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Liesbet Jacobs · Olivier Dewitte · Jean Poesen · Damien Delvaux · Wim Thiery · Matthieu Kervyn

The Rwenzori Mountains, a landslide-prone region?

Abstract With its exceptionally steep topography, wet climate, and active faulting, landslides can be expected to occur in the Rwenzori Mountains. Whether or not this region is prone to landsliding and more generally whether global landslide inventories and hazard assessments are accurate in data-poor regions such as the East African highlands are thus far unclear. In order to address these questions, a first landslide inventory based on archive information is built for the Rwenzori Mountains. In total, 48 landslide and flash flood events, or combinations of these, are found. They caused 56 fatalities and considerable damage to road infrastructure, buildings, and cropland, and rendered over 14,000 persons homeless. These numbers indicate that the Rwenzori Mountains are landslide-prone and that the impact of these events is significant. Although not based on field investigations but on archive data from media reports and laymen accounts, our approach provides a useful complement to global inventories overlooking this region and increases our understanding of the phenomenon in the Rwenzori Mountains. Considering the severe impacts of landslides, the population growth and related anthropogenic interventions, and the likelihood of more intense rainfall conditions, there is an urgent need to invest in research on disaster risk reduction strategies in this region and other similar highland areas of Africa.

Keywords Mass movement · Inventory · Equatorial mountains · Archive analysis · Triggering factors

Introduction

Landslides are considered an important cause of fatalities and economic losses worldwide (Petley 2012; Corominas et al. 2014). The East African highlands, due to their wet climate, steep topography, and high weathering rates, are often considered to be prone to landslides (Knapen et al. 2006). In these highlands, landslides cause large-scale land degradation and loss of property, livelihood, and human lives (e.g., Davies 1996; Knapen et al. 2006; Mugagga et al. 2012).

One of the most remarkable highlands in this region is the Rwenzori Mountains. The Rwenzori Mountains (up to 5109 m above sea level, a.s.l.) lie on the equator at the border between Uganda and the Democratic Republic of the Congo (Fig. 1). This asymmetric horst mountain has been the subject of interest for researchers in various disciplines. Bauer et al. (2012) provide insight into its genesis. Eggermont et al. (2009) examined its ecology. Seismicity and faulting have been extensively studied by Maasha (1975), Koehn et al. (2010), and Lindenfeld et al. (2012a, b). Its glaciers have been studied by several authors (e.g., Taylor et al. 2009), while long-term erosion processes are studied by Roller et al. (2012).

Because of its steep topography and high population density, the Rwenzori Mountains are comparable to other mountainous regions in tropical Africa where landslides are common disasters. This is also suggested by Knapen et al. (2006) who mentioned Kasese and Bundibugyo as landslide-prone districts in the Rwenzori Mountains while Bauer et al. (2010) state that landslides play a significant role in erosion processes in the region. However, except for a brief description of a landslide damming the Bujuku River (Eggermont et al. 2009) and a landslide killing two people in Kasese during the 1994 earthquake (Mavonga 2007), no case studies of landslides in the Rwenzori Mountains have been described in scientific papers.

Several global-scale inventories are constructed to identify landslide hotspots worldwide. A global database for fatal landslides with a non-seismic trigger that occurred between 2004 and 2010 is compiled by Petley (2012) and referred to as the Durham Fatal Landslide Database (DFLD). For rainfall-triggered landslides, a database is compiled by Kirschbaum et al. (2010) for the years 2003, 2007, 2008, and 2009. In the DFLD, no landslide events are reported for the Rwenzori Mountains while the database of Kirschbaum et al. (2010) includes only one event for the Rwenzori Mountains. From these databases, the Rwenzori Mountains do not appear to be landslide-prone; however, some methodological considerations should be made. First, these global databases are compiled by considering (non)-governmental reports, news articles, aid agency reports, and academic papers (Kirschbaum et al. 2010; Petley 2012). A search in these sources is rarely exhaustive, especially for inventories covering very large areas. The fact that seismically triggered landslides are not considered in either of the two databases and that non-fatal landslides are not included in the DFLD can be a second factor explaining the lack of events. Furthermore, as stated by the authors, the DFLD can underestimate national figures by 20 % (Petley 2012) while the database of Kirschbaum et al. (2010) might have an underrepresentation of events in remote areas, with only 3–4 % of the events occurring in Africa.

Global landslide hazard and susceptibility maps have been constructed by Nadim et al. (2006), Hong et al. (2007), and Hong and Adler (2008). The global hazard map by Nadim et al. (2006) is constructed using base layers for lithology, climate, seismic activity, and topography. For the base layers of rainfall and lithology, the entire Rwenzori Mountains fits within one pixel. Furthermore, none of the datasets used for the calibration of this model originate from African case studies. In this global map, the Rwenzori Mountains do not appear as very landslide-prone. Hong et al. (2007) use a similar approach, taking into account topography, soil type, soil texture, and land cover type. The maximum grid size for these layers is 0.25° (Hong et al. 2007). According to this susceptibility map, the broader region around the Rwenzori Mountains is indicated to have moderate to high susceptibility (Hong and Adler 2008).

At a continental scale, it is assessed by the World Health Organization (WHO 2011) that the Rwenzori Mountains are a landslide hotspot by applying a deterministic modeling approach that does not require landslide inventory data (El Morjani 2011). At the national scale, the Rwenzori Mountains are considered as landslide-prone in the New Geological Map of Uganda (Geological Survey of Finland together with the Uganda Department of

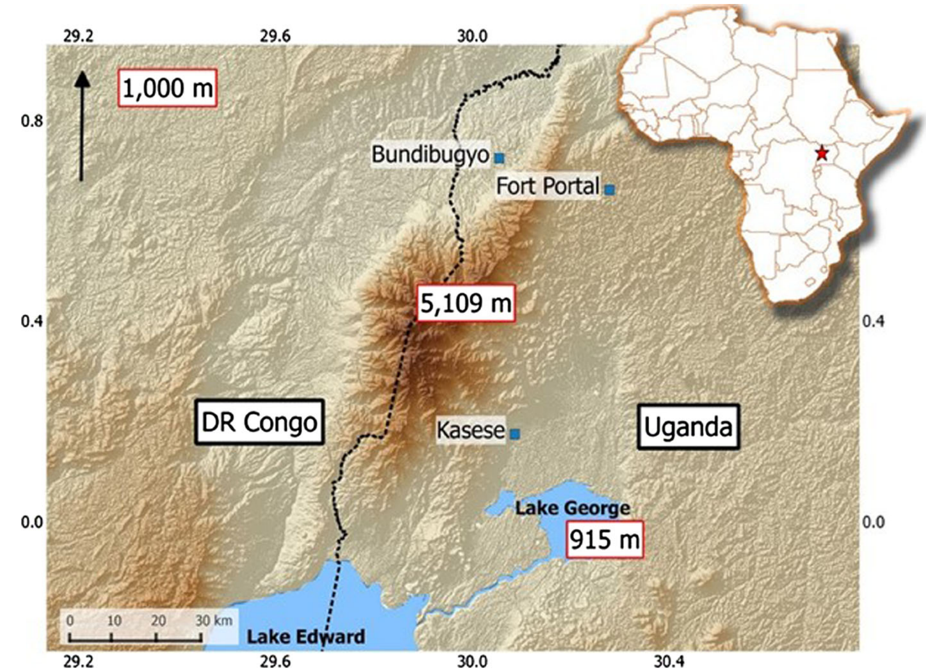

Fig. 1 Location of the Rwenzori Mountains in Africa, *shaded relief* and elevation from SRTM digital elevation model (Jarvis et al. 2008; USGS 2014a). Values for altitude are in meters a.s.l. The *dotted line* represents the border between the Democratic Republic of the Congo and Uganda

Geological Survey and Mines, GTK consortium 2012). This regional awareness is in contrast with the lack of information in global landslide inventories, global hazard maps, and scientific literature. Thereby, the questions whether or not the Rwenzori Mountains is a landslide-prone region and, more generally, whether global landslide inventories and hazard assessments are accurate in data-poor regions remain unanswered.

In this paper, the first landslide inventory for the Rwenzori Mountains is constructed based on archives. The archive information used for this study is similar to the sources used by Kirschbaum et al. (2010) and Petley (2012); however, the scope is on one focus area, allowing to go in more detail for all available sources. This will allow determining whether or not landslides are a hazard of serious impact in the Rwenzori Mountains. Subsequently, an overview of the knowledge on the controlling and triggering factors of landslides in the study area is given. Finally, through this review, the gaps in information on landslide events and their conditions of occurrence are presented. This will serve the long-term objective of better understanding landslide processes in this highly populated region and by extension in similar areas of sub-Saharan Africa with frequent but largely unreported hazardous landslide events.

Landslide inventory of the Rwenzori Mountains

Materials and methods

Because field information is scarce, archive sources were used to reconstruct a landslide inventory: newspaper articles, governmental and non-governmental reports, and Internet sources. An overview of all data sources used and the number of events they report is given in Table 1.

In this database, all mass movement events are considered independently from their cause, nature, and impact. The type of process is generally not described, but if the source mentions details about the type of movement or material moved, these are included in the inventory. For each event, the timing of occurrence is determined as precisely as the source allows. The location (district, county, sub-county (S/C), parish or village, roads or rivers) is determined using Google Earth (Google 2014), the GeoNames website (2014), and administrative boundaries from Global Administrative Areas (2012). If one source mentions several landslide events which are either clearly spatially separated (as they occur in a different parish or S/C) or separated in time (as they occur on different dates), these events are considered separately.

Impact information such as the number of fatalities, the number of persons that lost their houses, the occurrence of infrastructural damage, and damage to crops is also included in the inventory if reported in the source. To estimate the number of persons that lost their houses, the reported number of houses or households affected was multiplied by the average number of persons per household in the S/C where the event took place (2002 Ugandan census, Uganda Bureau of Statistics 2003). Cases where the actual number of houses destroyed or number of persons affected is missing are not included in this calculation. The number of affected persons is also included although it is not always clear which criteria the author uses to consider persons to be affected. Additional information on rainfall conditions, seismic activity, or anthropogenic influences before or during the landslide occurrence is noted as this information is valuable for the interpretation of these events.

Upon assembly of the historic inventory, it became apparent that debris-rich flash flood events are a second major type of disaster in the region. Landslides could play a role in the triggering mechanism of flash floods by dam formation or simply by the supply of material for debris-rich flash floods (Cui et al. 2013; Gill and Malamud 2014). Because of the possibility that flash floods coincide with landslides, these events are included in the inventory

Table 1 Overview of the archive sources used for inventory compilation with the respective number of events described in each source

Source type	Number of events described	Source code
Intergovernmental reports		
UNESCO (1966): Earthquake reconnaissance mission report	4	1
Governmental reports		
Mahango sub-county local government (2013a; 2013b), Bugoye sub-county local government (2014)	3	2
Report of the Parliament of Uganda (2010)	3	3
USGS (2010)	1	4
Simmons (1930)	1	5
NGO reports		
Red Cross Uganda (http://www.redcrossug.org/)	1	6
Scientific literature		
Mavonga (2007)	1	7
Eyewitness descriptions, blogspots, others		
Causes of River Nyamambwa floods by Alex Kwatampora Binego	1	8
http://thembokahungu.blogspot.be	1	9
www.primeugandasafaris.com	1	10
International news sites		
www.news24.com	1	11
www.business.highbeam.com	1	12
www.africancrisis.org	1	13
www.theextinctionprotocol.wordpress.com	4	14
www.chimpreports.com	1	15
www.allafrica.com	1	16
www.irinnews.org	1	17
National news sites		
www.newvision.co.ug	2	18
www.monitor.co.ug	3	19
www.redpepper.co.ug	1	20
www.wougnet.org	1	21
www.ugandapicks.com	1	22
www.nape.or.ug	1	23
www.ugandaradionetwork.com	8	24
International disaster-relief websites		
www.desinventar.net	17	25
www.reliefweb.int	4	26

All websites were last accessed on the 26th of June 2014. Sources not referred to by website addresses can be found in the reference list

as well. In contrast to landslide events, flash flood events are considered as one event if they are located within the same valley.

Results

In total, 48 landslide or flash flood events have been retrieved from all sources available, of which 41 are landslide events while 7 are flash flood events or combinations of flash floods and landslides (Table 2). The earliest record reports landslides and rock falls triggered by tremors in February 1929 (Simmons 1930; UNESCO 1966). The latest event that could be found in the archives at the time of the compilation of this work (June 2014) was a flash flood occurring in May 2014. Most events (41/48) that are reported occurred between 2001 and 2014. All events except seven could be precisely dated; six out of these seven could still be situated in the month and year of occurrence. Most events could be located at the village or parish level; in some cases, only a localization at (sub-)county or district level was possible. In several cases, landslides are located at the roadside or landslide events are reported to have damaged or blocked a road.

All landslide events that could be located as accurately as the parish level are depicted in Fig. 2 together with population densities estimated by the Center for International Earth Science Information Network and the Centro Internacional de Agricultura Tropical (CIESIN and CIAT 2005) as well as measured population densities at parish level (Uganda Bureau of Statistics 2003). Details on the type of material moved were scarce. In six cases, the material moved was reported to be mud; in two cases, the mass movement is described to be rock falls, and in all road blockages, the material is described to consist mostly of rocks or debris. All mass wasting events, except for the rock falls, are reported in the parishes below 2400 m a.s.l where the population densities range from 180 to over 700 inhabitants/km^2 (Uganda Bureau of Statistics 2003). The parishes lying above 2400 m a.s.l. are covered by the Rwenzori Mountains National Park where population densities are negligible.

On the Congolese side of the mountain range, no reports of landslide or flash flood events were found. Although the search for events in this inventory was conducted both in English and in French, reports of events written in local languages will be overseen.

The consequences of landslides and flash floods in this region include loss of life, damage to or loss of buildings, and loss of crops and livestock (Table 2). While landslides cause damage and loss of life in discrete areas on the mountain slopes, sediment-loaded flash floods cause damage over several villages along the river. An example of boulder deposition by a flash flood destroying infrastructure is given in Fig. 3. This image is extracted from Google Earth and is located in the Kilembe valley, where several houses have been swept away by the flash flood of 1 May 2013 in this small part of the valley.

In total, 34 persons lost their lives in landslide events while 22 persons lost their lives in flash floods or in an event consisting of a combination of landslides and flash floods. In total, an estimated 14,418 persons have lost their houses, among which was a great fraction during the 1 May 2013 event (~7000 people). When considering events for which data on the number of people rendered homeless is available, this number is on average higher for flash floods (3520 per event) compared to landslides (335 per event). These numbers are likely to be an underestimation of the total number of fatalities, damage to buildings, and number of persons affected considering the fact that the archive inventory information is most likely non-exhaustive, although events with high impacts are usually more reported than those with a small impact (Ronan et al. 2005).

The loss of crops or livestock is often reported (in 13 cases), and in some reports, the fear of hunger is explicitly stated. Damage to basic infrastructure (roads, utility lines, or water supply installations) is also mentioned. In nine cases, the roads were affected or blocked, while in total 22 bridges are reported to be destroyed. Finally, schools were (partially) destroyed by five different landslide events.

State of knowledge on triggering and controlling factors of landslides

In this section, the potential controlling and triggering factors for landslides in the Rwenzori Mountains are discussed. The choice for the different controlling and triggering factors is based on the recommendations of Corominas et al. (2014).

Controlling factors for landslide occurrence

Geology and tectonics

The Rwenzori Mountains are bounded by the Albertine rift on the west and the Lake George rift on the east (Lindenfeld et al. 2012a). The southward propagation of the Lake Albert rift and the northward propagation of the Lake George rift lead to the clockwise rotation of the horst with complex intersecting faults in the NE of the Rwenzori Mountains (Koehn et al. 2010). On its west side, the normal Bwamba fault borders the Rwenzori Mountains, while in the NE, the normal Ruimi-Wasa fault is present (Fig. 4a) (Koehn et al. 2010). Around the center of the eastern flank, a more complex faulting structure is apparent (Koehn et al. 2010). The majority of the tectonic activity takes place in the faults' zones bordering the eastern and western flanks, and the most active area is located in the NE of the Rwenzori Mountains (Lindenfeld et al. 2012b). This tectonic activity is related to active rifting processes, under an overall WNW-ESE extension (Delvaux and Barth 2010).

The geology of the horst mountain is mainly built up of Precambrian metamorphic rock which consists of gneiss, schists, and amphibolites belonging to the Toro-belt and the Archean basement of the Democratic Republic of the Congo and Tanzania cratons (Bauer et al. 2010). Gneiss dominates in the northern part of the mountain range, while gneiss with schists of the Kilembe and Bugoye group prevails in the southern part (Fig. 4a) (Bauer et al. 2010, 2012; Roller et al. 2012). Concerning rock strength characteristics, the schists are considered to have a medium erodibility, the gneisses a low erodibility, while the amphibolites have a very low erodibility (Roller et al. 2012). As to the weathering of the bedrock, the weathering rates in the Rwenzori Mountains are low, leading to weathering-limited slope evolution dominated by physical erosion processes (Garzanti et al. 2013). The slow weathering of the bedrock in the Rwenzori Mountains is also confirmed by limnological research of Eggermont et al. (2007). Hence, the lithology as such is not inherently favoring unstable conditions.

Geomorphology and topography

Slope gradient, slope aspect, profile curvature, plan curvature, and distance from a drainage network are commonly the main topographic features controlling the occurrence of landslides (Corominas et al. 2014). Steep slopes with plan concave shape are generally most susceptible to landslides, as shown in similar regions in tropical Africa (e.g., Knapen et al. 2006).

In contrast to other mountain systems in East Africa exceeding 5000 m (Mount Kilimanjaro and Mount Kenya), the Rwenzori Mountains are not of volcanic origin (Bauer et al. 2012). The morphology of the horst mountain is the result of Paleogene and Neogene uplift, with a marked acceleration in Plio/Pleistocene times (Bauer et al. 2012), rendering the topography rugged with locally very steep slopes. The slopes on the east side are in general less steep than on the west side where elevation can increase from 1000 to 4500 m a.s.l. in less than 15 km (Bauer et al. 2012).

The quaternary glaciation cycles further shaped the topography. The last three glaciation maxima took place ~300, ~100, and 22–15 kyr ago and are referred to as the Katabarua, Rwimi basin, and Mahoma lake stage (Ring 2008), with equilibrium line altitudes between 3900 and 4000 m a.s.l (Kaser and Osmaston 2002). The Lake Mahoma stage reached down to 2070 and 2400 m a.s.l. on the eastern and western flanks, respectively (Fig. 4b) (Ring 2008).

Table 2 Inventory details for landslides (LS) and flash floods (FF), with their date of occurrence, material displaced, potential infliction of earthquake influence by indication with Y (yes) or N (no), source used (for codes, see Table 1), location, damage, and fatalities reported

No.	Type	EQ	Date	Source no.	Material	Location	Damage	No. of fatalities
1	LS	Y: $Ms = 5.7^{a}$	10–20 Feb 1929	1, 5	Rocks	Tremors in Fort Portal, causing LSs and rock falls southwest of Fort Portal, one rock fall is located on the Kakaka hills	n.a.	n.a.
2	LS	Y: M=?	7–11 Mar 1929	1	n.a.	Numerous aftershocks around the Rwenzori causing LSs	n.a.	n.a.
3	LS	Y: M=6.1	20 Mar 1966	1	Rocks	Fort Portal-Bundibugyo road (mile 10.5), Kilembe Mines, Bigu Hut, Nyamileju (rock fall, located), minor LSs in Bwamba County	n.a.	0
4	FF	?	7 Apr 1966	8	n.a.	Kilembe floods, Kasese district	n.a.	n.a.
5	LS	Y: M=6.3	18 May 1966	1	n.a.	LS on the Ruimi (Rwimi) River, Kabarole district	n.a.	n.a.
6	LS	Y: M=6.1	5 Feb 1994	4, 7	n.a.	Kasese district	1 person injured	2
7	LS	N	4 Sept 2001	11	Rocks/debris	Budinbugyo road towards Fort Portal, 11 km from Budinbugyo town, Bundibugyo district	Road block	n.a.
8	LS	N	2 Nov 2001	25	n.a.	Kasitu parish, Kasitu S/C, Bundibugyo district	12 persons injured, 3356 affected, 2000 relocated	18
9	LS	N	2 Nov 2001	17, 25	n.a.	Ntandi parish, Kasitu S/C Bundibugyo district		
10	LS	N	3 May 2003	12	n.a.	Katulu village, Kilembe S/C, Kasese district	30 persons homeless, church destroyed, crops and livestock destroyed	n.a.
11	LS	N	23 Aug 2005	25	n.a.	Bwesumbu parish, Kyabarungira S/C, Kasese district	28 houses destroyed, 40 houses damaged, 1448 persons affected, affected crops: coffee, vanilla, cassava, and beans	n.a.
12	LS	N	23 Aug 2005	25	n.a.	Buhuhira parish, Kyabarungira S/C, Kasese district		
13	LS	N	23 Aug 2005	25	n.a.	Kasangari parish, Kyabarungira S/C, Kasese district		
14	LS	N	17 May 2009	24	Rocks at road block	Kihondo parish, Kichwamba S/C, Bundibugyo district	70 families displaced, food crops destroyed, road block of the Karugutu-Bundibugyo road at Itojo	n.a.
15	LS	N	18 May 2009	24		Kyamaiga parish, Kichwamba S/C, Bundibugyo district		
16	LS	N	15 Oct 2009	24	Rocks	Fort Portal-Bundibugyo road (Kasisi, 6 km to Karugutu town), Kabarole district	Road block	n.a.

Table 2 (continued)

No.	Type	EQ	Date	Source no.	Material	Location	Damage	No. of fatalities
17	LS	N	Feb 2010	3, 25	n.a.	Bwendero parish, Kyabarungira S/C, Kasese district	55 houses destroyed, 1 school affected, 300 ha of crops	n.a.
18	LS	N	5 Mar 2010	3, 25, 26	n.a.	Mitandi parish, Katebwa S/C, Kabarole district	13 houses destroyed, 3000 persons affected, 3 education centers affected, 600 ha crops affected, 3 bridges destroyed, 3 schools affected	n.a.
19	LS	N	5 Mar 2010	3, 25, 26	n.a.	Mutumba parish, Katebwa S/C, Kabarole district		
20	LS	N	5 Mar 2010	25	Mud	Buhuhira parish, Kyabarungira S/C, Kasese district	356 houses destroyed, 249 families affected, 1 school affected, 117 ha crops destroyed	n.a.
21	LS	N	5 Mar 2010	25		Bughendero parish, Kyabarungira S/C, Kasese district		n.a.
22	LS+FF	N	17 May 2010	13	n.a.	Nyabirongo Parish, Kisinga S/C, Kasese district	300 persons homeless	n.a.
23	LS	N	25 May 2010	25	n.a.	Kateebwa parish, Kateebwa S/C, Kabarole district	28 houses destroyed, 67 persons affected, destroyed crops: coffee, bananas, Irish potatoes, cassava, beans	n.a.
24	LS	N	25 May 2010	25	n.a.	Bunaiga parish, Kateebwa S/C, Kabarole district		n.a.
25	LS	N	25 May 2010	25	n.a.	Kyondo S/C, Kasese district	91 persons affected	n.a.
26	LS	N	25 May 2010	25	n.a.	Rukoki S/C, Kasese district	30 houses destroyed, 38 persons affected	n.a.
27	LS	N	Early October 2010	24	Rocks	Fort Portal-Bundibugyo road	Road block	n.a.
28	LS	N	End of October 2010	24	Mud	Bundikeki parish, Kikuyu S/C, Bundibugyo district	>2000 persons displaced, >100 acres of cocoa, cassava, rice, and vanilla plantations destroyed, numerous houses and food stores destroyed	n.a.
29	LS	N	End of October 2010	24		Bundimulangya parish, Kikuyu S/C, Bundibugyo district		
30	LS	N	End of October 2010	24		Nyankiro parish, Kikuyu S/C, Bundibugyo district		
31	LS	N	End of October 2010	24		Busunga parish, Bubandi S/C, Bundibugyo district	n.a.	n.a.
32	FF	N	6 May 2011	25	Mud	Kanyangeya, Nyakasanga parish, Kasese TC S/C, and Kilembe headquarters Kilembe S/C, Kasese district	300 households affected	n.a.
33	LS	N	2 Oct 2011	25	n.a.	Busambo, Muhindi, Kighuthu, and Busalya village in	1396 persons affected	n.a.

Table 2 (continued)

No.	Type	EQ	Date	Source no.	Material	Location	Damage	No. of fatalities
						Nyakiyumbu S/C Kasese district		
34	LS	N	8 Oct 2011	9, 22	n.a.	Mahango village, Mahango S/C, Kasese district		5
35	LS	N	14 Oct 2011	25	n.a.	Kasese district	Crops and houses were destroyed; many people were left homeless	n.a.
36	FF+LS	N	1 May 2012	2	n.a.	Muhokya S/C, Mahango S/C, Kasese district	Crops have been swept away by landslides, 205 households affected by flash flood	9
37	LS	N	17 May 2012	14	n.a.	Katumba village, Kyalhumba S/C, Kasese district	n.a.	1
38	LS	N	17 May 2012	14, 19	Mud	Butalimuli village, Mahango S/C, Kasese district	23 houses destroyed	3
39	LS	N	17 May 2012	14, 19	n.a.	Nyakabingo village, Rukoki S/C, Kasese district	n.a.	1
40	LS	N	17 May 2012	14	n.a.	Bibwe village, Muhokya S/C, Kasese district	n.a.	1
41	FF	N	1 May 2013	6, 18, 23, 26	n.a.	Kyalumba, Kyondo, Bulembia, Nyamwamba, Maliba, Karusandara, and Bwesumbu S/C, Kasese district	Latrines and water supply affected, 19 bridges destroyed, cut off of Kasese-Fort Portal road, >7000 people displaced	8
42	LS	N	7 May 2013	26	n.a.	Bwathu and Kalonge village, Maliba S/C, Kasese district	21 houses destroyed, livestock killed and crops destroyed	n.a.
43	LS	N	Early May 2013	21	n.a.	Kirumya S/C, Budinbugyo district	2 families homeless	n.a.
44	LS	N	25 Sept 2013	2, 16	Mud	Kabukero village, Kyabwenge parish, Mahango S/C, Kasese district	Kasese-Kilembe road blocked, food and cash crops destroyed, 1 house destroyed	3
45	LS	N	9 Oct 2013	20	Rocks	Fort Portal-Bundibugyo road (Kasisi, 6 km to Karugutu town)	Road block	0
46	FF	N	1 Feb 2014	2, 15	Mud	Bugoye S/C, Kasese district	7 households displaced, 57 households lost their land or crops, Ibanda-Nykalengingo road was washed (2.5–3 km), 1 hospital without power	n.a.

Table 2 (continued)

No.	Type	EQ	Date	Source no.	Material	Location	Damage	No. of fatalities
47	FF	N	8 May 2014	18, 19	n.a.	Kasese municipality	1 school partially destroyed, Katiri-Bulembia road destroyed	5
48	LS	N	/	10	n.a.	Around Mubuku River, before reaching Mahoma River, Kasese district	n.a.	n.a.

For fatalities and damage reported, the notation "n.a." is used when there is no information available in the source. If explicitly stated in the source that there were no fatalities, this is indicated by a zero value

[a] Additional source: GSHAP (2000)

During these glacial maxima, glacier erosion formed U-shaped valleys with oversteepened walls (Roller et al. 2012; Bauer et al. 2012). The oversteepening of valley walls in combination with debutressing reduces slope support, thereby decreasing the stability of the slopes (e.g., Evans and Clague 1994). According to Davies et al. (2013), this process can have its effect up to several thousand years after deglaciation.

In order to increase the understanding of slope gradients, an analysis is performed using Shuttle Radar Topography Mission (SRTM) data at 90 and 30 m spatial resolution (Jarvis et al. 2008; USGS 2014a) (Fig. 4b). Average slope gradients at successive 100-m elevation intervals were calculated using the MORVOLC algorithm (Grosse et al. 2012). Because of some major holes in the SRTM 30 m, especially above 4500 m a.s.l. we have applied this algorithm to both the SRTM 30 and 90 m resolution (Fig. 5). This figure shows that slope values generally increase with elevation for both SRTM DEMs. The average slope gradients increase rapidly from 12° at 1100 m to more than 24° above 2000 m a.s.l. The highest average slopes occur between 4200 and 5000 m a.s.l. and reach an inclination of 30°. The sharp increase in average slope between 3900 and 5000 m a.s.l. for SRTM 90 m could be a consequence of intense erosion during the last three glaciation maxima.

To estimate the potential instability, these slopes are compared to global slope thresholds for landsliding. According to Brady and Weil (2008), the global threshold lies on 31°, while Sidle et al. (1985) consider a threshold of 24°. The threshold proposed for western Uganda is 26° (Temple and Rapp 1972). The analysis of SRTM 30 m shows that 46 % of the slopes lie above the minimum threshold of Sidle et al. (1985), and 22 % of the slopes is above the threshold of Brady and Weil (2008). Above the last glacial maxima, Lake Mahoma stage, the threshold of Sidle et al. (1985) is exceeded for 63 % of the slopes while the threshold of Brady and Weil (2008) is exceeded here for 40 % of the slopes.

Soil characteristics

Soil types and physical characteristics are determinant in slope stability (Sidle and Ochiai 2006). Some data on the dominant soil types in the Rwenzori Mountains can be retrieved from the harmonized soil map of the Soil Atlas of Africa, which uses the World Reference Base for Soil Resources (WRB) classification (Dewitte et al. 2013; Jones et al. 2013) (Fig. 4c). Above 3300 m a.s.l., Leptosols are the dominant soil type. Between 2000 and 3300 m a.s.l., Leptosols together with Ferralsols occur on the east side. On the west side, Phaeozems also occur. Below 2000 m a.s.l., Phaeozems are dominant on both east and west. Leptosols are characterized by their shallow profile which overlies hard rock or profiles that are gravelly or stony, typically occurring in mountainous areas, while Ferralsols are characterized by highly weathered deep profiles (FAO 2001; Jones et al. 2013). Phaeozem soils are organic rich and commonly found in tropical highlands (FAO 2001; Jones et al. 2013). Between 1000 and 1500 m a.s.l., the east side of the mountain range is covered by Phaeozems, Andosols, Nitisols, Leptosols, Fluvisols, and Luvisols. A detailed description of the WRB soil classification is provided by FAO (2001) and Jones et al. (2013).

The WRB map in the Soil Atlas of Africa does not allow to deduce the physical soil properties identified by Sidle and Ochiai (2006) that are needed to assess the stability of the soil. The

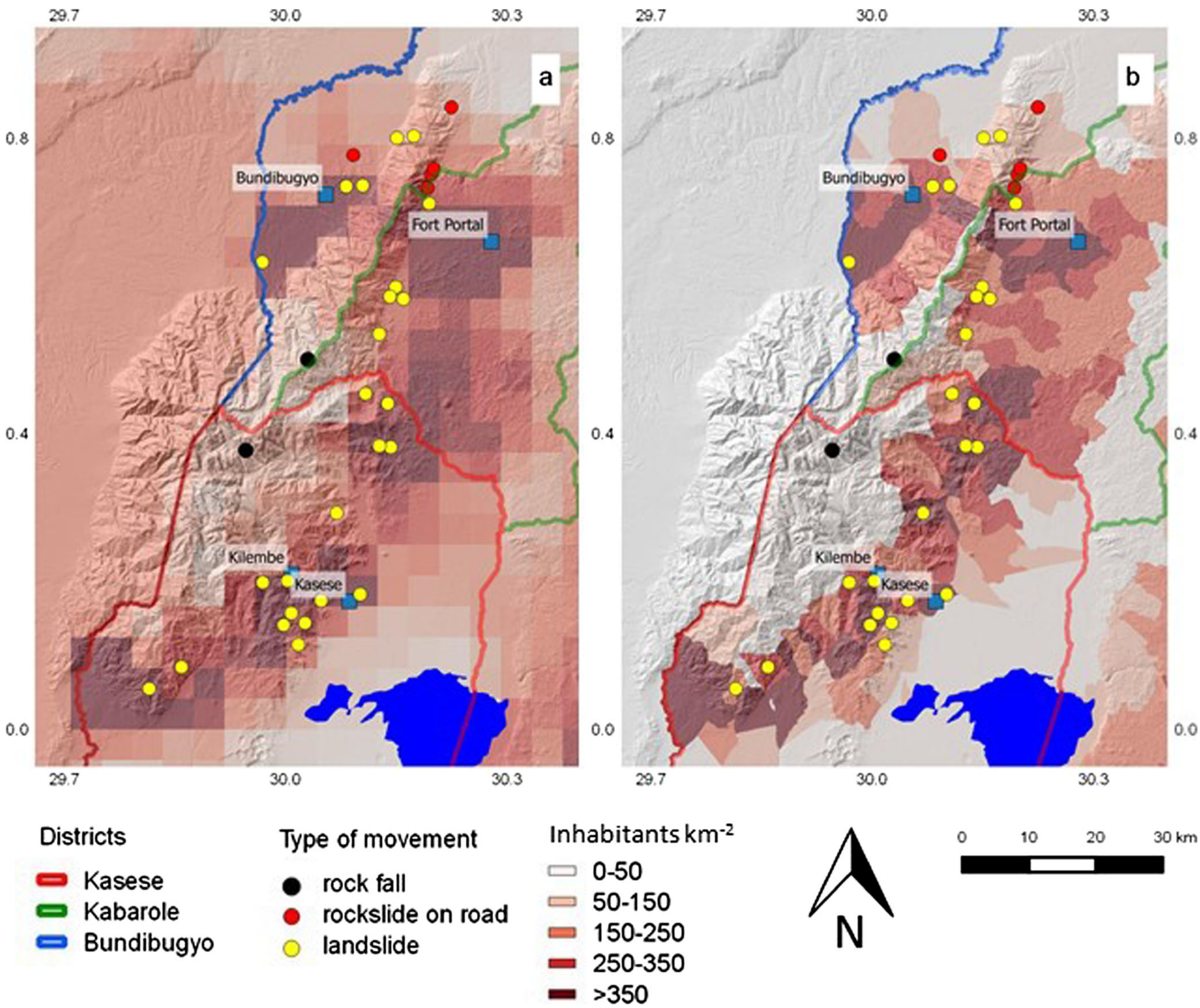

Fig. 2 Location of inventoried landslides combined with population density (inhabitants/km^2) **a** as simulated by SEDAC for 2000 (CIESIN and CIAT 2005) and **b** as measured by the Uganda Bureau of Statistics (UBS) (2003)

Harmonized World Soil Database (HWSD) does provide information on soil properties, such as soil drainage and soil depths (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). The Leptosols are imperfectly drained with a clay loam texture, while Phaeozems and Ferralsols are classified as moderately well-drained soils with clay to clay loam texture. These physical properties are, however, estimated values using standard FAO guidelines which are based on soil type, texture, soil phase, and slope (FAO/IIASA/ISRIC/ISSCAS/JRC

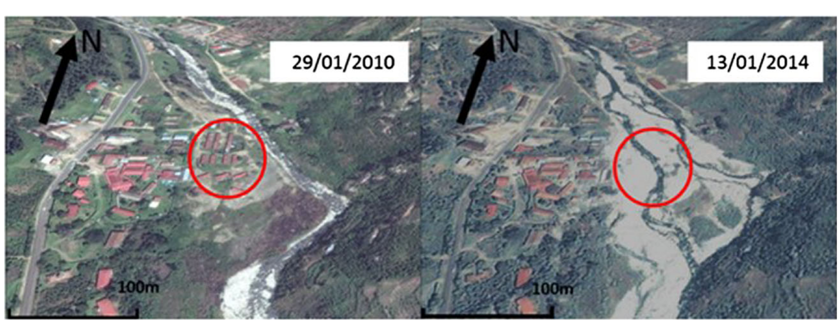

Fig. 3 Google Earth imagery before (*left*) and after (*right*) the flash flood of 1 May 2013 in Kilembe valley (source: "detail of Kilembe Valley" 0° 11′ 38″ N, 30° 00′ 59″ E, Google Earth, 29th of January 2010 (*left*) and 13th of March 2014 (*right*), accessed on 7th of July 2014)

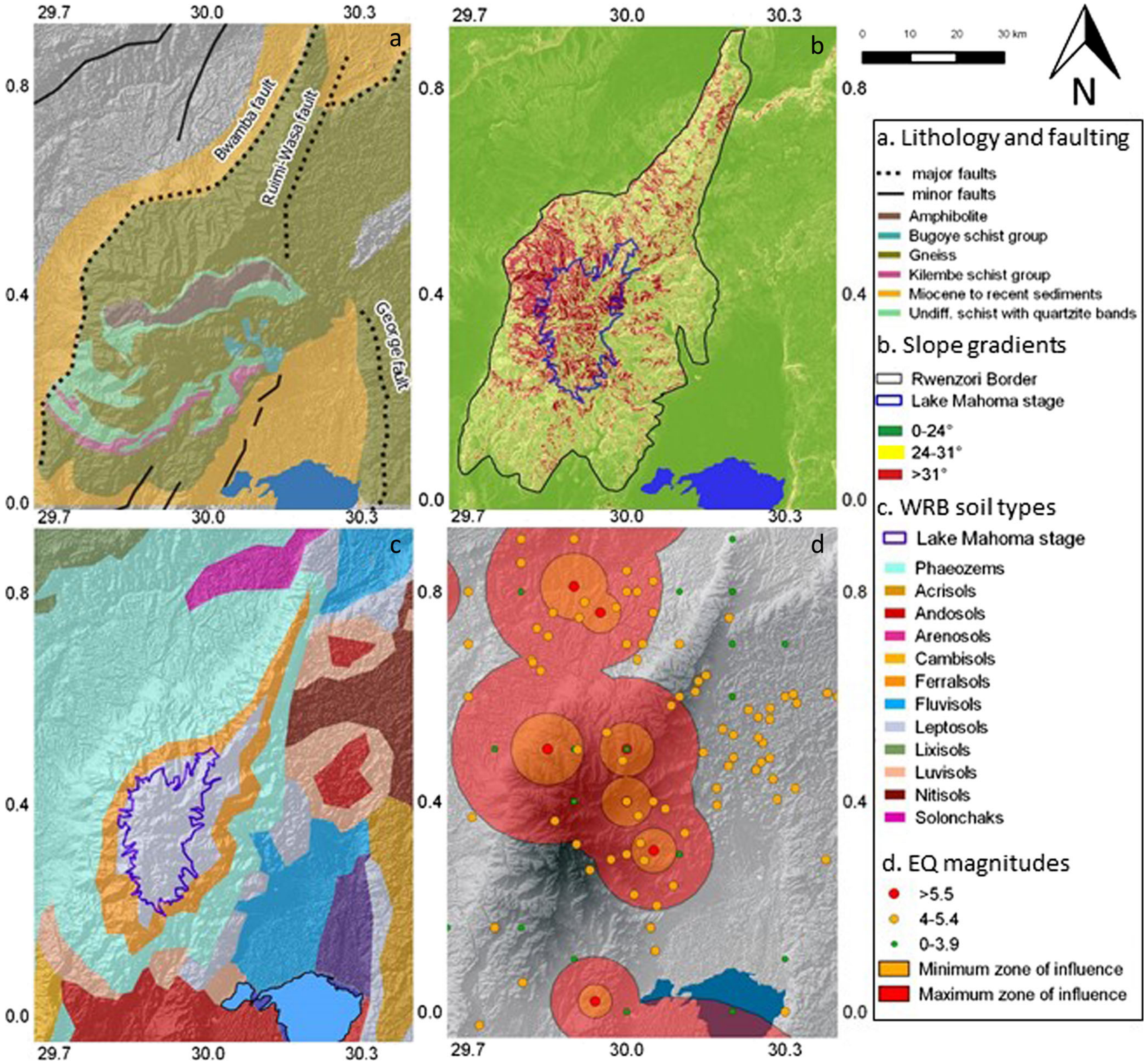

Fig. 4 **a** Geology and faults of the Rwenzori Mountains, based on Koehn et al. (2010) and Bauer et al. (2010, 2012). **b** Topography of the Rwenzori Mountains; slope gradients are calculated based on the SRTM 30 m DEM (Jarvis et al. 2008; USGS 2014a). Mahoma lake glaciation boundaries are based on Kaufmann and Romanov (2012). **c** WRB soil classification from the Soil Atlas of Africa (Dewitte et al. 2013; Jones et al. 2013). **d** Earthquake activity from 1903 to 2013 from the catalogue compiled by D. Delvaux in the framework of the GeoRisCA project. For earthquakes with M>5.5, the maximum and minimum zones of influence as proposed by Keefer (2002) are depicted in *red* and *yellow circles*, respectively

2012), thus not based on in situ measurements. Furthermore, the HSWD and the Soil Atlas of Africa are on a scale of 1:1 M to 1:2 M, so local variability is not taken into account.

Land-use change and deforestation

In many East African highlands, deforestation is identified as a major factor increasing landslide susceptibility (Davies 1996; Knapen et al. 2006; Mugagga et al. 2012). Deforestation reduces not only root cohesion and evapotranspiration of trees but also their weight and wind effects (Sidle and Ochiai 2006). Due to these different effects, the interaction of land cover and landslide susceptibility depends on the landslide type and is of a complex nature (Sidle and Ochiai 2006).

The population density roughly doubled in just more than two decades in the three Rwenzori Mountains districts (Table 3). These numbers include sparsely populated parishes in the surrounding plains and in the Rwenzori Mountains national park, indicating that the population densities given in Table 3 are in fact an underestimation of the effective density on the footslopes of the Rwenzori Mountains. This is also clear in Fig. 2b where population densities in landslide-affected parishes are often above 350 inhabitants/km^2.

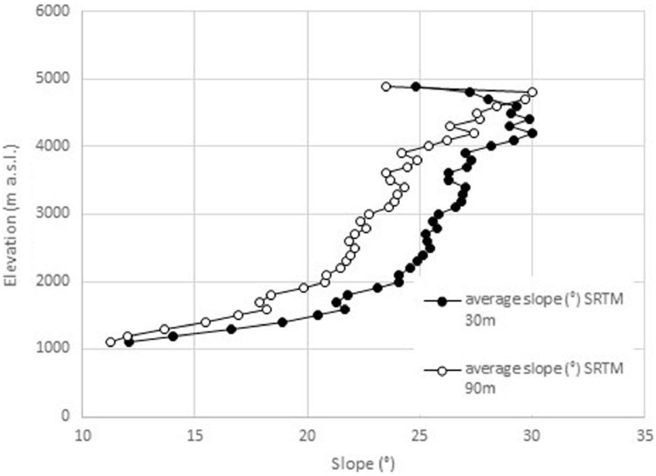

Fig. 5 Mean slope (°) for 100-m elevation intervals of the Rwenzori Mountains based on the SRTM 90 m and the SRTM 30 m DEM

Due to population increase, pressure on natural resources is high. In East Africa, deforestation occurred at rates of 0.22 and 0.39 % per year between 1990–2000 and 2000–2010, respectively (Brink et al. 2014). However, for the Rwenzori Mountains, this trend of deforestation seems to have stopped at least from 2003 onwards (Jagger and Shively 2014). The stabilization in forest cover is attributed to the effective forest management and an increase in area for woodlots and tree plantations (Jagger and Shively 2014).

Triggering factors for landslide occurrence

Rainfall

Rainfall is by far the main landslide trigger in equatorial Africa (e.g., Davies 1996; Claessens et al. 2007; Che et al. 2011). In the Rwenzori Mountains, temporal variation of rainfall is characterized by a bimodal pattern with a rainy season from March to May and one from August to November while spatial distribution is controlled by orographic variation (Taylor et al. 2009). Spatially and temporally explicit data on rainfall conditions triggering landslides is indispensable for predicting landslides, damage minimization, and mitigation of loss of life. From Sansa and Waisswa (2012), it appears that two rainfall stations at the base of the Rwenzori Mountains are operated by the Department of Meteorology in Uganda but no stations seem to be operational on the mountain range itself. Despite the importance of assessing the relation of rainfall on landslides, no rainfall data with detailed spatial and temporal resolution is available for the Rwenzori Mountains.

In remote areas with limited field measurements available, modeling rainfall intensities has been a much favored approach. Thiery et al. (2015) applied the regional climate model COSMO-CLM² (Davin and Seneviratne 2012; Akkermans et al. 2014) to the African Great lakes region to assess the climatic impact of the lakes. The spatial resolution of their simulation is 7 km (Fig. 6a), an accuracy which is unprecedented in the region, and model results are shown to outperform both a state-of-the-art reanalysis product and a continent-scale regional climate model simulation. Based on this modeling approach, annual mean precipitation is calculated and shown in Fig. 6b for the years 1999–2008 together with a delineation of what is considered the NW and SE flanks of the Rwenzori Mountains. Modeled precipitation is highest on the NW flank and is generated by orographically induced convection of moist air transported from the Congo River Basin into the Albertine rift through a gap in elevation at 0.5° latitude (Fig. 6a). As a result, modeled precipitation exceeds 7000 mm/year at an altitude of 4000–5000 m a.s.l. Average annual precipitation on the NW flank is 1835 mm/year while this is only 785 mm/year on the SE flank, the rain shadow side of the Rwenzori Mountains. The precipitation quantities on the NW flank are comparable to those of Mount Elgon (~1500 mm/year) which is highly landslide-prone (Kitutu et al. 2009).

To assess the potential for rainfall intensities to induce landslides, rainfall intensities can be compared to critical intensity-duration (ID) rainfall thresholds for landslides. Because the specific rainfall threshold for the Rwenzori Mountains remains to be constrained using temporally explicit landslide inventories and locally measured rainfall sequences, the global composite ID threshold of Guzzetti et al. (2008) is chosen for this assessment. Although this threshold only considers shallow landslides and debris flows, it is the most recent global threshold published which also holds for longer-duration rainfall events (up to 1000 h) (Guzzetti et al. 2008). Global thresholds considering deep-seated landslides could not be found. In applying the threshold, we consider example rainfall durations of 2 and 10 days (Fig. 7a and b, respectively). Finally, as an illustration of the impact of rainfall on the occurrence of landslides, all landslide events from the archive inventory which could be dated are plotted per 10-day period together with the 10-day moving average daily precipitation averaged over the years 1999–2008 as calculated by COSMO-CLM² (Fig. 8).

Seismic activity

According to Keefer (2002) earthquakes of $M>4$ can already induce rock falls, rock slides, soil falls, and disrupted soil slides. However, also smaller earthquakes occurring together with other triggering factors such as high or intense rainfall could induce landslides (Keefer 1984). Earthquakes do not only cause landslides at their time of occurrence, but they are known to cause a reduction of soil shear strength, rendering the area more susceptible to slope failure. This effect can last up to several years after an earthquake event (Chang et al. 2007).

Table 3 Evolution of population density in the three Rwenzori Mountains districts between 1980 and 2002 (based on Uganda census data retrieved from Statoids 2013)

	Area (km²)	Population density 1980 (inhabitants/km²)	Population density 1991 (inhabitants/km²)	Population density 2002 (inhabitants/km²)
Kasese	3205	71.04	107.21	166.30
Kabarole	8361	26.87	35.83	42.96
Bundibugyo	2338	48.00	49.86	91.05

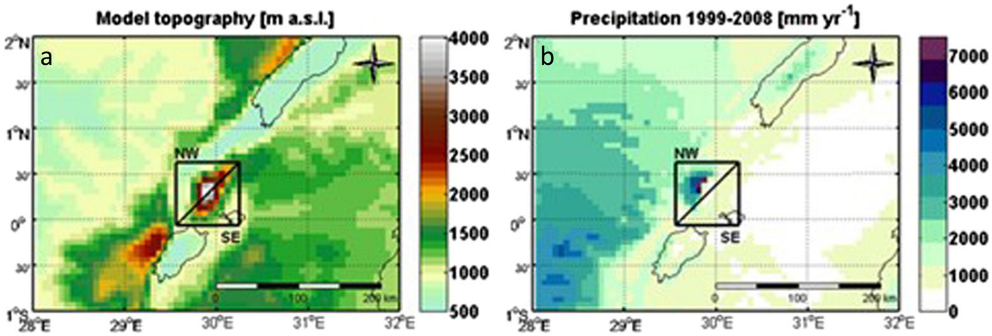

Fig. 6 **a** Model topography used in the COSMO-CLM^2 model by Thiery et al. (2015). **b** The average yearly precipitation between 1999 and 2008 as calculated by Thiery et al. (2015). The *black lines* represent the boundaries for the calculation of rainfall quantities on the NW and SE flanks of the Rwenzori Mountains

The Rwenzori Mountains are one of the most tectonically active regions of East Africa (Maasha 1975; Lindenfeld et al. 2012a). Therefore, it is expected that earthquake activity does influence the spatial and temporal distribution of landslides. Historical data on earthquakes in East Africa (1903–2013) is compiled by the Royal Museum for Central Africa (Delvaux et al. 2015) within the framework of the GeoRisCA project (Kervyn et al. 2013). The catalogue compiles several global and local catalogues together with regional databases from literature. To provide an overview of the potential spatial influence of earthquakes on slope stability, this catalogue is depicted in Fig. 4d. For earthquakes with M>5.5, these data are combined with the empirical correlation proposed by Keefer (2002):

$$\log_{10} A = M - 3.46(\pm 0.47)$$

where M is the moment magnitude of the earthquakes (between 5.5 and 9.2) and A the area (km^2) potentially affected by earthquake-triggered slides. Figure 4d shows that a large part of the Rwenzori Mountains is covered by the potential zones of influence of earthquakes with M>5.5. Furthermore it is clear that earthquakes with M>4 occur frequently, with more than 30 events between 1920 and 2013 having the epicenter located on the horst mountain itself. The last major earthquake (M=4.5, USGS 2014b) on the horst mountain occurred on 31 October 2014. Concentrations of earthquakes in this inventory coincide with the observations of Lindenfeld et al. (2012b) and cluster near the major faults bordering the horst mountain.

Discussion

Inventory

Quality of the inventory

The landslide and flash flood events included in the archive inventory are not evenly distributed in time, and the cumulative number of events increases sharply from 2001 onwards. This can partially be attributed to an increase in available sources via online reporting. Recent land-use changes, overpopulation, and meteorological changes could, however, also increase the landslide risk (Knapen et al. 2006; Crozier 2010). Given that this inventory is non-exhaustive, it is impossible to ascertain the contribution of these factors to the rising frequency of reported landslide and flash flood events.

The quality of the sources is highly divergent, ranging from intergovernmental reports to blog sites written by eye witnesses. Furthermore, information for most events (certainly those before 2013) is withdrawn from single sources. It is expected that some events are not described accurately while other events are not recorded in our inventory, for example if they did not cause significant damage or if they went unnoticed. This inventory does not have the ambition to be exhaustive and is likely to be biased towards high-impact and recent events.

Location of the landslides

Reported landslides are clustered at elevations below 2400 m a.s.l. and only occur at the Ugandan side of the mountain range. The low prevalence of events above 2400 m a.s.l. could be attributed to

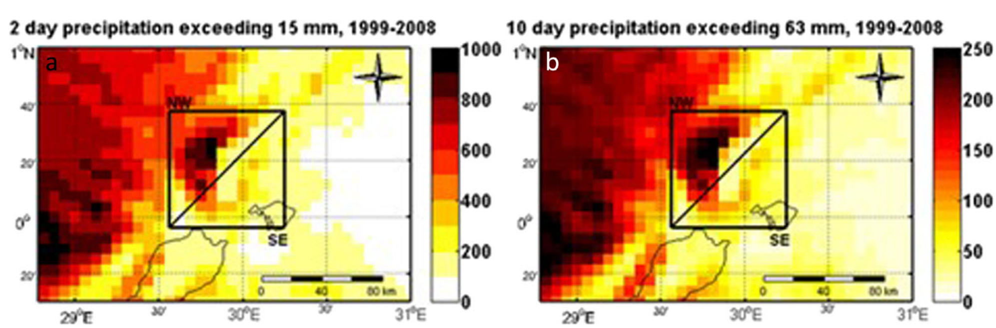

Fig. 7 Number of exceedance counts of the threshold proposed in Guzzetti et al. (2008) for rainfall events of 2 days (*left*) and 10 days (*right*) between 1999 and 2008. Each daily precipitation depth can only be taken up in one exceedance event for a specific intensity-duration, meaning that rainfall events longer than 2 and 10 days, respectively, but also exceeding the intensity-duration threshold, are counted as one exceedance event in the *left* and *right figures*, respectively

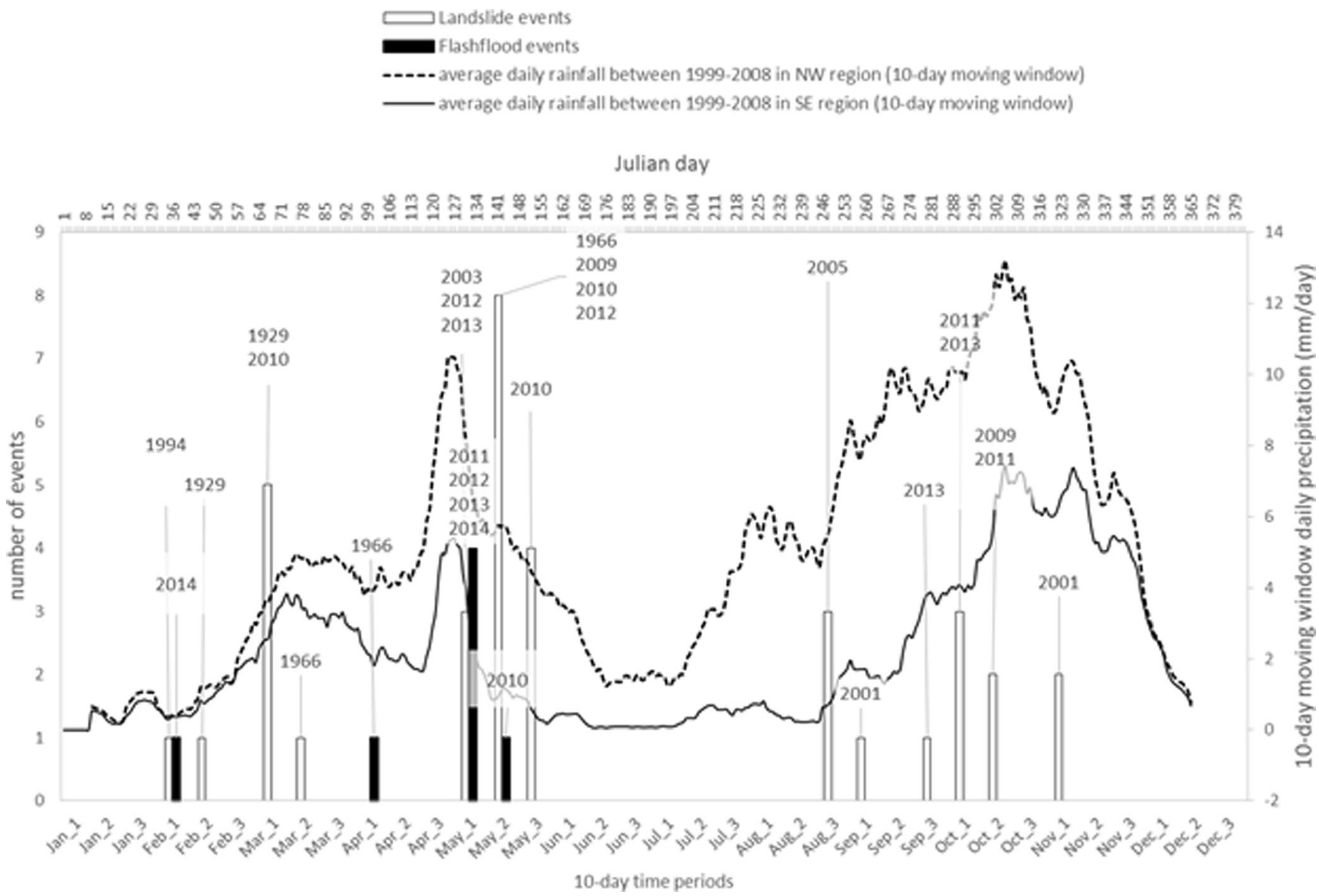

Fig. 8 Number of landslide events (*white bars*) and flash flood or combinations of these events (*black bars*) per 10 days with corresponding long-term 10-day moving average daily precipitation (Thiery et al. 2015). The boundary used to separate the NW and SE flanks of the Rwenzori Mountains is shown in Fig. 6

the fact that population densities are negligible in these locations (Fig. 2). It is likely that on the steep slopes with a high population density, landslide events have a larger damaging potential and are therefore more likely to be reported (e.g., Petley 2012), but the prevailing forest cover above 2400 m a.s.l. and on the Congolese side of the mountain range might contribute to a lower susceptibility to (shallow) landslides. The complete lack of landslide and flash flood events for the Congolese side could also be attributed to the different political and economic situations in the Democratic Republic of the Congo where inhabitants and reporters have less easy access to media, the Internet, or any other written dissemination of information. Population density also appears lower on the Congolese side, which could induce a smaller impact or less reporting (Fig. 2a). However, it should be stated that the grid size of the population data in the Democratic Republic of the Congo used in Fig. 2a is only 124 km, while it is 7 km in Uganda (CIESIN and CIAT 2005). It could be possible that clustering of the population on the Congolese side is hidden by the low resolution of the data.

In several cases, landslides are also linked to the presence of roads. Because of the interference with (sub)surface water flow and removal of support material in combination with overloading, it is likely that these landslides are associated with road construction (Swanson et al. 1975; Van Den Eeckhaut et al. 2013). From the archive sources alone, the contribution of road construction to slope instability is, however, unclear.

Consequences of landslides and flash floods

The events of the Rwenzori Mountains as described above are within the same order of magnitude in terms of impacts and numbers as the Limbe region (Cameroon), where 30 fatalities due to landslides are reported over the past 20 years (Che et al. 2011). The inventory shows that landslides are common in the Rwenzori Mountains where they cause significant damage, but very large-scale events with large impact like the Nametsi landslide in Mount Elgon with over 300 fatalities (Mugagga et al. 2012) do not seem to have occurred here. Although the Rwenzori Mountains are landslide-prone, it cannot be compared to major clusters of fatal landslides as those occurring in the Himalayans, Southeast Asia, or mountainous areas in Central and South America (Petley 2012).

In terms of fatalities, the events in the Rwenzori Mountains are numerous but small, partially explaining why they are missing from global databases like the EM-DAT International Disaster Database (EM-DAT 2009) or the DFLD (Petley 2012). Although the sources used for the compilation of the DFLD or the global landslide database by Kirschbaum et al. (2010) are of the same nature as this local database, the energy and time allocated for this study could be concentrated on a much smaller region, which explains why this inventory contains events that do not appear in these two global landslide inventories. The underrepresentation of the Rwenzori Mountains is probably indicative for a general underrepresentation of African highlands in global databases of Petley (2012) and Kirschbaum et al. (2010). The findings from this

Table 4 Overview of factors controlling or triggering the occurrence of landslides based on Keefer (2002) and Corominas et al. (2014) together with the available data for the Rwenzori Mountains, their resolution, and source

	Parameters	Controlling (C) or triggering (T)	Available data and resolution	Source
Topography	Elevation, internal relief	C	90 m DEM, 30 m DEM 30 m DEM 1:50,000 topographic maps	SRTM (Jarvis et al. 2008; USGS 2014a) ASTER (http://asterweb.jpl.nasa.gov/gdem.asp) Department of Lands and Surveys, Uganda (1972)
	Slope gradient	C		
	Slope direction	C		
	Slope length, shape, curvature, roughness	C		
	Flow direction and accumulation	C		
Geology	Rock types	C	1:100,000 geological maps	GTK consortium and the Department of Geological Survey and Mines, Entebbe, Uganda (2012)
	Weathering	C		
	Discontinuities	C		
	Structural aspects	C		
	Faults	C		
EQs	EQ magnitude	T	EQ map: location and magnitude of EQ with Richter magnitudes >1.5 from 1903 to 2013	GeoRisCA, www.georisca.africamuseum.be, Delvaux et al. (2015)
	Location of EQ source	T		
	Focal depths	T	n.a.	n.a.
	Ground motion characteristics	T	Global Seismic Hazard Program (GSHAP)	GSHAP (2000)
Soil	Soil types	C	WRB soil types 1 km resolution	Soil Atlas of Africa (Dewitte et al. 2013; Jones et al. 2013)
	Soil depth	C	n.a.	n.a.
	Geotechnical properties	C	n.a.	n.a.
	Hydrological properties	C	n.a.	n.a.
Hydrology	Groundwater	C/T	n.a.	n.a.
	Soil moisture	C/T	Worldwide 0.5° long-term average mean humidity	Willmott and Feddema (1992)
	Components in hydrological cycle	C/T	n.a.	n.a.
	Stream network and drainage density	C	30 m DEM 30 and 90 m SRTM DEM 1:50,000 topographic maps AfrHySRTM (90*90 m^2)	ASTER (http://asterweb.jpl.nasa.gov/gdem.asp) SRTM (Jarvis et al. 2008) Department of Lands and Surveys, Uganda (1972) Vagen (2010)
	Rainfall intensity	T	1999–2008, hourly data on 7-km resolution	COSMO-CLM[2]
Geomorphology	Geomorphological environment (glacial, alpine, tropical, paraglacial…)	C	n.a.	n.a.
	Old landslides	C	Archive study (fragmented and biased)	This publication

Table 4 (continued)

	Parameters	Controlling (C) or triggering (T)	Available data and resolution	Source
	Past landslide activity	C		
Anthropogenic influence	Current land use	C	High- and moderate-resolution remote sensing imagery 1:50,000 topographic maps Google Earth imagery	MODIS, ASTER, LANDSAT (http://glovis.usgs.gov/) Department of Lands and Surveys, Uganda (1972) GOOGLE EARTH
	Land-use changes	C/T		
	Transportation infrastructure	C		
	Buildings	C/T		
	Drainage and irrigation networks	C/T		
	Quarrying and mining	C/T		
	Dams and reservoirs	C/T		

n.a. not available

inventory are in line with and validate the global assessment model by Hong et al. (2007).

Controlling and triggering factors

Controlling factors

The strength of the main rock types in the Rwenzori Mountains (i.e., gneiss and amphibolites) is high, indicating inherent stability. However, it can be expected that fault activity increases internal fracturing of the lithology, thereby potentially weakening the inherently stable lithology of the Rwenzori Mountains.

The basic analysis using SRTM digital elevation models shows that a large portion of the Rwenzori Mountains has slopes above the global and regional threshold values for stability (Fig. 4b). For the entire Rwenzori Mountains, one fifth to almost half of the slopes is above thresholds of stability. This portion is even higher when only considering the area above the Lake Mahoma glacial extent, where more than 60 % of the slopes exceed the threshold by Sidle et al. (1985), indicating a potential for slope failure. This is supported by the observation of Bagoora (1988), who reported mass wasting processes associated with glaciation processes on the upper slopes of the Rwenzori Mountains.

As for soil information, the Soil Atlas of Africa shows only dominant soil types per polygon at scale 1:1 M to 1:2 M, so local variability is not taken into account (Dewitte et al. 2013; Jones et al. 2013). The Leptosols at high altitudes are partly associated with the glaciation stages, which resulted in a large-scale removal of soil and rock. Deglaciation often delivers poor underdeveloped soil underlain with glacial till. This is the case for the Katabarua stage glaciation which is associated with the Rwanoli tills consisting of silty clays and gravel (Ring 2008). Because of the limited infiltration capacity of these soils, failure in the form of shallow debris flow avalanches is possible (Sidle and Ochiai 2006). The lower-lying Ferralsols and Acrisols are considered to have stability-favoring properties (Knapen et al. 2006). However, it remains difficult to assess stability of WRB soil types due to the lack of information on physical soil properties. This also applies to the other soil types occurring in the Rwenzori Mountains like Nitisols, Phaeozems, and Andosols. While in the Nyandarua range in Kenya, Nitisols and Andosols are found to be prone to landsliding (Davies 1996), Kitutu et al. (2009) show that in the landslide-prone area of Mount Elgon, these soil types were not directly linked to landslide susceptibility. Information on soil physical properties is only available through global databases like the HWSD (FAO/IIASA/ISRIC/ISSCAS/JRC 2012), but they lack the necessary spatial resolution or sufficient field measurements to be reliable for regional and local landslide studies.

As the population of the Rwenzori Mountains has nearly doubled between 1980 and 2002, it could be expected that deforestation and anthropogenic impacts play major roles in landslide susceptibility. Indeed, Bagoora (1988) reported that landslips and mass wasting are increasingly common in the Rwenzori Mountains due to high population densities causing vegetation removal, particularly on lower-lying slopes. This deforestation trend was, however, inverted over the last 10 years (Jagger and Shively 2014), but increased slope cuttings for the construction of roads and houses might still contribute to decreasing slope stability. As a final remark, a growing population in unstable areas can imply an increased exposure to landslide hazards.

Triggering factors

Figure 6b shows that the Rwenzori Mountains are much wetter than the surrounding plains. The potential for rainfall-triggered landslides is investigated by counting the exceedances of critical precipitation amounts for shallow landslides as defined by the most recent global rainfall threshold assessment (Guzzetti et al. 2008) for two example rainfall events (2- and 10-day durations) (Fig. 7). In both cases, this threshold is exceeded several times per year. Furthermore, between 1999 and 2008, no pixels on the Rwenzori Mountains have an exceedance count equal to zero. As this is a global, minimal threshold, this does not imply that every exceedance of the threshold triggers landslides, but rather, it shows that rainfall events could be strong enough to trigger landslides. The NW flank, in general, counts more exceedance events than the SE flank. However, intense rainfall seems to cross this topographic axis in the south of the Rwenzori Mountains with numerous exceedances of both thresholds. Figure 8 illustrates the impact of rainfall on the landslide and flash flood events of the archive inventory. This figure again shows that the SE side is much drier than the NW side, especially during both wet seasons, when 10-day averaged daily precipitation is up to four times larger on the NW side relative to the SE side. Of the 35 landslide events where the date of occurrence could precisely be retrieved, 33 took place during the wet seasons which occur from March to May and from August to November (Taylor et al. 2009). Furthermore, all flash flood events, except one in February 2014, occurred during the wet season. This indicates that rainfall acts as an important triggering factor in the Rwenzori Mountains. The steeper slopes and higher rainfall on the NW flank of the Rwenzori could suggest a higher potential for landslides. However, much of this area is still under forest, thereby potentially decreasing susceptibility to landslides. Unfortunately, given the bias of the archive inventory towards densely populated areas on the Ugandan side, the role of higher rainfall and slope gradients together with the stabilizing land cover cannot be adequately assessed.

Earthquake activity is likely to trigger landslides as well. Figure 4d shows that earthquakes potentially have a large influence on landslide occurrence. In the archive inventory, five landslide events are reported to be triggered by earthquakes according to their sources (UNESCO 1966; USGS 2010). For the particular cases of the LS events of February 1929 and February 1994, which lie outside of the typical rainy season and are not reported to be triggered by exceptional rainfall, it is expected that earthquake activity acted as a major trigger. The contribution of earthquakes interacting with other triggers for other landslide events can, however, not be analyzed in detail due to the lack of accurate data on location and magnitude of earthquakes and landslides in the inventory.

Perspectives and gaps in knowledge

Based on recommendations of Keefer (2002) and Corominas et al. (2014), Table 4 is compiled showing data availability and resolution for the study of spatial and temporal distribution of landslides, together with data gaps. This overview shows that data on both triggering and controlling factors and inventories of past landslides are scarce and/or of insufficient temporal or spatial resolution. With regard to controlling factors, the lack of spatially explicit data for soil physical properties in particular is problematic. Considering information on triggering factors, information on groundwater depths, soil moisture contents, pore water pressure, and other components of the hydrological cycle is entirely missing. Data on rainfall conditions are often used as a proxy for these factors. However, in situ systematic rainfall records with sufficient spatial and temporal resolution that capture the orographic gradient are also lacking. This assessment for the Rwenzori Mountains is representative of the problem of many regions, especially in sub-Saharan Africa, lacking detailed data to properly document and characterize landslide events and assess hazards.

Conclusion

Although the Rwenzori Mountains are identified as a landslide-prone region on a national and continental level, the region is only marginally represented in global landslide inventories. With 56 fatalities, an estimation of more than 14,000 persons left homeless, and large-scale destruction of road infrastructure, utility lines, houses, schools, and crops reported in the archive sources, it is clear that landslides and related phenomena do occur in the Rwenzori Mountains and that their impact cannot be neglected.

Building resilience to landslide risk requires a full understanding of the factors controlling and triggering landslide occurrence. Given the lack of spatially explicit data, especially on soil physical properties, rainfall conditions, and past landslides, a proper susceptibility and hazard analysis is hampered. This study demonstrates that using archive data, despite its limitations, combined with an analysis of datasets available at global or continental scale, one can provide first constraints on the frequency, spatial and temporal distribution, as well as on some potential triggering and controlling factors. A similar approach could be conducted in other highlands to identify zones that should urgently be studied in more detail for landslide hazard. Considering the interactions of landslides with other potential hazards (Gill and Malamud 2014), current population growth, the consequent increasing anthropogenic impacts on slope stability, and the potential increase in frequency of extreme precipitation events for East Africa (IPCC 2012), we highlight the need for systematic research on landslide issues which, despite the importance for local inhabitants, is largely neglected. This statement holds not only for the Rwenzori Mountains but also for other similar regions in Equatorial Africa which are underrepresented in global landslide inventories.

Acknowledgments

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L. Jacobs (✉) · M. Kervyn
Department of Geography, Earth System Science,
Vrije Universiteit Brussel,
Pleinlaan 2, 1050, Brussels, Belgium
e-mail: liesbet.jacobs@vub.ac.be

L. Jacobs · O. Dewitte · D. Delvaux
Department of Earth Sciences,
Royal Museum for Central Africa,
Leuvensesteenweg 13, 3080, Tervuren, Belgium

J. Poesen · W. Thiery
Department of Earth and Environmental Sciences,
KU Leuven,
Celestijnenlaan 200E, 3001, Leuven-Heverlee, Belgium