POLITIQUE SCIENTIFIQUE FEDERALE - FEDERAAL WETENSCHAPSBELEID

RESEARCH PROGRAMME FOR EARTH OBSERVATION STEREO III

FINAL REPORT

CONTRACT SR/00/358

MODUS

A Multi-sensOr approach to characterize ground Displacements in Urban Sprawling contexts

17/12/2021, Royal Museum for Central Africa, Tervuren

For the partnership: Antoine Dille, François Kervyn and Olivier Dewitte

1 CONTENT

2 PROJECT INFORMATION

DURATION[1]

01/12/2017 – 31/11/2021

The project was prolonged for a 12-month period to cope with delays associated with the cancellation of a mission at project partner EOST (Strasbourg) in March-Avril 2020 due to COVID19. This extension also offered the opportunity to co-organize with the HARISSA project a regional two-day workshop in Bukavu (eastern DR Congo) in November 2021 on natural hazard risks in Africa and a two-day training on drone and photogrammetry at the Université Officielle de Bukavu (UOB). The HARISSA project is funded by the Development Cooperation programme of the Royal Museum for Central Africa with support of the Directorate-General Development Cooperation and Humanitarian Aid (Belgium-DGD)

STAFF / CHANGES IN STAFF[2]

NAMES AND JOB SITUATION AT THE END OF THE PROJECT

Antoine Dille has obtained a postdoc position at the Royal Belgium Institute of Natural Sciences (RBIN).

MISSIONS[3]: STAYS AT PARTNERS'S ORGANISATION, MEETINGS AND CONFERENCES

Name staff member: François Kervyn

Assignment: Coordinator

30 May – 10 June 2018

Field mission to Bukavu (DR Congo): UAV acquisitions, meeting with local partners

29 September – 12 October 2018

Field mission to Bukavu (DR Congo): dGNSS measurements, UAV acquisitions, meeting with local partners

8 April – 12 April 2019

Participation to the 2019 European Geosciences Union General Assembly, Vienna, Austria

12 May – 17 May 2019

Participation to the 2019 ESA Living Planet Symposium, Milan, Italy

11 March 2020

Participation Workshop "Slope processes in challenging environments - tools, approaches and perspectives", Tervuren, Belgium**4 May – 8 May 2020** – Virtual

Participation the 2020 European Geosciences Union General Assembly, Vienna, Austria

19 April – 30 April 2021 – Virtual

Participation the 2021 European Geosciences Union General Assembly, Vienna, Austria

[1] State whether and why project was prolonged
[2] Per partner
[3] Since last activity report

15-17 September 2021
Participation 7th International Geologica Belgica Meeting 2021, Tervuren, Belgium
25 November – 6 December 2021
Organisation of MODUS-HARISSA workshop in Bukavu. In addition, provided a 2-day training course on drone and photogrammetry.

Name staff member: Olivier Dewitte
Assignment: Coordinator

8 April – 13 April 2018
Participation to the 2018 European Geosciences Union General Assembly, Vienna, Austria
30 May – 10 June 2018
Field mission to Bukavu (DR Congo): UAV acquisitions, meeting with local partners
29 September – 12 October 2018
Field mission to Bukavu (DR Congo): dGNSS measurements, UAV acquisitions, meeting with local partners
7 December 2018
Participation to the Young Researcher Overseas Day, Brussels
8 April – 12 April 2019
Participation to the 2019 European Geosciences Union General Assembly, Vienna, Austria
12 May – 17 May 2019
Participation to the 2019 ESA Living Planet Symposium, Milan, Italy
11 March 2020
Participation Workshop "Slope processes in challenging environments - tools, approaches and perspectives", Tervuren, Belgium**4 May – 8 May 2020** – Virtual
Participation the 2020 European Geosciences Union General Assembly, Vienna, Austria
19 April – 30 April 2021 – Virtual
Participation the 2021 European Geosciences Union General Assembly, Vienna, Austria
15-17 September 2021
Participation 7th International Geologica Belgica Meeting 2021, Tervuren, Belgium**02-06 November 2021**
Participation 5th World Landslide Forum
25 November – 6 December 2021
Organisation of MODUS-HARISSA workshop in Bukavu. In addition, provided a 2-day training course on drone and photogrammetry.

Name staff member: Antoine Dille
Assignment: RMCA PhD student

27 January – 2 February 2018
Research stay at EOST (Strasbourg, France): image correlation of HR optical images using EOST's CoreGIS and MPIC tools
8 April – 13 April 2018

Participation to the 2018 European Geosciences Union General Assembly, Vienna, Austria
06 August – 17 August 2018
Research stay at ECGS (Luxembourg); Mastering of CIS/MSBAS processing chain
29 September – 12 October 2018
Field mission to Bukavu (DR Congo): dGNSS measurements, UAV acquisitions, meeting with local partners
7 December 2018
Participation to the Young Researcher Overseas Day, Brussels
8 April – 12 April 2019
Participation to the 2019 European Geosciences Union General Assembly, Vienna, Austria
12 May – 17 May 2019
Participation to the 2019 ESA Living Planet Symposium, Milan, Italy
16 June – 22 June 2019
Participation to the *Summer School of Alpine Research 2019*, organised by the University of Innsbruck in Obergurgl, Austria
22 July – 26 July 2019
Participation to the *Summer School on InSAR: Split Band Interferometry and displacement time series* organised by ECGS (Luxembourg)
3 August – 18 August 2019
Work on pore-water pressure modelling during a two-week research stay at Caltech/NASA Jet Propulsion Laboratory (USA)
14 Oct. – 18 Oct. 2019
Participation the 2019 MDIS (*Mesure de la Deformation par imagery satelitaire*) Autumn School and workshop in Strasbourg (Invited speaker)
11 March 2020
Participation Workshop "Slope processes in challenging environments - tools, approaches and perspectives", Tervuren, Belgium
March 2020 – cancelled because of COVID19
Research stay at EOST Strasbourg for working on image correlation
4 May – 8 May 2020 – Virtual
Participation the 2020 European Geosciences Union General Assembly, Vienna, Austria1 Dec. – 17 Dec. 2020 – Virtual
Participation the American Geophysical Union Fall Meeting (USA)
15 Dec. 2020
Participation Young Researchers' Overseas Day - Royal Academy for Overseas Sciences, Brussels
19 April – 30 April 2021 – Virtual
Participation the 2021 European Geosciences Union General Assembly, Vienna, Austria **25 November – 6 December 2021**
Organisation of MODUS-HARISSA workshop in Bukavu. In addition, provided a 2-day training course on drone and photogrammetry.

3 SUMMARY OF RESULTS[4]

3.1 OVERVIEW OF ACTIVITIES AND ACHIEVEMENTS

Our incomplete understanding of the causes and triggers of landslide failure and controls on later motion is a major source of uncertainty in assessing their impacts on human communities. It is especially true in mountainous regions of the tropics, where landslide impacts are disproportionally high, but our understanding of local controls remains elusive. Analysing how tropical environmental conditions (e.g., intense rainfalls, deep weathering of rocks) and a growing human influence on landscapes control the occurrence and motion of landslides and how to measure it in a data-scarce context was the main objective of this research project. Using mostly remote sensing data, we circumvent the lack of historical records, difficult field accessibility conditions, and constraints brought by the tropical context to build unprecedented datasets detailing the processes and mechanisms of two large slow-moving landslides in the Kivu Rift (DR Congo) over the last 70 years: the Ikoma landslide (in a rural environment) and the Funu landslide (in a urban environment). These are analysed in perspective with landslides located elsewhere on the globe, and the influence of human activity on landslides considered alongside the rapid landscape changes observed over large parts of the tropics.

We provide detailed analyses of landslide mechanisms in a tropical mountain region, but also a case for prime exploitation of the large and growing archive of short revisit satellite imagery that now offers opportunities to meet the needs to quantify and monitor landslides nearly all around the globe. As such, the datasets created indeed offer a level of detail only available for a few landslides worldwide. While our knowledge on landslide processes typically relies on the study of landslides developing in natural environments of high-latitude/high-income countries, we believe this research paves the way for further analyses of landslides and other Earth surface processes in under-researched climate regions such as the tropics. There, rates and relative importance of dynamic processes can indeed be different from temperate or paraglacial regions where most of the attention is set. Such considerations are especially important given the rapid changes in landscape conditions observed, that are increasing the occurrence of landslides and the number of people at risk.

A detailed description of the results is provided in Annex in the PhD dissertation of A. Dille entitled "*Remote sensing of slow-moving landslides in the tropics: natural and anthropogenic controls*".

[4] Give a summary of the activities and describe to what extent objectives were met – list problems encountered and how they were solved - lessons learned / experience gained - / - a detailed description of the results can be put in annex

3.2 REALISATION OF OBJECTIVES[5]

The general objective of this research project was to investigate the mechanisms of ground displacements of landslides in an urban-sprawling context in the tropics. More specifically, we investigated how tropical environmental conditions (e.g., intense rainfalls, deep weathering of rocks) and the growing human influence on landscapes control the occurrence and motion of large deep-seated slow-moving landslides. How to measure landslide motion in a data-scarce context was also an objective of this research project. Two landslides were studied. Together, they represent end members of the landslide characteristics found in the area. The first, called Ikoma landslide, is a recent deep-seated landslide sited in the rural outskirts of the city of Bukavu, where subsistence agriculture can be assumed to be of negligible influence on the landslide activity. Because only a few decades old, it offers exceptional opportunities to study the almost complete development of a slope failure in the area. The second, called Funu landslide, is much older (probably a few thousand-year-old). Sited within the rapidly expanding city of Bukavu, it experienced rapid and informal urbanisation over the last decades. Only ten kilometres apart, these two landslides share largely similar tropical environmental conditions at the notable exception of the degree of human influence. Together, they thus represent perfect natural laboratories to unravel the respective influences of the environment (climate, geology, tectonics settings, etc.) and external forcings (rainfall, earthquakes, urbanisation) on landslide motion.

To address this main research objective, we answered the following specific research questions:

- *What are the causes and triggers of slow-moving and deep-seated landslides in the tropics? Are specific tropical conditions linked to the occurrence of such slope instabilities?*
- *What are the controls on their seasonal and multi-decadal dynamics?*
- *Can we identify human-induced stress perturbations in their evolution?*
- *Do factors causing initial failure differ from factors controlling subsequent landslide movement?*
- *What are the most effective (remote sensing) methods (or combination of) to study the current (and past) dynamics of landslides in such a data-scarce context?*

An overview of the result is provided in section 3.5 'Lessons learned', and a more detailed description in the PhD dissertation of A. Dille entitled "*Remote sensing of slow-moving landslides in the tropics: natural and anthropogenic controls*" (see Annex material). Hereafter is provided a Table with the different tasks for each specific objectives that were planned at the beginning of the project. Most of them were fully achieved however, due to some readjustments that were considered necessary:

- The image correlation technique was initially planned to be applied on pictures taken from the ground (Task 4.2). However, in agreement with the steering committee, given the field context and the timeframe of the project, it has been decided to focus the efforts on the other approaches (SAR, satellite and UAS optical images).

[5] Please provide table with objectives and deliverables and indicate whether achieved: YES, NO, PARTIALLY

- The Task 5.1 was dedicated to ground based data acquisition for validation purpose. As a result of the point mentioned above, the validation of satellite measurements has been achieved using UAS datasets.
- The landslide inventory update (Task 6.2) planned in the initial version of the project would cover the whole city of Bukavu. However, in agreement with the steering committee, we focussed our analysis on two specific landslides; one (Ikoma) being outside of the city. The update the inventory for the city was then partial, but nevertheless, in replacement, came the information gathered at the Ikoma site.

	Tasks and deliverables	Achieved
Work package 1	**Coordination project management and PhD supervision**	
Task 1.1.	Project management and coordination and outreach	YES
Task 1.2.	Completion of a new PhD research – PhD supervision	YES
Task 1.3.	Field missions	YES
Work package 2	**Remote sensing and ancillary data management**	
Task 2.1.	Satellite data	YES
Task 2.2.	Archived aerial photographs	YES
Task 2.3	RESIST networks (rainfall, seismic, DGPS)	YES
Work package 3	**Ground displacements from InSAR time series**	
Task 3.1	Various methods and various images	YES
Task 3.2	Data fusion	YES
Work package 4	**Ground displacements from satellite and ground-based optical image correlation**	
Task 4.1	Image correlation applied on optical HSR & VHSR satellite data and on SAR amplitude image (e.g. offset tracking)	YES
Task 4.2	Image correlation applied on time series of ground-based optical cameras	PARTIALLY
Task 4.3	Data fusion	YES
Work package 5	**Validation**	
Task 5.1	Ground-based data acquisition	PARTIALLY
Task 5.2	Comparison of methods and data	YES
Work package 6	**Landslide dynamics and data integration for hazard prediction**	
Task 6.1	Time series analysis and landslide characterization	YES
Task 6.2	Inventory update and hazard integration	PARTIALLY
Work package 7	**Valorisation and dissemination**	
Task 7.1	Website	YES
Task 7.2	PhD thesis	YES
Task 7.3	Conferences, reports, networking	YES

3.3 PROBLEMS ENCOUNTERED AND SOLUTIONS

- Measurement of the deformation of the Funu (urban) landslide
    - In the initial project description, we were planning to take ground deformation measurements from automatic time-lapse cameras that would be installed in the two landsides: Funu (urban) and Ikoma (rural). The time-lapse cameras would allow, from image correlation processing, to capture deformation patterns different from what satellites allow. For the Funu landslide, it soon appeared that the deformations were too small (overall a few centimetres per year) with respect to what the cameras could measure in the specific topographic context of the study area (cameras had to be installed at a distance of more than one kilometre from the site). In agreement with the steering committee this task was cancelled as it would require a high technical investment time for little to no reward. The cancellation of this task had no impact on the study of the landslide as the urban context, with its numerous permanent coherent features, allowed to use of InSAR at its full potential with very high frequency deformation measurements.

- Measurement of the deformation of the Ikoma (rural) landslide
    - At the Ikoma landslide, the ground displacements are much more rapid than those of Funu. The motion is up to 15 m over a period of 3 months. In addition, the site offers a very few permanent coherent features. Moreover, the displacement velocity is too fast to preserve coherence between acquisitions.. Furthermore, in this cloud-covered environment, the image correlation of optical satellite imagery allows to measure deformation patterns at a frequency much lower than InSAR. The solution to capture landslide displacement at a frequency similar to that of InSAR was then to use time-lapse cameras. However, measurements of surface deformation patterns from cameras were made complex by the remoteness and the intrinsic difficulties to maintain ground instrument in that region of DR Congo. Here also the steering committee suggested to cancel this activity. To circumvent those difficulties, we developed a new method based on image correlation that combines very large number of SAR-amplitude images (see Dille et al. 2021, *Remote Sensing of Environment*). The characteristics of these SAR-amplitude data (low dependence to weather conditions, repetitiveness, spatial resolution, etc.) make them particularly well-suited to study surface processes in zones affected by persistent cloud cover. Further, the level of detail reached stresses that this method represents a performing alternative to optical images in any context, and should be considered for the study of landslide anywhere on the globe.
- Field missions
    - A third and last field campaign in Bukavu was planned for September 2019. Because of an Ebola outbreak that hit South Kivu during end August/beginning of September 2019, it had to be cancelled. The impacts of this cancellation on the analysis carried in this project are however thought to be limited. The two previous campaigns already provided the datasets fundamental for (field) validation of remote sensing products (i.e., multi-year UAS cover of Funu and Ikoma landslide, dGNSS acquisitions, etc.) and further understanding of the processes at play and local condition through field visits. The cancellation mostly impacted the length of acquisition time series that could not be followed up by local partners at that time (i.e., UAS (drone) time series of displacement). Regarding the latter, we had to cancel as well a seminar/training on the use of UAS to map surface topography planned at the Université Officielle de Bukavu (UOB). The seminar was given later on to researchers from the UOB that were present in Brussels in January 2020. Note that an on-site session could finally be organised at the UOB in November 2021 thanks to the extension of the project.
- Research stay at Strasbourg
    - An important research stay was planned at the partner EOST (Université de Strasbourg; France) in March 2020 but had to be cancelled due to COVID19. Yet, a remote collaboration strategy was set up to reach the targeted objectives (apply image correlation on Ikoma landslide).

3.4 LESSONS LEARNED

On landslide processes and mechanisms:

- **Slopes in the tropics can fail without external dynamic triggers:** By studying the early development (and respective failure phases) of a recent landslide close to Bukavu (the Ikoma landslide), we could stress that local tropical environmental conditions strengthened the role of so-called underlying causes to landsliding, ultimately eluding the need for a high-magnitude trigger of instability to explain the main failure phase of the landslide. Because favouring deep weathering, tropical climatic conditions were found to be a key factor to explain the weakening of the slope material trough time until failure occurred. Field observations of the slope material further showed that the reduction of the slope strength was accentuated by the characteristics of the lithology (successive basaltic layers) and local environmental stresses (e.g., regional tectonic activity or precursor slope movements) that eased the development of a dense fracture system. These zones of weakness affecting the hydrology, rates of weathering and the general strength of the slope, we hypothesised that they had a considerable influence on the failure of the slope, but also on the style of movement and the general characteristics of the landslide. Such consideration of the key role of a reduction of material strength to explain the failure of slopes without apparent trigger is not new. We could however advocate that its relative importance as a driver of slope failure should be further emphasised in contexts favouring more significant weakening of the slope mechanical properties such as in the tropics. These reflections do not discount the importance of external forcing to explain the complete evolution of the hillslope, but stress the relevance of considering multiple dynamic Earth processes and their interactions at different time scales to unravel hillslope development. Similar environmental conditions being found over many hillslopes in tropical mountain contexts, consideration of these interactions is thus crucial for the accurate evaluation of regional landslide susceptibility and hazards, and in the broader analysis of how surface processes influence landscape evolution.
- **Rainfalls exerts key controls on the day-to-day motion of tropical landslides – but considering internal landslide dynamics is as well important to be able to predict landslide motion.** Alongside an exploration of the causes behind the occurrence of landslides in tropical environments, we investigated the controls on the motion of landslides. By studying two landslides developing in seemingly similar environments but with different degree of anthropic influence, ages and depths, we could gain insights into the respective influences of i) internal factors, ii) the natural environment (climate, geology, tectonics settings, etc.) and iii) external forcings (rainfall, earthquakes, urbanisation). Unsurprisingly, rainfall (or more specifically, rainfall-induced variations of pore-water pressure in the slope) was found to exert the main control on the dynamics of the two landslides. Seasonal velocity variations are following seasonal patterns of rainfall, and brief and episodic landslide acceleration episodes are typically observed after intense rains (particularly for Ikoma landslide). However, the behaviour of both landslide contrasts with most studies in how tied this relationship is: the ~10-20 days delay generally observed between the onset of the wet season and landslide acceleration is remarkably short, especially considering the estimated depth of the landslides (10-50 m for Ikoma and 30-80 m for the urbanised Funu landslide). Such behaviour has been observed at very few landslides, but the high sampling frequency used to measure landslide motion may also captured a response that is

usually missed with conventional InSAR or satellite optical measurements. Yet, we comprehensively described how many local environmental constraints may influence this relatively singular kinematic response: i) intense rainfalls typical for tropical climate exacerbate the importance of preferential infiltration pathways; ii) urbanisation leads to drastic changes in how and where water infiltrates; iii) weathering processes modify the mechanical and hydrological properties of slopes; iv) the recurrent and long-lasting influence of seismicity in the context of the Kivu Rift further favours the formation of preferential infiltration pathways and deep weathering, etc. Our results moreover highlighted that internal landslide dynamics (extension, compression, material redistribution, etc.) and interactions between landslide units are also exerting strong controls on the kinematic behaviour of the two landslides. Nonetheless, an interesting observation is that both Funu and Ikoma showed such a tied relationship between rainfall and landslide velocity, despite large differences in depth and an order magnitude difference in velocity scale (a few centimetres per year for Funu compared to a few to dozens of meters per year for Ikoma). Are the responses of both landslides similar because of the shared environmental context, or is Funu able to mimic the kinematic behaviour of a relatively shallower landslide because of the impacts of urbanisation on its hydrology? Untangling those respective influences will require further detailed and long-term studies of landslides sited in (tropical) urban environmental settings. Altogether, it undoubtedly highlights the challenges in predicting the velocity of landslides.

- **Urbanisation can influence the behaviour of long-lived, deep-seated landslide:** While it is difficult to unravel the role of individual parameters over seasonal or yearly timescales, the analysis of the multi-decadal dynamics of the urban Funu landslide showed that urbanisation can interfere with the natural behaviour of long-lived, deep-seated landslides. Through a comparison of the overall hydrological conditions, urban fabric, and failure history of the different landslide units, we could show that the acceleration of a large landslide unit was probably driven by self-reinforcing feedbacks involving slope movement, rerouting of water flows due to urbanisation and pipes rupture. Such relationship is not surprising given the influence of urbanisation on slope hydrology, how slope hydrology regulates slope stress state and how small changes in effective stress modulates the motion of slow-moving landslides. Yet, such observations are rare and call for a better understanding of how anthropogenic activity influences surface processes, notably considering that hillslopes of the world's cities are being urbanised at accelerating paces.

  Note that while we assembled an unprecedented amount of remote sensing data never used to study a landslide (2500+ interferograms from different SAR sensors and orbits, (tri)stereo VHR optical satellite images, UAS surface topography and orthomosaics, historical aerial images for three different dates, etc.), we will never be able to install/obtain the density of ground-based information gathered for the few laboratory landslides in natural environments in high-income/high-latitude countries that are studied and monitored for decades. Our analyses and hypothesis therefore have to rely on spatio-temporal quantifications and observations made based on remote sensing data – and supported by robust field observations and measurements – that we yet always reasonably justify given the relevant uncertainties. A country that would have the means to invest in monitoring such a large landslide over long periods would a priori never have let a city expand on such constraining slopes. The impact of urbanisation on large landslides can therefore only be studied in such "data-scarce" contexts, with their intrinsic limits in terms of quantitative data availability. To our knowledge, there are currently no large deep-seated landslides in urban sprawling environments that are being intensively monitored and studied as the Funu landslide we present here.

- **MODUS brought (first) new scientific insights on landslide processes in the tropics:** MODUS is a key step towards understanding geomorphological processes in the under-researched regions of the tropics. For example, in a recent paper published in 2020 in Nature Reviews Earth & Environment that provides a worldwide analysis of the issue of slow-moving landslides, Ikoma is clearly highlighted as the only landslide in the tropics that has been analysed in detail (note that the Funu landslide would probably have been highlighted too if our worked had been published at that time). It is however important to keep in mind that while MODUS provided unprecedented insights on key aspects of our comprehension of Earth surface processes and of the interactions between human and landscapes, its focus was only on two representative slow-moving landslides – which remains too limited to really draw robust conclusions on the highlighted natural and human-induced processes. To further unravel the fundamental but intricate influences of climate, lithology, tectonics and man-made environmental changes on the activity of slow-moving landslides, a change in scale is required, from two to possibly hundreds of landslides spread across diverse landscape and climate conditions. This is on objective that our research group at the RMCA hopes to address in the coming years. For further information on research perspective, see Section 4.

<u>**On methodological aspects:**</u>

- **Exploiting synergies between methods and sensors is key:** Acquiring accurate, high spatial and temporal resolution measurements of landslide motions was central to the completion of this research project. We strongly relied on satellite remote sensing and on the exploitation of synergies between platforms and methods. This combination was key to circumvent constraints brought by i) difficult field accessibility conditions that hampered the use of ground-based instruments, ii) the persistent cloud cover and rapid vegetation growth associated with tropical climates, iii) the large ranges of potential landslide velocities (from a few cm yr^{-1} for Funu to dozens of m yr^{-1} for Ikoma landslide) and iv) the lack of historical records. A key to increase the temporal resolution (and robustness) of the measurements was the integration of deformation maps obtained from different sensors (e.g., ascending and descending SAR or different optical satellite missions) into time series. While it is a standard approach for SAR interferometry, it was only recently used in association with optical satellite images (and to our knowledge never using images from different missions), and typically using only a few or a few dozen images when using SAR-amplitude. Our work also illustrated the advantages of SAR for working on landslides in the tropical zone. Depending on the landslide velocity, orientation, and surface vegetation, we exploited either the phase or the amplitude component of SAR images. SAR interferometry was particularly suited to study the mm to cm-scale motion of the urban Funu landslide: combining ascending and descending interferograms from Sentinel-1 and COSMO-SkyMed sensors we could measure 2D and 3D landslide motion with a sub-weekly temporal resolution over a 4.5+ year period. On the other hand, our work on the Ikoma landslide demonstrated the interest of applying a combination of sub-pixel image correlation and time series inversions on long series of SAR-amplitude images to obtain similar, detailed measurements of surface motion but for landslides showing m-scale motion in vegetated contexts. The characteristics of these SAR-amplitude data (low dependence to weather conditions, repetitiveness, spatial resolution, etc.) make them particularly well-suited to study surface processes in zones affected by persistent cloud cover. Further, the level of detail reached stresses that this method represents a performing alternative to optical images in any context, and should be considered for the study of landslide anywhere on the globe.

- **Drone data is cheap[6], and highly informative on the processes at play:** Portrays of the surface morphology of the two landslides from (multi-temporal) very-high-resolution topographic datasets created from UAS-SfM greatly improved our analysis of the landslide mechanisms. They were also an essential component of the validation of the deformation measured from satellite remote sensing. Our work demonstrates how, by combining surface deformation measurements and very-high-resolution topographic datasets, one can address more complex landslide mechanisms and geometries. Considering how useful they are, their low cost and the relatively straightforward workflows for acquiring and processing UAS data, collecting such datasets should always be considered when field access is possible – even if limited to a one-time survey.
- **Exploiting historical aerial images offers possibility to investigate long-term changes to the landslides and its environment:** The unique archive of historical aerial photographs available for the region conserved at the Royal Museum for Central Africa was also key to investigate the development over time of the Funu and Ikoma landslides. Such images can now be relatively easily exploited thanks to Multiview Stereo Photogrammetry approaches. These datasets open immense opportunities to better comprehend the influence of human-induced and natural environmental changes on Earth surface processes and landscapes.
- **Simple simulation tools can offer key insights into the landslide controls**: Finally, we used relatively simple simulation tools to cope with the absence of in-situ instruments for estimating two key landslide constraints: landslide depth and changes in pore-water pressure. Landslide depth was inferred from 3D measure of landslide motion by performing a thickness inversion based on the measured surface velocity and laws of volume conservation. Rainfall-induced changes in pore-water pressure were simulated through a homogenous 1D diffusion model fed by rainfall data – itself fed by satellite rainfall estimate when no rain gauge was operational. These open-access tools, able to rely on sole satellite data, allow to efficiently gain insights into the landslide controls.
- **We now have opportunities to meet the needs to accurately quantify and monitor landslides all around the globe:** While local knowledge and field characterisation will always remain crucial, we illustrated in this research project that available tools and the large and growing archive of

[6] From the logistic point of view, carrying a drone in the region is subject to regulations in Rwanda where the equipment must be declared while in transit. The use of the drone in the field in both Bukavu and Ikoma was greatly facilitated by the close collaboration the RMCA is maintaining with the local institutions. Moreover, landslides in the Kivu is a major issue and the population and authorities are eager to collaborate in the hope mitigation solutions could be found in the future. Finally, the transport of such equipment by plane also requires the batteries be transported as hand luggage.

satellite images offer opportunities to meet the needs to accurately quantify and monitor landslides all around the globe.

3.5 INTERACTION WITH STAKEHOLDERS - SOCIETAL IMPACT[7]

Better understanding of landslide processes and mechanisms is at the centre core of the evaluation of the landslide hazard and risk. The information gathered in this project should therefore serve for such evaluations in the area, and in other regions sharing similar environmental characteristics. Key findings to be considered are **that i) tropical environmental conditions strengthen the role of underlying causes to landsliding**, sometimes eluding the need for a high-magnitude dynamic trigger of instability to explain slope failure; ii) **urbanisation can interfere** (e.g., trigger destabilisation) **with the natural behaviour** of long-lived, deep-seated landslides. The latter is of crucial importance considering that hillslopes of the world's cities are being urbanised at accelerating paces. **But our findings, by highlighting that landslide motion are controlled by sometimes small changes in slope stress, also provide indications on how to mitigate such hazard**. When avoidance is not possible – typical in developing countries where informal urbanisation generally outstrips any regulation – mitigation strategies aiming at reducing water infiltration by a comprehensive management of all forms of surface water should undoubtedly be backed.

Through workshops and collaborations with the Université Officielle de Bukavu (UOB) and the Protection Civile du Sud Kivu, this research project participated to the strengthening of research networks in Central Africa. To further share learnings from the MODUS project with local partners and institutions, a regional two-day workshop was organised at the end of the project, 29 and 30 November 2021. It regrouped 35 local experts from 10 different institutions from DR Congo, Uganda, and Burundi; all working on the incidence of natural hazards and associated risks in Central Africa.

MODUS was also framed around several field missions that each contributed to many (often informal) interactions with local stakeholders, villagers and city dwellers. MODUS also provided support to the UOB to carry out field activities, whether in Ikoma (climate data collection, observation of recent changes in the landslides) or in Funu (repetitive DGPS surveys). These field activities each time raised attention to and foster exchanges with local stakeholders and members from the civil society at large.

MODUS is also a research project that is framed within several research and development cooperation activities of the RMCA. Among the > 15 PhD students of the RMCA GeoRiskA team, many of them are from the region around Bukavu (DR Congo, Burundi, Rwanda, Uganda) and 8 of them are actually working on landside-related topics. These PhD students who belong to the staff of local universities and research institutes use the outcomes of MODUS in their teaching material.

Research outputs of the project have been used for the scientific content and visuals of the permanent exhibition on natural hazards, risks and disasters that is hosted in the premises of CIRRINA at the UOB. this exhibition is a dissemination and outreach activity that is aimed at student and general public

[7] Include minutes last user meeting in annex

awareness. It is supported by MRAC-KMMA projects and it already involves the participation of local MRAC-KMMA -supervised Phd students.

One could expect that such scientific results are turned into decision processes to mitigate the effects of geo-hydrological hazards. Actually, that is a very long and multi fold process where the hazard assessment is at the forefront. The MODUS project is one contribution of the holistic transdisciplinary research-action approach the GeoRiskA team is leading in the region. The end-of-project workshop was a joint event co-organized with the HARISSA project which is supported by the Belgium Cooperation (DGD) and where awareness raising activities based on scientific results are achieved. Understanding the processes and raising awareness at the society and political levels are the necessary steps towards the future implementation of mitigations measures.

3.6 USE OF BELGIAN RS INFRASTRUCTURE AND INSTRUMENTS

We extensively used Sentinel images provided by the European Commission Copernicus program and distributed by the ESA. The Terrascope platform was used over the end of the project for download of images.

3.7 UPTAKE OF RS BY NEW USERS

- We provided two one-day and one two-day training courses on the use of UAS photogrammetry to local research scientists of the region (DR Congo, Rwanda, Burundi; 23 people trained). The aim was to allow them to independently carry out multi-temporal surveys of surface processes using ground-based and drone photogrammetry. These training courses have always received a very warm welcome from the researchers and the institutions. The RMCA also gave a drone to the UOB so that they are autonomous at initiating their own research relying on this imagery.
- As a user, MODUS has contributed to the improvement of the MASTER toolbox co-developed by CSL and ECGS whose use is growing for slow ground deformation monitoring.
- At the RMCA, in partnership with the VUB, a new PhD research relying in the use of SAR imagery to detect landslide and flash flood events in the western branch of the East African Rift strongly benefits from the progresses of MODUS in terms of radar image processing.
- MODUS also contributed to make progress in the analysis of historical photographs through the use of digital photogrammetry approaches. This directly served to the PhD research of another student working in collaboration between the KU Leuven and the RMCA.
- Two PhD students from the UOB and one student form the University of Burundi currently work on landslide-related topics. Their research directly relies on topographic data that were generated via MODUS.

4 PERSPECTIVES FOR FUTURE RESEARCH

- **On the underlying causes to landsliding.** Field investigations, discussions with local researchers and a regional landslide inventories (e.g., Depicker et al., 2020a, 2020b; Dewitte et al., 2021) show no similar deep-seated landslides in the close surroundings of the Ikoma landslide. This may be surprising when the discussion related to the drivers of slope failure stressed the importance of considering the underlying causes to landsliding, which are processes (such as weathered-related weakening) acting on an area that exceeds by far the failed slope. This relative antagonism brings the question as to why the vast majority of slopes does not fail? Such consideration is of high relevance considering the evaluation of the landslide hazard, but probably requires even longer term and larger-scale investigations of landslide processes [4]. As for rainfall triggers, where it is difficult to determine why a large precipitation event destabilised the slope while previously similar scale events do not [5], it is crucial to deepen our understanding of the factors activating an intrinsically local failure mechanism, which requires considerations of all processes acting on the slope.
- **On factors controlling landslide processes – and how changing landscape conditions are influencing them.** Further unravelling the intricate influences of climate, lithology, tectonics and man-made environmental changes on the activity of slow-moving landslides requires a change in scale to acquire a larger dataset across more diverse landscape conditions. The fundamental challenge is to be able to disentangle the baseline dynamics of slow-moving landslides, i.e., the rates and patterns that would occur under natural conditions (in terms of geophysical, biophysical, and climatic conditions), so that the way in which humans are affecting slow-moving landslides can be unravelled. Because they rely mostly on open-access satellite data, the radar and optical remote sensing approaches used in this research project could be suited to such a change in scale. Such an investigation could be realised in the western branch of the East African Rift System (wEARS), of which the Kivu Rift is part of. Likewise, the wEARS is landslide-prone and affected by rapid and large-scale landscape transformations associated with agricultural expansion and urbanisation. It is, however, characterised by a larger natural landscape diversity. Shaped by a strong north–south climate gradient [6,7], active continental rifting [3,8], and contrasting histories of human occupation [2], it would be an ideal location for such regional-scale analysis.

  Combining image correlation and InSAR would, in theory, offer an exhaustive view on landslide activity in the region because it enables the measurement of landslides with velocities ranging from a few millimetres to a few meters per year in both dense urban to vegetated environments. A change in scale will, however, bring new challenges, amongst other difficulties in discerning landslide signal from e.g., volcanic activity (e.g., Smets et al., 2015)), subsidence (e.g., Nobile et al., 2018)), tectonic activity [10,11] and noise related to decorrelation of the signal over time. In those cases, strategies are typically applied on top of visual investigation to be able to identify active landslides. The combination of double difference time-series (e.g., Bekaert et al., 2019; Handwerger et al., 2019a), local and regional spatial filters and pixel clustering methods [14,15] could be used to better identify the location of landslides and analyse their spatial patterns. Such approaches are often applied for the automation and operational monitoring of landslides and other geophysical phenomena with localised deformation patterns (i.e., sharp deformation gradient; Bekaert et al., 2020). By analysing the spatial distribution of active landslides in the area and considering i) the local environmental conditions (climate, lithology, tectonic settings, slope, degree of anthropogenic activity, etc.) as well as ii) the landslide spatial attributes (size, shape, position in the slope, connection to rivers, distance to knickpoint, etc.), we could estimate the proportion of the landscape that is active, and which environmental factors best explain it. It could be complemented by an analysis of the dynamics of the landslides over different timescales to analyse how the controls on landslide motion vary in function of their spatial characteristics and the local environmental conditions. By combining the analysis with aerial photographs conserved at the RMCA and declassified, high-resolution Hexagon KH9 US spy satellite images (e.g., Lacroix et al., 2019b; Dehecq et al., 2020), we could in addition investigate landslide motion and landscape changes over the long-term. Finally, while research (e.g., Broeckx et al., 2020) has highlighted the importance of the contribution of slow-moving landslides to contemporary sediment fluxes, it remains poorly constrained – particularly in tropical regions. The information gathered on the activity of the landslides in the wEARS could be used to estimate the landslide mobilisation rates [LMR; $m^3/km^2/y$], and ultimately the annual sediment delivery attributable to landsliding.

- **Implications for landslide hazard, risks and mitigation strategies.** Better understanding of landslide processes and mechanisms is at the centre core of the evaluation of the landslide hazard and risk. The information gathered in this study should therefore serve for such evaluations in the area, and in other regions sharing similar environmental characteristics. Key findings to be considered are that i) tropical environmental conditions strengthen the role of underlying causes to landsliding, sometimes eluding the need for a high-magnitude dynamic trigger of instability to explain slope failure; ii) urbanisation can interfere (e.g., trigger destabilisation) with the natural behaviour of long-lived, deep-seated landslides. The latter is of crucial importance considering that hillslopes of the world's cities are being urbanised at accelerating paces. But our findings, by highlighting that landslide motion are controlled by sometimes small changes in slope stress, also provide indications on how to mitigate such hazard. When avoidance is not possible – typical in developing countries where informal urbanisation generally outstrips any regulation [19] – mitigation strategies aiming at reducing water infiltration by a comprehensive management of all forms of surface water (e.g., Anderson and Holcombe, 2013) should undoubtedly be backed.

Cited references:

[**1**] Depicker, A. *et al.* (2020) The added value of a regional landslide susceptibility assessment: The western branch of the East African Rift *Geomorph.* 353, 17; [**2**] Depicker, A. *et al.* (2020) Interactions between deforestation , landscape rejuvenation , and shallow landslides in the North Tanganyika - Kivu Rift region , Africa *Earth Surf. Dyn. Discuss.* 1–27; [**3**] Dewitte, O. *et al.* (2021) Constraining landslide timing in a data-scarce context: from recent to very old processes in the tropical environment of the North Tanganyika-Kivu Rift region *Landslides* 18, 161–177; [**4**] Marc, O. *et al.* (2019) Long-term erosion of the Nepal Himalayas by bedrock landsliding: the role of monsoons, earthquakes and giant landslides *Earth Surf. Dyn.* 7, 1–41; [**5**] Bogaard, T. A. *et al.* (2016) Landslide hydrology: from hydrology to pore pressure *Wiley Interdiscip. Rev. Water* 3, 439–459; [**6**] Monsieurs, E. *et al.* (2018) Evaluating TMPA Rainfall over the Sparsely Gauged East African Rift *J. Hydrometeorol.* 19, 1507–1528; [**7**] Nicholson, S. E. (2017) Climate and climatic variability of rainfall over eastern Africa *Rev. Geophys.* 55, 590–635; [**8**] Smets, B. *et al.* (2015) Spatio-temporal dynamics of eruptions in a youthful extensional setting: Insights from Nyamulagira Volcano (D.R. Congo), in the western branch of the East African Rift *Earth-Science Rev.* 150, 305–328; [**9**] Nobile, A. *et al.* (2018) Multi-Temporal DInSAR to Characterise Landslide Ground Deformations in a Tropical Urban Environment: Focus on Bukavu (DR Congo) *Remote Sens.* 10, 626; [**10**] Delvaux, D. *et al.* (2017) Seismic hazard assessment of the Kivu rift segment based on a new seismotectonic zonation model (western branch, East African Rift system) *J. African Earth Sci.* 134,

831–855; [**11**] d'Oreye, N. *et al.* (2011) Source parameters of the 2008 Bukavu-Cyangugu earthquake estimated from InSAR and teleseismic data *Geophys. J. Int.* 184, 934–948; [**12**] Bekaert, D. P. S. *et al.* (2019) Exploiting UAVSAR for a comprehensive analysis of subsidence in the Sacramento Delta *Remote Sens. Environ.* 220, 124–134; [**13**] Handwerger, A. L. *et al.* (2019) Widespread Initiation, Reactivation, and Acceleration of Landslides in the Northern California Coast Ranges due to Extreme Rainfall *J. Geophys. Res. Earth Surf.* 124, 1782–1797; [**14**] Bekaert, D. P. S. *et al.* (2020) InSAR-based detection method for mapping and monitoring slow-moving landslides in remote regions with steep and mountainous terrain: An application to Nepal *Remote Sens. Environ.* 249, 111983; [**15**] Bontemps, N. *et al.* (2018) Inversion of deformation fields time-series from optical images, and application to the long term kinematics of slow-moving landslides in Peru *Remote Sens. Environ.* 210, 144–158; [**16**] Lacroix, P. *et al.* (2019) Irrigation-triggered landslides in a Peruvian desert caused by modern intensive farming *Nat. Geosci.* 13, 56–60; [**17**] Dehecq, A. *et al.* (2020) Automated Processing of Declassified KH-9 Hexagon Satellite Images for Global Elevation Change Analysis Since the 1970s *Front. Earth Sci.* 8, 516; [**18**] Broeckx, J. *et al.* (2020) Landslide mobilization rates: A global analysis and model *Earth-Science Reviews* 201, 102972; [**19**] Satterthwaite, D. *et al.* (2007) Adapting to Climate Change in Urban Areas : The Possibilities and Constraints in low- and middle-income nations *Int. Inst. Environ. Dev.* 1–112; [**20**] Anderson, M. G. *et al.* (The World Bank, 2013) Community-Based Landslide Risk Reduction

5 STEERING COMMITTEE

5.1 REPORT OF THE LAST STEERING COMMITTEE

Report of the third Steering Committee is provided in annex ('MODUS - Report SC Meeting 2020 – ThirdMeeting').

5.2 FEEDBACK TO STEERING COMMITTEE

Answer to comments from the third Steering Committee is provided in annex ('MODUS - Answers to SC Meeting 2020 – ThirdMeeting').

6 DESSIMINATION ACTIVITIES

6.1 SCIENTIFIC PAPERS

PUBLISHED[8]

Scientific papers published in international peer-reviewed journals:

[1.] Kubwimana, D., Ait Brahim, L., Nkurunziza, P., Dille, A., Depicker, A., Nahimana, L., Abdellah, A., Dewitte, O., 2021. Characteristics and distribution of landslides in the populated hillslopes of Bujumbura, Burundi. Geosciences 11, 259. https://doi.org/10.3390/geosciences11060259

[2.] Dille, A., Kervyn, F., Handwerger, A., d'Oreye, N., Derauw, D., Samsonov, S., Malet, J-P, Kervyn, M., Dewitte, O., 2021. When image correlation is needed: unravelling the complex dynamics of a slow-

[8] Full bibliographic reference, including doi – separate conference papers

moving landslide in the tropics with dense radar and optical time series. Remote Sensing of Environment 258, 112402. https://10.1016/j.rse.2021.112402 [IF: 10.0]

[3.] Dewitte, O., Dille, A., Depicker, A., Kubwimana, D., Maki Mateso, J.-C., Mugaruka Bibentyo, T., Uwihirwe, J., Monsieurs, E., 2021. Constraining landslide timing in a data-scarce context: from recent to very old processes in the tropical environment of the North Tanganyika-Kivu Rift region. Landslides 18, 161-177. https://doi.org/10.1007/s10346-020-01452-0 [IF: 6.6]

[4.] Samsonov, S., Dille, A., Dewitte, O., Kervyn, F., d'Oreye, N., 2020. Satellite interferometry for mapping surface deformation time series in one, two and three dimensions: A new method illustrated on a slow-moving landslide. Engineering Geology 266, 105471. https://doi.org/10.1016/j.enggeo.2019.105471 [IF: 6.7]

[5.] Dille, A., Kervyn, F., Mugaruka Bibentyo, T., Delvaux, D., Bamulezi Ganza, G., Mawe Ilombe, G., Moeyersons, J., Monsieurs, E., Smets, B., Kervyn, M., Dewitte, O., 2019. Causes and triggers of deep-seated hillslope instability in the tropics – Insights from a 60-year record of Ikoma landslide (DR Congo). Geomorphology 345, 106835. https://doi.org/10.1016/j.geomorph.2019.106835 [IF: 3.8]

[6.] Nobile, A, Dille, A., Monsieurs, E., Tchangaboba, J., Mugaruka Bibentyo, T., d'Oreye, N., Kervyn, F., Dewitte, O., 2018. InSAR time series to characterize landslide ground deformations in a tropical urban environment: focus on Bukavu, East African Rift System (DR Congo). Remote Sensing 10, 62. https://doi.org/10.3390/rs10040626 [IF: 4.1]

Two book chapters where MODUS results were used

[1.] Dewitte, O., Depicker A., Moeyersons, J., Dille A., 2022. In: Shroder, J.J.F. (Ed.), Treatise on Geomorphology, vol. 5. Elsevier, Academic Press, pp. 338–349. https://doi.org/10.1016/B978-0-12-818234-5.00118-8

[2.] Dewitte, O., Dille, A., in press. Mouvements en milieux subtropicaux et équatoriaux. In: Traité sur les glissements de terrain (eds. M. Jaboyedoff, Locat, J., Michoud, C.)

In conference proceedings

[3.] Dille, A., Kervyn, F., Monsieurs, E., Smets, B., d'Oreye, N., Kervyn, M., Dewitte, O., 'Dynamics of slow-moving deep-seated landslides in the tropics: insights from combined analyses of long InSAR time series and ground-based measurements' in Close Range Sensing Techniques in Alpine Terrain. Proceedings of the Innsbruck Summer School of Alpine Research 2019, 16.-22.06.2019 in Obergurgl, Austria; Rutzinger M. and Heinrich K.; Publisher: Verlag der Österreichischen Akademie der Wissenschaften (VÖAW), (2019), ISBN: 978-3-7001-8565-9

[4.] Dewitte, O., Dille, A., Delvaux, D., Michellier, C., Monsieurs, E., Nobile, A., Mugaruka Bibentyo, T., Basimike, Jacobs, L., Kervyn, F., (2018). 'Landslide hazard assessment in an urban-sprawling context: a geomorphological approach in Bukavu (DR Congo). In: Micu, M., Comanescu, L. (eds.), Proceedings of the Romanian Symposium on Geomorphology and the Joint Geomorphological meeting (Vol. 02): From field mapping and landform analysis to multi-risk assessment: challenges, uncertainties and transdisciplinarity. Asociatia Geomorfologilor din Romania (AGR) – Editura Universitatii din Bucuresti, pp. 36-38. ISSN2559-3021.

SUBMITTED

[1.] Dille, A., Dewitte, O., Handwerger, A., Derauw, D., d'Oreye, N., Moeyersons, J., Monsieurs, E., Mugaruka Bibentyo, T., Samsonov, S., Smets, B., Kervyn, M., Kervyn, F., (*in review*) '*Urban growth and the dynamics of a large deep-seated landslide in the tropics*', Nature Geoscience, [IF: 13.6]

[2.] Two manuscripts are in preparation: (i) one review manuscript on the use of remote sensing for landslide studies; this manuscript being issued from MODUS collaboration with the CEOS landslides. (ii) one manuscript on the landslides in the Ruzizi Gorge in Bukavu, a research that is carried out by a PhD student from the Université Officielle de Bukavu in partnership with the RMCA. This work is relying on topographic data produced via MODUS.

6.2 POSTERS

Poster presentations during conferences

[1.] Dewitte, O., Deijns, A., Depicker, A., Dille, A., Kanyigina, V., Kubwimana, D., Maki Mateso, J.-C., Mugaruka Bibentyo, T., Sekajugo, J., 2021. Landslide timing in the changing environments of the North Tanganyika-Kivu Rift region, Africa. 7th International Geologica Belgica Meeting 2021 "Geosciences Made in Belgium", Tervuren, Belgium, 15 – 17 September 2021 (Poster).

[2.] Dille, A., Kervyn, F., Kervyn, M., Dewitte, O., 2020. Unravelling natural and anthropogenic controls on the dynamics of deep-seated landslides in the tropics. Young Researchers' Overseas Day - Royal Academy for Overseas Sciences, Brussels, 15 December 2020. (Online-poster).

[3.] Dille, A., Kervyn, F., Handwerger, A., Monsieurs, E., Mugaruka Bibentyo, T., Smets, B., d'Oreye, N., Kervyn, M., Dewitte, O., 2020. Controls on the dynamics of slow-moving deep-seated landslides in the tropics - insights from landslides of the Kivu Rift. Workshop "Slope processes in challenging environments - tools, approaches and perspectives", Tervuren, Belgium, 11 March 2020 (Poster).

[4.] Dille, A., Kervyn, F., Smets, B., Monsieurs, E., d'Oreye, N., Kervyn, M., Dewitte, O., 2019. Dynamics of slow-moving deep-seated landslides in the tropics: insights from combined analysis of long InSAR time series and ground-based measurements. Innsbruck Summer School of Alpine Research "Close range sensing techniques in Alpine terrain", Innsbruck, Austria, 16 – 22 June 2019 (Poster).

[5.] d'Oreye, N., Derauw, D., Libert, L., Samsonov, S., *Dille, A., Nobile, A., *Monsieurs, E., Dewitte, O., Kervyn, F., 2019. Automatization of InSAR mass processing using CSL InSAR Suite (CIS) software for Multidimensional Small Baseline Subset (MSBAS) analysis: example combining Sentinel-1 and Cosmo-SkyMed SAR data for landslides monitoring in South Kivu, DR Congo. ESA Living Planet Symposium 2019, Milan, Italy, 13-17 May 2019 (Poster).

[6.] Samsonov, S., d'Oreye, N., Dille, A., Monsieurs, E., Dewitte, O., 2019. MSBAS3DT – A software for computing 3D displacements from DInSAR data sets. Application on a large deep-seated landslide in Bukavu, DR Congo. ESA Living Planet Symposium 2019, Milan, Italy, 13-17 May 2019 (Poster).

[7.] Dille, A., Kervyn, F., Mugaruka Bibentyo, T., Delvaux, D., Bamulezi Ganza, G., Ilombe Mawe, G., Moeyersons, J., Monsieurs, E., Smets, B., Kervyn, M., Dewitte, O.,2018. Questioning causes and drivers of slope instability in a tropical context – insights from the Ikoma Landslide (DR Congo). Young Researchers' Overseas Day - Royal Academy for Overseas Sciences, Brussels, 07 December 2018 (Poster).

[8.] Dille, A., Kervyn, F., Bamulezi Ganza, G., Ilombe Mawe, G., Kalikone Buzera, C., Mugaruka Bibentyo, T., Delvaux, D., Smets, B., Dewitte, O., 2018. High resolution characterisation of a recent landslide in a tropical environment. Geophysical Research Abstracts 20, EGU2018-15606, EGU General Assembly, Vienna, Austria, 08 - 13 April 2018 (Poster).

[9.] Dille, A., Nobile, A., Monsieurs, E., d'Oreye, N., Kervyn, F., Dewitte, O., 2017. Multi-temporal InSAR measurements to characterise landslide ground deformations in a tropical urban environment: focus on Bukavu (DR Congo). Abstract NH43A-0198. AGU Fall Meeting. New Orleans, USA, 11-15 December 2017 (Poster).

Oral presentations during conferences

[1.] Dewitte,O., Deijns, A., Depicker, A., Dille, A., Kanyiginya, V., Kubwimana, D., Maki-Mateso, J.-C., Mugaruka Bibentyo, T., 2021. Landslide timing in a changing tropical environment: the North Tanganyika-Kivu Rift region, Africa. 5th World Landslide Forum, Kyoto, Japan, 2 – 9 November 2021 (Online-oral).

[2.] Mugaruka Bibentyo, T., Dille, A., Depicker, A., Smets, B., Vanmaercke, M., Nzolang, C., Dewaele, S., Dewitte, O., 2021. Landslides, river incision and environmental change: the Ruzizi gorge in the Kivu Rift. CRGM - Les IXème journées scientifiques - Les risques naturels : leur connaissance, impact environnemental et sociétal en RD. Congo, Kinshasa, DR Congo, 28-29 October 2021 (Oral).

[3.] Dewitte,O., 2021. Landslide hazard in the North Tanganyika-Kivu Rift region, Africa. Rifts and Rifted Margins Seminar - Geohazards in the East African Rift, online, 20 September 2021 (Oral). Youtube

[4.] Dewitte,O., 2021. Landslides in the Western Branch of the East African Rift. LandAware MayDay round-the-clock Conference - Session 06 Landslide inventories and data gathering, online, 19-20 May 2021 (Oral).

[5.] Mugaruka Bibentyo, T., Dille, A., Depicker, A., Smets, B., Vanmaercke, M., Nzolang, C., Dewaele, S., Dewitte, O., 2021. Landslides, river incision and environmental change: the Ruzizi gorge in the Kivu Rift. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-11067, https://doi.org/10.5194/egusphere-egu21-11067, Vienna, Austria, 19 – 30 April 2021 (Online-oral).

[6.] Dille, A., Kervyn, F., Handwerger, A., d'Oreye, N., Derauw, D., Mugaruka Bibentyo, T., Samsonov, S., Malet, J.-P., Kervyn, M., Dewitte, O., 2021. When image correlation is needed: combining very dense radar-amplitude and optical times series for unravelling the complex dynamics of a not so slow slow-moving landslide in the tropics. EGU General Assembly 2021,

online, 19–30 Apr 2021, EGU21-10627, https://doi.org/10.5194/egusphere-egu21-10627, Vienna, Austria, 19 – 30 April 2021 (Online-oral).

[7.] Dille, A., Kervyn, F., Kervyn, M., Dewitte, O., 2020. Dynamics of deep-seated landslides in the tropics: natural and anthropogenic controls. Abstract NH031-03, AGU Fall Meeting, San Francisco, USA, 1-17 December 2020 (Online-oral).

[8.] Dille, A., Dewitte, O., d'Oreye, N., Derauw, D., Malet, J-P, Kervyn, M., Kervyn, F., 2020. MODUS: A multi- sensor approach to unravel natural and anthropogenic controls on landslides dynamics in the tropics. BEODay: Virtual Border-crossing Earth Observation Day 2020, Brussels, Belgium, 24 November 2020 (Online-oral). Invited speaker

[9.] Dille, A., Dewitte, O., Handwerger, A., Derauw, D., d'Oreye, N., *Monsieurs, E., Samsonov, S., Smets, B., Kervyn, M., Kervyn, F., 2020. Urban growth changes the pulse of a large deep-seated landslide. EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-17805, https://doi.org/10.5194/egusphere-egu2020-17805, Vienna, Austria, 04 – 08 May 2020 (Online-oral).

[10.] Dille, A., Dewitte, O., Derauw, D., Libert, L., *Monsieurs, E., Smets, B., Kervyn, M., d'Oreye, N., Kervyn, F., 2019. Dynamics of slow-moving landslides from dense InSAR time series: insights from a tropical urban environment. MDIS-2019 : Mesure de la Déformation par Imagerie Satellitaire, Strasbourg – La Petite-Pierre, France, 14-18 October 2019 (Oral). Invited speaker

[11.] Dille, A., Dewitte, O., Derauw, D., Libert, L., Monsieurs, E., Smets, B., Kervyn, M., d'Oreye, N., Kervyn, F., 2019. Kinematics of deep-seated landslides in a tropical urban environment: insight from combined analysis of long InSAR time series and ground-based measurements. ESA Living Planet Symposium 2019, Milan, Italy, 13-17 May 2019 (Oral).

[12.] Dille, A., Kervyn, F., Mugaruka Bibentyo, T., Delvaux, D., Bamulezi Ganza, G., Ilombe Mawe, G., Moeyersons, J., Monsieurs, E., Smets, B., Kervyn, M., Dewitte, O., 2019. Questioning causes and drivers of slope instability in a tropical context – insights from the Ikoma Landslide (DR Congo). Geophysical Research Abstracts 21, EGU2019-7680, EGU General Assembly, Vienna, Austria, 07 - 12 April 2019 (Oral).

[13.] Dewitte, O., Monsieurs, E., Dille, A., Depicker, A., Maki Mateso, J.-C., Mugaruka Bibentyo, T., Jacobs, L., Kirschbaum, D., 2019. The Kivu Rift: a landslide-prone region? 100th Journée Luxembourgeoises de Géodynamique, Luxembourg, Luxembourg, 25-27 March 2019 (Oral). Invited speaker

[14.] Dille, A., Kervyn, F., d'Oreye, N., Delvaux; D., Derauw, D., Libert, L., Kervyn, M., Monsieurs, E., Nobile, A., Smets, B., Dewitte, O., 2019. Landslide ground deformation and hillslope evolution. 100th Journée Luxembourgeoises de Géodynamique, Luxembourg, Luxembourg, 25-27 March 2019 (Oral). Invited speaker

[15.] Dille, A., Kervyn, F., Malet, J.-P., d'Oreye, N., Kervyn, M., Dewitte, O., 2018. Developing a multi-sensor approach to characterize Dynamics of slow-moving landslides in the tropical environments of Bukavu (DRC): from ground deformation analysis to hazard prediction. RMCA PhD Day, Tervuren, Belgium, 20 November 2018 (Oral).

[16.] Dille, A., Kervyn, F., Bamulezi Ganza, G., Ilombe Mawe, G., Kalikone Buzera, C., Mugaruka Bibentyo, T., Safari Makito, E., Monsieurs, E., Delvaux, D., Smets, B., Dewitte, O., 2018. Characterising drivers and mechanisms of landsliding in a tropical context – Ikoma landslide, DR Congo. 6th International Geologica Belgica Meeting 2018 "Geology Serving Society", Leuven, Belgium, 12 – 14 September 2018 (Oral).

[17.] Dewitte, O., Dille, A., Delvaux, D., Michellier, C., Monsieurs, E., Nobile, A., Mugaruka Bibentyo, T., Basimike, Jacobs, L., Kervyn, F., 2018. Landslide hazard assessment in an urbgan-sprawling context: a geomorphological approach in Bukavu (DR Congo). 19th Joint Geomorphological Meeting (JGM) "From field mapping and landform analysis to multi-risk assessment: Challenges, uncertainties and transdisciplinarity", Buzau, Romania, 16 – 20 May 2018 (Oral).

[18.] Dille, A., Monsieurs, E., Nobile, A., d'Oreye, N., Derauw, D., Malet, Jean-Philippe, Kervyn, F., Kervyn, M., Dewitte, O., 2017. A multi-sensor approach to characterise the spatio-temporal dynamics of landslides in tropical urban environment: focus on Bukavu. Multidisciplinary Workshop: Disasters and Resilience in the 21st century, Royal Academy for Overseas Sciences, Brussels, Belgium, 11 December 2017 (Oral).

[19.] Dille, A., Monsieurs, E., Nobile, A., d'Oreye, N., Derauw, D., Malet, Jean-Philippe, Kervyn, F., Kervyn, M., Dewitte, O., 2017. A multi-sensor approach to characterize landslide dynamics in a tropical urban environment. 7th Belgian Geography Day, University of Liège, Liège, Belgium, 17 November 2017 (Oral).

[20.] Dille, A., Monsieurs, E., Nobile, A., d'Oreye, N., Derauw, D., Malet, J.-P., Kervyn, F., Dewitte, O., 2017. A multi-sensor approach to characterize landslide dynamics in a tropical urban environment. 99th Journée Luxembourgeoises de Géodynamique, Luxembourg, Luxembourg, 6-8 November 2017 (Oral). Invited speaker

[21.] Dille, A., Monsieurs, E., Kervyn, F., Kervyn, M., Dewitte, O., 2017. Characterizing landslide dynamics in a tropical urban environment: focus on Bukavu (DR Congo). 5ème Journée Aléas Gravitaires, Besançon, France, 24 – 25 October 2017 (Oral).

6.3 SOFTWARE

The work carried out in MODUS project served as test case for the MASTER Toolbox workflow developed alongside many BELSPO Stereo projects (e.g., RESIST, MUZUBI, see Derauw et al. 2020). A lot of contact between our team and the developers were made to further improve the later.

Derauw, D., Jaspard, M., Caselli, A. and Samsonov, S., 2020. *Ongoing automated ground deformation monitoring of Domuyo-Laguna del Maule area (Argentina) using Sentinel-1 MSBAS time series:*

Methodology description and first observations for the period 2015–2020. Journal of South American Earth Sciences, 104, p.102850.

6.4 DATA ACCESS[9]

- All the results will be made available once the paper on Funu landslide is published. Similarly, all data that are not licensed (e.g., CSK SAR data cannot be shared due to licensing) or subjected to MoU and Data Sharing Agreement with partners are willingly shared upon request.
  The sharing of such MODUS output products is considered as part of a global ongoing reflexion at RMCA. GeoRiskA is in the process of inventorying all their geodata whose some could be considered for sharing (GIS vectors, maps, imagery). Practical considerations are discussed like sharing platform, format, licence etc. The plan is the development of a geoportal.
  Beside, the UAV-SfM data acquired within MODUS should be made available in OpenTopography in 2022.

6.5 OTHER TYPES OF OUTREACH

SOCIAL MEDIA

Recent activities were shared on Twitter and can be found with the #GeoRiskA hashtag (https://twitter.com/search?q=%23georiska&src=typed_query).

23/07/2020 ESA Sentinel News – Copernicus Sentinel-1 used to better understand active volcanic areas and landslide mechanism. https://sentinels.copernicus.eu/web/sentinel/news/-/article/copernicus-sentinel-1-used-to-better-understand-active-volcanic-areas-and-landslide-mechanisms

17/06/2019 BELSPO/BEO: MODUS – keeping an eye on landslides – Belgian Earth Observation platform https://eo.belspo.be/en/news/modus-keeping-eye-landslides

PRESS

PHD DISSERTATION

Antoine Dille This research project has led to a PhD dissertation successfully defended in March 2021 and entitled: "Remote sensing of slow-moving landslides in the tropics: natural and anthropogenic controls". This PhD research was carried out under the supervision of Dr. Olivier Dewitte and Dr. François Kervyn (Royal Museum for Central Africa) and Prof. Dr. Matthieu Kervyn (Vrije Universiteit Brussel). The dissertation provides an in-depth

[9] Give to link of data repository where project data can be accessed by the community.

investigation of Bukavu landslides processes using a combination of ground-based and remote sensing techniques. The manuscript of the dissertation is provided in annex.

POPULARISATION ACTIVITIES

- Organization of a 1-day workshop *"Slope processes in challenging environments - tools, approaches and perspectives*" at RMCA (Tervuren), 11 March, 2020. (attendance: 45 people). We provide pictures of the event as illustrative material.
- Organization of a regional two-day workshop in Bukavu on natural hazard risks in Africa, and a two-day training on drone and photogrammetry at the Université Officielle de Bukavu (DR Congo), 29-30 November 2021. (attendance: 35 people from Burundi, DR Congo and Rwanda). We provide pictures of the event as illustrative material.
- Organization of a two-day training "*Introduction to drone piloting and digital photogrammetry - theoretical and practical aspects in relation to the study of natural hazards and associated risks*" at Université Officielle de Bukavu (DR Congo), 01-02 December 2021. (attendance: 9 young researchers from the UOB). We provide pictures of the event as illustrative material.
- Antoine Dille presented his PhD results during a Geo-Webinar organized the 25 March 2021 by the Department of Earth Sciences of the RMCA. Attendance: ~50 people, mainly from DR Congo, Burundi, Rwanda and Uganda.
- Olivier Dewitte gave a presentation entitled "Landslides: an overlooked danger in the East Arican Rift" for the "Museum Talks" of the RMCA on 24 October 2019 Youtube (attendance: ~60 people)

OTHER (AWARDS, GUEST LECTURES, …)

- "**Best Poster Award**" awarded by the Royal Academy for Overseas Sciences of Belgium during the Young Researcher Overseas Day 2018 for a poster entitled: *'Questioning causes and drivers of slope instability in a tropical context – insights from the Ikoma Landslide (DR Congo)';* December 2018
- A. Dille (2019) received a European Commission Student Grant for the participation at the 2019 ESA Living Planet Symposium.
- A. Dille was invited as to provide a lecture on the use of satellite interferometry for measuring earth surface deformation (Université Libre de Bruxelles, Télédétection (Master), *Measuring Earth's topography and its deformation from space,* November 2019 and 2020). He also gave the practical of the class Natural Hazards at the Vrije Universiteit Brussel, Belgium.

- A. Dille was invited to present MODUS' work at three international conferences:
    - Dille, A., Dewitte, O., d'Oreye, N., Derauw, D., Malet, J-P, Kervyn, M., Kervyn, F., *'MODUS: A multi- sensor approach to unravel natural and anthropogenic controls on landslides*

dynamics in the tropics'. BEODay: Virtual Border-crossing Earth Observation Day 2020, Brussels, Belgium, 24 Nov. 2020 – Invited speaker

- Dille, A., Kervyn, F., d'Oreye, N., Handwerger, A., Monsieurs, E., Smets, B., Kervyn, M., Dewitte, O., *"Dynamics of slow-moving landslides from dense InSAR time series: insights from a tropical urban environment",* MDIS 2019, Strasbourg – Invited speaker
- Dille, A., Kervyn, F., d'Oreye, N., Delvaux; D., Derauw, D., Libert, L., Kervyn, M., Monsieurs, E., Nobile, A., Smets, B., Dewitte, O., '*Landslide ground deformation and hillslope evolution'*. 100th Journée Luxembourgeoises de Géodynamique, (2019), Luxembourg, Luxembourg – Invited speaker

6.6 COLLABORATION WITH OTHER BELSPO PROJECTS

2013 – 2018 **AfReSlide**: *Landslides in Equatorial Africa: Identifying culturally, technically and economically feasible resilience strategies*. Belgian Federal Scientific Policy (BELSPO). Research project BR/121/A2/AfReSlide (Research action BR), BRAIN-be (Belgian Research Action through Interdisciplinary Networks). Project leader: VUB, Belgium. O. Dewitte is WP leader.

2015 – 2019 **RESIST**: *Remote Sensing and In Situ Detection and Tracking of Geohazards*. MODUS' mother project founded by the Belgian Science Policy. It benefits from, amongst other, RESIST's rain gauge and seismic networks, landslide inventory, CIS and MSBAS software developments etc,. Project leader: François Kervyn.; O. Dewitte, N. d'Oreye and D. Derauw are WP leaders

2016 – 2018 **MUZUBI**: *MUlti Zone phase Unwrapping using advanced split-Band Interferometry*. MODUS benefits from the developments in CIS and MSBAS software operated in the frame of Belspo MUZUBI (Multi Zone phase Unwrapping using advanced Split Band Interferometry).

2016 – 2021 **PAStECA**: *Historical Aerial Photographs and Archives to Assess Environmental Changes in Central Africa*. Belgian Federal Scientific Policy (BELSPO). Research project BR/165/A3/PASTECA (Research action BR), BRAIN-be (Belgian Research Action through Interdisciplinary Networks). Study of the long-term evolution of surface processes in the region of Bukavu realised within MODUS greatly benefits from the defined workflows and the scanning of the historical aerial photographs available at the RMCA. Work on the regional landslide susceptibility realised in PAStECA help in the understanding of the landslide processes in the area. Project leader: O. Dewitte.

7 NEW PROJECTS AND INTERNATIONAL COLLABORATIONS STARTED (PARTLY) BASED ON RESULTS OF THIS PROJECT

- NASA Jet Propulsion Laboratory Pasadena (United States): Collaboration with Dr. Alex Handwerger for developing simple 1D simulations of slope pore-water pressures changes. From this collaboration: a 3-week research stay and 2 collaborative publications.
- 2018 – 2020 CEOS-Landslide: Committee on Earth Observation Satellites – Landslide Pilot Working Group. Project co-leaders: NASA, USGS, Université de Strasbourg, GFZ German Research Centre for Geosciences. O. Dewitte is regional point of contact for Central Eastern Africa region. Website: http://ceos.org/ourwork/workinggroups/disasters/landslide-pilot/
- 2020 – now LandAware: The international network on Landslide Early Warning Systems. O. Dewitte is member of the "Innovations" and "LEWS data" working groups. Website: https://www.landaware.org/
- 2019 – 2023 HARISSA (Natural Hazards, RISks and Society in Africa: developing knowledge and capacities): lead by RMCA and funded by the Development Cooperation programme of the RMCA with support of the Directorate-General Development Cooperation and Humanitarian Aid of Belgium.. The project is oriented towards the reduction of geo-hydrological hazard impacts for he society. It involves 10 partners in Central Africa. Learnings from MODUS are integrated into the project. As an example, in South-Kivu, the Official University of Bukavu (UOB) is taking advantages of the methodologies developed within MODUS fort the use of UAS imagery acquisition.

8 COPY OF PUBLISHED PAPERS

A copy of published papers is provided in the attached material (published papers).

9 ADDITIONAL INFORMATION[10]

A copy of the PhD dissertation of A. Dille is provided the attached material (additional material).

10 PROJECT ILLUSTRATIVE MATERIAL[11]

We provided pictures of fieldwork and steering committee in the attached material (project illustrative material) .

11 PROJECT SHEET (separate form)[12]

[10] Detailed description methodology, statistics, reports, …

[11] In attachment by Wetransfer or ftp link; high resolution photographs of field campaigns, graphs and maps. You may also provide us with pictures of the team members if so wished. By sending us photographs, you agree that BELSPO can use them for its websites and other forms of communication.

[12] Form available on project management website

12 PROJECT WEBSTORY (separate form) [13] [14]

[13] Form available on project management website

[14] Story for broader audience on interesting aspect of project, e.g. fieldcampaign, cross border cooperation