-size slow-moving earthflows that are often in contact to the rivers (Fig. 2g). Through cascading effect, similarly to what has been described in Uvira (Moeyersons et al., 2010), they can temporally dam the rivers, which, when they breach, cause (sometimes deadly) flash floods (Monsieurs et al., 2018a; Nibigira et al., 2018). These earthflows have been active for at least several decades as witnessed though their continuous damages to road infrastructures. Large and deep gully systems are also present in urbanized slopes. Their incision removes lateral support of hillslope foot slopes (Poesen, 2018) and cause landslides, sometimes > 1 km² (Fig. 4a). These gully-landslide systems were almost absent in the 1950s, i.e. before the urbanization and the subsequent changes in the water runoff patterns (e.g., Makanzu Imwangana et al., 2014).

Fig. 4 Landslides caused by human disturbances. a Landslides developed along a large gully system linked to urban growth in Bujumbura, Feb. 2015 (-3.409°, 29.381°). b Deep-seated (flow) slide in Rwanda (Sept. 2018) developed on a terraced hillslope carved in regolith (-2.049°, 29.460°). c Mining (Coltan) triggers gullying, which triggers landslides, Rwanda, Sept. 2018 (-1.987°, 29.604°). d Flowslide in regolith affecting a gold mining site in South Kivu, DR Congo, June 2016 (-2.857°, 28.736°). e River incision in colluvium/alluvium in Bujumbura (Sept. 2013) and subsequent bank erosion and landsliding (-3.399°, 29.383°). f Rock avalanche at a road cut in Rwanda, Sept. 2018 (-1.825°, 29.627°)

5. Landslides and geomorphic markers

In the absence of absolute dating, an approach to unravel the period of occurrence of historical landslides is to analyse their spatial distribution with regard to geomorphic markers of the landscape (Korup et al., 2010; Burbank and Anderson, 2012). The level of Lake Kivu is such an identifiable feature. The lake is rather young compared to the other great lakes in the East African Rift. It was formed during the late Pleistocene, when lavas from VVP dammed the then upper part of the Rift basin draining north towards the Nile River system (Fig. 1; Haberyan and Hecky, 1987). The level of the lake rose, reaching its maximum ~100 m above the current one at ~10 ka BP when it started to drain southwards into Lake Tanganyika (Felton et al., 2007; Ross et al., 2014).

Outflow took place in a region where is now sited Bukavu, developing into a gorge along a pre-existing fault system and forming the upper reach of the Ruzizi River (Figs. 1 and 5). Landscape features show that the initiation of this new sediment-starving river reach was accompanied by a very rapid incision of the bedrock, reaching in some places more than 200 m. In its current morphology, the Ruzizi Gorge consists in a knickzone with an elevation drop of 500 m over a distance of 30 km. If we are conservative and assume linearity since the initiation of the gorge formation, we have an extremely high incision rate of ~20 mm yr^{-1} (Burbank et al., 1996). If we consider overtopping and knickpoint retreat, incision rate could be much higher (Cook et al., 2013; Anton et al., 2015). Such incision rates create threshold hillslopes highly prone to landsliding (Burbank et al., 1996; Ouimet et al.; 2007, Larsen and Montgomery, 2012) as witnessed by the ~50 deep-seated landslides (size up to 2 km^2) we identify along the gorge (Fig. 2f). Note that these landslide debris could serve to stall bedrock erosion (Ouimet et al., 2007), which reinforces the hypothesis that a linear incision rate is conservative. The landslides of the Ruzizi Gorge have morphologies that look more recent than others that are distributed, for example, along major fault systems (Fig. 2a,b).

Apart from the landslides along the Ruzizi Gorge, the other large landslides in the city of Bukavu form a cluster of deep-seated landslides at the regional level (Fig. 1). Moeyersons et al. (2004) identified several fault morphologies in the city, landslides being positioned along them. Delineating the level of Lake Kivu ~100 m above the current one, we can see that some of the landslides were at that time in contact with the water highstands (Fig. 5). Pánek et al. (2016) linking the occurrence of large landslides to highstands of the Caspian Sea, this cluster of landslides could be explained by such a combination of Holocene water highstands and specific morpho-tectonic conditions (Fig. 6a shows a typical example of landslide that could be linked to the highstands). Looking at field evidence, we found in Bukavu a landslide deposit area covered with lacustrine material/sub-horizontal colluvium, proving that this landslide, classified as very old (see Section 4), occurred or was reactivated at least 10000 years ago (Fig. 5).

The shoreline of the lake is characterised by the presence of many prograding deltas, formed at the current lake level along the steep slopes of flooded valleys. We observe that some rock slides and rock avalanches distributed along those slopes have their deposit area buried in the lake sediments (Fig. 6b). This shows that their occurrence either preceded the lake formation or happened when the delta extension was still limited. We suggest that these landslides are easily a few thousand years old. They are surely older than the landslides that have their deposit area that cover the deltas (Fig. 6c). Similar patterns of landslides with buried deposit area are observed in post-glacial sediments that fill the Rhone valley in Switzerland (Pedrazzini et al., 2016).

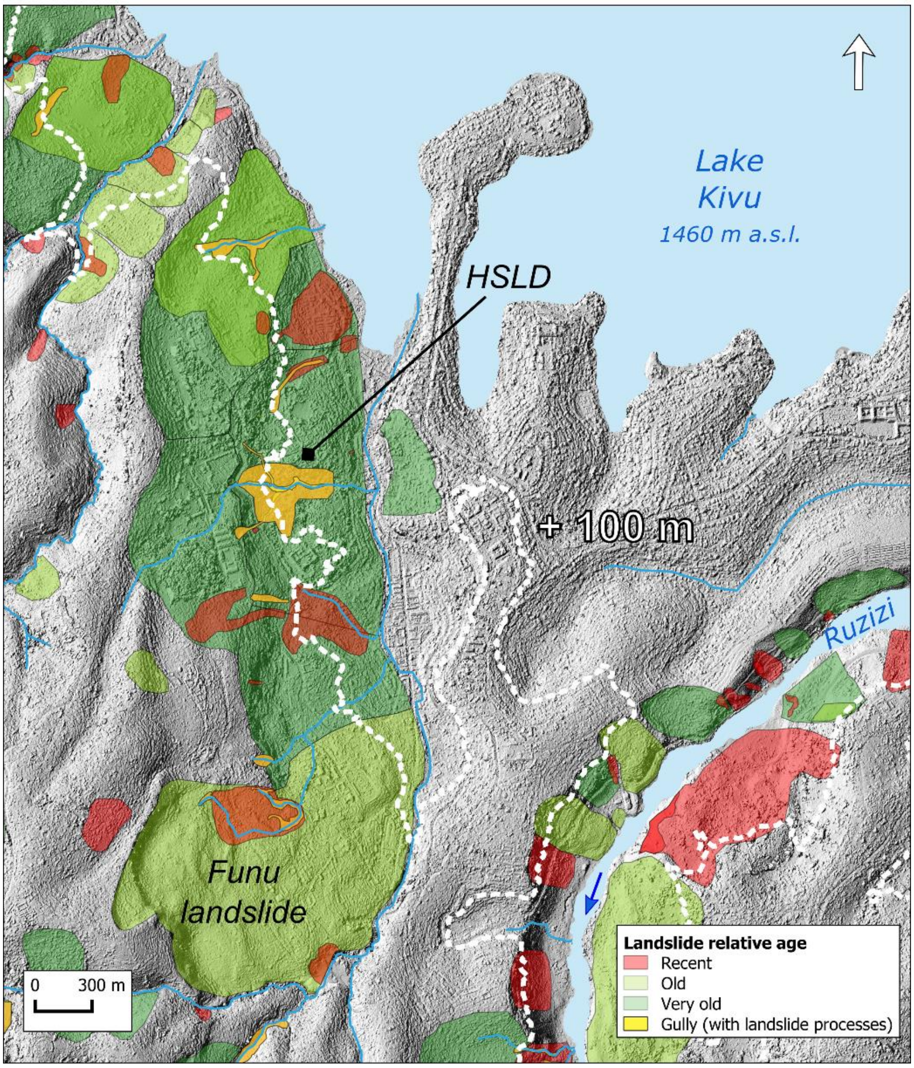


Fig. 5 Landslides in Bukavu, their relative age (see text for details) and distribution with regard to Holocene lake highstands (+ 100 m, dashed white contour line). HSLD: highstands lacustrine material deposit. Hillshade derived from 1 m resolution DSM built from Pléiades tri-stereo images of 2013. It highlights the dense urban fabric of the city centre

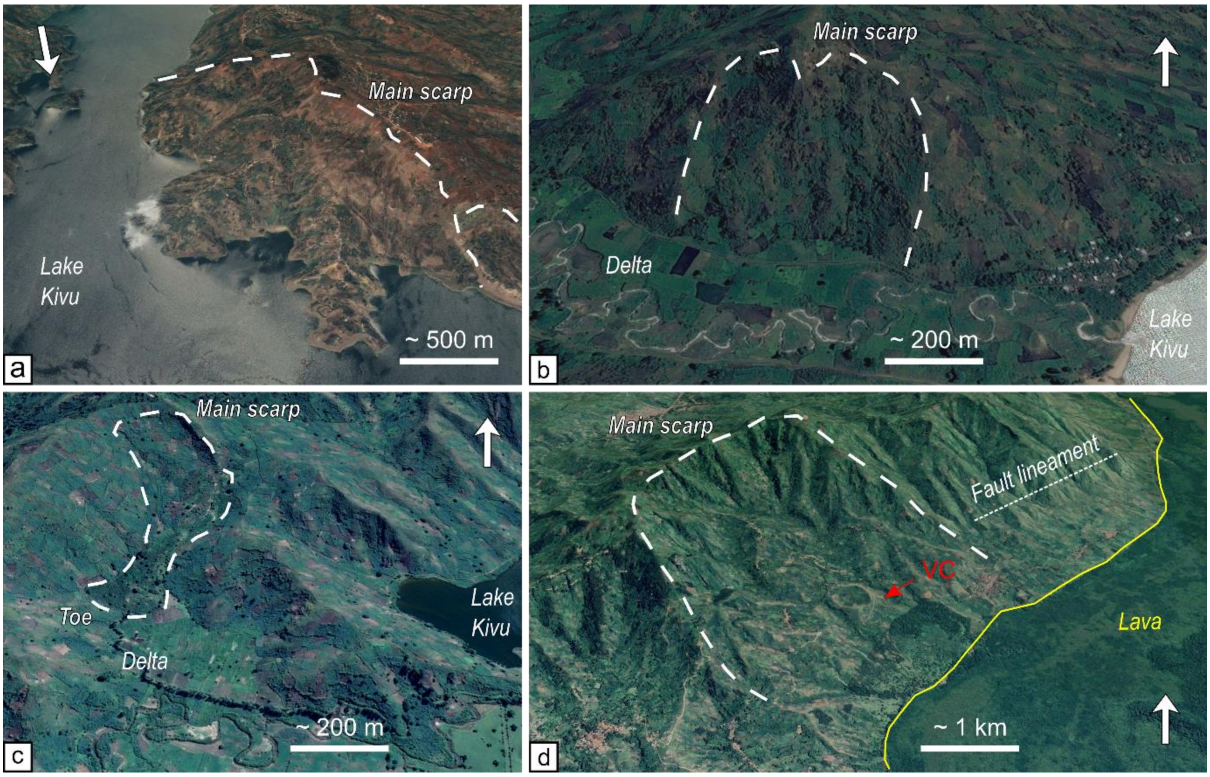


Fig. 6 Google Earth images of landslides in contact with a dynamic base level; either Lake Kivu highstands or Nyamuragira lava flows. a Slide in Rwanda with a direct contact with the lake (-2.368°, 29.052°). b Landslide in DR Congo with a buried deposit area (-1.721°, 29.049°). c Active earthflow in DR Congo that covers a delta (-1.762°, 29.008°). d Landslide in DR Congo affected by a volcanic cone (VC) with a partly-buried deposit area (-1.187°, 29.275°)

The largest landslide in Bukavu (Funu landslide, Fig. 7a) is located along the same ridge as the very old landslide where lake deposits are observed (Fig. 5). The Funu landslide has morphology features attesting of a more recent process (either new landslide failure or reactivation) and is here classified as old. Its position above the water highstands indicates that its origin is not linked to the lake formation. Although the detected InSAR ground deformation patterns of this landslide show that it is one of most active in the city (Nobile et al., 2018), the presence of ~20 cm of colluvial soil developed on debris deposited at the base of its main scarp (Fig. 7a) attests an origin (or reactivation) that could be around 5000 years if average rates of soil formation are considered (Montgomery, 2007).

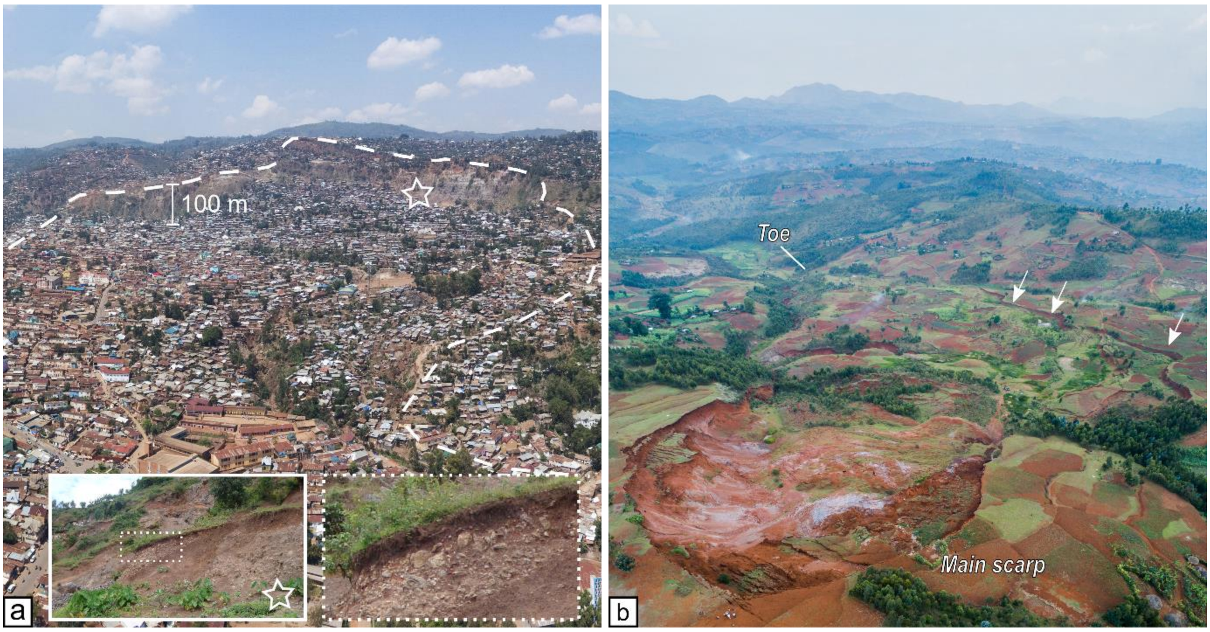


Fig. 7 Deep-seated slow-moving landslides in highly weathered environments of the SKVP. a Funu landslide in Bukavu (-2.520°, 29.845°; Fig. 5).The landslide covers an area of 1.5 km², with elevations ranging from 1525 m (toe)to 1905 m (head scarp) . Inserts show colluvial soil formation on debris deposited at the base of main scarp. b Ikoma landslide (-2.539°, 28.734°) The landslide covers an area of 0.2 km², with elevations ranging from 1910 m (toe) to 2060 m (head scarp). The main scarp has a height of up to 35 m. Both images were taken from UAV in October 2017 and 2018 respectively

A noticeable lithology feature in the region is the presence of two volcanic provinces: the South Kivu and the Virunga volcanic provinces (SKVP and VVP; Fig. 1). SKVP is a soil-mantled rolling landscape made of deeply-weathered (up to tens of metres) sequences of sub-horizontal lava layers of Late Miocene to Pleistocene origin (10 to 1.6 Ma) (Kampunzu et al., 1998; Moeyersons et al., 2004; Pouclet et al., 2016). The province is also crossed by the Ruzizi Gorge. VVP consists in a series of lava-dominated volcanoes made up of various alkaline silica-undersaturated lava materials (e.g., Kampunzu et al., 1998; Barette et al., 2017). Nyiragongo and Nyamuragira volcanoes, west of VVP (Fig. 1), are the two most recent volcanoes and are mostly covered with few-year to few-century lava flows (Smets et al., 2010, 2015; Poppe et al., 2016). The other volcanoes, in central and eastern VVP, are covered with lavas flows of 10 ka to 250 ka ages (Kampunzu et al., 1998; Pouclet et al., 2016), with, in some places, layers of pyroclastic deposits (Jost, 1987). As a large part of VVP is forested and belongs to the Virunga National Parks, we can argue that its pattern of shallow landslides is not influenced by human activities. There, for similar slope gradients, shallow landslides are nearly absent from the flanks of the two youngest volcanoes (Fig. 1, Fig. 3a). Although the tropics are known for very high weathering rates (Thomas, 1994), and that the different properties of the lithologies could influence this process, it shows that a substantial amount of time (here thousands of years) is needed to accumulate enough regolith/colluvium available for a slope failure to occur (e.g., Parker et al., 2016). While in VVP the age of the rocks is the main controlling factor on the shallow landslide distribution, in SKVP, the availability of regolith across the landscape let suppose that slope gradient could be the main natural driver as attested, e.g., by a slightly higher concentration of shallow landslides along the Ruzizi Gorge (Fig. 1). However, at this stage, such an analysis derived from few observations from the regional inventory must be considered with caution. Firstly, anthropogenic pressure is high in SKVP. In addition, the spectral signature differences that characterize a recent shallow landslide in such a human-influenced landscape are less important than in the VVP forest and therefore the number of landslides delineated from Google Earth is underestimated.

Deep-seated slides (sometimes km-size) are frequent in SKVP. Apart from the slides along the Ruzizi Gorge that occur on threshold hillslopes and the potential role of the Lake Kivu highstands, we can assume that this spatial pattern attests of a depth-dependent control of the regolith on the slope failure mechanism (Migon, 2013;

Dille et al., 2019). Due to its steep hillslopes, VVP is close to a slope-controlled weathering-limited environment (Jost, 1987; Garzanti et al., 2013). Assuming a similar control of the regolith depth in both provinces, it makes sense that deep-seated landsliding is barely observed on the oldest volcanoes and absent from the more recent ones (Fig. 1). However, outside VVP, on similar slope gradients carved in other lithologies that have been exhumed for few million years a least (van den Haute, 1984) and where regolith thickness is rather limited, deep-seated landslides are more frequent (Fig. 1). We suggest that the decrease in rock strength due to bedrock fracturing associated with seismic activity and rock uplift is still limited in VVP compared to the much older surrounding hillslopes (Clarke and Burbank, 2010; Delvaux et al., 2017; Vanmaercke et al, 2017). The presence of rejuvenated hillslopes through knickpoint migration, limited in VVP, must certainly be considered too in the occurrence of bedrock landsliding (Burbank et al., 1996; Larsen and Montgomery, 2012).

The setting-up of VVP was accompanied by the filling of the western side of the rift depression by volcanic products and the burying of part of the rift escarpment (Smets et al., 2016). This process, such as the one associated with the sediment fill of the Lake Kivu deltas, has certainly buried (part of) landslides developed along the escarpment. In that context of interactions between rift escarpment evolution and the setting-up of the volcanism, Fig. 6d shows a unique example of a partly-buried landslide deposit area where a small volcanic cone has developed. This part of the escarpment has a morphology clearly influenced by fault lineaments (Smets et al., 2016).

6. Combining techniques for site-specific characterisation

The analysis of geomorphic markers is a first step towards the understanding of the causes and triggers of the large landslides and their evolution. In order to know more about these processes and therefore be able to better predict the hazard associated with their occurrence and/or reactivation, we focus on the timing and the mechanisms of the landslides of Funu and Ikoma (Fig. 7), both developed in the weathered lavas of SKVP (Fig. 1). If the two are deep-seated slow-moving landslides, they contrast by their age (Funu, clearly preceding human activity in the area; while Ikoma is much more recent, experiencing its main phases of instability during the last decade), the degree of anthropic influence (Funu is one of the most densely inhabited district of Bukavu while Ikoma is located in a rural environment), as well as their current rates of displacement. By these differences, they represent two end-members of the characteristics of the deep-seated landslides that can be found in the area while sharing similar natural environmental conditions.

The first results are promising. For Ikoma, by confronting rainfall time series and earthquake sequences with the different deformation episodes reconstructed over the last 60 years (via several methods, Table 1), we show that the role of weathered-related weakening of the slope strength through time must be considered in the occurrence of some of the main deformation phases (> 10 m year^{-1}). In other words, we show that the relation between slope instability triggers and slope failure is not always straightforward, and that the role of intrinsic evolution of the hillslope must not be ignored when assessing landslide hazard in tropical montane regions (Dille et al., 2019). This role of the weathering in the occurrence of slope failure could also partly explain the cluster of large landslides in Bukavu (Fig. 1). For Funu, the four-year DInSAR time series at a weekly resolution we have computed show deformation patterns up to 0.05 m year^{-1} that seem to vary in space and time (Samsonov et al., 2020). Further assessments are needed to understand them.

The analysis of these two slides relies on intensive use of spaceborne and ground-based remote sensing techniques (DInSAR, UAV, image correlation, etc.) and the high spatial and temporal resolution tracking of the ground deformation behaviours (Table 1). With this focus on remote sensing, we also want to address the methodological question as to what (remote sensing) methods (or combination of) are the most effective to study the current (and past) dynamics of landslides in such an environment. Funu landslide represents an ideal candidate for DInSAR applications due to is location in an urban setting (where coherence is kept though time) and on a hillslope oriented towards the east (Nobile et al., 2018). Thanks to a unique dataset of more than 300 COSMO-SkyMed images acquired between March 2015 and January 2019 a new method to track ground deformation time-series in 3D from DInSAR has been validated on this site (Samsonov et al., 2020). Ikoma landslide is sited in a rural environment with a constantly changing vegetation and ground displacements that are too large for being processed via DInSAR. There, image correlation will be needed to characterise ground deformations (e.g., Stumpf et al., 2014).

7. Conclusion: the way forward

Progress in the characterisation of the timing of landslides has been achieved in the NTK Rift over the last years through a holistic approach that combines field work, satellite remote sensing, historical photograph processing and geomorphic maker understanding. We now have a better understanding of how these thousands of highly diverse surface processes are connected to both natural and human-induced evolution of the landscape. We also bring information that contributes to a better evaluation of the hazard in the area, and potentially across other regions sharing similar environmental conditions.

While an unprecedented amount of information has been collected for a data-scarce and low capacity tropical environment; yet, we remain far from comprehensive more quantitative analyses that can lead to accurate and reliable hazard assessment and early warning system development (Guzzetti et al., 2020). For such a large region, it is obvious that scope for further work at every level of action exists. We identify future research opportunities through which we believe that a better time constrain of the landslides could be achieved:

- For the (sub-)daily timing accuracy, we must look at the citizen-science sphere and the opportunity of crowdsourcing. Participatory approach has demonstrated success in accurate data collection and monitoring in resource-constrained settings (Hicks et al., 2019). The geo-observer approach developed in the Rwenzori Mountains in Uganda holds huge promise for an environment very similar to the NTK Rift (Jacobs et al., 2019). Such an approach allows also to collect unprecedented information on the processes at play;
- For several days to weeks timing accuracy, frequent satellite acquisition inevitably offers opportunities for better constraints (Belward and Skøien, 2015). Since the tropics are frequently cloud-covered, an accurate characterisation of the timing of landslides can only be achieved through the joint analysis of optical and SAR information (Joyce et al., 2009; Poursanidis and Chrysoulakis, 2017). Knowledge from the field, and by extension, citizen-based data is a must for the calibration and validation of the methods;
- For multi-month to multi-year time constraining, continuous mapping of the events from Google Earth will help to estimates recent landslides rates and their patterns with human disturbances;
- For multi-decadal information, we are producing orthomosaics from the thousands of historical photographs that are available for the region at the Royal Museum for Central Africa (Dewitte et al., 2018; Smets et al., n.d.). This will allow progress in the understanding of e.g. the pace of large landslide occurrence and their dynamics;
- For the geomorphic markers, a better knowledge of the geology of the region is key. Besides, constraining dates in different sites such as landslides or within the sediment record would be an asset. Although dating effort has been negligible in the tropics (Pánek, 2015), we believe that in the future, some could be applied successfully in a region like the NTK Rift.

Finally, a key objective is that our research outputs meet the needs of local research institutions and stakeholders. Therefore, we can anticipate that future actions will also depend on the occurrence of specific landslide events and the associated research responses required. Although this study targets a specific region, we believe that the adopted strategy and methods have the potential for being used in other low-capacity environments where field accessibility is difficult and information on landslide occurrence scarce.

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