3rd 2017 NASL
3rd North American Symposium on Landslides
June 4-8 2017, Roanoke, Virginia, USA

Constraints on Landslide-Climate Research Imposed by the Reality of Fieldwork in Central Africa

Monsieurs, E., elise.monsieurs@africamuseum.be
Royal Museum for Central Africa, Leuvensesteenweg 13, 3080 Tervuren, Belgium
NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA
Kirschbaum, D.B., dalia.b.kirschbaum@nasa.gov
NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA
Thiery, W., wim.thiery@env.ethz.ch
Eidgenössische Technische Hochschule Zürich, Rämistrasse 101, 8092 Zürich, Zwitserland
van Lipzig, N., nicole.vanlipzig@kuleuven.be
Katholieke Universiteit Leuven, Oude Markt 13, 3000 Leuven, Belgium
Kervyn, M., makervyn@vub.ac.be
Vrije Universiteit Brussel, Pleinlaan 2, 1050 Elsene, Belgium
Demoulin, A., ademoulin@ulg.ac.be
University of Liège, Quartier Village 4, clos Mercator 3 4000 Liège, Belgium
Jacobs, L., liesbet.jacobs@vub.ac.be
Kervyn, F., francois.kervyn@africamuseum.be
Dewitte, O., olivier.dewitte@africamuseum.be
Royal Museum for Central Africa, Leuvensesteenweg 13, 3080 Tervuren, Belgium

ABSTRACT. Climate change is reported to be 'very likely' associated with an increasing trend in extreme rainfall intensity over the tropics. Its impact on the timing of landslide initiation however remains poorly understood. Central Africa, located in the tropics, has repeatedly been highlighted as lacking landslide catalogs and landslide-climate studies. We present a research approach, adapted to the data-poor context of Central Africa, to study regional rainfall controls on landslides conditioned by climate change. Preliminary results are presented, including a description of the current rain gauge network installed, an inventory of 83 landslide events with known date and location, and a case study of a landslide occurrence. We show that the underrepresentation of Central Africa in current landslide-climate research is related to the dearth of adequate rainfall ground monitoring networks and spatiotemporal data on landslide occurrence, rather than to the lack of landslide occurrence. Research constraints imposed by the context of Central Africa are highlighted. In presenting this challenging research setting, our aim is not to discourage research in the region, but to identify lessons learned from previous field work and emphasize the abundant opportunities inviting natural hazard studies in Central Africa.

INTRODUCTION

The tropics (Peel et al., 2007) are strongly affected by landslides due to high precipitation and weathering rates, specifically in zones with steep topography and tectonic activity (Sidle et al., 2006). In addition, landslide frequency in the tropics is expected to increase in the future in response to increasing demographic pressure, deforestation and land use changes (Gariano and Guzzetti, 2016). Processes controlling the timing of landslide initiation in the tropics however remain poorly understood. In this region, rainfall is by far the main landslide trigger (Sidle et al., 2006), with different responses of shallow and deep-seated landslides (Guzzetti et al., 2008). The quantification of rainfall amount and intensity needed to trigger landslides is a key parameter to predict the timing of landslides and minimize damage and loss of life. It requires an accurate determination of rainfall thresholds specific to the various landslide processes and their environmental conditions. Two main approaches are generally used: (1) empirical (statistical) models based on historical landslide data and related rainfall (Guzzetti et al., 2008), and (2) physical (process-based) models which combine infiltration models with slope stability models (Corominas et al., 2013), the latter requiring a larger amount of input data. The challenge inherent in both approaches is the lack of landslide inventories, and rain gauge data (Guzzetti et al., 2008; Kirschbaum et al., 2015a), explaining the scarcity of such thresholds in the tropics.

Climate change is reported to be 'very likely' associated with an increasing trend in extreme rainfall intensity over the tropics (IPCC, 2013). While some researchers (e.g., Crozier, 2010; Gariano and Guzzetti, 2016) suggest modification of landslide processes associated with these altered rainfall conditions, high levels of uncertainty remain, because of the errors affecting scenario-driven global climate predictions, and the insufficient spatial resolution of downscaled projections (Crozier, 2010). Regional studies of the effect of climate change on sudden landslide initiation or reactivation in data-poor areas are to the authors' knowledge nonexistent. Currently, the easiest way to achieve comprehensive rainfall estimates at a regional scale comes from remote sensing data, whose increasing availability offers a new opportunity to address landslide hazard assessment in remote areas. Tropical Rainfall Measuring Mission (TRMM) data provided the first quantitative estimates of precipitation from space-borne radar at a 0.25° × 0.25°, 3-hourly resolution for a 17-year period (1998-2015). The Global Precipitation Measurement (GPM) Core Observatory, launched in 2014, builds upon the TRMM instruments and methodology. GPM data (half-hourly, 0.1° × 0.1° resolution) improves the ability to identify small, intense precipitation features, which frequently trigger landslides (Kirschbaum et al., 2015b). Though never calibrated or validated for Africa, TRMM and GPM are currently the most accurate freely available precipitation products over the tropics.

The underrepresentation of Africa in landslide research has been repeatedly highlighted (e.g., Gariano and Guzzetti, 2016; Jacobs et al., 2016a; Kirschbaum et al., 2015a), notably due to field constraints. Africa is lacking in global landslide catalogs (Kirschbaum et al., 2015a; Petley, 2012), in landslide susceptibility, hazard, and risk research (Maes et al., 2017), and in landslide-climate studies (Gariano and Guzzetti, 2016). Priority 1 for action addressed by the recent UN Sendai Framework for Disaster Risk Reduction (2015-2030), is the understanding of disasters, which implies a strong focus on hazard assessment (UNISDR, 2015).

The objective of our research is to investigate at a regional scale the unexplored interplay between rainfall controls of landsliding (hazard) and climate change in the tropical climate zone of Central Africa. The study area lies within the western branch of the East African Rift. In this paper, we present a methodology that applies for this region, with preliminary results focusing on the part lying in the Democratic Republic of Congo.

The general constraints and challenges we faced during the first two years (2015-2016) of the method's development are summarized. Then, we present preliminary results on rainfall and landslide data collection, with their respective associated difficulties. We conclude with a landslide case study illustrating these difficulties.

STUDY AREA

The study area covers ca. 200,000km² in the central section of the western branch of the East African Rift, located in the tropical climate zone of Central Africa (Fig. 1). 'WEAR' is used in this paper to refer to the study area. Through research projects during the past 10 years in Central Africa (e.g., http://afreslide.africamuseum.be/, http://georisca.africamuseum.be/, http://resist.africamuseum.be/) at the Royal Museum for Central Africa in Belgium (RMCA), landslides have been found to be a major natural hazard in this densely populated region, causing fatalities every year and resulting in structural and functional damage to infrastructure, as well as serious disruptions of the organization of societies (Jacobs et al., 2016a; Maki Mateso and Dewitte, 2014; Michellier et al., 2016). WEAR is thus a highly suitable study area through the experience gained in the region, the large environmental gradients (e.g., seismicity and land use; Delvaux et al., in press), and its representativeness for tropical mountainous regions.

Currently, two temporal inventories (partly) cover the study area: an inventory of 48 landslides in the Rwenzori Mountains (Jacobs et al., 2016a), and a natural hazard database for Central Africa (Vandecasteele et al., 2010). Both of them lack consistent information on the timing of landslide events and acknowledge the likelihood of greatly underestimated numbers of events due to limited communications in the region (Jacobs et al., 2016a; Vandecasteele et al., 2010). Maki Mateso and Dewitte (2014) mapped more than 600 landslides in the study area. However, although valuable for susceptibility analyses, the lack of temporal information prevents using them for hazard studies. Due to the absence of a rain gauge network at the time of mapping, rainfall considerations were not included in their study (Maki Mateso and Dewitte, 2014).

An extensive review of the past and current socio-economic situation of DR Congo is presented by Trefon (2016), of which the following characteristics are noted for the WEAR: lack of governance; abundant natural resources; enduring (armed) conflicts; strong cultural pressure for large families; high population density; very fast urban expansion; dependence of a large majority of the population on agriculture; slash-and-burn practices as a major driver of deforestation. Michellier et al. (2016) found that human-related parameters such as high population densities, high poverty levels, and poor political stability are major drivers of increased vulnerability to, and risk of, geo-hazards in the WEAR.

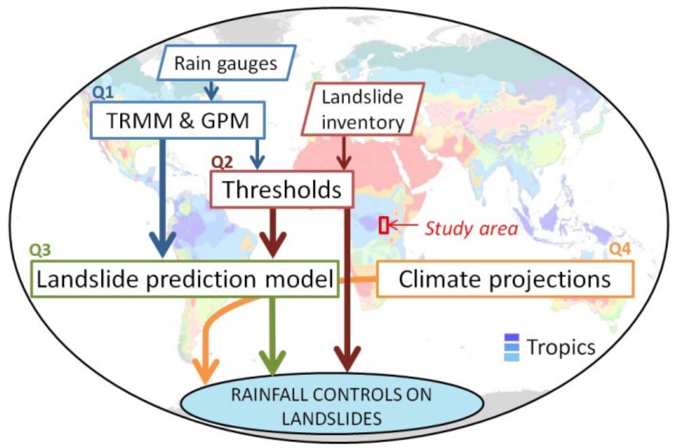

Figure 1. Proposed workflow for a regional assessment of rainfall controls on landslide hazard in Central Africa in the context of climate change. The workflow comprises four key steps based on four underlying questions (Q). Rain gauge data and a spatiotemporal landslide inventory serve as primary inputs. The study area along the western branch of the East African Rift, situated in the Tropics (Peel et al., 2007), is located on the map.

PROPOSED METHODOLOGY

We developed a methodology adapted to the regional assessment of rainfall controls on landslide hazard in the context of climate change, taking into account (1) the limited field accessibility, (2) variations in data availability and quality over different countries, and (3) limited baseline data (Michellier et al., 2016). This methodology relies mainly on state-of-the-art remote sensing, supported by targeted field validation. Four key base questions are considered (Fig. 1), namely (1) How do the best available rainfall satellite products perform?, (2) Which rainfall intensity and duration characteristics do trigger landslides?, (3) Where will future landslides occur?, and (4) What will be the impact of climate change on the frequency of rainfall-triggered landslides?

Rain gauge and spatiotemporal landslide data are the principal inputs for subsequent steps in the workflow (Fig. 1). We installed and currently maintain a rain gauge network in places previously uncovered.

A spatiotemporal landslide inventory has been assembled through archive research, field observations, and collaboration with local partners. Collaborations are achieved thanks to the wide network created through long-term partnerships of RMCA with institutions such as the Civil Protection in DR Congo, the Centre de Recherche en Science Naturelles (DR Congo), the Université Officielle de Bukavu (DR Congo), Meteo Rwanda (Rwanda), and the Université du Burundi (Burundi). Both inventories (rainfall, landslides) are continuously updated.

Two years of rain gauge data (2015-2016) will be used to validate TRMM and GPM precipitation estimates (Q1, Fig. 1). TRMM- and GPM-based Intensity-Duration (ID) thresholds for landslides in the WEAR will be calculated using the spatiotemporal landslide inventory (Q2, Fig. 1). In this way we contribute to a better understanding of the impact of different satellite rainfall estimates on landslide threshold analysis.

Threshold analyses will be performed separately for different landslide types. Subsequently, thresholds will be regionalized by taking account of various landslide-controlling factors (Sidle and Bogaard, 2016), based on freely available datasets, in particular the recently developed seismotectonic zonation model over the WEAR (Delvaux et al., in press), global land cover data (Bai et al., 2014), and land use change products (Meiyappan and Jain, 2012).

Once rainfall thresholds have been established, they will be combined with validated GPM data and applied in the regional model for Landslide Hazard Assessment for Situational Awareness (LHASA) developed by NASA (Kirschbaum et al., 2015b) (Q3, Fig. 1). Among the different hazard models proposed in the literature (Guzzetti et al., 1999; Nichol et al., 2006), LHASA seems the most suitable for application in the WEAR whilst estimating potential landslide activity across broad regions with sparse landslide inventories and other local information. LHASA integrates a regional susceptibility map, rainfall threshold and satellite-based rainfall estimates generating a pixel-by-pixel landslide forecast in near real time at a resolution of 30 arcsec (approximately 1 km) (Kirschbaum et al., 2015b). A landslide susceptibility map for the WEAR is being produced at 30 m resolution by RMCA. LHASA will be validated for the WEAR through (1) comparison of the current spatiotemporal landslide inventory and the results of a retrospective LHASA model run over the time period covered by the landslide inventory, and (2) a similar comparison for newly recorded landslides in the study area.

Finally, the regional impact of climate change on landslide triggering in Central Africa will be assessed using COSMO-CLM² state-of-the-art climate change projections (Q4, Fig. 1). These are developed by Thiery et al. (2015) at a horizontal resolution of 0.0625° (±7 km), unprecedented for climate studies in this region. The model performs excellently in reproducing mean and extreme precipitations of the present-day climate (Thiery et al., 2015). Regional COSMO-CLM² simulation for the present (1999-2008) will first be used as an input for the LHASA landslide prediction model and the results will be validated through comparison with the output of the GPM-fed LHASA model run. Next, the COSMO-CLM² simulations for the future (2071-2100) will be incorporated into LHASA, assuming that the present-day landslide threshold remains valid in a future warmer world. By comparing the present-day and future simulations, we will evaluate which of changes in rainfall intensity or duration will most impact future landslide frequency.

GENERAL CONSTRAINTS

Initially, fieldwork was planned in Burundi and a collaboration was established with local partners for setting up the field survey approach. However, we were forced to cancel fieldwork at the very last moment as a consequence of the political context in the country (Grauvogel, 2016). In Rwanda, we could not get the authorizations required for conducting fieldwork due to hierarchical and time-consuming bureaucratic processes (Purdeková, 2011). Because of the current activities of RMCA in eastern DR Congo (Michellier et al., 2016), which facilitated collaborations with local partners, we thus opted to start fieldwork in Congo. Simultaneously, research on landslide hazard in Uganda is conducted by partners at RMCA (Jacobs et al., 2016a,b). In the period Dec. 2016 – Jan. 2017, fieldwork in DR Congo was hampered because of potential unrest the country could have to face in relation with the presidential election (Vlassenroot and Berwouts, 2016). The transnational situation of the study area makes traveling and related bureaucracy not attractive for research, illustrating a main challenge related to the poor political stability in the region (Uganda, Rwanda, Burundi, DR Congo).

A second major constraint is the cost of safe fieldwork in eastern DR Congo. Transport and storage of expensive research equipment (e.g., rain gauges, differential GPS) require secured conditions, which means using expensive high-standing hotels and a private driver who knows the local road customs, including checkpoints during the frequent road blockages, places to avoid, poor road condition, time of driving (to avoid police baksheesh after dark). A private driver may charge up to 100 USD per day. Additionally, there is no low-cost flight to eastern DR Congo, even from other African countries, and the closet airport is in Rwanda.

Limited data availability represents a third constraint on research in the region. Among several reasons, we note the absence of longstanding tradition of systematic data recording. Only Rwanda is an exception in this respect but detailed data collected by the government remain inaccessible for research purposes (Michellier et al., 2016), lack of governance plays also a role in the deficient of data recording (Trefon, 2016). Civil Protection was only very recently established in eastern DR Congo (in 2002 in North Kivu, 2012 in South Kivu) and lacks a defined mission, dedicated staff, and means for intervention (Michellier et al., 2016). The overall communication problems are another major limitation. Most areas are too remote for information to reach a bigger city and the media. Moreover, on the advice of local colleagues informed about the presence of rebel groups, remote areas are avoided for fieldwork. Roads are scarce and poorly maintained in large parts of the WEAR. Access to the Internet is very limited, whereas the use of mobile phones boomed from the late 1990s (Trefon, 2016). Although first attempts for data collection through crowdsourcing in the region have proven to be ineffective, we continue to explore the potential of mobile phones.

Despite all these constraints, institutions such as RMCA continue doing research in the WEAR because North-South collaborations are expanding, promising and enriching for both parties. Besides the long-term key objective ofcapacity building, these collaborations aim to meet the urgent need for improved understanding of geo-hazards that represent an important threat for these densely populated regions.

RAIN DATA COLLECTION

We set up a rain gauge network including 12 tipping buckets (Self-Contained Automatic Logging Rain Gauge) and 3 weather stations (Davis Vantage Pro2) in DR Congo (Fig. 2). Installation was constrained by (1) the budget for the number and type of rain gauges, (2) the limited accessibility of the area, (3) the availability of secure emplacements, and (4) the need of an open environment, free of trees or buildings. Our rain gauge network satisfyingly covers the latitude range from the northern zone of Lake Tanganyika to north of Lake Kivu. Variation in longitude (from 28.8E to 29.4E) was mainly hampered through low levels of security and limited accessibility east of Lake Kivu. Minimum and maximum rain gauge elevations in this network are 798 m and 2412 m, respectively, with a mean of 1616(±405) m. The main objective of this distribution in latitude, longitude, and elevation is to validate TRMM and GPM satellite rainfall estimates, rather than perform trend analyses or regional interpolations. All rain gauges are secured by a fence and surveilled by people living in the close vicinity (e.g., a parish, university, research institution, hospital, or National Natural Park).

Rain gauges have a 9-month storage capacity and a battery capacity exceeding 9 months for 30 min data resolution. Data are collected in collaboration with local institutions. A limited budget is available for transport of the local partners to the rain gauges every ± 7 months. At the time of writing, 14 months of rainfall data were collected. We found that daily rainfall variability in the WEAR is high, with no between-gauge correlation higher than 0.57 (absolute value). The time series is too short to allow for further analyses on rainfall trends in means and extremes so far.

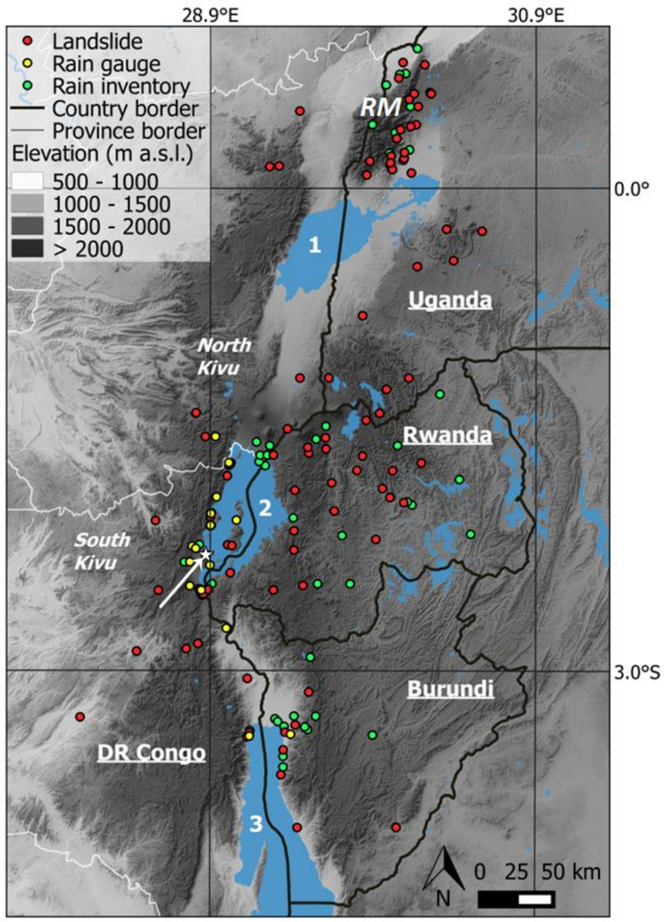

Figure 2. Spatial distribution of the current landslide inventory and rain gauge network over the study area. 'Rain gauge' are the rain gauges in the network we installed and continue maintaining. 'Rain inventory' are the rain gauges from which data is collected from a variety of different sources. RM = Rwenzori Mountains; 1 = Lake Edward; 2 = Lake Kivu; 3 = Lake Tanganyika. The landslide in Djikumbo is presented as a star and highlighted with an arrow. Hillshading from SRTM 90m.

Problems in data collection included (1) batteries discharged after a few months, with loss of several months of data before the problem was noticed at the time of data download; (2) gauge blockage through dust during the dry season; (3) blockage through leaves; (4) gauge manipulation by children; (5) gauge tilting due to quick degradation of the supporting structure. The impact of these problems was mainly related to the low frequency of rain gauge visits and the difficulty of finding gauge locations that are ideal and secure at a time. The above mentioned problems could have been avoided if a good road network were present in the study area, making visits to the rain gauges less dangerous, time-consuming, and costly.

To avoid such problems in the future, we have now established a systematic two-weekly check of remote rain gauges by local partners. This check consists in contacting by mobile phone each person appointed to a rain gauge, in order to confirm that everything is all right. Each contact person is someone in charge over the area where the rain gauge is installed. In this way, local partners can intervene quickly if a problem arises, thus minimizing data losses.

In addition to the data from the installed rain gauge network, we collected data from 58 existing rain gauges scattered over the study area (Fig. 2). We obtained these data through a variety of sources, including (1) research projects AfReSlide (http://afreslide.africamuseum.be/) and RIDEC (http://cordis.europa.eu/project/rcn/195341_en.html), where RMCA is directly involved, (2) another research project in the WEAR, named EAGLES (http://www.eagles-kivu.be/project.htm), (3) research institutions (University of Burundi, Burundi; Centre de Recherche en Hydrobiologie, DR Congo; Observatoire Volcanologique de Goma, DR Congo), (4) the Appalachian State University (USA), (5) a religious institution (Pères Blancs Bukavu, DR Congo), and (6) governmental institutions (Meteo Rwanda, Rwanda; NOAA, USA; United States Geological Survey, USA). Temporal resolution, covered time period, and data quality vary over all these sources. Based on our own experience, we are aware of possible errors from rain gauge measurements. An elementary testing procedure, such as the one described by Isotta et al. (2013), will be systematically applied across the entire study area to homogenize and validate the rain gauge data from this variety of sources.

LANDSLIDE DATA COLLECTION

The goal was to include as many events in the study area as possible, regardless of size, impact, date of occurrence, or trigger. The only constraints imposed are that (1) date and location (primary attributes) must be known to enable hazard analyses (Guzzetti et al., 1999) and (2) landslides in mining areas are excluded, because these areas do not represent natural conditions (e.g., slope, soil structure) and hence would bias hazard assessment. Secondary attributes provide additional information when available, including: time of occurrence, number of fatalities, number of injuries, trigger, and type

Our main source of spatiotemporal landslide data, accounting for 91% of the current landslide inventory, was a structured keyword-based search on the Internet in both English and French (lingua franca in this region of Central Africa). We explored the scientific literature, (inter)governmental and Non-Governmental Organization (NGO) reports, international disaster relief websites, (inter)national news sites, and eyewitness descriptions and blogspots. One third of all sources were in French, the two other thirds in English. Biases and uncertainties inherent to the compilation of landslide inventories have been documented in previous studies (Kirschbaum et al., 2015a; Petley, 2012; Vandecasteele et al., 2010). A major bias was due to the contrasting political and economic situations over the study area, associated with limited communication, as illustrated by the Rwenzori Mountains (Jacobs et al., 2016a). We faced also difficulties with untraceable village names and wrongly spelled locations. Uncertainties regarding reported fatalities and injured people have been acknowledged by Petley (2012), and are here specifically related to the assumption of zero fatalities or injuries when nothing was mentioned.

Field observations have contributed for 9% of the current landslide inventory through collaboration with local partners including the Civil Protection, for which no other sources were found describing the landslide occurrence. Although still in an embryonic stage (Michellier et al., 2016), the Civil Protection provided us with valuable information on landslide occurrences. Current security levels and inadequate road network in most parts of the study area preclude systematic field observation on a regional scale. For instance, the region east of Lake Kivu (Fig. 2) is known by local partners to be regularly affected by landslides but event dates could not be verified because of continuous tension, road blockage, and armed groups present in this area. Also fast vegetation growth rapidly hampers recognition of small landslides in Central Africa. For these reasons, we found that the potential for data collection through local collaborators was not fully reached.

Confined field observations revealed the severe underreporting of landslide occurrences, mainly caused, as stated above, by the remoteness of most areas and the lack of systematic records. Multitemporal satellite image analysis is promising to track landslide events (Nobile et al., 2016), whereas it stays challenging to extract the exact day of landslide occurrences, required for hazard analyses. Evidence of smaller landslides is quickly vanished due to modifications by subsequent erosional processes, anthropic influences, and high vegetation growth rates. We also had difficulties in tracing dates of landslides observed in the field, which were considered reliable only if a group discussion with local inhabitants could lead to their precise determination (Nyssen et al., 2006). Based on limited field observation, we found a broad variety of landslide types, including debris flows, deep-seated rotational slide, and shallow slides (Hungr et al. 2014). This differentiation is not represented in the inventory when only using Internet sources. We subscribe this bias to the lack of scientific knowledge when reporting the event.

Second only to rainfall as reported causal factor of landslide, demographic pressure is very high in the WEAR (Michellier et al., 2016; Trefon and Cogels, 2006), plausibly interfering with recent, usually shallow landslide events (Appendix A). We do not know so far how land use changes affect slope stability at the regional scale. In the absence of systematic data recording and archiving, people aware of potential risks through oral information tend to leave a hazardous area, after which new residents unaware of the hazard come and settle down in the vacant spaces.

The spatial distribution of the 83 landslides of the inventory is presented in Fig. 2, with 44% of the landslides reported in DR Congo, 29% in Uganda, 20% in Rwanda, and 7% in Burundi. This number is significantly higher than the 35 landslides recorded in the WEAR by the Global Landslide Catalog of Kirschbaum et al. (2015a). However, detailed spatiotemporal analyses of the inventory will require that the ongoing extensive archive research be achieved and the targeted systematic search of the Internet and field data collection be continued. In particular, we now take advantage of the two-weekly checking of rain gauges to ask for possible landslide activity in the area. This approach seems promising, as attested by the information we obtained recently on landslide occurrences not reported in the media.

CASE STUDY IN DJIKUMBO (DR CONGO)

During fieldwork in February 2016, rainfall and the resulting bad road conditions forced us to take alternative ways to reach one of the rain gauges for data download. We noticed traces of recent landsliding by chance in Djikumbo (DR Congo) (Fig. 2), in the form of agricultural land covered with debris. Local colleagues participating to the field work translated information in Swahili from local inhabitants about the event. It was told that heavy rain on 20 February 2016 (9 days before our passing through, during the wet season) caused this debris flow destroying large parts of agricultural fields, without fatalities or injuries (Fig. 3). The event was reported neither in the national radio station (http://www.radiookapi.net/) broadcasting news facts, nor by the Civil Protection. While going upstream with a local inhabitant who was guiding us to the trigger zone, we noticed big boulders up to approximately 2 m³ that had just been transported during the event (Fig. 3). In the detachment zone (2.27815S, 28.869038E), fresh shallow planar slides connected to the channel were found (Fig. 3).

Shallow slides in saturated conditions and debris flows are generally triggered by high rainfall intensities, rather than large cumulative rainfall (Sidle and Bogaard, 2016). The rainfall record of the gauge in Birava, nearest to the event (10 km), which worked correctly in this time, shows that the closest intense rainfall event occurred on 13 February 2016 (Fig. 4), one week before the landslide. There are two possible ways to explain the occurrence of the debris flow on February 20. The first one is that intense rainfall occurred locally at the debris flow site on February 20 but did not affect the rain gauge site. The second is that planar slides were triggered during the intense rainfall event on 13 February 2016 but got unnoticed by the inhabitants because dams limited the mass transport, until dam breaching triggered the debris flow that was observed one week later.

This case study is important, because it highlights that (1) landslides occurring in remote areas without fatalities have little chance to reach even local media or Civil Protection, (2) attention should be paid to very careful interpretation of rain gauge data and the link between rainfall and landslide events, and (3) landslides in the study area may involve complex interactions of different processes.

Figure 3. Case study of a landslide event in February 2016 in Djikumbo (DR Congo): (1) upstream planar slide (2.27815S, 28.869038E); (2) transported debris during debris flow; (3) downstream damage of the debris flow to agricultural land.

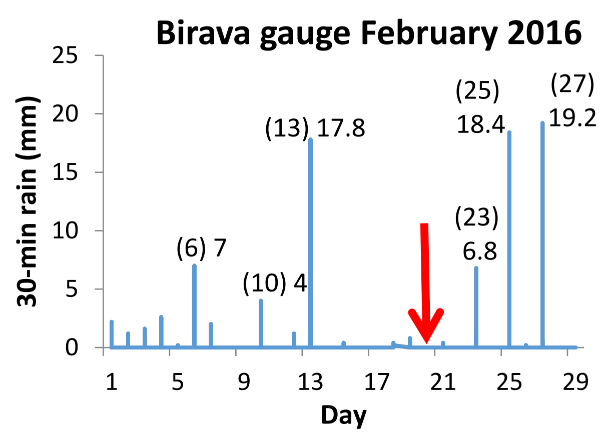

Figure 4. Rain tipping bucket results for February 2016 in Birava (DR Congo), located 10 km from Djikumbo (DR Congo) where a landslide event was reported on 20 February 2016 (red arrow). The amount of rain is shown for intense rainfall events, with the day of the event in brackets.

CONCLUSION

Central Africa is strongly underrepresented in current landslide-climate research. This is not because of the lack of landslide occurrence, but rather results from the severe constraints inherent to its political; economic, and environmental context. We propose a four-step methodological workflow for a regional assessment of rainfall controls on landslide hazard in the context of climate change, relying mainly on remote sensing supported by targeted field validation. Rain gauge and spatiotemporal landslide data are principal inputs for this methodology. A rain gauge network of 15 gauges has been installed in the WEAR. Problems during the first months of rainfall data collection were related to the general remoteness of the study area hampering frequent rain gauge checking, and the difficulty of finding gauge emplacements secure and environmentally ideal at once. To bypass these problems in the future, we set up a two-weekly remote rain gauge check by local partners. Additional rain gauge data are collected from 58 rain gauges scattered over the study area, obtained from a variety of different sources. The current landslide inventory consists of 83 precisely dated features. The primary source for spatiotemporal data was Internet searches in English and French. Major biases for these sources are related to the unequal coverage of the area, mainly due to limited communication. Field observation revealed the severe underrepresentation of reported landslides and the variety of the processes at work. Demographic pressure, including deforestation, slope undercutting for constructions, agriculture on steep slopes, and mining, most likely affects slope stability in the study area. Landslide data collection in the field was constrained by the current low security level, inadequate road network, fast vegetation growth, and lack of systematic recording. Collaboration with the local Civil Protection and contact persons from the rain gauge network are promising for data collection in the field. A landslide case study in eastern Congo evidenced that landslides occurring in remote areas and causing no fatality have little chance to reach the media. It also showed that the link between recorded rainfall and landslide events can be indirect, thus difficult to deduce, and landslides in the study area may involve complex interactions between various processes.

Despite these constraints, we built a climatic and spatiotemporal landslide dataset unique for the region, which will help us explore the consequences of climate change in Central Africa. Even though such a working environment may appear harsh and difficult, we show that a specifically cut out methodology allows reliable results to be obtained.

ACKNOWLEDGMENTS

Financial support came from the BELSPO RESIST, GeoRisCA and AfReSlide projects; and a F.R.S.-FNRS PhD scholarship for the first author. The Belgian American Education Foundation facilitated her one-year research stay at the Hydrological Sciences Laboratory at NASA Goddard Space Flight Centre. Special thanks go to colleagues at the Centre de Recherche en Science Naturelles (DR Congo) and the Université Officielle de Bukavu (DR Congo), who facilitated fieldwork in the WEAR. We also gratefully acknowledge the reviewers C.F. Watts and J.R. Keaton for their helpful feedback on this article.

REFERENCES

Bai, Y., Feng, M., Jiang, H., Wang, J., Zhu, Y., and Liu, Y. 2014, Assessing consistency of five global land cover data sets in China. Remote Sensing, Vol. 6, No. 9, pp. 8739–8759.

Corominas, J., van Westen, C.J., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M.G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., and Smith, J.T. 2013, Recommendations for the quantitative analysis of landslide risk. Bulletin Engineering Geology Environment, Vol. 73, No. 2, pp. 209–263.

Crozier, M. J.J. 2010, Deciphering the effect of climate change on landslide activity: A review. Geomorphology, Vol. 124, No. 3–4, pp. 260–267.

Delvaux, D., Mulumba, J.-L., M. Ntabwoba Stanislas Sebagenzi, S. Fiama Bondo, F. Kervyn, and Havenith, H.-B., in press, Seismic hazard assessment of the Kivu rift segment based on a new seismotectonic zonation model (western branch, East African Rift system). Journal African Earth Sciences.

Gariano, S.L., and Guzzetti, F. 2016, Landslides in a changing climate. Earth-Science Reviews, Vol. 162, 227–252.

Grauvogel, J. 2016, Burundi after the 2015 Elections: A Conference Report. Africa Spectrum, Vol. 51, No. 2, pp. 3–14.

Guzzetti, F., Carrara, A., Cardinali, M., Reichenbach, P., Carrara, A., Cardinali, M., and Reichenbach, P. 1999, Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology, Vol. 31, No. 1–4, pp. 181–216.

Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C.P. 2008, The rainfall intensity-duration control of shallow landslides and debris flows: An update. Landslides, Vol. 5, No. 1, pp. 3–17.

Hungr, O., Leroueil, S., and Picarelli, L. 2014, The Varnes classification of landslide types, an update. Landslides, Vol. 11, No. 2, pp. 167–194.

IPCC. 2013, The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change.

Isotta, F.A., Frei, C., Weilguni, V., Percec, M., Lassegues, P., Rudolf, B., Pavan, V., Cacciamani, C., Antolini, G., Ratto, S.M., Munari, M., Micheletti, S., Bonati, V., Lussana, C., Ronchi, C., Panettieri, E., Marigo, G., and Vertacnik, G. 2013, The climate of daily precipitation in the Alps : development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data. International Journal Climatology, Vol. 34, No. 5, pp. 1657-1675.

Jacobs, L., Dewitte, O., Poesen, J., Delvaux, D., Thiery, W., and Kervyn, M. 2016a, The Rwenzori Mountains, a landslide-prone region? Landslides, Vol. 13, No. 3, pp. 519–536.

Jacobs, L., Maes, J., Mertens, K., Sekajugo, J., Thiery, W., van Lipzig, N., Poesen, J., Kervyn, and Dewitte, O. 2016b, Reconstruction of a flash flood event through a multi-hazard approach: focus on the Rwenzori Mountains, Uganda. Natural Hazards, Vol. 84, No. 2, pp. 1–26.

Kirschbaum, D.B., Stanley, T., and Zhou, Y. 2015a, Spatial and temporal analysis of a global landslide catalog. Geomorphology, Vol. 249, pp. 4–15.

Kirschbaum, D.B., Stanley, T., and Simmons, J. 2015b, A dynamic landslide hazard assessment system for Central America and Hispaniola. Natural Hazards Earth System Science, Vol. 15, No. 10, pp. 2257–2272.

Maes, J., Kervyn, M., de Hontheim, A., Dewitte, O., Jacobs, L., Mertens, K., Vanmaercke, M., Vranken, L., Poesen, J. 2017, Landslide risk reduction strategies: A review of practices and challenges for the tropics. Progress Physical Geography.

Maki Mateso, J.-C., and Dewitte, O. 2014, Towards an inventory of landslide processes and the elements at risk on the Rift flanks west of Lake Kivu DRC . Geo-Eco-Trop, Vol. 38, No. 1, pp. 137–154.

Meiyappan, P., and Jain, A.K. 2012, Three distinct global estimates of historical land-cover change and land-use conversions for over 200 years. Frontiers Earth Science, Vol. 6, No. 2, pp. 122–139.

Michellier, C., Pigeon, P., Kervyn, F., and Wolff, E. 2016, Contextualizing vulnerability assessment: a support to geo-risk management in central Africa. Natural Hazards, Vol. 82, S. 1, pp. 27–42.

Nichol, J.E., Shaker, A., and Wong, M.S. 2006, Application of high-resolution stereo satellite images to detailed landslide hazard assessment. Geomorphology, Vol. 76, No. 1–2, pp. 68–75.

Nobile, A., Monsieurs, E., Dewitte, O., d'Oreyes, N., and Kervyn, F., 2016, Multi-temporal InSAR monitoring of landslides in a tropical urban environment: focus on Bukavu (DR Congo). In EGU General Assembly Conference Abstracts, Vol. 18, pp. 3927.

Nyssen, J., Poesen, J., Veyret-Picot, M., Moeyersons, J., Haile, M., Deckers, J., Dewit, J., Naudts, J., Teka, K., and Govers, G. 2006, Assessment of gully erosion rates through interviews and measurements: A case study from northern Ethiopia. Earth Surface Processes Landforms, Vol. 31, No. 2, pp. 167–185.

Peel, M.C., Finlayson, B. L., and Mcmahon, T.A. 2007, Updated world map of the K oppen-Geiger climate classification. Hydrologycal Earth Systems Science Discussion, Vol. 4, No. 2, pp. 439–473

Petley, D.N. 2012, Global patterns of loss of life from landslides. Geology, Vol. 40, No. 10, pp. 927–930.

Purdeková, A. 2011, “Even if I am not here, there are so many eyes”: surveillance and state reach in Rwanda. Journal of Modern African Studies, Vol. 49, No. 3, pp. 475–497.

Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R., and Turkelboom, F. 2006, Erosion processes in steep terrain _ Truths, myths, and uncertainties related to forest management in Southeast Asia. Forest Ecology Management, Vol. 224, No. 1, pp. 199-225.

Sidle, R.C., and Bogaard, T.A. 2016, Dynamic earth system and ecological controls of rainfall-initiated landslides. Earth-Science Reviews, Vol. 159, pp. 275–291.

Thiery, W., Panitz, H.-J., Davin, E., and van Lipzig, N. 2015, The impact of the African Great Lakes on the regional climate. Journal of Climate, Vol. 28, No. 10, pp. 4061-4085.

Trefon, T. 2016, Congo’s Environmental Paradox: Potential and Predation in a Land of Plenty. African arguments: Zed Books Ltd, London, 176 p.

Trefon, T., and Cogels, S. 2006, Remote control research in central Africa. Civilisations, Vol. 54, No. 1, pp. 145–154.

UNISDR. 2015, Sendai Framework for Disaster Risk Reduction 2015–2030. World Health Organization Publication, 37 p.

Vandecasteele, I., Moeyersons, J., and Trefois, P. 2010, An assessment of the spatial and temporal distribution of natural hazards in Central Africa. African Palaeoenvironments Geomorphic Landscape Evolution. Series Palaeoecology of Africa, Vol. 30, pp. 279–300.

Vlassenroot, K., and Berwouts, K. 2016, Congo’s political crisis after 19 December: Electronic document, available at http://africanarguments.org/2016/12/21/congos-political-crisis-after-19-december

APPENDIX A

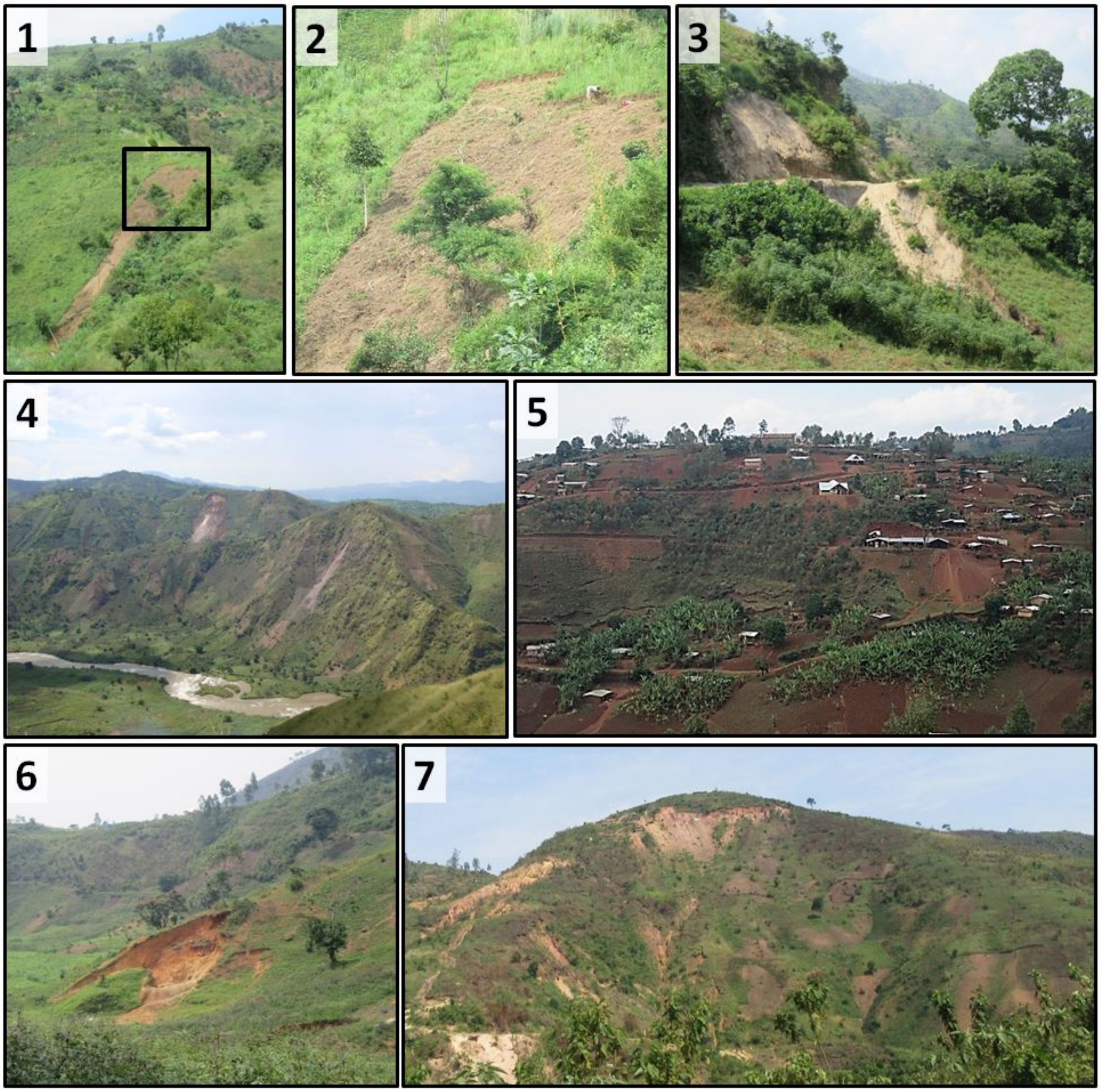

Figure A-1 Demographic pressure in the Kivu rift with potential effect on slope stability: (1) soil alteration for agriculture on steep slopes causing a shallow landslide, the frame indicates the location of the zoom in (2); (3) shallow landslide caused by slope undercutting for road construction; (4) debris slides on steep deforested slopes; (5) anarchic construction of houses on an old deep-seated landslide; (6) colocation of mining and landslide activity; (7) mining activity at the principal landslide escarpment of an old deep-seated landslide. (1),(2),(3),(6),(7) are photos taken on the Rift flanks west of Lake Kivu during fieldwork in February 2016 (DR Congo); (4) is a photo taken along the Ruzizi river from DR Congo towards Rwanda during 2012-2013 wet season; (5) is a photo taken in Bukavu in September 2016 (DR Congo)