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# Application of geospatial and ICT technologies for landslide disaster risk reduction in Rwanda☆

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## ABSTRACT

This study provides a new insight into landslide advancement based on the state-of-art mapping technology, time-series imagery, and disaster informatics in Rwanda, where 40 % of its lands susceptible to landslides. This is the first nationally supported and locally evidenced use-case of the iMaster/DocuCam, a scalable system for landslide monitoring and detection in the African continent, originally developed for advanced industrial automation. The system continuously collects high-resolution images and weather data to monitor landslides and alert relevant authorities. We used "Quadtree" Computer Vision algorithms to automatically detect landslides by pre-processing images and measuring brownish pixels. Using statistical modelling, comparison with previous images is made and deviation in the number of brown pixels is determined. If deviation exceeds the threshold, a landslide is detected, and a warning is sent out. The results are also stored in the Open-Source SQL database and accessible via web-based Graphical User Interface. We also explored user requirements, needs and demands of stakeholders at national and local level for developing the people-centered early warning system in Rwanda, as promoted by the Sendai Framework. This study manifests the commitments of the Rwandan government to accelerate the localized disaster risk reduction action for societal resilience in the tropics.

## 1. Introduction

Rwanda is densely populated country in Africa and the impacts of landslide disasters in Rwanda are intensifying, resulting in a growing threat to social-economic development [1,2,3,4,5]. The disasters in a single night of May 2nd to 3rd 2023, over 130 individuals lost their lives, thousands became homeless, infrastructures (roads, hospitals, schools, electricity power lines, and more) were severely damaged, and over USD 300 million were lost [6]. Existing research and government reports indicate that landslides in Rwanda are mainly caused by heavy rainfall and its unique topography, which is characterized by high mountains, steep slopes, and deep valleys [7,8,9]. Additionally, Rwanda is located in the East African Rift System (EARS) which is associated with tectonic stresses that cause seismic activities and structure deformations [10,11,12]. This makes over 40 % of Rwanda landslide-prone [13,4,14]. The landslide vulnerability is expected to increase in the future as the population will double in a decade [15,6].

Rwanda is very committed to the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR2030) [16,17]. Despite that it faces extreme weather events, climate-induced disasters, e.g. landslides, debris flow and floods resulted in disruption to the critical sectors like infrastructure, health, ecosystem, water, and food security [3,14], its readiness to fight against these impacts prevailed [6].

Currently, Rwanda has gaps in climate adaptation efforts, in the

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absence of early warning system (EWS). Modern EWS are required to automatically generate real-time and actionable information [18,19] for disaster mitigation, preparedness, response, and recovery, ultimately reducing risk from climate disasters [20]. Thus, real time accuracy of data is critically needed coupled with metadata and geolocation information, easy multi-channel accessibility, sophisticated versatile alarm systems, community engagement, and scalability [21,22]. An investment in a reliable EWS would provide actionable data, resulting in reducing disaster losses for a cost significantly lower than past impact costs [23,3,24].

As a proof-of-concept towards the establishment of an EWS for landslides in Rwanda, the patented "iMaster/DocuCam" system (EP3236440A1, European Patent Office (EPO), 2016) was setup in 2022 in Rambura, one of 12 sectors of Nyabihu district, in the western province of Rwanda, through the pilot national project titled *"Piloting an optical surveillance technology for landslide monitoring in Rwanda"*. It was led by the Rwanda Ministry in Charge of Emergency Management (MINEMA) and Rwanda Space Agency (RSA), using grant funding from Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), and implemented by Hesotech GmbH [25]. The iMaster/DocuCam is an automated Agent-Server-Client system that uses onsite Pan-Tilt-Zoom (PTZ) cameras to scan an area currently tested up to about 12 km$^2$. The two cameras installed are co-located with a weather station that records weather data including rainfall, humidity, temperature, sunshine, and wind speed. Using a mobile data connection, all collected data is transferred to a server where evaluations are done on-the-fly for every incoming data.

In Rwanda, efforts have been made to set a scientific foundation for landslide EWS [26,27]. According to [3], MINEMA has taken a step forward to develop EWS for landslide disasters based on the existing Standard Operating Procedures (SOPs). The used SOPs are expected to assist in creation of protocols for the early detection of landslide events [5]. In the development of EWS, four main components are considered namely as risk knowledge, warning, information dissemination, and response capacity. The methodologies and approaches such as inventory-based probabilistic, statistics, deterministic, and heuristic are used to standardize the system. The successful development of the system will lead to exclusive sympathy for the potential landslides that are likely to occur in Rwanda [3].

Globally, a few technology-driven solutions have been tested in the development of EWS for landslide disasters. For instance, in 2005 the Government of Japan established a Landslide EWS (LEWS) by using Artificial Neural Networks (ANN) to set a danger threshold for landslide events and disseminate early warning information via TV. The principle of this system uses a Radial Basis Function (RBF) network to approximate cumulative rainfall within sixty minutes across Japan and calculate the associated soil moisture index [28]. However, this system relies on rainfall alone, potentially increasing uncertainty when applied in areas with localized nonlinear landslide hazards. Recently, SKY Perfect JSAT, a Japanese satellite communication company has also harnessed the power of AI to extract landslides-related measurements from images taken by Low Earth Orbit Satellites. This system uses a Synthetic Aperture Radar (SAR), a microwave image processing technique, and a dataset to detect ground movement from reflected signals by comparing images collected in different timestamps [29]. However, in-depth data processing is required for SAR to avoid errors and noise in data. Combining the limitations of SAR being expensive to access and utilize, it is very difficult to scale this system in other places [30].

In China, a series of monitoring and real-time landslide prediction approach was proposed. This system uses ad-hoc technology, Beidou terminals, and fracture monitors to build a rapid area surveillance network. A model made from a combination of Kernel Function-Fast Fourier Transform-Support Vector Machine (KF-FFT-SVM) was trained to predict the occurrences of landslide events using deformation data [31]. However, this system's accuracy was limited to specific types of landslides, necessitating the expensive continuous collection of data to train and improve the model's accuracy. This research aims at better understanding the needs of demands of landslide DRR strategies in Rwanda by advancing a specific use-case of the iMaster/DocuCam, an automated system that supports efficient collection, storage, integration with other databases, and retrieval of various geospatial and scalar data streams for over long-term periods (typically >30 years). The objectives of this study are to:- a) present the architecture and working principles of the iMaster/DocuCam system, b) demonstrate the status, and contribution of iMaster/DocuCam for co-designing a comprehensive LEWS, and c) explore national- and local needs for development of the people-centered, end-to-end, and impact-based EWS for landslide disaster in Rwanda.

## 2. Materials and methods

### 2.1. Study area

The iMaster/DocuCam system was installed in Rambura sector, Nyabihu District, a 64 km$^2$ sector with over 28,820 inhabitants. Located at 1° 40′ 30"S and 29° 30′ 0″E, it contains critical infrastructure such as health centers, schools, roads, and powerlines (Fig. 1). Furthermore, the area features numerous rivers from groundwater discharge and is dominated by angular and rounded hills [27].

Rambura has a tropical highland climate, with 1300 mm - 1600 mm annual rainfall and temperature between 10 and 18 °C (WBG, 2024). Its mountains range from 2048 m to 2985 m above sea level, (CIA, 2024), with steep (15 % - 60 %) to very steep (> 60 %) slopes (Fig. 2) [32,33].

The geology of the area includes igneous, sedimentary, and metamorphic rocks (Fig. 1) [10]. The main lithologies are granite, meta schist, quartzite, shale, and volcanic rocks that weather into clay-rich soils [34]. Over 35 % of soil consists of clay minerals, reducing the resistance of soil, resulting in a higher probability of landslides to occur [35,36,37]. The combination of the above factors makes Rambura highly susceptible to landslide hazards, especially during the rainy seasons, causing risks to live, agriculture, and infrastructure [26,14,38].

### 2.2. iMaster/DocuCam system architecture

The iMaster/DocuCam is a modular automated software system, which contains two main modules known as the iMaster handles scalar measurements and events/alarms, whereas the DocuCam captures images. The DocuCam acts as an on-site agent and iMaster as a server providing user-friendly access to data and interaction and a versatile platform for evaluations (Fig. 2). Certificate-based authentication is used to ensure secure system and data access. Moreover, the system can monitor 12 km$^2$ using standard PTZ cameras. A single optimally positioned camera can monitor a 360°view. It is worth mentioning that a multi-camera approach by mounting cameras on walls may be advantageous.

#### 2.2.1. DocuCam module

The DocuCam captures real-time high-resolution images and collects weather data through a co-installed local weather station. Unlike standard video cameras, DocuCam records spatial information and collects time-series images for each location. All data is transferred to a secure server. The DocuCam is composed of PTZ cameras, and an electronics cabinet with a power connection and Raspberry-Pi microcontroller (Fig. 3). The software part uses autonomous agents (drivers) to operate the hardware, facilitate connections, and transfer data. The DocuCam software is divided into two parts, 1) agents that get data from the camera and weather station and transfer them to the server, and 2) a module that buffers data and images in case of issues with connectivity and transfers them to the iMaster system for subsequent tasks.

*2.2.1.1. Pan-Tilt-Zoom camera.* In this study, we utilized a Pan-Tilt-

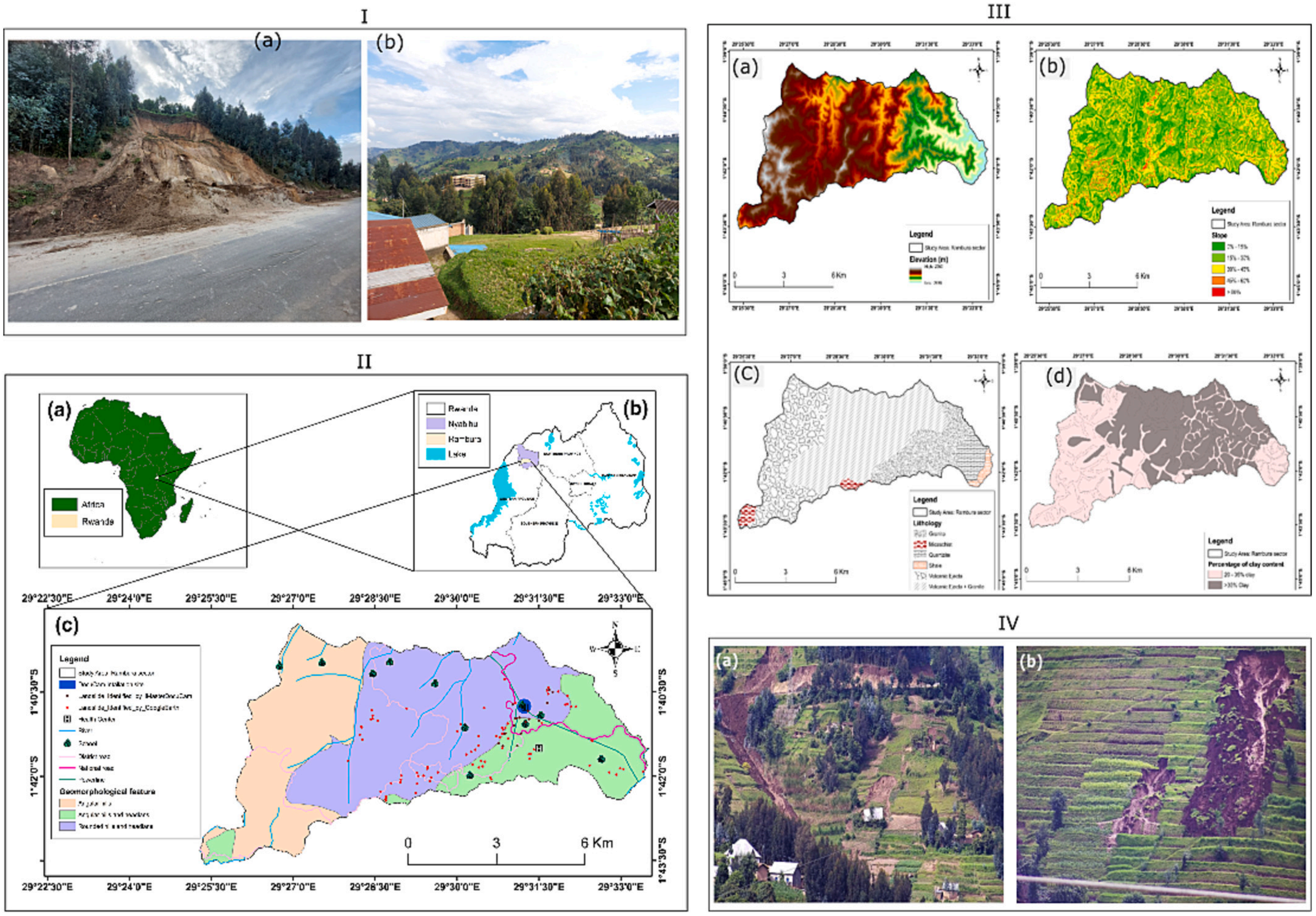


**Fig. 1.** I (a) Landslide affecting district road in Rambura sector. I (b)Mountainous topography of Rambura sector taken by DocuCam mounted at about 2400 m above sea-level. II(a) Geographical Location of Rwanda in Africa; II(b) Location of Rambura sector in Nyabihu district in Rwanda; II (c) Study area, Location of DocuCam installation site, landslide inventory (identified by iMaster/DocuCam and Google Earth), rivers, and facilities. III (a) Elevation map, III (b) Slope map, III (c) Lithological map, and III(d) clay content map of Rambura. IV (a) Images from the iMaster/DocuCam system (from May 03rd 2023) highlighting the impact of landslide disaster in Rambura. IV (b) impact of landslides on settlement and critical infrastructure (e.g. national road, powerline, and agriculture land).

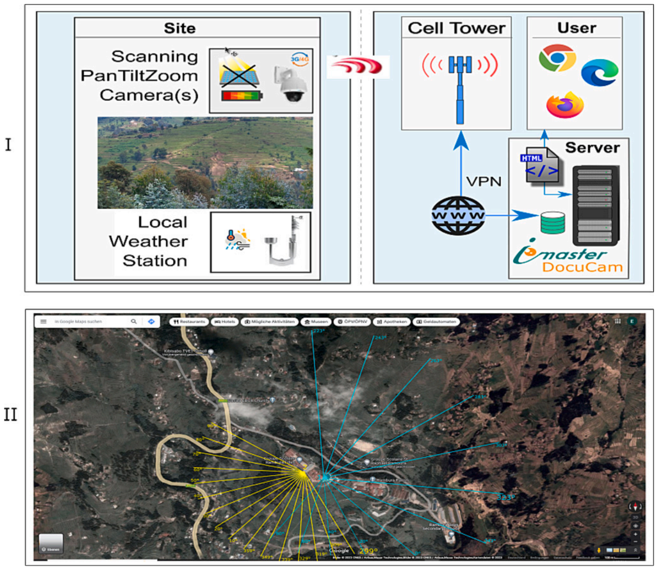


**Fig. 2.** (I) Illustration of the iMaster/DocuCam as an on-site Agent-server-client System. (©Hesotech);(II) Positions of the two DocuCams and their respective scanning areas, 1 = hospital view (cyan), 2 = school view (yellow).

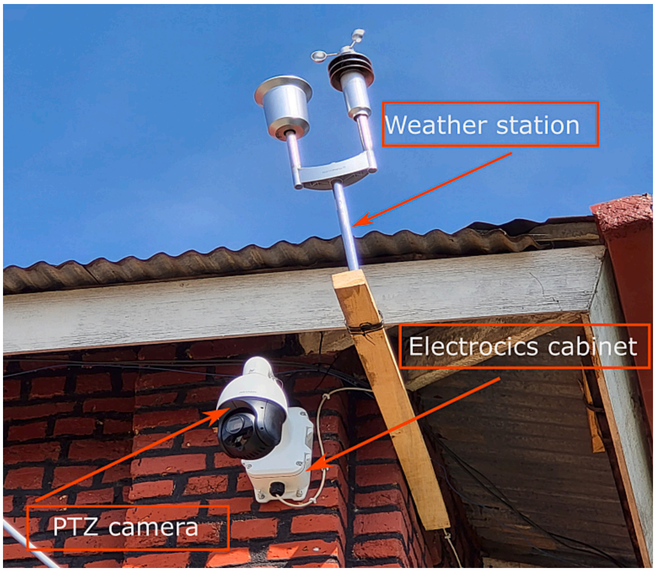


**Fig. 3.** DocuCam Module and its specification for landslide monitoring system.

Zoom (PTZ) camera with remote-control ability to adjust zoom level and direction of view (see Fig. 4). It automatically documents ground displacements by capturing over 1000 high-resolution images per scan twice a day. A Raspberry–Pi controls automatic horizontal pan angle, vertical tilt angle and zoom. Zoom is measured by its aperture angle, also known as Field of View (FOV). Zooming allows a resolution smaller than 1 cm in a distance of 2 km.

The number of images captured and documented depends on the size of the scene. In Rambura, the PTZ cameras make two daily scans at 8:00 am and 4:00 pm. The transfer to the server costs approximately 1 Megabyte per image. All images are buffered together with timestamps and PTZ angle coordinates. One DocuCam operates on less than 16 watts via the normal power line or a solar panel.

*2.2.1.2. Weather station.* The weather station's built-in wireless sensors measure rainfall, temperature, wind speed, humidity, brightness, and sunshine duration (Fig. 5). Weather data is collected every 15 s and averages over 10 min. However, this frequency can vary to suit user needs. Thereafter, all data with metadata is stored in a well-structured relational Open-Source SQL database (PostgreSQL). Users can visualize and analyze data through a Graphical User Interface (GUI) with a web browser. The weather data is displayed on the GUI as dynamic time-series charts. Images corresponding to a timestamp can be displayed in parallel by mouse-scrolling on the chart. (See Fig. 6.)

*2.2.1.3. Connections implemented in the electronic cabinet.* The electronic cabinet, which includes all equipment for connectivity and power supply, covering the Raspberry-Pi 4 Model B controller with 8GB of Random Access Memory (RAM)). Other components are receiver for the weather station, 128 GB SD card, 4G Long-Term Evolution (LTE) stick and external antenna, and SIM card enabling mobile data connectivity. The mobile data connection is secured with a Virtual Private Network (VPN).

*2.2.1.4. DocuCam principle.* Images are complex and challenging data in terms of recording, processing, and storing, using only classic or industrial automation approaches. Based on the Artificial-Intelligence and/or Computer-Vision, measurements can be extracted from images. The DocuCam systematically scans a region of interest in a real-time. It is worth mentioning that the DocuCam is not a video surveillance but a stack of fast and easily searchable images by spatial coordinates and time separately. The protocol starts by scanning an overview image, and then progressively zooming in by dividing the region into 4 rectangles until the maximum or desired zoom level is reached, mimicking a mosaic of tiles in a bathroom. This principle makes it easy to compare the sequence of images of a tile over time.

Each tile has a unique coordinate (Layer, Row, Column) to localize a specific area within the image (see Fig. 7). It also helps with efficient storage, retrieval, visualization, mathematical operations, and AI-labeling. The Layer-Row-Column coordinate of a tile is directly related to its geo-location (longitude, latitude, altitude) represented by its center. This enables automated relational information merging between the DocuCam, Geographical-Information-Systems (GIS), and maps. As the DocuCam platform does not rely on the source of images for evaluations, it can also handle time series of satellite and drone images, as long as geo-location is provided. A user-friendly web-based GUI offers a live-view mode and historical records of all collected datasets. The user can navigate through different tiles in the scene, download high-resolution images and create time-lapse videos of images in a tile over a specific time range to observe ground change. (See Fig. 8.)

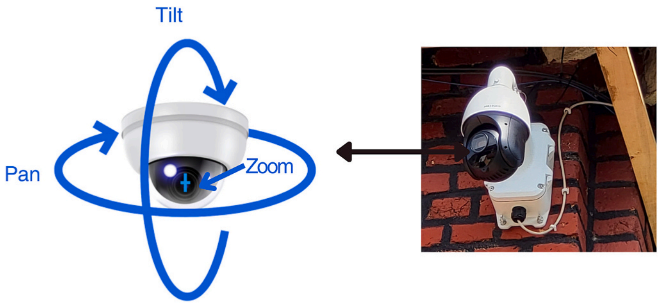


**Fig. 4.** A standard PTZ camera used in the DocuCam Module.

**Fig. 5.** Parts of the weather station used in the DocuCam Module. Where 1: Rainfall drop collector, 2: Anemometer, 3: Batteries, 4: Sensors (Temperature, Humidity, and Sunshine duration).

### 2.2.2. iMaster module

The iMaster module consists of drivers to get data from various data sources, a PostgreSQL database, an event system and a web-API. In the Rambura installation, two drivers collect data from the camera and weather station and transfer them to the server where subsequent tasks including evaluations can be performed by external applications e.g. machine learning models, GIS, etc. The modern database management strategies make the iMaster a unique and novel solution for handling big data. PostgreSQL database supports near real-time data storage and transfer in different formats (binary, XML, JSON), accommodates different retrieval strategies, and event system management.

The data stream includes an incoming data controller and a ring buffer to minimize transactions. On storage of data packages from the ring buffer, also aggregated values (average, minimum, maximum, last value) are stored. Retrieval can be accelerated by built-in strategies using aggregated data. If millions of data are requested over a long-time interval – because of the limited resolution of the screen - only about 2000 aggregated data points are transferred for display.

Alarms, Warnings and Messages are events with different severity. Events are defined by value or gradient thresholds. Events can be active or inactive. They are checked automatically on each incoming data. With each event, a list of actions can be defined when becoming active: E.g. (2) sent an email with report1 to Mrs. X (2) a SMS to Mr. Y. Action lists for going events can also be defined. Also, they provide a complete searchable documentation of "What happened", "Where" and "When".

The event system analyzes all suspicious areas in images and sends

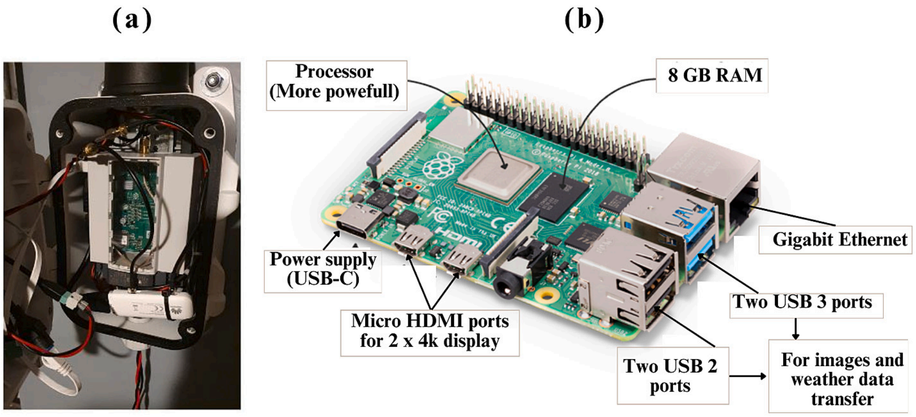


**Fig. 6.** Electronic cabinet of DocuCam module. Connection inside electronic cabinet (a); parts of Raspberry-pi 4 B used in higher resolution images (b). Where USB: Universal Serial Bus, HDMI: High-Definition Multimedia Interface.

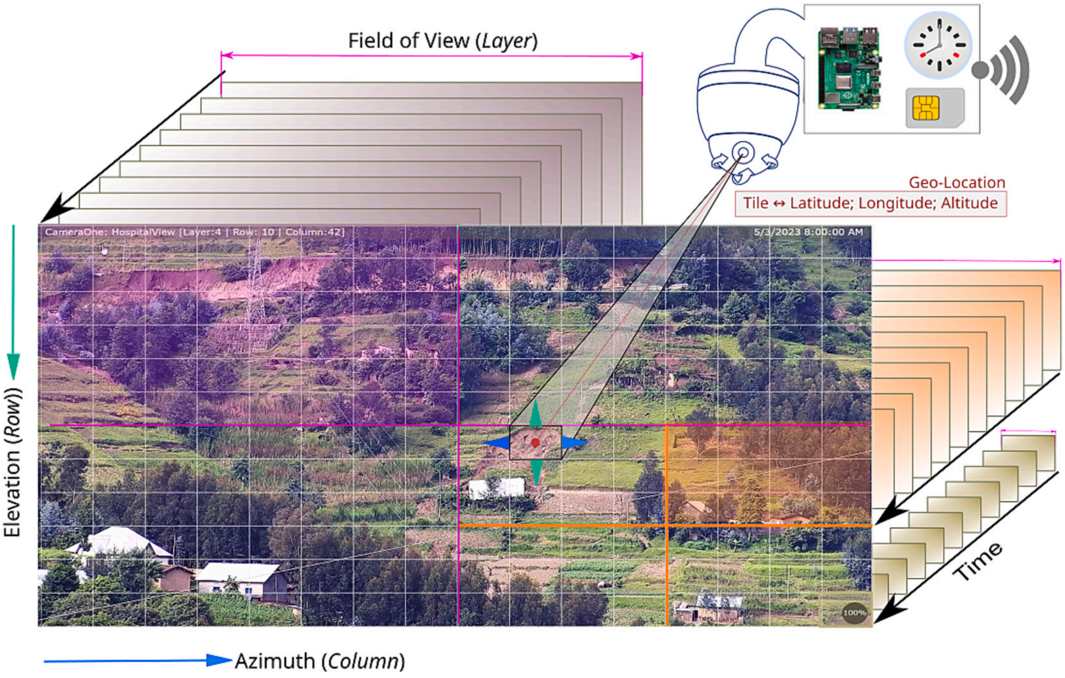


**Fig. 7.** DocuCam principle. The higher the zoom, the smaller the Field-of-View (FOV). The optical resolution of the images (e.g., 2560 × 1440 Pixel) is constant, independent of the FOV. Dividing the scene into layers has the advantage of having both details and overview information. (©Hesotech).

out an alarm/warning when a threshold is exceeded. To handle large image data, iMaster partitions the database by time intervals (e.g. yearly). This improves storage efficiency, backup and prevents storage overflow by automatically deleting the oldest partitions when storage is small.

Transferring one image from Rwanda to Germany takes approximately one second which costs bandwidth. This becomes expensive and time-consuming for evaluations and other external users. To overcome this, a twin database acting as a cache on the developer's PC was developed. When a user requests an image for the first time, the cache retrieves it from the server, saves it locally, and then delivers it to the respective users. Future requests for the same image are directly read from the twin database. iMaster has a GUI that displays all scalar measurements with units, system values like power consumption, and helps the user to download weather data in a Comma Separated Value (CSV) format.

### *2.2.3. Automated evaluation software*

Evaluation follows two steps: (i) Identification of relevant structures – here area of landslide - in an image. (ii) Significant changes of the structures in the previous time sequence of images are the results of an evaluation to be reported by the event system. This can be an instantaneous occurrence of a landslide or a continuous growth of landslide, as described in the next section.

To support continuous assessment and real-time evaluation, the automated software runs as soon as an image reaches the server. The expandable plug-in-like structure allows images to be intelligently evaluated by different algorithms from different developers. We used one existing algorithm, which is based on the computer vision algorithm "Quadtree" so-called "Qtree". It detects and measures the number of brownish pixels in the image. The Qtree starts by blurring the image to remove undesired details (Fig. 9).

Then it recursively divides that image into four equal quadrants and evaluates if each quadrant lies in the same color range. If a quadrant is in

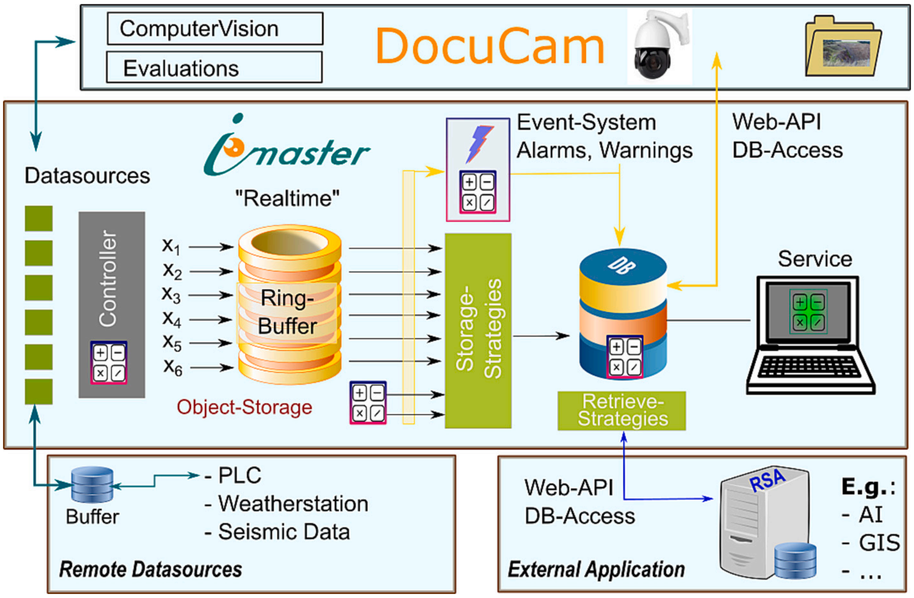


**Fig. 8.** The existing architecture of the iMaster/DocuCam system. Where API: Application Programming Interface, X: Ring, DB: Database, PLC: Programmable Logic Controller, AI: Artificial Intelligence, and GIS: Geographic Information System. (©Hesotech).

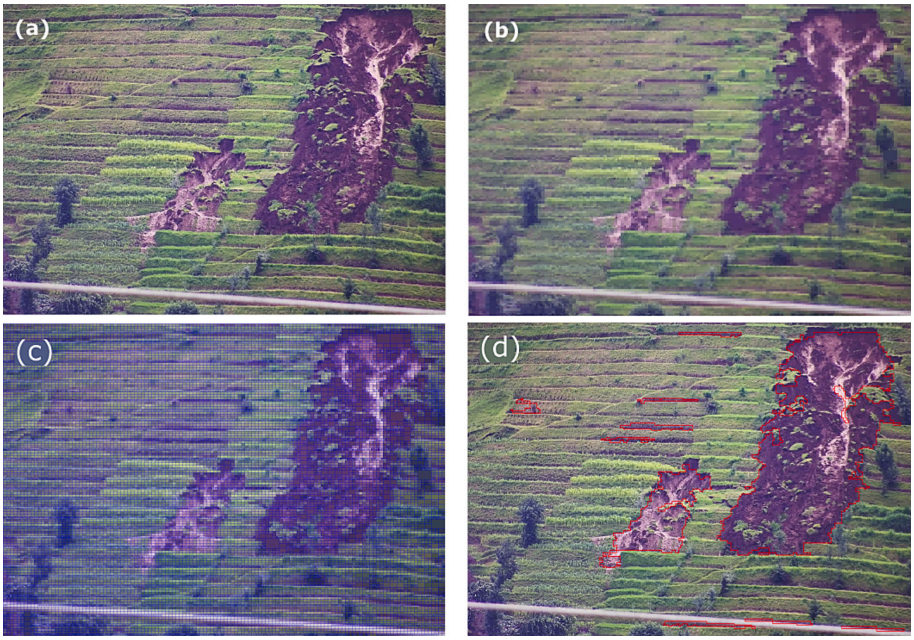


**Fig. 9.** Original image (a), blurred image (b), Segmented image into quadrants of the same color range (c) and image with overlay contours (red lines) highlighting the detected landslides (d). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the same color range, its evaluation is completed, else the quadrant is again divided into four equal quadrants until every quadrant lies in one color range. After that, contours are applied to the targeted color range and the algorithm sums up contoured pixels. The system supports unlimited evaluations without premature termination, with image configuration as an unchangeable basis.

Detected structures are saved as contours in an overlay table in Scalable Vector Graphics (SVG) which can be lossless overlayed on the original image to preserve the original image. The sent-out event provides early information to decision-makers and emergency responders. Changes can be ground movement such as cracks, faults, uprooting of vegetation or tilting of geological features.

### 2.3. *Technological needs assessment for people-centered early warning system*

Multi-stakeholder engagements, focus-group-discussion (FGD) sessions, and workshops were held to conceptualize the integration of iMaster/DocuCam technology towards developing an end-to-end Multi-Hazard EWS (MHEWS) (Fig. 10). The stakeholders included the MINEMA, Nyabihu district administration, Rambura sector administration, and Rwanda Red Cross. The Strength, Weakness, Opportunity, and Thread (SWOT) sessions during benchmarking visit were jointly conducted in the form of FGDs at a national and local level, as the situational and needs assessment.

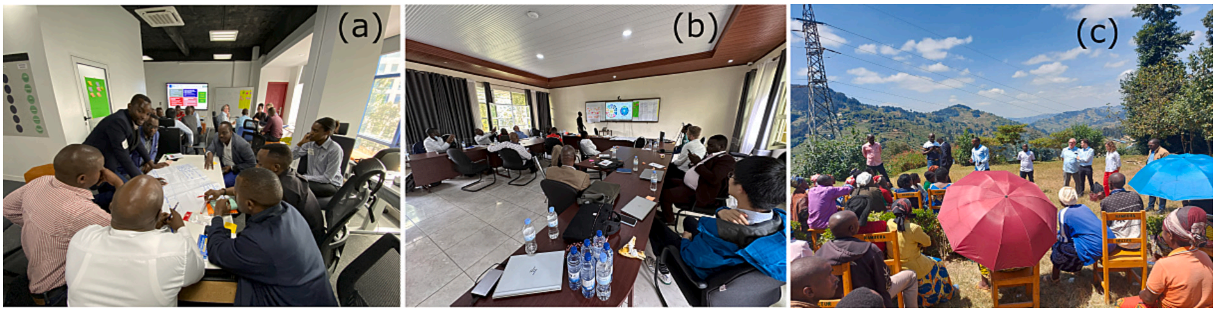


**Fig. 10.** Stakeholder consultation and SWOT analysis at (a) national level, and (b) local level (Nyabihu District). (c) Community engagement and disaster education in the Rambura sector.

These sessions were formulated based on five key elements including (1) governance, (2) disaster risk knowledge, (3) monitoring, detection, and assessment, (4) dissemination and communication, and (5) preparedness and response. Various activities were conducted to explore multi-scale requirements and local needs assessment for co-designing, co-developing, and co-implementing the MHEWS following the UNDRR guidelines. The local communities represented by the heads of villages in the Rambura area contributed local knowledge, challenges, and responsibilities to enhance landslides mitigation.

This study analyzed current opportunities and strengths including data readiness, communication platform, standard operating procedure (SOP), risk governance, and decision support system to help in risk-informed decision-making. The baseline and benchmarking assessment identified the available opportunities to scale up the landslide monitoring system into an MHEWS considering the presence of satellite images at RSA. Technology experts together with experts in DRR shared their insights during various workshops to equip local leaders, communities, and students with knowledge that facilitates understanding and responding to new, emerging hazards, systemic risk and compounding disasters in the tropical environment.

## 3. Results and analysis

This study captured millions of images and weather data that were collected in the last two year of observation by the iMaster/DocuCam system, the first system of its kind to collect real-time image and weather data pre-, during, and post-landslide events in Rwanda. Despite harsh weather conditions during this event, the system remained intact. Over 20 landslides were identified around the study area, with geo-location coordinates stated in the report to the stakeholders. Fig. 1 shows locations of landslides identified by the iMaster/DocuCam system. We also describe some lessons from the selected landslide observations. Due to limited space, only small selection of observations is presented to demonstrate how iMaster/DocuCam can help for a better understanding of the complexity of landslides and their impacts.

### 3.1. Landslide monitoring and automated detection

Fig. 11 shows time series of the number of brownish pixels in images in scene 4 = hospital view at Layer 4, Row 15, Column 24. On the 2nd of May 2023 at 4:00:00 PM, there were no suspicious changes detected on the image by the Qtree algorithm. However, on the 3rd of May 2023 at 8:00 AM, an earthflow landslide was detected, and the algorithm

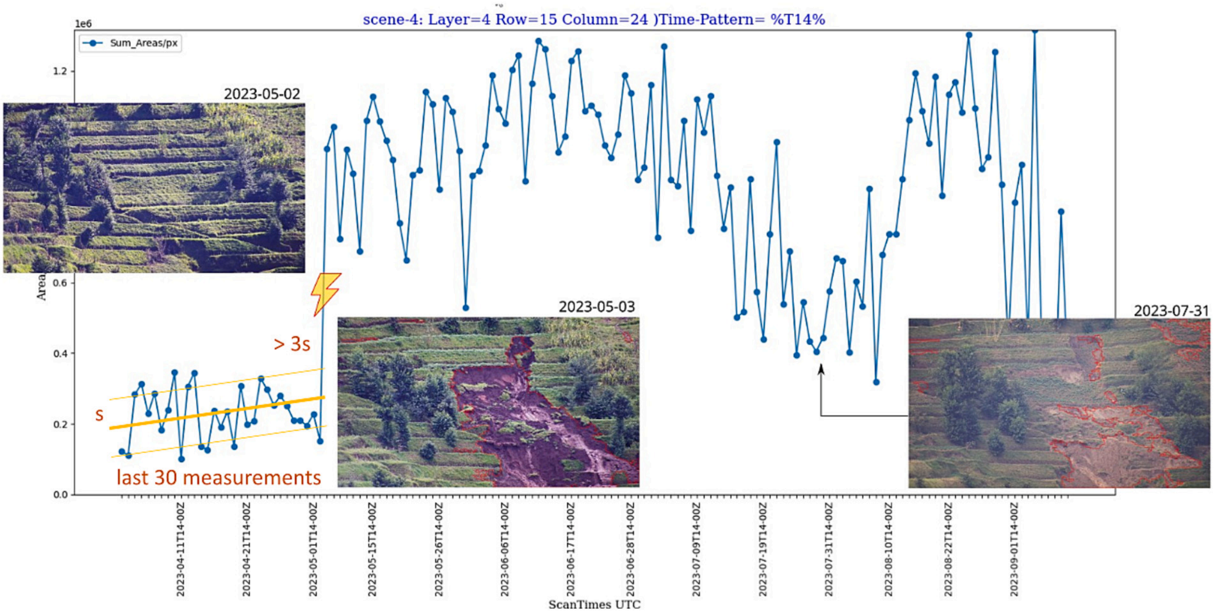


**Fig. 11.** Time series of number of brownish pixels in images in scene 4 = hospital view, at Layer 4, Row 15, Column 24. The yellow lines show predictions from regression and the corresponding confidence interval used to determine threshold for triggering the alarm system. The dates when the images were taken are indicated at the top right corner of each image and can be used to find the corresponding number of brownish pixels computed by the Qtree algorithm. Where 3 s is three times standard deviation. (©Hesotech). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

showed a rash increase in the number of brownish pixels, leading to the first physical evidence of landslide occurrence ever recorded.

Events are created considering 30 previous historical images. First, a linear regression and the deviation of the number of brownish pixels for those images are obtained. Afterward, the threshold is defined, this may be for example the 2 times the deviation. If the number of brownish pixels detected in the current image exceeds the threshold, a warning is sent out. The evaluations' results are finally fed back into the iMaster database and saved in the JavaScript Object Notation (JSON) table.

Due to shadows, the position of the sun strongly influences the Qtree algorithm. We only included images, taken at 14:00, as documented by the time pattern (Fig. 11). After the landslide, a decrease of brownish pixels was observed due to crops grown in the slide area, followed by an increase during harvesting. The dispersion of the measurements is due to environmental conditions like clouds, rain, and fog.

### 3.2. *Vertical erosion of road boundary wall as early warning sign*

In the night from May 2nd to May 3rd, many landslides caused large losses and cascading impacts in Rambura sector, Nyabihu district. Fig. 12 shows the affected house within one night can be seen, marked by a red ellipse in the center. A thin landslide happened within a cultivated area limited by edges of terrasses. Simultaneous, significant changes along the boundary wall can be observed, marked by the red ellipse in the top left. The marked areas are less than 100 m apart.

Over five days, a growing vertical erosion like a triangle starting from the bottom of the road wall is shown with a higher optical resolution. When reaching the first terrace it broadens, making the edge unstable and causing a landslide across the street, filling a little valley below up to the level of the destroyed house, as shown in Fig. 12.

The vertical erosion is probably caused by the heavy rain before and a Slope Wash Mechanism (SWM). This observation needs further research to optimize the construction of road boundary walls. The coincidence of landslide events in separate areas is remarkable. In this example, the occurrence of vertical triangular erosion would have given a pre-warning time of several days.

### 3.3. *Cracks alongside terrasses as early warning sign*

Fig. 13 shows a landslide preceded by cracks alongside terraces and vertical plant growth anomalies. With an automated system, approximately one day of pre-warning time could be achieved. This example also shows that more research is needed on the influence of terraces on landslides.

### 3.4. *Landslide disaster preparedness and people-centered early warning system*

Stakeholder engagements, SWOT analysis, and technical discussions were used to raise awareness and address urgent requirements in the policy, data, technical, and financial aspects. Current gaps, challenges, and future demands are explored to mitigate human- and economic losses and build community resilience in disaster-prone areas. Through technical sharing and SWOT/FGD sessions, cross-cutting enablers were identified, aligning with the UN's five-year EW for All agenda, namely partnerships, localization, financial sustainability, private sector, research and innovation. With clear directives from MINEMA and relevant stakeholders, the impact-based early warning system for landslide disasters can be implemented with technical assistance by the private sector, increased investments by government, and co-fundings from the international agencies or private sector to ensure the scalability, applicability, and sustainability.

The iMaster/Docucam's utility in the landslide disaster preparedness support was proven during community engagement and SWOT analysis. The participants revealed that there is a need for standardized processes to help govern the EW information effectively, by setting up a mechanism to systematically and automatically disseminate EW information at a fine scale. Additionally, continuous hazard assessments are recommended with direct observation, in-situ measurement, and assessment of their signs, and precursors based on the Local, Traditional and Indigenous Knowledge (LTIK). Three scenarios were identified using high-resolution images derived from the iMaster/DocuCam system (Fig. 14). The focus was to train relevant stakeholders to understand results from the system by preparing evacuation planning, analyzing disaster impacts, and selecting appropriate disaster prevention measures.

Baseline analysis revealed that there should be careful consideration in designing an EWS in such a way that the local needs and urgent demands for multi-scale LEWS implementation can be practically considered and realized. Mainly, five challenges were identified from SWOT analysis, including (1) integrated and meaningful data, (2) implementable policy and strong institutional framework, (3) cost-effective technology, (4) risk communication, and (5) decision-making for action. However, more strengths and opportunities were identified and if carefully considered, weaknesses and threats can be locally mitigated (Figs. 15 and 16). Following the discussion, the aim has been achieved, representing considerable progress, and collective commitments.

**Fig. 12.** Results show before- and after images of a disaster caused by landslides in different zoom levels (©Hesotech).

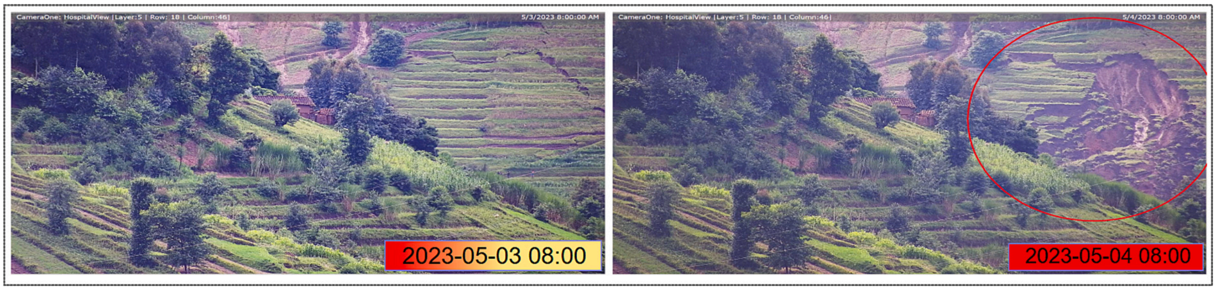
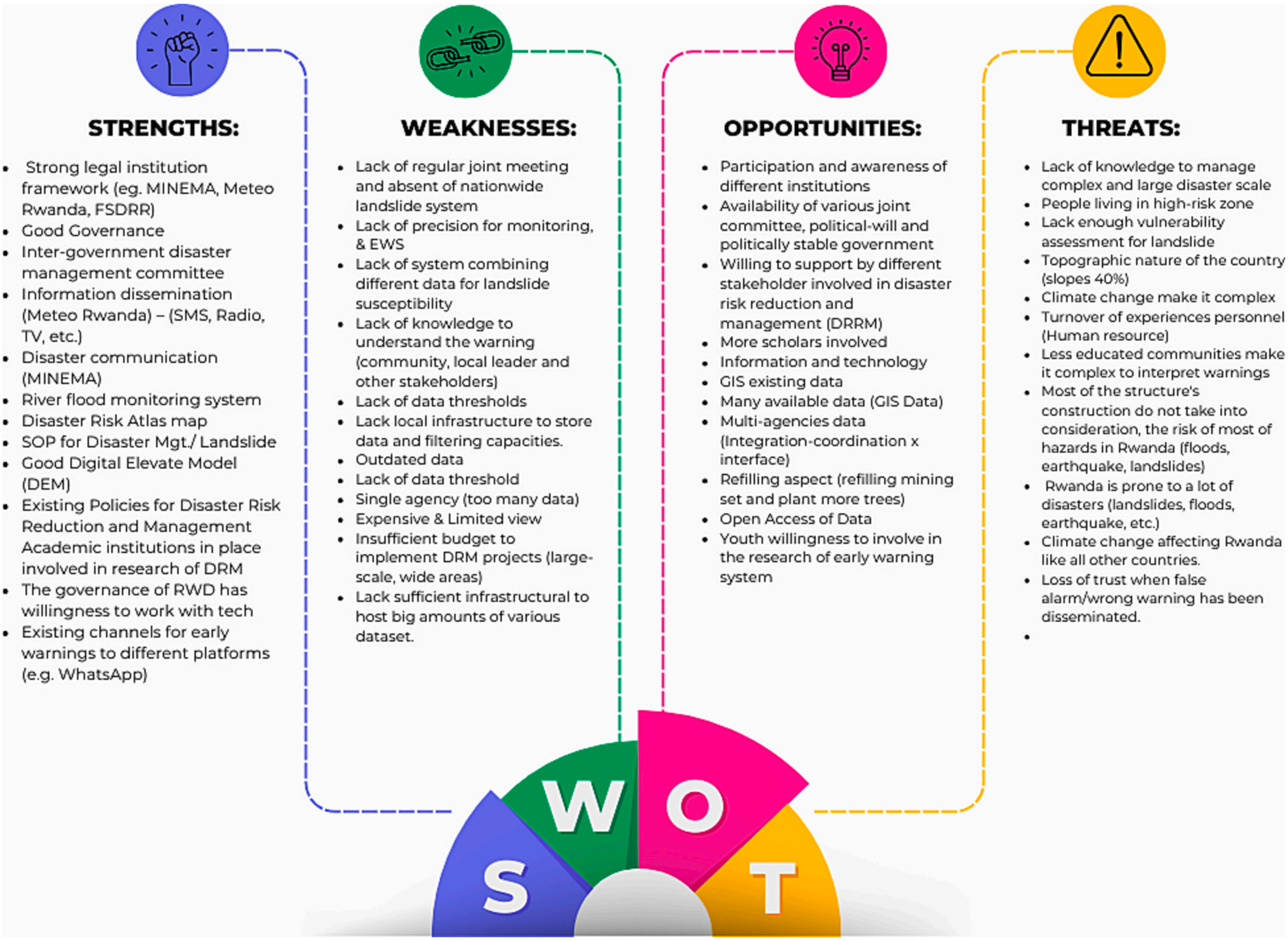


**Fig. 13.** Results show before- and after images of a landslide preceded by cracks (©Hesotech).

**Fig. 14.** Three scenarios for landslide impacts (a) terraced agriculture, b) farming (c) landslide affected the road and tower.



**STRENGTHS:**

- Strong legal institution framework (eg. MINEMA, Meteo Rwanda, FSDRR)
- Good Governance
- Inter-government disaster management committee
- Information dissemination (Meteo Rwanda) – (SMS, Radio, TV, etc.)
- Disaster communication (MINEMA)
- River flood monitoring system
- Disaster Risk Atlas map
- SOP for Disaster Mgt./ Landslide
- Good Digital Elevate Model (DEM)
- Existing Policies for Disaster Risk Reduction and Management Academic institutions in place involved in research of DRM
- The governance of RWD has willingness to work with tech
- Existing channels for early warnings to different platforms (e.g. WhatsApp)

**WEAKNESSES:**

- Lack of regular joint meeting and absent of nationwide landslide system
- Lack of precision for monitoring, & EWS
- Lack of system combining different data for landslide susceptibility
- Lack of knowledge to understand the warning (community, local leader and other stakeholders)
- Lack of data thresholds
- Lack local infrastructure to store data and filtering capacities.
- Outdated data
- Lack of data threshold
- Single agency (too many data)
- Expensive & Limited view
- Insufficient budget to implement DRM projects (large-scale, wide areas)
- Lack sufficient infrastructural to host big amounts of various dataset.

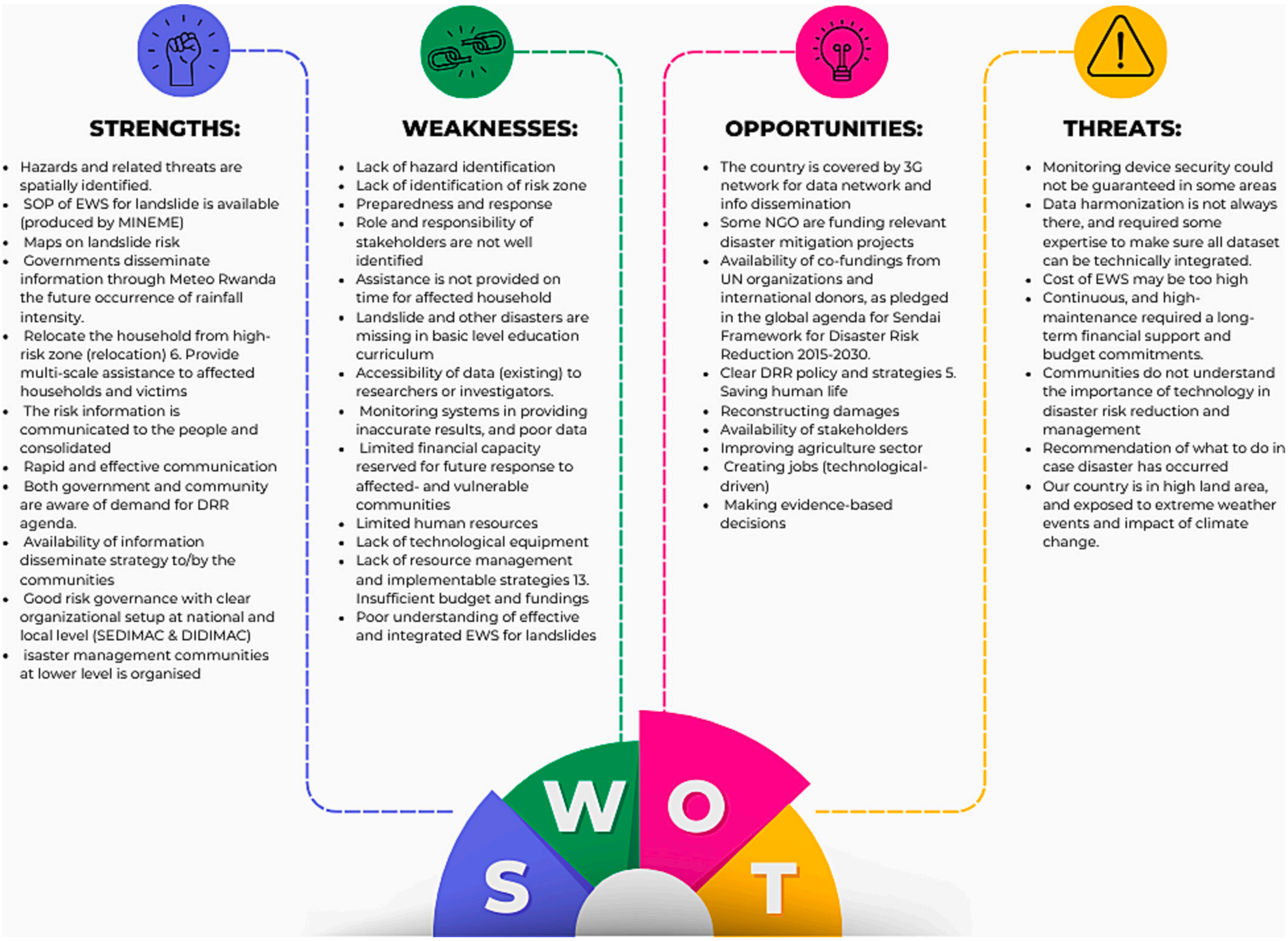
**OPPORTUNITIES:**

- Participation and awareness of different institutions
- Availability of various joint committee, political-will and politically stable government
- Willing to support by different stakeholder involved in disaster risk reduction and management (DRRM)
- More scholars involved
- Information and technology
- GIS existing data
- Many available data (GIS Data)
- Multi-agencies data (Integration-coordination x interface)
- Refilling aspect (refilling mining set and plant more trees)
- Open Access of Data
- Youth willingness to involve in the research of early warning system

**THREATS:**

- Lack of knowledge to manage complex and large disaster scale
- People living in high-risk zone
- Lack enough vulnerability assessment for landslide
- Topographic nature of the country (slopes 40%)
- Climate change make it complex
- Turnover of experiences personnel (Human resource)
- Less educated communities make it complex to interpret warnings
- Most of the structure's construction do not take into consideration, the risk of most of hazards in Rwanda (floods, earthquake, landslides)
- Rwanda is prone to a lot of disasters (landslides, floods, earthquake, etc.)
- Climate change affecting Rwanda like all other countries.
- Loss of trust when false alarm/wrong warning has been disseminated.
-

**Fig. 15.** Results from SWOT analysis at a national level.



**STRENGTHS:**

- Hazards and related threats are spatially identified.
- SOP of EWS for landslide is available (produced by MINEME)
- Maps on landslide risk
- Governments disseminate information through Meteo Rwanda the future occurrence of rainfall intensity.
- Relocate the household from high-risk zone (relocation) 6. Provide multi-scale assistance to affected households and victims
- The risk information is communicated to the people and consolidated
- Rapid and effective communication
- Both government and community are aware of demand for DRR agenda.
- Availability of information disseminate strategy to/by the communities
- Good risk governance with clear organizational setup at national and local level (SEDIMAC & DIDIMAC)
- isaster management communities at lower level is organised

**WEAKNESSES:**

- Lack of hazard identification
- Lack of identification of risk zone
- Preparedness and response
- Role and responsibility of stakeholders are not well identified
- Assistance is not provided on time for affected household
- Landslide and other disasters are missing in basic level education curriculum
- Accessibility of data (existing) to researchers or investigators.
- Monitoring systems in providing inaccurate results, and poor data
- Limited financial capacity reserved for future response to affected- and vulnerable communities
- Limited human resources
- Lack of technological equipment
- Lack of resource management and implementable strategies 13. Insufficient budget and fundings
- Poor understanding of effective and integrated EWS for landslides

**OPPORTUNITIES:**

- The country is covered by 3G network for data network and info dissemination
- Some NGO are funding relevant disaster mitigation projects
- Availability of co-fundings from UN organizations and international donors, as pledged in the global agenda for Sendai Framework for Disaster Risk Reduction 2015-2030.
- Clear DRR policy and strategies 5. Saving human life
- Reconstructing damages
- Availability of stakeholders
- Improving agriculture sector
- Creating jobs (technological-driven)
- Making evidence-based decisions

**THREATS:**

- Monitoring device security could not be guaranteed in some areas
- Data harmonization is not always there, and required some expertise to make sure all dataset can be technically integrated.
- Cost of EWS may be too high
- Continuous, and high-maintenance required a long-term financial support and budget commitments.
- Communities do not understand the importance of technology in disaster risk reduction and management
- Recommendation of what to do in case disaster has occurred
- Our country is in high land area, and exposed to extreme weather events and impact of climate change.

**Fig. 16.** Results from SWOT analysis at the Nyabihu district level.

## 4. Discussions and future works

Globally, 101 countries have committed to the multi-hazard EWS (MHEWS) and Early Warning for All agenda [20]. However, least-developed countries and African countries like Rwanda require public-private investment to establish EWS and increase their coverage [39,40,37]. According to the Executive Action Plan of the Early Warnings for All initiative launched in 2022, there is a need for USD 3.1 Billion within 5 years (2023-2027) to ensure every person on earth is protected by early warnings [40]. This study highlights the possibility of achieving accurate landslide hazard and impact prediction, using modern ICT technologies and a level of automation in industrial processes coupled together with community engagement and capacity building. The iMaster/DocuCam system applies different technologies including databases, internet, networks, geology, physics, artificial intelligence i.e., computer vision and machine learning, and industrial automation i.e., internet of Things (IoT) / Industry 4.0, to understand the landslide processes, extract useful early signs for the occurrence of the landslide disaster at a fine scale and co-develop an effective LEWS.

The Government of Rwanda and its partners have committed to reduce disaster risk even though the development of EWS is still in its infancy. Currently, the National Strategy for DRR (NSDRR) emphasizes effective risk governance i.e. ensuring evidence-based decision-making to address the root-causes of disasters and appropriate de-risk investment [25,41]. Rwanda is investing to assess the vulnerabilities and develop a national landslide susceptibility map hosted by RSA. They also focus on strengthening community-based Disaster Risk Reduction and Management (CDRRM), empowering local communities to undertake adaptation initiatives and educating them about the risks they face. To accelerate climate change adaptation, the Rwandan Ministry of Local Government (MINALOC) and MINEMA collaborated to manage soil erosion and declining soil fertility driven by unsustainable land use practices, namely deforestation and overcultivation without appropriate soil conservation measures including cultivation on steep slopes. Through these exercises, the two ministries help local communities build progressive terraces, manage tree nurseries, plant trees, and make compost, while reducing the landslides or slope failures.

Synergies across different sectors and harmonizing programs are observed, to ensure an efficient disaster response. Enhanced preparedness and readiness capabilities at all levels – individuals, communities, and organizations are invested. The integration of digital solutions, as demonstrated by the iMaster/DocuCam into the decision support system is of advantage to utilize real-time data provision and facilitate swift communication during crises. Similarly, with the support of UNDP, MINEMA is in the process of operationalizing the developed SOPs for LEWSs in the country. A national-scale model for predicting landslide hazards is envisaged as a key output from operationalizing the SOPs [5]. Lastly, the need for strategic and technical partnerships is also emphasized at national, regional, and international levels. This involves fostering collaborations, exchanges, and capacity building across various sectors to create a comprehensive, robust, and responsive localized DRR system. While Rwanda made remarkable progress, special emphasizes are required to operationalize automated landslide hazard identification, build technical know-how for early action, coordinate between agencies for impact assessment, access warning information, and develop effective disaster response plans [42,20].

So far, there is no operational EWS for landslide disasters in Rwanda yet. A dynamic and near-real-time national-scale landslide risk map can be complemented by the national network of iMaster/Docucams that provide vital validation data at a local scale. On the other hand, the national-scale landslide risk map supports the localization of the iMaster/DocuCam system. Therefore, the iMaster/DocuCam does not aim at wall-to-wall coverage at a national scale but provides local-scale wall-to-wall geospatial data and scarce local weather data. The installations could also provide national-scale validation dataset to improve predictions for the national-level LEWS [25].

Sahana et al. [43] stated that EWS's effectiveness relies on assessing current mitigation measures to capture all risks associated with the rising frequency of disasters. However, the technology of iMaster/DocuCam revealed that the effectiveness of an EWS depends also on the (1) accuracy of data for real-time alerts, (2) stakeholder's needs, and (3) capacity building. This combination could lead to the effective generation of real-time, actionable, and accurate EW information [44,45]. To our knowledge, there is no other automated technology that uses images of a standard camera to capture the nonlinear characteristics of landslides. The iMaster/DocuCam proved its effectiveness in maximizing the application of ICT technologies to enhance the EWS components. See Fig. 17 for details.

The system is designed to store and handle data, metadata, evaluations, and models for more than 30 years. To increase AI explainability, improved evaluations can be re-run and compared to previous ones [46]. To fulfill all demands of a comprehensive EWS, there is also a need for smart collaboration, as it is required diverse expertise and resources. The work is a step towards (1) an open-platform initiative to improve hazard and impact prediction using AI, (2) scaling the technology in other vulnerable areas to get more data for reliable evaluations, and (3) link each image with its geolocation for enhanced responses.

In the center the iMaster/DocuCam-service is running on a server at the RSA. All the data is organized, stored and handled in a well-structured PostgreSQL database. The system can be connected to multiple sites. Several cameras can be installed with a weather station at each site. If necessary, energy supply can be provided by onsite solar panels. The system can monitor different phenomena shown by different colors on the same site, e.g. the monitoring of construction work of terraces or flood protections. The future system is also used to monitor critical infrastructure such as electrical installations, or dams.

The onsite installations work like autonomous agents and are remotely configured and serviced. The communications are secured by VPN and certificates. In case of communication issues, data is buffered. According to the different application topics, various evaluations – shown by the gears - are necessary and they need to be executed permanently and in parallel. These evaluations get their data via an API from the database of iMaster/DocuCam and from other data sources like GIS or satellite images if needed. Results including alarms can be channeled and provided the feedback to the iMaster, for use by other evaluations and can be visualized via iMaster/DocuCam standard functionality in the browser of a client PC. In the case of a critical situation, the system can send an email directly to the disaster managers, or responsible officers who are on duty with an automated generated report and take necessary actions according to the SOP.

Setting up an Open-Source community is an efficient way to create sustainable expertise and generate creative applications for the public. Because of IT security, it is impossible to give every developer direct access to the server. As a solution, we can provide a subset of the data as an SQLite twin database by download or memory stick. A provided framework used by the local developer implements the same API as on the central database at RSA. This makes it easy to deploy a newly developed program on the server, after it is well checked by a committee, by considering also the relevant legal regulations.

Five (5) key recommendations are put forward to enhance the applicability of geospatial and ICT technologies and establish an effective DRR framework by incorporating an end-to-end, people-centered EWS for landslide disaster in Rwanda, as follows:-.

a. **There is a need for a sustainable automated storage system prepared for the wide future**

Currently, issues prevailed within metadata, discontinuity in data storage, and accessibility, which limit the flexibility of computer evaluation. However, reliable and well-structured data is the foundation for comprehensive EWS. There is a need to set up a sustainable system where data and metadata are consistently recorded, stored and updated according to current technologies of ICT. For sustainability, data and metadata must be available to many users for a long-term period (typically >30 years). The system should have an

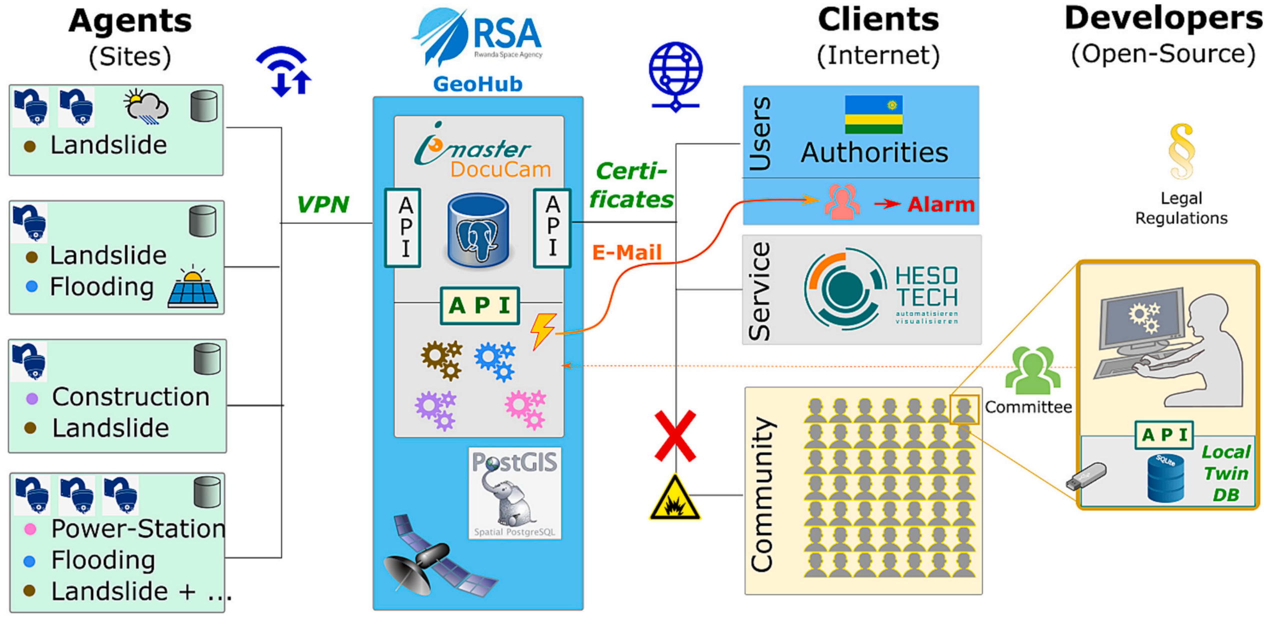


**Fig. 17.** System Architecture and Open-Source initiative with twin databases. Where VPN: Virtual Private Network, API: Application Programming Interface, and RSA: Rwanda Space Agency. (©Hesotech).

advanced database like SQL which (1) supports multiple types of data, (2) provides long-term storage of raw measurements in a compatible format with fast retrieval by using indexes, (3) guarantees consistency of data by using constraints, and (4) contain a storage for metadata for all measurements to make data understandable at any time. This will contribute to continuously improving an EWS for the next generation.

b. **It is crucial for an EWS to be adaptable to new circumstances**
Existing EWS often face issues with scalability and growth. This is because, in real life, new things always happen. Additionally, current AI models and algorithms are not expected to be sufficient in the future. This reveals that in the future, new technologies like quantum computing are expected to be developed to evaluate the same data with completely different algorithms. There is a need for a dynamic, end-to-end, people-centered EWS that continuously adapts to reality to address the challenges of scaling the EWS in various locations and for different purposes.

c. **Establishing an open platform to foster innovation in DRR**
Major actors and stakeholders in DRR particularly governments, emergency responders, technology developers, NGOs, researchers, and others should establish a people-centric, multi-disciplinary open platform that incorporates technology according to recommendations 1 and 2. It is needed to (a) understand the complex nature of landslide disasters at a fine scale, (b) assess the risks associated with those disasters, and (c) communicate risk information in the real-time from the national level to the local scale by learning from the past. This will contribute to developing innovative ideas and improve the level of application of geospatial and ICT technologies in DRR, hence helping the country to align with the SFDRR2030. This will also improve the capability to be scaled to other domains developing risk-informed urban planning, mining, energy, and agriculture. By including more people through open source, capacity will be largely created, and sustainability will be increased substantially.

d. **Continent-to-continent collaboration to accelerate the impact of emerging technologies**
Many efforts are needed to achieve the desired level of local DRR implementation. Globally, countries like Japan, Malaysia, India, China, and others have developed flagship technologies contributing to technological-based DRR by reducing the number of human losses, damage to assets, and economic losses. However, collaboration among countries is still at a low level. To eliminate this limitation, there must be continent-to-continent collaboration supported by Governments, NGOs, and other institutions for technological sharing and expert knowledge exchange through know-how training and mentorship. This will help countries to learn from others and to collaborate on scaling effectively.

e. **Continuously improvement of the multi-hazard EWS in Rwanda**
Some components of EWS often become ineffective when applied to real-world scenarios. Continuous research, development, and multi-tier training and drills like simulation exercise (SIMEX) for emergency response are needed to incorporate new knowledge learned after the EWS development. This requests disaster management agencies under the leadership of MINEMA and relevant agencies at district and local level to increase the investment and fundings in the applied research to set a strong foundation for co-implementing the end-to-end EWS supported by community resilience building. The focus areas in the impactful transdisciplinary research about EWS in Rwanda should include (a) analyzing all contributing parameters to landslides and geological hazards, (b) revisiting trends and establishing thresholds at which landslide disaster could occur, and (c) enhancing SOPs that involved the vulnerable communities at a local level, d) investing into anticipatory action for systemic risk reduction.

## 5. Conclusion

This study presents the development of the iMaster/DocuCam system and its wide application in supporting the landslide DRR action in Rwanda. The newly developed AI approach is effectively used in disaster mapping, monitoring, predictive analysis and prevention. It has great potential to be upscaled and upgraded into a people-centered early warning system based on the multi-stakeholder needs assessment. Five key elements are collectively identified namely (1) governance, (2) disaster risk knowledge, (3) monitoring, detection, and assessment, (4) dissemination and communication, and (5) preparedness and response. We successfully presented the architecture and working principles of the iMaster/DocuCam system, highlighted the possibilities of the current system to support a comprehensive EWS for landslide disaster in Rwanda. Furthermore, we also explored the national- and local needs for development of the people-centered, end-to-end, and impact-based EWS for landslides, and climate-induced disasters.

Moreover, an integrated system allows to improve multi-scale risk communication, risk governance, and landslide DRR strategies. To achieve that, the intelligent system uses a combination of various geospatial and ICT technologies, including AI, RS, internet, database, industrial automation, PTZ cameras, weather station, and others. This research revealed that EWS not only depends on technologies, but also on the accuracy of data and metadata used in generating real-time alerts, stakeholder commitments, and capacity building for disaster preparedness, response, and resilience at a multi-level (from local to national). Although this study shows a significant contribution of the iMaster/DocuCam to DRR, much effort is needed to translate this monitoring system into an end-to-end EWS. In the future, there is a need to establish an open platform that brings together data from various sources, allowing human-centered innovations into AI-based algorithms development for landslide prediction, modelling and assessment. The ability of the system to accommodate data from various sources should also be used to increase the quality of datasets, leading to higher accuracy in the results.

In the period of 2025–2030 and beyond, Rwanda needs to anticipate the emergence and reemergence of new, emerging hazards and compounding disasters that are caused by extreme weather events, climate changes, and anthropogenic activities. Therefore, it is encouraged to engage in transboundary cooperation and continent-to-continent initiative so that technology- and knowledge transfer, data accessibility, and resource mobilization for DRR impact are carried out in an equitable and effective manner to increase the capacity through the South-South, regional mechanisms, global initiatives, or UN-supported schemes.

## CRediT authorship contribution statement

**Willy Blaise Ineza:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Emelyne Clarisse Izere:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Roland Sonnenschein:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Collins B. Kukunda:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Fred Tumwebaze:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Richard Shumbusho:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Khamarrul Azahari Razak:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization.

## Declaration of competing interest

The iMaster/DocuCam system is patented under Hesotech GmbH. All authors declare no competing interest.

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## Data availability

Data will be made available on request.

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