# Landslide Risks Assessment and Mitigation in Four Urban Sub-Catchments in Rwanda

# 1. BACKGROUND

Landslides risks are pervasive in hilly and mountain landscapes of the globe, and are typical occurrences in Rwanda. The term landslide denotes the downhill movement of slope forming materials under the influence of gravity (Cruden and Varnes, 1996). Landslides are one of the most widespread and effective agents shaping the Earth's surface (Egholm et al., 2013; Wang et al., 2020). With the development and urbanisation of hilly and mountain terrains around the globe, landslide occurrence also frequently intersects with human activities and the built environment, often with disastrous consequences (Sidle and Ochiai, 2006; Lu and Godt, 2013; Froude and Petley, 2018; Haque et al., 2019). While landslides are pervasive Earth surface processes naturally occurring in hilly/mountain landscapes, human activities (e.g., roads, reservoir construction, deforestation, urbanisation, etc.) can also influence their occurrence, extent and timing (Sidle and Ochiai, 2006; Lacroix et al., 2020). Landslide characteristics reflect the very diverse geologic, topographic, environmental, and climatic conditions in which they can occur, resulting in a large diversity of landslide types and processes (Lu and Godt, 2013; Hungr et al., 2014).

Rwanda is a hilly, densely populated country that covers an area of 26, 338 km2. Based on topography, elevation and climate, the country is divided into 3 agro-ecological zones (AEZs), also known as altitudinal zones namely: Highlands, Midlands and Lowlands which occupy 17, 32 and 38 % of the territory respectively. The remaining 13 % of the country is constituted by escarpments, marshes, islands and lakes (Verdoodt and Van Ranst, 2003a). Rwandan soils are generated by physico-chemical weathering of basic schistose, quartzite, gneiss, granite and volcanic rocks that make up the superficial geology of the country. Due to the complexity of topography and parent materials, Rwanda's biophysical environment varies across very short distances (Birasa et al., 1990; Steiner, 1998).

The northwest region of Rwanda, which is a steeply sloping highland experiences abundant rainfall that usually leads to landslides. Also, landslides and soil erosion have been accelerated by deforestation attributed to high population density (Mbonigaba and Culot, 2010). During 2020 only, 232 people have been killed with landslides and floods, 7,769 houses destroyed, 4, 437 ha of crops damaged and 103 bridges destroyed (Annual Disaster Effects Report, GoR,2020). Also, it has been estimated that Rwanda is losing annually an average of 62 tons per ha and part of this loss goes with landslides (Rwanda NCA, ecosystems account, 2019).

Within the framework of building the resilience to climate change, the Global Green Growth Institute(GGGI)-Rwanda Program in partnership with the Rwanda Environment Management Authority (REMA) in its capacity as the National Designated Authority (NDA) for Green Climate Fund (GCF) in Rwanda has formulated a

National Adaptation Readiness Project proposal to GCF aiming at building flood resilience capacities in Rwanda in line with the governmental policies, strategies and priorities, and enhance Rwanda's capacity to respond to climate change in high risk zones by implementing an adaptation plan for integrated flood and landslide management in urban areas. The project outputs include:

a. Capacity and coordination strengthened;
b. Appropriate technical studies identified and prioritized, climate finance strategies and project pipeline strengthened;
c. Adaptation knowledge management, information sharing, and communications strengthened;
d. Mechanisms for reporting, monitoring and review of adaptation and resilience planning progress developed.

Within the framework of this project, five urban sub-catchments within the capital city, Kigali, and secondary cities (Huye and Rusizi) as well as a peri-urban area of Kamonyi district, have been selected for detailed assessment of landslide risks and mitigation measures in order to inform a funding proposal to the Green Climate Fund. The below map illustrates the location of the selected sub-catchments in Rwanda.

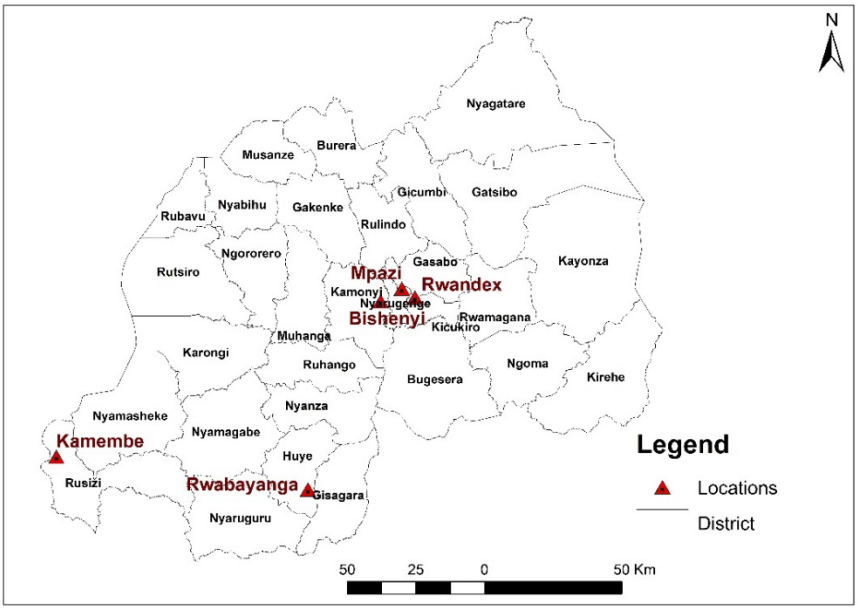



***Figure1:*** *Map showing the location of the selected sub-catchments*

# 2. METHODOLOGY

Under this study, the assessment of landslide risks was achieved in five steps (Figure 2). This approach relied on conventional methods that are recommended for local-scale landslide risk assessment (Corominas et al., 2014). The landslide inventory (Step 1) was the key step of this approach. The outcomes of the risk assessment are influenced not only by the quality of the inventory but also by the types of landslides and the abundance of their occurrence.

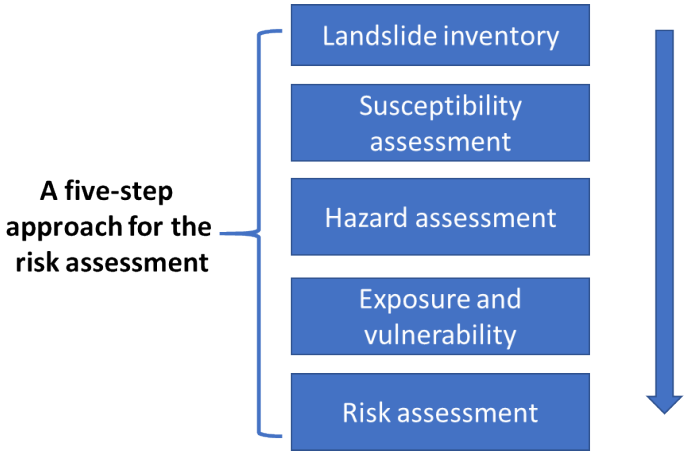



***Figure2:*** *Landslide risk assessment methodology*

## 2.1 Landslide inventory (Step 1)

The landslide inventory was built from a careful and detailed 3D (elevation exaggeration of 1) visual interpretation of Google Earth images. All images used in the analysis were of very-high spatial resolution, ranging from 30 to 60 cm. The images in Google Earth were provided by either © DigitalGlobe or © CNES/© Airbus and they were captured between 2000 and 2021. The analysis of Google Earth images has proven to be a successful and reliable method to map landslides (Fisher, et al., 2012). The reliability of the approach has been demonstrated by Depicker et al. (2020a; 2020b) for the Lake Kivu region, including the western part of Rwanda. The satellite images were analysed in parallel with the photographs taken in the field.

## 2.1 Landslide susceptibility assessment (Step2)

The goal of this step is to assess where landslides may occur in the study areas and to produce, for the four sub-catchments, landside susceptibility maps. These maps were classified in several susceptibility classes using a logistic regression model. The same model has already been used successfully in Kivu Rift region (Depicker et al., 2020). The logistic regression model is used to predict the presence/absence (1/0) of landslides. Logistic regression is an excellent data-driven multivariate modelling tool to predict binary events (Hosmer and Lemeshow, 2000), and is applied more than any other technique in the context of landslide susceptibility modelling (Reichenbach et al., 2018). The dependent variable will take values in a continuous range between 0 and 1.

## 2.3 Landslide hazard assessment (Step3)

The objective of this step is to assess of landslide occurrence (and associated magnitude) within a certain time frame and area. The landslide susceptibility (Step 2) was linked to landslide hazard by assessing the average hazard in different sub regions that are delineated according to their susceptibility. The first sub region encompasses all areas with a landslide susceptibility values between 0 and 0.1, the second sub region includes all areas with a landslide susceptibility value between 0.1 and 0.2, and so on up to 1. Concretely, for each susceptibility class, the total affected area by the landslide sources that have occurred over the whole period of observation (about 20 years – see Step 1) is averaged yearly. The resulting value provides a landslide affected area in $m^2$ year-1 km-2 , i.e. a landslide rate. The combination of a susceptibility (where a landslide occurs), with a rate (how often and how strong) characterizes the hazard (Guzzetti et al., 1999; Glade et al., 2006).

## 2.4 Landslide Exposure and Vulnerability Assessment (Step4)

The goal of exposure and vulnerability assessment is to build an exposure database and assess the vulnerability of the elements at risk to landslides. The assessment was done by carrying out a spatial overlap of hazard zonation and elements at risk. The results from the assessment were produced from a desktop exercise by spatially overlapping the hazard zonation (landslide rate) developed in Step 3 with the different land use categories. Results are presented for two scenarios namely:

- Elements at risk for the current land use situation;
- Elements at risk for the projected land use master plan 2050.

The ranking of the magnitude of exposure and vulnerability was subdivided into four categories as illustrated in the below table:

| Landslide rate ($m^2$ /year/$km^2$) |
|---|
| 1 |
| 18 |
| 90 |
| 365 |

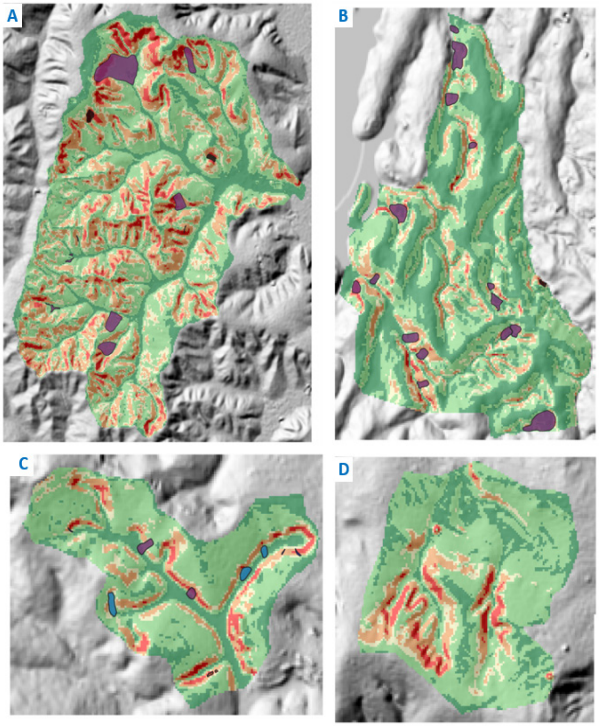
## 2.5 Landslide risks mitigation measures

The goal of this step was to produce a proposal (thematic designs and technical specifications) of potential landslide mitigation measures that could be tested for the areas identified in steps 1 to 4 as at risk and vulnerable to landslides. The methods that could be tested and proposed for the development of mitigation measures shall include, inter alia, the CROM DSS. This will be complemented with an analysis of the relevant literature on landslide and soil erosion mitigation.

# 3. FINDINGS

## 3.1 Landslides Inventory and susceptibility mapping

The outcomes from the landslide inventory which was done through visual interpretation of Google Earth images within the four the four catchments as well as the landslide susceptibility assessment conducted using a logistic regression model are presented under figure 3 below.




*igure3: Landslide susceptibility in the four study areas (purple and blue areas are inventoried landslides)*

A - Bishyenyi
B - Rusizi
C - Rwabayanga
D - Rwandex Magerwa

The outputs from of a logistic regression model used for landslide susceptibility assessment provide values that have no physical meaning as it is for data driven models in general. For the relevant interpretation of a data-driven susceptibility model, there is a need for classification (Corominas et al., 2014; Reichenbach et al., 2018). Here, the continuous values of the susceptibility models are classified into five unequally-spaced susceptibility classes (Figure 3). The category [0.80 – 1.0], in dark red under figure3, presents the class that is the most prone to land sliding. The opposite class is [≤ 0.2] in green. The class ]0.45-0.55] present the zone where the uncertainty on the model classification performance is the highest (Rossi et al., 2010). This way of classifying susceptibility models allows comparison between the sub-catchments (e.g., Jacobs et al., 2018).

From this comparison, looking at the average susceptibility values, Rwandex-Magerwa is overall the sub-catchment that is the most prone to shallow landslide initiation, while Rwabayanga is overall the sub-catchment that is the least prone. However, such average values are meaningless if the distribution patterns are not analysed.

The below table presents the coverage per landslide susceptibility class for each catchment.

*Table1: Areas per landslide susceptibility class per site*

| Susceptibility Class | Bishenyi | | Rwabayanga | | Rusizi | | Rwandex-Magerwa | |
|---|---|---|---|---|---|---|---|---|
| | Area ($km^2$) | Percentage of total area | Area ($km^2$) | Percentage of total area | Area ($km^2$) | Percentage of total area | Area ($km^2$) | Percentage of total area |
| <= 0.2 | 9.87 | 20.9% | 2.54 | 32.5% | 9.50 | 45.1% | 4.45 | 45.8% |
| 0.2 - 0.45 | 14.85 | 31.4% | 3.06 | 39.1% | 6.55 | 31.1% | 2.83 | 29.1% |
| 0.45 - 0.55 | 12.47 | 26.4% | 1.20 | 15.3% | 3.31 | 15.7% | 1.29 | 13.3% |
| 0.55 - 0.8 | 7.45 | 15.8% | 0.67 | 8.6% | 1.45 | 6.9% | 0.73 | 7.5% |
| 0.8 - 1.0 | 2.62 | 5.5% | 0.35 | 4.5% | 0.25 | 1.2% | 0.41 | 4.2% |

## 3.2 Landslide hazards assessment

As briefly described under section 2, the outcomes from the landslide hazards assessment with the four catchments are presented under figure 3 below.

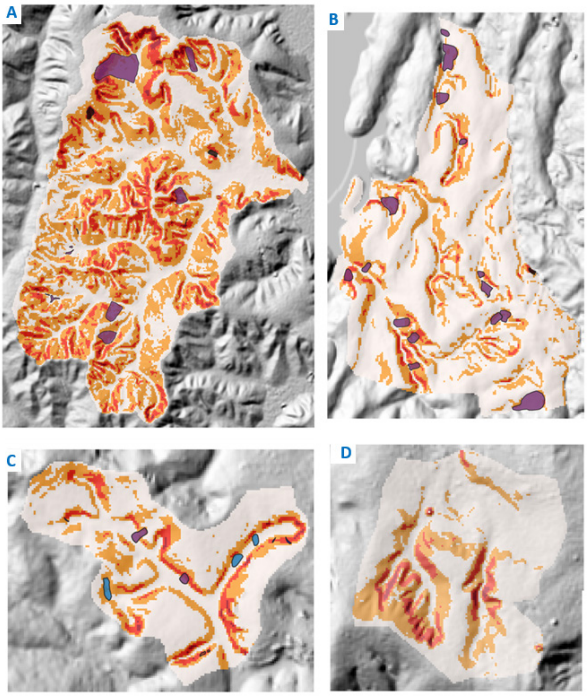



*Figure 3: Landslide hazard maps (purple and blue areas are inventoried landslides)*

A - Bishyenyi
B - Rusizi
C - Rwabayanga
D - Rwandex Magerwa

The different colors in the maps under figure 3 represent the magnitude of exposure and vulnerability as illustrated in the below table:

*Table2: Landslide rate classes*

| Landslide rate ($m^2$ /year/$km^2$) |
|---|
| 1 |
| 18 |
| 90 |
| 365 |

The below table presents the coverage of each landslide hazard rate class per catchment

*Table3: Areas per landslide hazard rate class per site*

| Hazard rate class ($m^2$/year/$km^2$ | Bishenyi | | Rwabayanga | | Rusizi | | Rwandex-Magerwa | |
|---|---|---|---|---|---|---|---|---|
| | Area ($km^2$) | Percentage of total area | Area ($km^2$) | Percentage of total area | Area ($km^2$) | Percentage of total area | Area ($km^2$) | Percentage of total area |
| 1 | 21.06 | 44.6% | 5.34 | 68.3% | 15.98 | 75.9% | 6.77 | 69.7% |
| 18 | 19.54 | 41.3% | 1.84 | 23.5% | 4.40 | 20.9% | 2.19 | 22.5% |
| 90 | 5.96 | 12.6% | 0.59 | 7.5% | 0.66 | 3.1% | 0.68 | 7.0% |
| 365 | 0.71 | 1.5% | 0.05 | 0.6% | 0.02 | 0.1% | 0.08 | 0.8% |

## 3.3 Landslide Exposure and Vulnerability Assessment

The goal of exposure and vulnerability assessment was to build an exposure database and assess the vulnerability of the elements at risk to landslides. This was done by carrying out a spatial overlap of hazard zonation and elements at risk in each catchment.

Results were produced from a desktop exercise by spatially overlapping the hazard zonation (landslide rate) developed in Step 3 (Figure 3) with the different land use categories. Results are presented for two scenarios summarised in tables 4 and 5 below:

- Elements at risk for the current land use situation (2018 land use map);
- Elements at risk for the projected land use master plan 2050.

| Landslide rate ($m^2$ /year/$km^2$) |
|---|
| 1 |
| 18 |
| 90 |
| 365 |

*Table4: Landslide exposure database for the current land use situation as per 2018 land use map*

| Site | Residential / Commercial area [ha] | | | |
|---|---|---|---|---|
| Bishenyi | 539.47 | 341.15 | 41.55 | 0.26 |
| Rusizi | 363.79 | 46.62 | 2.01 | 0.04 |
| Rwabayanga | 154.65 | 17.48 | 0.40 | - |
| Magerwa | 480.88 | 113.58 | 17.95 | 0.56 |
| | **Agricultural land [ha]** | | | |
| Bishenyi | 1,222.54 | 1,401.11 | 366.36 | 19.56 |
| Rusizi | 658.87 | 177.01 | 17.68 | 0.25 |
| Rwabayanga | 263.06 | 98.74 | 24.05 | 1.28 |
| Magerwa | 69.51 | 33.58 | 12.24 | 1.20 |
| | **Wetland [ha]** | | | |
| Bishenyi | 261.44 | 3.48 | 0.50 | 0.27 |
| Rusizi | 97.57 | 2.52 | 0.41 | - |
| Rwabayanga | 54.56 | 1.99 | 0.50 | 0.14 |
| Magerwa | 22.62 | 0.25 | | - |
| | **National roads (km)** | | | |
| Bishenyi | 5.86 | 2.06 | - | - |
| Rusizi | 7.00 | 2.40 | 0.39 | 0.04 |
| Rwabayanga | 2.82 | 0.71 | - | - |
| Rwandex-Magerwa | 2.14 | - | - | - |
| | **District roads (km)** | | | |
| Bishenyi | - | - | - | - |
| Rusizi | 6.54 | 0.92 | 0.25 | - |
| Rwabayanga | 0.28 | 0.64 | 0.30 | - |
| Rwandex-Magerwa | - | - | - | - |
| | **Other roads (km)** | | | |
| Bishenyi | 35.44 | 17.15 | 2.91 | 0.37 |
| Rusizi | 61.85 | 10.91 | 1.40 | - |
| Rwabayanga | 29.10 | 7.27 | 1.32 | 0.12 |
| Rwandex-Magerwa | 62.86 | 13.43 | 1.15 | 0.10 |

*Table5: Landslide exposure database for the projected land use masterplan 2050*

| Site | Agricultural [ha] | | | |
|---|---|---|---|---|
| Bishenyi | 976.10 | 1,256.68 | 384.20 | 17.29 |
| Rusizi | 154.09 | 99.73 | 19.64 | 0.81 |
| Rwabayanga | 80.97 | 56.61 | 20.21 | 1.27 |
| Rwandex-Magerwa | 0.56 | 6.57 | 0.29 | - |
| | **Forest [ha]** | | | |
| Bishenyi | 53.39 | 157.98 | 140.74 | 51.39 |
| Rusizi | 223.46 | 106.28 | 20.10 | 0.56 |
| Rwabayanga | 19.09 | 27.89 | 20.80 | 1.67 |
| Rwandex-Magerwa | 4.61 | 13.34 | 25.12 | 7.46 |
| | **Parks / Ecotourism zone [ha]** | | | |
| Bishenyi | 12.84 | 6.69 | 1.44 | 0.00 |
| Rusizi | 54.35 | 15.36 | 1.18 | 0.01 |
| Rwabayanga | 1.26 | 0.26 | 0.10 | - |
| Rwandex-Magerwa | 13.39 | 3.18 | | - |
| | **Public/commercial/industrial facilities [ha]** | | | |
| Bishenyi | 112.41 | 56.16 | 7.56 | 0.46 |
| Rusizi | 245.20 | 39.53 | 4.83 | 0.26 |
| Rwabayanga | 135.11 | 33.07 | 10.35 | 1.17 |
| Rwandex-Magerwa | 190.70 | 27.70 | 2.76 | 0.13 |
| | **Roads [km]** | | | |
| Bishenyi | - | - | - | - |
| Rusizi | 111.14 | 21.80 | 3.29 | 0.15 |
| Rwabayanga | 45.08 | 17.45 | 2.79 | 0.16 |
| Rwandex-Magerwa | 48.75 | 15.48 | 1.89 | 0.16 |
| | **Rural residential [ha]** | | | |
| Bishenyi | 86.71 | 77.33 | 15.35 | 0.17 |
| Rusizi | 64.47 | 20.15 | 1.08 | - |
| Rwabayanga | 25.12 | 5.07 | - | - |
| Rwandex-Magerwa | - | - | - | - |
| | **Urban residential [ha]** | | | |
| Bishenyi | 437.13 | 292.74 | 29.70 | 1.00 |
| Rusizi | 585.43 | 129.56 | 14.97 | 0.39 |

| | | | | |
|---|---|---|---|---|
| Rwabayanga | 146.46 | 31.38 | 3.39 | 0.12 |
| Rwandex-Magerwa | 392.22 | 128.50 | 19.50 | 0.16 |
| | **Wetland [ha]** | | | |
| Bishenyi | 295.37 | 10.12 | 2.53 | 0.36 |
| Rusizi | 128.60 | 5.01 | 0.95 | - |
| Rwabayanga | 72.64 | 4.87 | 1.16 | 0.06 |
| Rwandex-Magerwa | 21.11 | 0.14 | - | - |

The bar charts below provide a comparative assessment of impact of landslides on current and projected (2050) land use plans. The charts present results for 365 m²/year/km² landslide hazard rate class only which corresponds to a very high hazard.

Land use categorisation in the projected land use masterplan (2050) is not the same as that of the current land use plan (2018). Seeing there was no direct method for comparing the results, it was decided to select the results from categories of the master plan (2050) that are similar to land use plan (2018) categories, and these were added together in an attempt to arrive at values that could be compared. Results are presented below for the Building and Settlements, Roads, Wetlands, Forest and Agriculture categories.

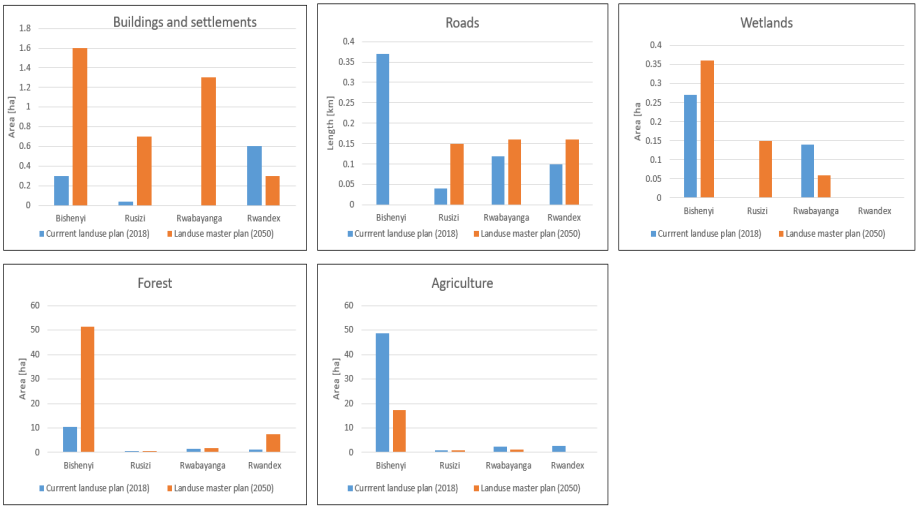



*Figure4: Comparative analysis of impacted land use categories – current and projected land use plans.*

# 4. POTENTIAL LANDSLIDE RISKS MITIGATION MEASURES

Because of the variety of the landsides processes, the nature of regolith and rock environments and landscapes in which they are found, virtually every slope mitigation design problem is unique. Designing a stable slope includes field investigations, laboratory tests, stability analyses, and proper construction control. Because most of the details involved in such a work cannot be standardized, good engineering judgment, experience, and intuition must be coupled with the best possible data gathering and analytical techniques to achieve a safe and economical solution to slope stabilization (Turner and Schuster, 1996).

The goal of this section is to provide a general overview of the potential mitigation measures that could be tested for the areas identified as at risk and vulnerable to landslides.

The risks associated with landslides can be mitigated by reducing:

- the Hazard – H- (i.e., the probability of occurrence of one or more phenomena);
- the Vulnerability – V - (i.e., the degree of loss to the elements at risk for a given hazard);
- the Elements at risk – E- (i.e., their number and/or specific value).

Table 6 makes the difference between structural and non-structural landslide mitigation measures. In general terms, it means:

- "structural" measures include, but are not limited to drainage, erosion protection, channelling, vegetation, ground improvement, barriers such as earth ramparts, walls, artificial elevated land, anchoring systems and retaining structures; buildings designed and/or placed in locations to withstand the impact forces of landslides and to provide safe dwellings for people, and escape routes;

- "non-structural" or more generally "consequence reducing measures" include, but are not limited to: retreat from hazard, land-use planning, early warning, public preparedness, (escape routes, etc.) and emergency management.

*Table6: General classification of mitigation measures (SafeLand, 2012).*

| Classification | | Component of risk addressed | Brief description | Notes and other terms used |
|---|---|---|---|---|
| STRUCTURAL | Stabilization | Hazard (H) | engineering works to reduce the probability of occurrence of landsliding | Preventive, remedial, hard, soft, active stabilization |
| | Control | Vulnerability (V) | engineering works to protect, reinforce, isolate the elements at risk from the influence of landsliding | Preventive, hard, soft, passive stabilization |
| NON STRUCTURAL | Avoidance | Elements (E) | temporary and/or permanent reduction of exposure through: warning systems and emergency evacuation or safe sheltering, land-use planning and/or relocation of existing facilities | Direct temporary and/or permanent reduction of the number and/or value of elements at risk. Monitoring and warning or alarm systems and associated civil protection procedures, often described as reducing vulnerability, in actual fact operate through temporary, selective avoidance. |
| | Tolerance | Elements (E) | Awareness, acceptance and/or sharing of risk | Indirect reduction of the number and/or value of elements at risk |

When avoidance is not an option, other mitigation measures must be considered. Mitigation measures which aim to reduce the hazard must reduce the probability of triggering the landslide(s) which the specific measure is intended to address. These types of mitigation measures are sometimes referred to as "stabilization" measures. In order to reduce the probability of triggering landslides, mitigation measures which aim to reduce the hazard of landslides occurring must act in the system in the opposite direction, by:

- A: increasing the resisting forces; and/or
- B: decreasing the driving forces.

The below table illustrates landslide hazards mitigation measures adapted from Popescu & Sasahara.

| Physical process | Brief description |
|---|---|
| Surface protection; control of surface erosion | • Vegetation (hydroseeding, turfing, trees/bushes)<br>• Fascines/brush.<br>• Geosynthetics.<br>• Substitution; drainage blanket<br>• beach replenishment; rip-rap.<br>• Dentition |
| Modifying the geometry and/or mass distribution | • Removal of material from the area driving the landslide (with possible substitution by lightweight fill).<br>• Addition of material to the area maintaining stability, with or without gravity, catilever, crib/cellular and/or reinforced soil walls.<br>• Reduction of the general slope angle.<br>• Scaling (removal of loose/unstable blocks/boulders). |
| Modifying surface water regime – surface drainage | • Diversion channels<br>• Check dams<br>• Surface drains (ditches, piping) to divert water from flowing onto the slide area.<br>• Sealing tension cracks.<br>• Impermeabilization. (*)<br>• Vegetation. (*)<br>Note (*): associated with control of surface erosion |
| Modifying groundwater regime – deep drainage | • Shallow or deep trenches filled with coarse grained free-draining geomaterials and geosynthetics<br>• Subhorizontal drains<br>• Vertical small diameter wells; self draining (where they provide relief to artesian pressures or underdrainage to a perched acquifer) or drained by siphoning, electropneumatic or electromechanical pumps<br>• Vertical medium diameter wells with gravity drainage through a base collector<br>• Caissons (large diameter wells), with or without secondary subhorizontal drains and gravity drainage<br>• Drainage tunnels, galleries, adits, with or without secondary subhorizontal or subvertical drains and/or as gravity outlet for wells drilled from the surface |
| Modifying the mechanical characteristics of the unstable mass | • Substitution<br>• Compaction<br>• Deep mixing with lime and/or cement<br>• Permeation or pressure grouting with cementitiuous or chemical binders<br>• Jet grouting<br>• Modification of the groundwater chemistry |
| Transfer of loads to more competent strata | • Shear keys: counterforts, piles; barrettes (diaphragm walls); caissons<br>• Anchors: soil nails; dowels, rock bolts; multistrand anchors (with or without facing consisting of plates, nets, reinforced shotcrete)<br>• Anchored walls (combination of anchors and shear keys) |

Other measures to reduce the vulnerability of the elements at risk consist of "passive" solutions which are not intended to prevent the triggering of the landslide but to reduce the resulting degree of loss.

They can be subdivided in two main categories, depending on the approach followed to achieve this objective:

- Measures to increase the resistance of elements at risk (reduction of vulnerability s.s.) – existing structures can be strengthened; for new structures, the potential effects of impact from landslide material can be taken into account from the outset. This approach is typically applicable only in relation to relatively shallow slides, since it is practically impossible to build structures capable of withstanding the impact form larger landslides.
- Measures to stop or to deviate the path of the landslide debris (reduction of vulnerability s.l.) - Works can be carried out to intercept and block or at least to deviate or to slow down the sliding materials. This type of works relates mainly to the fall of massive blocks or to flows of all types, in those cases where a large slope is affected and stabilization is not feasible for environmental impact reasons or because of cost.

# 5. CONCLUSION

The study findings have shown that, although there are few inventoried landslides within the four sub-catchments; the outcomes from the landslide hazards assessment illustrate high percentages of areas under the two highest risk classes (see table2). The two hazard rate classes cover 14.1 %; 8.1%; 7.8% and 3.2 % respectively for Bishenyi, Rwabayanga, Rwandex-Magerwa and Rusizi sub-catchments.

Considering that the four sub-catchments are under urban areas or peri-urban area (Bishenyi), this implies that the cost of elements at risks becomes higher for both the current land use (2018 land use map) and the projected land use (2050) as illustrated under table 4&5.

Therefore, the main recommendation from this study is to ensure that appropriate precautions are taken while developing the areas categorized under high landslide risks especially within urban zones, and conduct further detailed investigations to assess the problem, not only in terms of landslide process understanding (location, mechanism, deformation rate), but also in terms of vulnerability as well as direct and indirect impacts.

This study has provided general landslide mitigation measures that could be tested for the areas identified as at risk and vulnerable to landslides within the four sub-catchments after deep investigation of each site specifics.

Lastly, special attention needs to be taken in regards to the current predominant on-site stormwater and wastewater management practices in urban zones which could accelerate the risks of landslides within the already vulnerable zones.

To learn more about our work, please contact us.

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