Landslide Risks Assessment and Mitigation in Four Urban Sub-catchments in Rwanda

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EXECUTIVE SUMMARY

1.1 Landslide risk assessment

The landslide risk assessment was undertaken for the sub-catchments of Rwandex-Magerwa, Bishenyi, Rwabayanga and Rusizi. The deliverable has been landslide risk maps for each watershed (refer to pdf maps accompanying report). Maps are classified in several classes.

The landslide risk maps are provided in the form:

- Landslide inventories (included in accompanying PDF maps);
- Landslide susceptibility maps (included in accompanying PDF maps);
- Landslide hazard maps (included in accompanying PDF maps);
- Exposure databases (included in report)

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%

Results for landslide susceptibility are summarised in the table above. The continuous values of the susceptibility models are classified into five unequally-spaced susceptibility classes. The category [0.80 – 1.0] presents the class that is the most prone to landsliding. The opposite class is ≤ 0.2]. The class]0.45-0.55] present the zone where the uncertainty on the model classification performance is the highest (Rossi et al., 2010).

Results for landslide hazard are summarised in the table below.

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%

The risk maps submitted together with the report provide visual combinations of landslide process scenarios and land use categories. They allow to highlight the places where the risk could be more problematic. Depending on the slope instability processes and the land use, the risk is different. For example, places where deep-seated landslides are located are areas where ground deformations are expected to be the larger (independently from soil creep, which is not discussed here, although highlighted in step 1). Such deformations can be very slow (a few centimetres per year or even less; e.g. Nobile et al., 2019; Dille et al., 2021) and therefore be not at all a problem for agricultural land. On the contrary, building a new road or heavy infrastructures on such areas could create problems (fractures, etc.) as most foundations cannot be deep enough to reach a stable bedrock below the surface of rupture of the landslides. While slow-moving deformations can have pervasive impacts difficult to mitigate, people are not in immediate dangers.

When looking at such documents, we must be aware that further investigations are needed to really 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.

1.2 Proposal of landslide mitigation measures

The goal of the study was to provide a general overview of the potential mitigation measures that could be tested for the areas of the watersheds that have been identified at risk and vulnerable to landslides.
The structure of the study is as follows:

- First, the mitigation measures are detailed;
- Along with criteria for the selection of the mitigation measures, details are provided on measures at the level of the hazard, the vulnerability, and the elements at risk;
- The measures are then discussed in the context of the Catchment Restoration Opportunity Mapping upport System (CROM DSS);
- A high-level Bill of Quantities for specific landslide mitigation measures in the study areas has been provided. The specific measures were developed with the assumption that, should landslides occur in the highest susceptibility zones, they would be shallow landslides that are likely to cause to soil erosion.

Together with the presentation of the mitigation measures, additional figures and appendixes explaining and illustrating key concepts are proposed to ease the understanding of the study. As a last note, a brief focus is provided on gully erosion.

One have to keep in mind that the purpose of this section is not to go beyond the sole role of the literature review. Further research and expertise actions are needed if one want to move towards the implementation of concrete mitigation measures. The measures presented here are therefore not catchment-specific, and to some extent not specific to a type of landslide in particular.

SECTION 1: LANDSLIDE RISK ASSESSMENT

2.1 Introduction

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).

The UN's Sendai Framework for Disaster Risk Reduction identifies four priorities for action in order to substantially reduce global landslide disaster risk and related fatalities (UNDRR, 2015). A cornerstone among these priorities is understanding landslide hazard, which describes the likelihood of a landslide of a given magnitude to occur in time and space (Guzzetti et al., 1999). In other words, landslide hazard is ideally characterized by statements of 'what', 'where', 'how strong' and 'how frequent' (Glade et al., 2006).

Authorities and decision makers need maps depicting the areas that may be affected by landslides so that they are considered in development plans and/or that appropriate risk mitigation measures are implemented. A wide variety of methods for assessing landslide susceptibility, hazard and risk are available (Galde et al., 2006; Corominas et al., 2014; Reichenbach et al., 2018).

In this study, the assessment of landslide risk was achieved in five steps (Figure 1). 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 is influenced not only by the quality of the inventory but also by the types of landslides and the abundance of their occurrence.

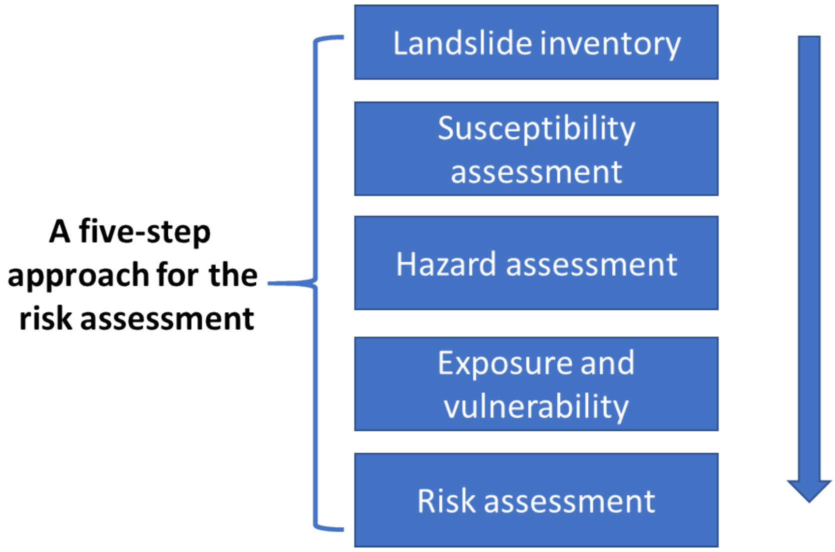

Figure 1 – *Landslide risk assessment methodology*

2.2 Available knowledge and required data

There are several research works on landslide susceptibility, hazard and risk assessment that have already been carried out in Rwanda and in the Lake Kivu region in particular (e.g. Jacobs et al., 2018; Depicker et al., 2020a, 2020b, in review; Dewitte et al., 2021). Our approach is to build the risk assessment as much as possible upon this existing knowledge and the methods that have already proved to be successful.

One important issue related to the risk assessment at the scale of the four sub-catchments is the quality of the ancillary data that are provided. These data are used to inventory the landslides and to derive the environmental factor maps that will be used for the susceptibility analysis. The following ancillary data were used for the for susceptibility, hazard and risk assessment in this project:

- Digital Elevation Model (DEM) – SRTM 30 m resolution (Source: Farr et al. 2007) and Rwanda 10m DEM (Source: GGGI / RWB). Note that the latter does not cover the Kamembe-Gihundwe sub-catchment;
- Soil data (Source: GGGI);
- Land cover and land use 2008 (Source RWB), 2018 (Source: GGGI);
- Mapping of road network and drainage lines (Source: RTDA);
- Fault lineaments (Smets et al., 2016 ; Delvaux et al., 2017);
- Peak ground acceletration – PGA (Delvaux et al., 2017);
- Database of landslides in western Rwanda collected via other research projects from the Royal Museum for Central Africa: locations and timing of the landsides (Depicker et al., 2020a, 2020b ; Dewitte et al., 2021).

2.3 Step 1: Comprehensive multi-temporal landslide inventory

2.3.1 Objective

The goal of this step is to identify where and when landslides occurred, the types of slope failure processes, the level of ground deformation activity, the history and origin of the landslides (causes and triggers). Concerning the latter point, understanding the role of human disturbances in the slope failure is important.

2.3.2 Method

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 are of very-high spatial resolution, ranging from 30 to 60 cm. The images in Google Earth are 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 analyzed in parallel with the photographs taken in the field.

The term landslide encompasses a large range of gravity-driven mass movements, that differ by their failure mechanisms, size, depth, velocity and the material mobilised (Lu and Godt, 2013; Hungr et al., 2014). We used the updated Varnes' classification (Hungr et al. 2014) for defining the landslide typology; the classification schemes being the most widely used. Defining the landslide typology is a key step when predicting the associated risk as the variety of the slope processes (size, speed, origin, etc.) is large and hence the types of impacts (Corominas et al., 2014).

The landslide depth is an important element when analysing landside causes and triggers; the occurrence of shallow landslides being for instance much more sensitive to disturbances of the landscape surface and rainfall conditions than deep-seated landslides (Sidle and Bogaard 2016). For example, the removal of trees, due to either human or natural causes, decreases the slope stability through the alteration of hydrological and geotechnical conditions, such as the loss in soil cohesion due to tree root decay (Sidle et al., 2006; Sidle and Bogaard, 2016). Deep-seated landslides, both rapid and slow-moving, are also controlled, like the shallow landslides, by water routing through the regolith (see Text Box 1). Slow, deep-seated landslides (e.g., slides and earthflows; Figure 20) typically require an extended period of water recharge to initiate movement, while rapid, deep-seated failures may initiate by either direct response to individual storms or prolonged water inputs (Sidle and Bogaard, 2016). The depth of the surface of rupture of shallow landslides is usually defined in the range of 2-5 m (Keefer, 1984; Mackey and Roering, 2011; Sidle and Bogaard, 2016). Here, we considered landslides to be shallow when their estimated depth is < 5 m. We estimated the relative depth of the landslides visually analysing the shape and size of the landslide scarp and deposits in Google Earth imagery. We have validated such an visual analysis through in situ field observations in similar context in Rwanda and the Kivu Rift (Depicker et al., 2020a, 2020b). The landslides occurring in mining and quarrying sites were all classified as quarrying landslides, regardless of their depth.

Landslides were classified into (i) recent and (ii) old movements following the approach proposed by Depicker et al. (2020b) and Dewitte et al. (2021). Recent landslides are all new slope failures; the moment of failure must be situated between the timing of two satellite images. All recent landslides are considered active since they present disturbed vegetation patterns and bare soil surfaces that are visible on the satellite images. Landslides were classified as old if present on the eldest satellite images but showing no signs of activity.

Text Box 1: *Regolith and colluvium*

Regolith: rock that is weathered to any degree (physically and chemically). Three layers are considered: weathered rock, saprolite and mobile regolith. Weathered rock is the deepest layer of the regolith overlying the hard, unweathered rock. Saprolite is material that is more altered than weathered rock and that can readily be augured through or dug with a shovel. Saprolite retains the original rock structure. Mobile regolith has been detached from the weathered rock and saprolite below it, and is in motion both vertically and laterally. Where it is present, soil forms the upper part of the mobile regolith that is organized into horizons by soil-forming processes. In tropical climates where temperature are high and conditions are humid, the weathered materials typically show red and yellow colors.

Colluvium: material that has been transported across and deposited downslope by the action of mass movement and wash processes. The material forms a loose (generally unsorted) sedimentary deposit usually in topographic depressions and at the base of the hillslopes. Colluvium is typically composed of a heterogeneous range of sediments of various sizes.

2.3.3 Results

The inventory for the four sub-catchments contains 22 old deep-seated landslides and five recent deep-seated flow slides/earthflows (examples of inventoried landslides are shown in Figure 2). Other features associated with hillslope dynamics, i.e. soil creep and gully erosion, have also been identified. Each landslide (and the other features) is manually assigned a polygon. Based on this inventory, we can draw the following conclusion about the identified landslide and other hillslope processes in the four sub-catchments:

<u>Old deep-seated landslides:</u> The landslides classified as old deep-seated features are natural slope failures of undetermined age. The morphology of these landslides and the alteration due to weathering and erosion of their main scarps (i.e. the head the landslides, also referred to the source area of the landsides) attests an origin, for some of them, that may be easily a few thousand years old (Dille et al., 2019; Dewitte et al., 2021).

Such slope failures could be associated with environmental conditions that used to be different (Dewitte et al., 2021). It is indeed known that the climate and the seismicity conditions of the region have changed over the past tens of thousands of years. For example, the region experienced an abrupt shift from drier conditions to more humid conditions around 13,000 BP (Felton et al., 2007; Wassmer et al., 2013). Although they look non active to the naked eye and that buildings and other infrastructures are present in several of them, old deep-seated landslides can be prone to slope deformations (see Step 2 – Susceptibility assessment for details).

<u>Recent deep-seated landslides:</u> The recent deep-seated landslides seem to be generally associated with quarrying/mining activities as attested by the presence of roads in proximity. These landslides clearly show signs of activity. Caution must be taken when assessing the cause and triggers of these landslides as quarrying/mining sites could either play a cause/trigger role (for example slope undercutting and over steepening) or be the consequence of a landslide. In the latter case, a landslide is at the origin of a fresh regolith/rock outcrop that can be exploited as a commercial opportunity.

<u>Shallow landslides:</u> for the shallow landslides; no features were observed from the satellite images in the four sub-catchments over the last 20 years. However, the fact that we were not been able to identify such landslides, does not allow us to conclude with certainty that shallow slope failures did not occur during that period. Shallow landslides can be very small and therefore happen unnoticed at the resolution of the satellite images. Furthermore, their scars can quickly be altered from weathering, erosion, vegetation regrowth and human activities (Malamud et al., 2004; Dewitte et al., 2021). It should be noted therefore that the identification of the shallow landslides from satellite images is always an underestimation.

Nonetheless, what we can conclude, is that clusters of landslides triggered by heavy rainfall events associated with convective systems (often associated with thunderstorms) did not occur in the studied areas over the last 2 decades. Usually, in the Lake Kivu region, such rainfall events are associated with clusters of hundreds to thousands of slope failures occurring over areas of a few (tenths of) km^2 (Monsieurs et al., 2018; Dille et al., 2019; Depicker et al., 2020a, 2020b, Dewitte et al., 2021); i.e. a disturbance of the landscape that cannot be unnoticed when analysing satellite images. On a yearly basis, a few of such events are observed in the Lake Kivu region and their spatial distribution is controlled by the randomness of the extreme convective rainfall events. In Figure 3 a, two clusters of landslides corresponding to such climatic events are observed.

<u>Soil creep:</u> Soil creep is a movement under the influence of gravity, temperature and moisture fluctuations, and the action of biota that occur on hillslopes. It is characterized by an extremely slow, generally imperceptible displacement of surficial unconsolidated materials that can occur over long periods of time, easily over thousands of years (Thomas, 1994; Heimsath and Jungers, 2013). This process is common in many tropical regions, particularly where, like in Rwanda, the regolith is thick, and, although imperceptible, it can displace a considerable volume of hillslope material downstream (Thomas, 1994).

Moeyersons (1988,1989) studied creep movements within a 3 m thick mobile regolith mantle on a hillslope located 2 km west of the Rwabayanga sub-catchment, at a place called Rwaza hill. He showed that fissure/sliding plane configurations, typical for landslides, could develop in the silty-clayey mantle in the region. In the Rwabayanga sub-catchment we have delineated several areas where we believe that soil creep is taking place. This inventory of the hillslopes affected by creep is certainly not comprehensive and care must be taken with our interpretation. However, we believe that it is important to stress that issue as the effect of such a process could be pervasive and in the long run cause damage to infrastructures.

Creep sediment accumulation and associated landslides: Through the volume of weathered material it displaces, soil creep can contribute significantly to the formation of colluvium deposits (Thomas, 1994 – and Text Box 1). When colluvium accumulates on slopes, it can become the preferred site for landslides, as observed in neighbour regions is Uganda (Jacobs et al., 2017; Nseka et al., 2019). In the example highlighted in Figure 2 e, we identify a landslide that could be associated with this creep-related process.

Gully erosion: The conditions of mobile regolith and colluvium accumulation are also favorable to the formation of gullies (Mackey and Roering, 2011; Migoń, 2013). In some cases, also occurring as a consequence of landsliding, the interactions between landslides and gullies are typically complex and sometimes involve self-reinforcing feedbacks (Mackey and Roering, 2011; Migoń, 2013). Large gully erosion systems in which landslides are present are identified, for example, in Bujumbura in the neighbour Burundi (Dewitte et al., 2021). The origin of these large gullies is assumed to be partly associated with urban infrastructures, especially with the road network (as observed in other urban environments such as in Kinshasa, Makanzu Imwangana et al., 2014). Here we have mapped a few gullies that present such anthropogenic characteristics (Figure 2 f). Here also we must stress that the gully inventory is certainly not comprehensive. Similarly to the detection of shallow landslides, gullies can be unnoticed at the resolution of the satellite images.

Roads and trail networks: Similarly to what is observed in other mountainous regions, the frequency of landslide occurrence in Rwanda is highly increased along the roads where inadequate drainage systems, hillslope undercutting, overloading and landfills are common (Dewitte et al., 2021). These human-induced changes alter environment where landslides occur. Usually rather small landslides, often rockfall, are observed; especially during the wet seasons. Most of these landslides along the roads are usually too small to be identified in Google Earth. In this study, we were able to delineate only a few road fillings. Despite that, we can easily assume that road and trails play a role in the occurrence of landsliding.

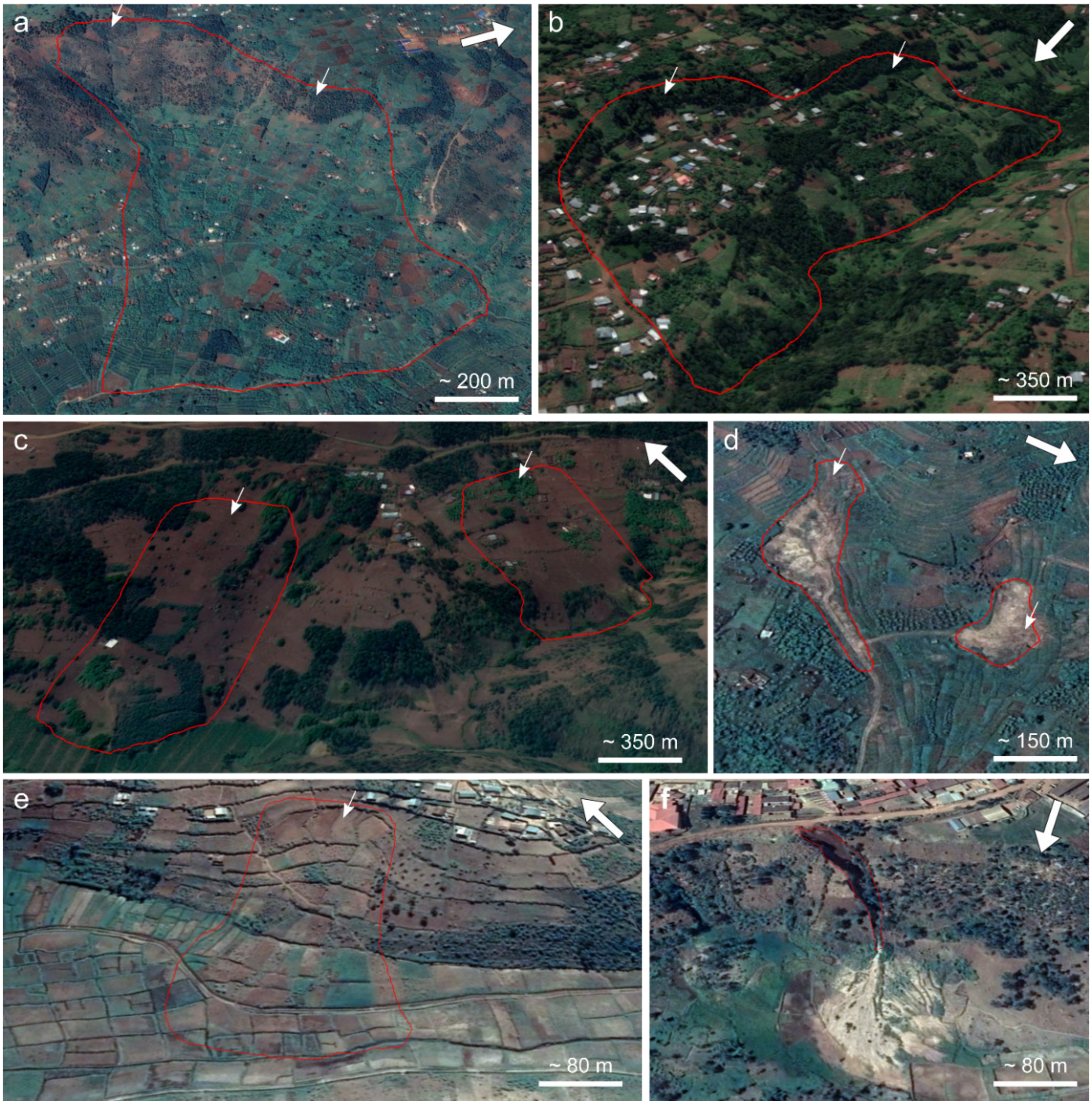

Figure 2 – *Examples of landslides and other slope processes inventoried from Google Earth*

In Figure 2 above, red polygons delineate the landslides. Small white arrows locate the landslide headscarps, i.e. the landslide source areas. Large white arrows indicate the north. a) Old large deep-seated landslide in Bishenyi sub-catchment, Jan. 2021 (-1.958, 29.948°). b) Old large deep-seated landslide in Kamembe-Gihundwe sub-catchment, Sept. 2020 (-2.454, 28.912°). c) Old large deep-seated landslides in Kamembe-Gihundwe sub-catchment, Sept.2020 (-2.502, 29.906°). d) Recent flow landslides (mixture of flow slides and earthflows) in Bishenyi sub-catchment, January, 2021 (-2.000°, 29.939°). e) Deep-seated landslide, probably associated with soil creep in Rwabayanga sub-catchment, July. 2018 (-2.602°, 29.718°). f) Active gully associated with a road in the Rwabayanga sub-catchment. Note the vegetation free gully features as well as the colluvium deposit downslope (clear sediment) that attest the activity of the system, July 2018 (-2.602°, 29.739°).

2.4 Step 2: Landslide susceptibility assessment

2.4.1 Objective

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.

2.4.2 Method

2.4.2.1 The role of the landslide inventories

The number of inventoried landslides in Step 1 is much too limited for applying any data-driven susceptibility and hazard assessment at the scale of the four, relatively small, sub-catchments (Corominas et al., 2014; Reichenbach et al., 2018; Depicker et al., 2020b). Therefore, to specifically compute data-driven models and meet the commitments that we could have expected if more landslides were present in the sub-catchments, we decided to use, as an extra, an existing regional inventory of shallow landslides that covers the Lake Kivu region. In Rwanda, this inventory covers all the regions west of Kigali (Figure 3). The inventory has already been used for several susceptibility and hazard assessments in the region (Depicker et al. 2020a, 2020b) and should be made publicly available once a manuscript currently in review (Depicker et al., in review) is published. From this inventory, it is possible to calibrate regional data-driven susceptibility (and subsequently hazard) models that cover the four sub-catchments at once. Since the assessments are made at the regional level, it also allows us to compare the four study sites with each other.

In this study, we therefore used two inventories for two types of susceptibility assessments, one produced specifically here (Inventory 1 – see Step 1 for details) and one from other works (Inventory 2):

- **Inventory 1 – used for sub-catchment susceptibility to ground deformations within the old and recent deep-seated landslides:**

For the old and recent deep-seated landslides, the hazard assessment, even at the regional level, cannot be assessed without any accurate information on their timing of occurrence. For the sole susceptibility assessment, although a regional model for these landslides is already available (Depicker et al., 2020b), its use at the local scale is meaningless; a regional model for deep-seated landslides provides only an information on their general distribution patterns. At the local scale, the exact location of a future deep-seated slope failure is here impossible to predict from a data-driven model since it depends on heterogenous local conditions associated with the lithology and hydrogeology that are not known (Dille et al., 2019).

However, deep-seated landslides are places where the hillslope material has been disturbed. Therefore, the landsides are portions of hillslopes that are more easily prone to ground deformations (e.g. Nobile et al., 2018; Dille et al., 2021). For the recent landslides, such deformations are often visible and the delineation of the active zones is straightforward (Figure 2 d).

For the old landslides, although such deformations can be unnoticed to the naked eye, their effect can be pervasive and, on a relatively long period, impacts the infrastructures (fissures, cracks).

Old deep-seated landslides also present a range of hydrological and geotechnical conditions that can favour the occurrence of new landslides. This path-dependency of landslides (Temme et al., 2020) is something important when assessing the potential of landslide disturbances in a landscape. Old landslides can sometimes reactivate. Although such transition from relatively stable conditions to important failure is relatively rare (Lacroix et al., 2020), this hazard is something not to be ignored. In a landscape, old deep-seated landslides represent a potential constraint.

Therefore, the inventory map of the old and recent deep-seated landslides that we have identified is here considered as a landslide susceptibility product that locates the places that are the most prone to be affected by ground deformations. A caveat for the delineation of the deep-seated landslides, especially for the old ones, is that, due to the interpretation of the morphology of the hillslopes, identifying the exact limits of the failed mass may not be easy and that the delineated areas must be considered with caution.

Old and recent landslides are shown on the landslide susceptibility maps for the four study areas that have been produced and are submitted together with the present report.

- **Inventory 2 – used as a dependent variable for the regional shallow landside initiation susceptibility and hazard assessment:**

For the susceptibility of the initiation of new shallow landslides, we used the 2,544 recent shallow landslide observations we made in previous research in western Rwanda. These landslides were identified by Depicker et al. (2020a) through the visual analysis of Google Earth images over the 2000-2019 period. As explained in Step 1, all recent landslides have their timing of initiation well constrained between the timing of two satellite images; which is mandatory for the hazard assessment (Step 3). The recent shallow landslides were not triggered by seismic activity and we can expect that in most situation rainfall is at their origin (Monsieurs et al., 2018; Depicker et al., 2020a, 2020b, Dewitte et al., 2021), although the role of rock weathering cannot be excluded for some landslides occurring in isolation (Dille et al., 2019). Since we look at the susceptibility associated with the occurrence of new landslides, we used the source area of each landslide in our assessment. More specifically, the source area is represented by one initiation point that was manually defined (e.g. Jacobs et al., 2018; Depicker et al., 2020a, 2020b). For the shallow susceptibility assessment we therefore used a dependent variable containing 2,544 landslide initiation points. In other words, each landslide is represented by 1 pixel in the analyses, either at 10 or 30 m resolution, depending on the topographic data source that is used (Table 1).

The impact zone of the landslides was not considered in the susceptibility analysis (Figure 3 b). The average area of these shallow landslides is 725 m^2, with 121 m^2 and 604 m^2 for the source and impact areas respectively.

We stressed earlier when explaining the shallow landslides, (see page 82) that an inventory from satellite images will always provide an underestimation. This concerns of course the inventory we use here. Since our inventory was compiled with the consistent use of Google earth images, we know that this underestimation is similar across the whole region. Therefore, the use of this inventory will not impact the reliability of the susceptibility assessment, the latter being data-driven and therefore relying of relative assessment. For the underestimation of the landsides, more details are provided in Depicker et al. (2020a). For the susceptibility assessment more details are provided in Depicker et al. (2020b)."

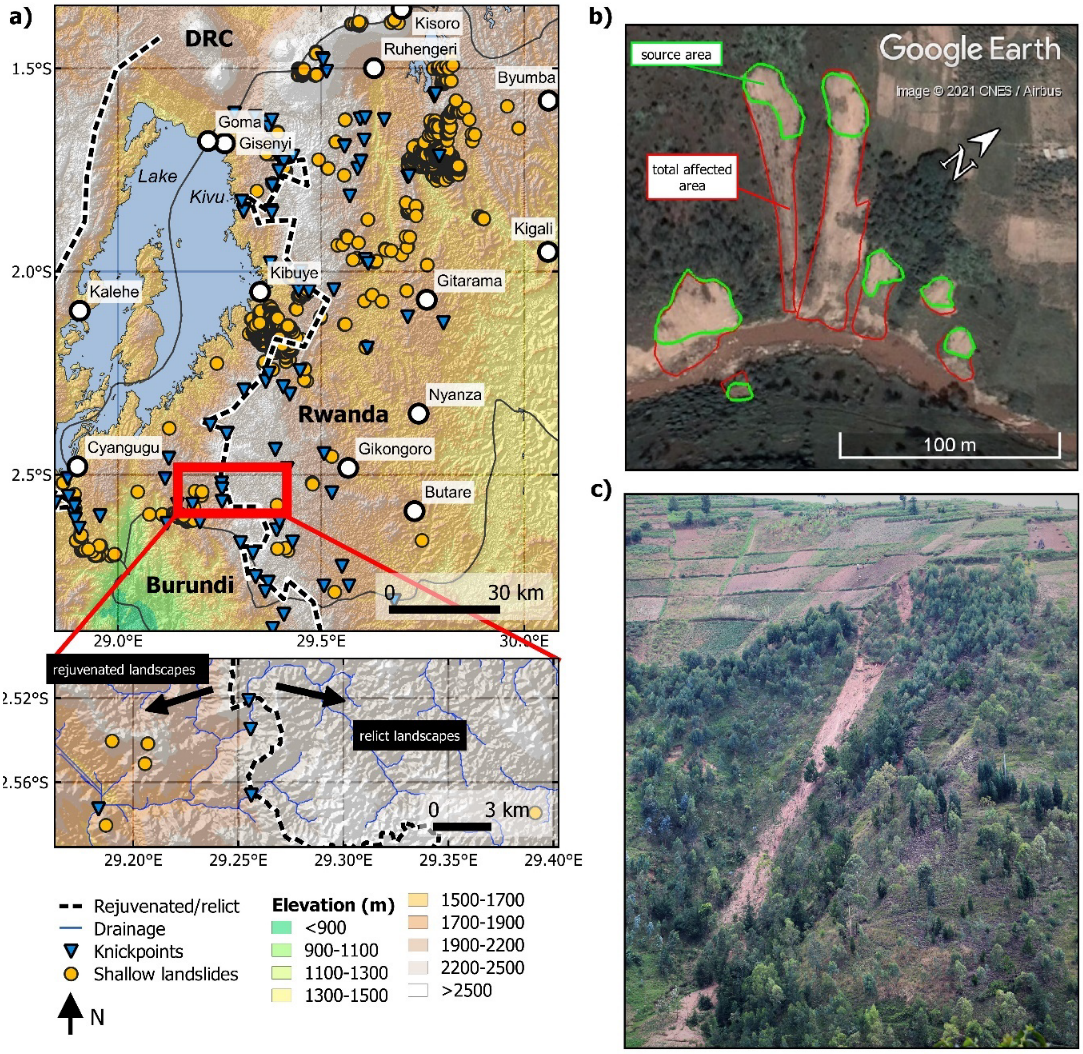

Figure 3: *Landslide and knickpoint inventory for Rwanda (from Depicker et al., 2020a)*

a) Location of the 2,544 shallow recent landslides used in the landslide susceptibility and hazard assessment and 83 non-stationary knickpoints. These knickpoints were used to separate the rejuvenated landscapes between the Rift shoulders from the surrounding relict landscapes (black-and-white line) (see Text Box 2 for more details). The zoom in the red rectangle show the delineation between the rejuvenated and the relict landscapes. Note the two landslides clusters that correspond to intense convective rainfall events (see Step 1)

b) Example of shallow landslides on a Google Earth image in Rwanda (-1.715°, 29.790°) and the delineation of their total area (red) and source area (green);

c) Example of a shallow landslide (namely a debris avalanche), Sep. 2018 (1.967°, 29.588°).

2.4.2.2 Predictor variables for the shallow landslide susceptibility assessment

Based on the work of Depicker et al. (2020a), we selected the following predictor variables for the shallow landslide susceptibility assessment (Table 1):

- Slope;
- Planar curvature;
- Profile curvature;
- North exposedness;
- East exposedness;
- Peak ground acceleration (PGA, a measure of seismic activity);
- Distance to faults;
- Distance to rivers;
- Land use/cover;
- Presence in the rejuvenated landscape (i.e. the influence of the formation of the Rift mountains on the river erosion of the landscape – see Text Box 2 and Figure 3); and Lithology.
- Additionally, we used the elevation, the presence of roads within 50 m, and the clay content of the soil. We distinguished six (6) land use/cover types: closed agriculture, open agriculture, irrigated lands, forests, open lands, and built-up land. We distinguished five (5) types of lithology: schists, granites, quartzites, volcanic rocks, and alluvial depositions.

These natural and human-related environmental predictors are environmental characteristics that could explain the occurrence of the landslides. The environmental characteristics were extracted for the landslide source area. Statistical criteria assessed to validate the use the predictor variables listed in table below and are presented in Appendix 1.

Table 1: **Landslide predictor variables evaluated for the susceptibility analysis, themes according to Reichenbach et al. (2018)**

Theme	Predictor variable	Units	Resolution/scale	Source
Morphology	Elevation	m	10, 30	DEM Rwanda, SRTM
	Slope	°	10, 30	
	Profile curvature	m^{-1}	10, 30	
	Planar curvature	m^{-1}	10, 30	
	North exposure	–	10, 30	
	East exposure	–	10, 30	
	Presence in rejuvenated landscape	–	1/1000	Depicker et al. (2020a)
Hydrology	Distance to rivers	m	10, 30	DEM Rwanda, SRTM
Geology	Lithology	–		
	Distance to faults	m	10, 30	Smets et al. (2016) and Delvaux et al. (2017)
	Peak ground acceleration (PGA)	$m\ s^{-2}$	2.2 km	Delvaux et al. (2017)
Land cover	Land use/cover types	–		GGGI / RWB
	Distance to roads within 50 m	m		RTDA
	Clay content (soil with >35% clay)	% clay		

Text Box 2: *Rejuvenated vs relict landscapes*

The concept of rejuvenated landscape is detailed in the Depicker et al. (2020a). This is a geomorphological parameter that is commonly not used in landslide susceptibility assessment (Reichenbach et al., 2018). One of the novelties of the research carried out by Depicker et al. (2020a) is to highlight the importance of considering such a geomorphological context when studying the landslide distribution in tectonically active landscapes. In short, the four sub-catchments that we study here are situated within a mountain range – namely the North Tanganyika - Kivu Rift region in the western branch of the East African Rift - that has been developing through rifting over the last ca. 11 Ma. The associated tectonic uplift has created a specific structure where the center of the mountain range has "collapsed". This collapsed part is where Lake Kivu is located. In terms of geomorphological context, the hillslopes draining towards Lake Kivu are younger that the hillslopes draining off the mountain range. The younger hillslopes are called "rejuvenated landscape" and the older hillslopes "relict landscapes". The difference of topographic age is highly associated with the incision of the rivers in the landscapes and the presence of knickpoints; i.e. dynamic convex oversteepening of the river longitudinal profiles (a waterfall being an knickpoint). These hillslope age and incision differences have an implication on, e.g. the weathering of the rock, and hence the availability of regolith material (i.e. the slope material where most shallow landslides are usually occurring). In addition, the mountain morphology is associated with climatic conditions that are different whether we are in the rejuvenated or in the relict landscapes. The Kamembe-Gihundwe sub-catchment is located in the rejuvenated landscape, while the other three are in the relict landscape.

2.4.3 Results

Note: for further technical details on the application of the logistic regression and all the other statistical analysis performed for the landslide susceptibility assessment we encourage the reader to look at the paper published by Depicker et al (2020b) for the lake Kivu region as we follow their approach. Below are the main outcomes of our analysis in Rwanda.

2.4.3.1 Calibration and validation of the landslide susceptibility model

We used logistic regression 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.

In total we used the 2,544 recent shallow landslide initiation observations (i.e., pixels) (Figure 3) and an equal number of random points taken across the landscape outside the landslide areas that served as 'non-landslide' locations. The model was trained twice; once with the morphological data (elevation, slope, curvature, exposure) derived from the 30 m SRTM elevation data, and one time with the same morphological data derived from the 10 m resolution DEM for Rwanda. We apply a forward stepwise regression in order to obtain the highest model quality using the lowest possible number of predictors (Hosmer and Lemeshow, 2000). We used the area under the ROC (AUC) curve as a metric for model quality (e.g., Jacobs et al., 2018; Depicker et al., 2020b). The AUC is a measure of the discriminatory power of the model, i.e. the probability that a random landslide location will receive a higher susceptibility score than a random non-landslide location.

Following the approach proposed by Depicker et al. (2020b), we applied 10-fold cross-validation in order to ensure that our model is not overfit (i.e. it works well for the training data of the susceptibility model, but performs poorly on locations that were not used for model training). Hence, we randomly split our data in 10 groups of equal size. Subsequently, we tried to predict the susceptibility for each group and assess the associated AUC value, each time using the other nine groups for model training. We reported the average AUC value of these 10 observations. The validation shows that overall the model performance are better with the 30m SRTM (Table 2). Data-driven models are the most performant when a good balance between data resolution and model complexity is kept. This is something that we have already observed for the landslide susceptibility assessment in the Rwenzori mountains (Jacobs et al., 2018).

Table 2: **Validation of the susceptibility models using a 10-fold cross validation procedure**

Model	AUC (10-fold CV) %	
	lithology	No lithology
10 m DEM	89.3	85.0
30 m DEM	91.1	88.8

The difference of model prediction performance is marginal whether the lithology is used or not. As the lithological information is coarse at the watershed scale, we selected the model without lithology (highlighted in yellow in Table 2).

To summarize, we used in this study the regional susceptibility model that was computed with all the predictor variables but the lithology at a 30m resolution (Table 2). The hazard assessment (Step 3) is based on this susceptibility model.

2.4.3.2 Variable importance analysis and the origin of the landslides

To investigate the impact of each separate predictor variables on landsliding, we calibrated a univariate susceptibility model of which the AUC value is a metric for the importance of the one used variable for landslide occurrence (Figure 4). This approach is commonly used in the literature (Reichenbach et al., 2018) and was already applied successfully by Depicker et al. (2020b) for the Lake Kivu region.

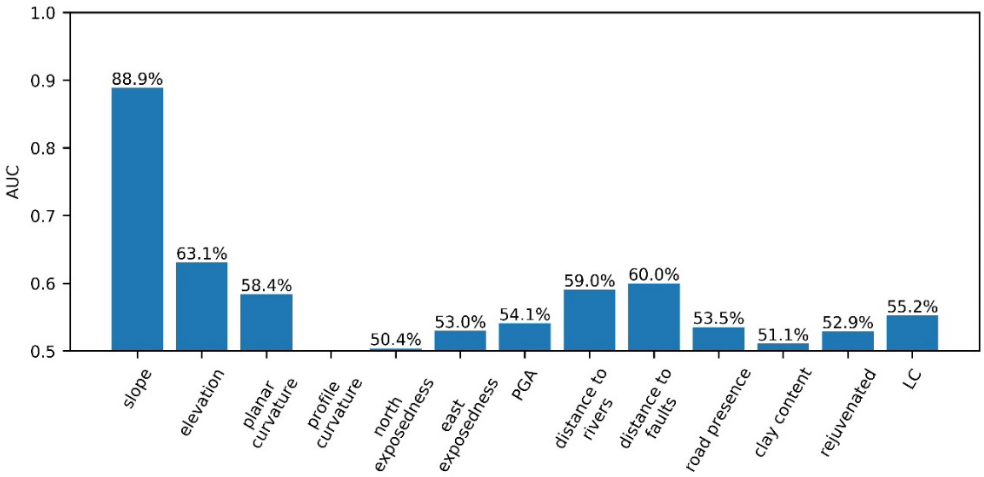

Figure 4: *Variable importance in the logistic regression model*

Figure 4 shows that slope is the main explanatory variable, followed by elevation, distance to fault, etc. The role of slope is not unexpected, as relief is the ultimate driver of landslide activity (Schmidt and Montgomery,1995), especially in hilly and mountainous landscapes such as those of Rwanda. The role of elevation could be explained by the general increase of convective rainfall with altitude. Depicker et al. (2020a, 2020b) showed that rainfall thresholds for landsliding are exceeded more often at higher elevations in the Lake Kivu region. At first sight, it might seem strange that distance to faults and PGA, proxies for seismicity, seem to play a role, despite our observation that all recent landslides were rainfall-triggered. A possible reason for the high importance of these variables could be the role of seismo-tectonic activity as a preparatory factor for landsliding, rather than a triggering factor. Seismicity weakens the hillslope material and hence reduce the minimum critical area for landslide initiation (Depicker et al., 2020a). Distance to river is certainly to be explained with presence of knickpoints and the continuous adaptation of the hillslope to river incision (Bennett et al., 2016).

The other variables play a minor role. It is however important here to keep in mind that the inventory used in the analysis was built from Google Earth images. As stressed in the inventory section, this implies that many of the very small landsides that are found along the roads are not mapped; which could be a reason why the role of roads on the occurrence of landsliding is less highlighted through the susceptibility assessment. Another reason of this limited role of roads is certainly to be found in the resolution of the topographic information used to derive the predictors. Road landslides are linked to engineered slope controls that cannot be constrained from topographic products such as the 10 m and 30 m resolution DEM (Jacobs et al., 2018; Dewitte et al., 2021).

2.4.3.3 Susceptibility maps

The outputs of a logistic regression model, as well as for data-driven models in general, provide values that have no physical meaning. 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 5). The category [0.80 – 1.0] presents the class that is the most prone to landsliding. The opposite class is ≤ 0.2]. 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).

The susceptibility of the models are presented together with the inventory of the recent and old deep-seated landslides (Figure 5). As explained earlier, these landslides are here considered as a specific susceptibility zonation where the probability of ground deformations is expected to be higher than outside these slope instabilities. We propose two categories (old and recent), the susceptibility to ground deformations being higher for the recent deep-seated landslides.

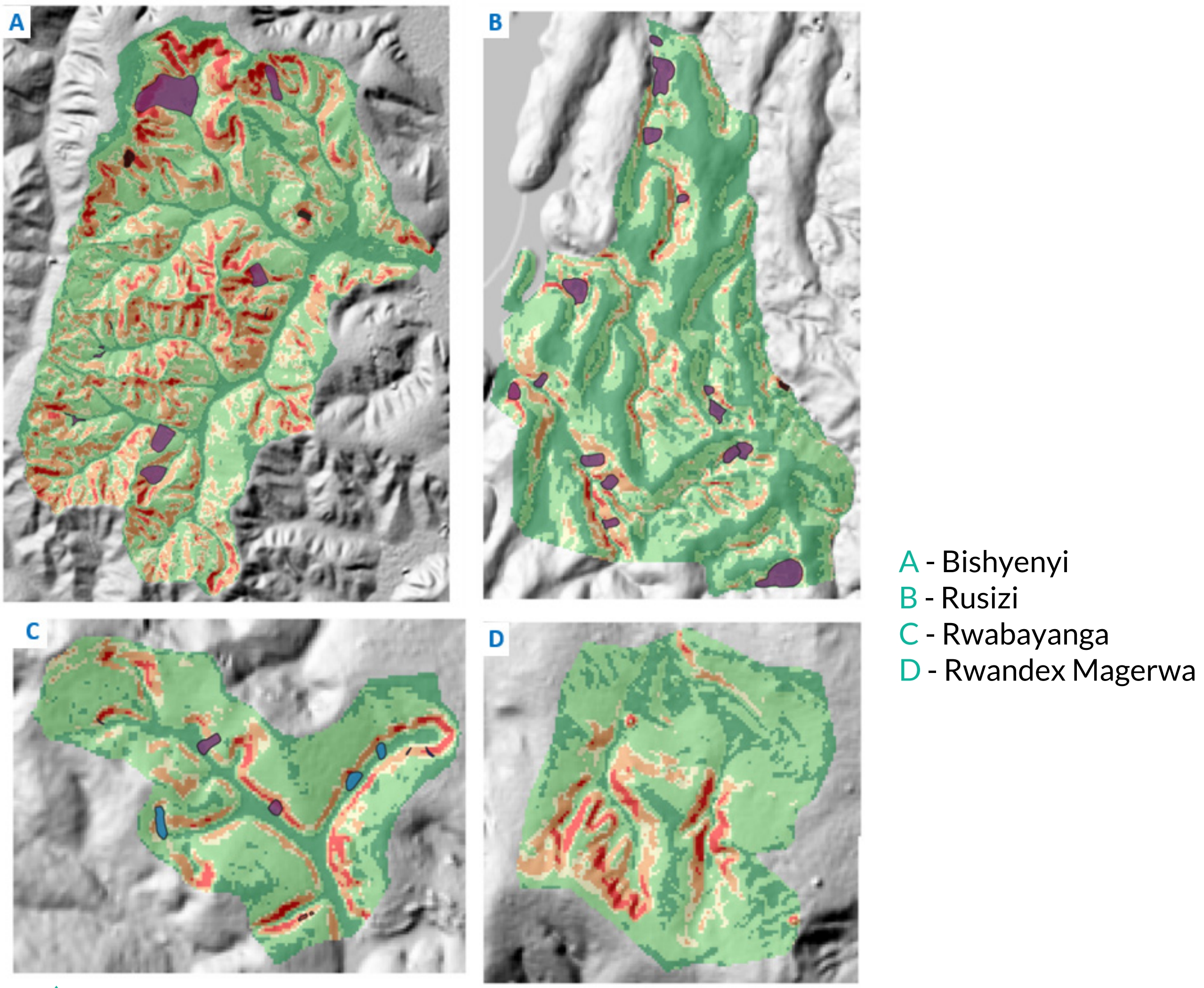

Figure 5: *Landslide susceptibility in the four study areas (purple and blue areas are inventoried landslides)*

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.

Table 3: **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%

Table 4: **Sub-catchment average values of landslide susceptibility**

Sub -catchment	Average landslide susceptibility
Bishenyi	0.37
Kamembe-Gihundwe	0.34
Rwandex-Magerwa	0.46
Rwabayanga	0.26

Table 5: **Sub-catchment average values of landslide frequency (mean landslide frequency and mean landslide affected area)**

Sub -catchment	Average frequency LS/year/km^2	Average affected area m^2/year/km^2
Bishenyi	0.023	16.40
Kamembe-Gihundwe	0.016	11.5
Rwandex-Magerwa	0.037	26.9
Rwabayanga	0.009	6.62

The landslide susceptibility values are derived directly from the logistic regression. The landslide frequency and affected area values are obtained from the combination of susceptibility values and landslide frequency and size (see Step 3 for details).

From a visual interpretation of the two susceptibility classes with the highest values, the Bishenyi sub-catchment displays the susceptibility pattern that is the most evenly distributed across the landscape, whereas Rwandex-Magerwa sub-catchment is the landscape where concentration of the highest susceptibility areas is the most concentrated (Figure 5).

The distribution of the deep-seated landslides is different from that of the shallow landslide susceptibility. The Kamembe-Gihundwe sub-catchment is affected by 15 old landslides while no such slope failure processes are observed in the Rwandex-Magerwa landscape (Figure 5).The largest old landslides is located in the Bishenyi. This is also in that sub-catchment that the five recent deep-seated landslides are present (Figure 5).

The difference between the susceptibility patterns of shallow and deep-seated landslides is not something uncommon, and particularly at this scale of investigation. As explained in the inventory section (Step 1), deep-seated landslides can have a complex origin that spans a very long period of changing environmental conditions while shallow landslides reflect more the current environment where human-activities (land use/cover and roads) also play a role.

At the local scale, the exact location of deep-seated landslides highly depends on heterogeneous local conditions associated with the lithology and hydrogeology (e.g. Dille et al., 20019) that are much more difficult to constrain than slope and other topographic conditions that usually have a stronger direct control on shallow slope failures (Sidle and Bogaard, 2016).

2.5 Step 3: Landslide hazard assessment

2.5.1 Objective

The objective of this step is to assess of landslide occurrence (and associated magnitude) within a certain time frame and area. As explained earlier this assessment is carried out for the initiation of the shallow landslides alone. The hazard is therefore estimated for the landslide source area.

2.5.2 Method

We linked the landslide susceptibility (Step 2) to landslide hazard by assessing the average hazard in different sub regions that are delineated according to their susceptibility (Figure 6). The first sub region encompasses all areas with a landslide susceptibility values between 0 and 0.1, the second sub region all areas with an LSS value between 0.1 and 0.2, and so on. Concretely, for each susceptibility class, the total affected area by the landslide sources (Figure 3 b) 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 m² year-1 km-2 , i.e. a landslide rate. The combination of a susceptibility (where a landslide occur), with a rate (how often and how strong) characterizes the hazard (Guzzetti et al., 1999; Glade et al., 2006). More details on the assessment of the hazard can be found in Depicker et al. (in review).

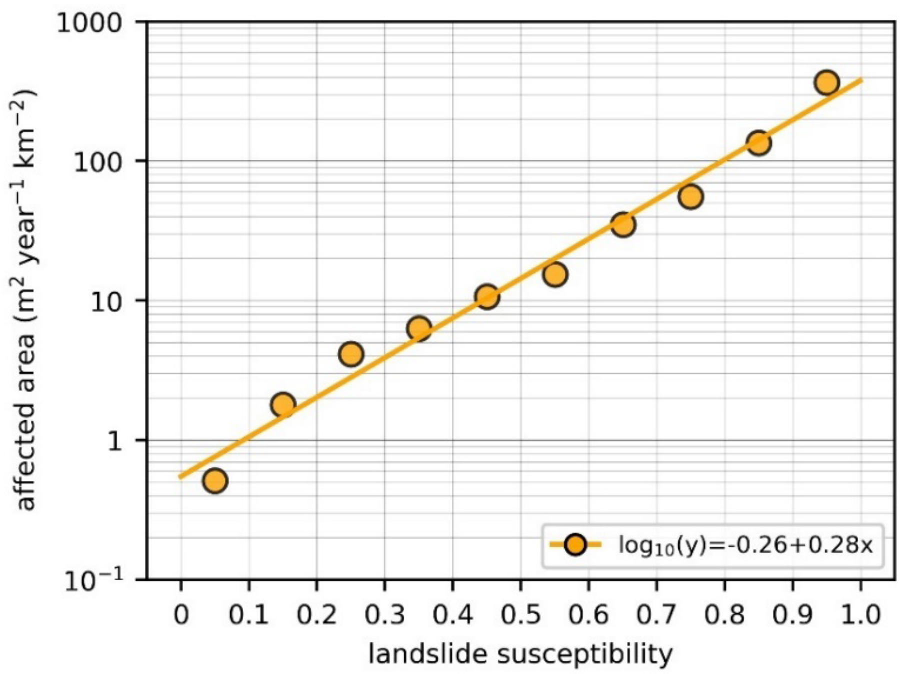

Figure 6: *Relationship between landslide susceptibility and landslide affected area (i.e. landslide rate)*

The relationship between landslide susceptibility and landslide affected area represents the landslide hazard. The landslide affected area increases exponentially with susceptibility. For the susceptibility class 0.9-1.0, the landslide rate is ~400 m² year-1 km-2, for the class 0.8-0.9 it is ~150 m² year-1 km-2, and so on.

2.5.3 Results

2.5.3.1 Landslide hazard maps

Looking at the average landslide frequency and landside affected area values (Table 6), we observe the same ranking as for the susceptibility maps. Rwandex-Magerwa is overall the sub-catchment that has the highest average hazard, while Rwabayanga is with the lowest values. However, the comparison of the landslide hazard maps is even less obvious than the susceptibility as it includes the exponential behaviour of the landslide rate component (Figure 6). Therefore, to make the comparison of the hazard maps more robust, we have first calculated the probability density of the susceptibility values (Figure 7 a) that were weighted, using equation of Figure 6, via the multiplication of the landslide rates (Figure 7 b). This gives a better view of the actual hazard in the different sub-catchments, showing the importance of the highest susceptibility classes.

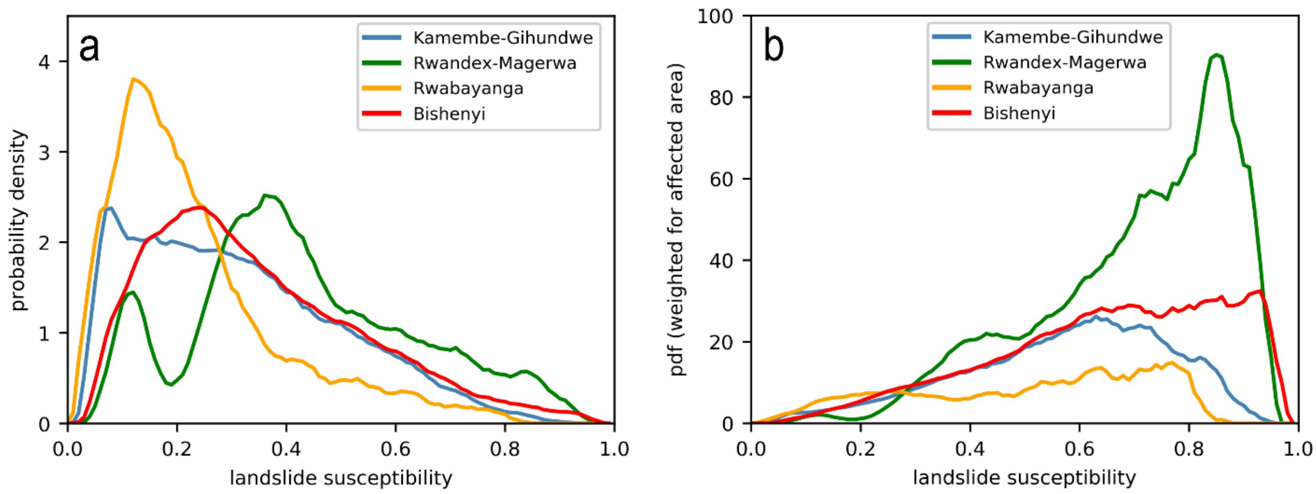

Figure 7: *A) Probability density. B) Probability density weighted for landslide rates (i.e. affected area)*

Therefore, the regional landslide susceptibility model has been classified in four classes, starting from the most susceptible pixel. In other words, the class 0-10% contains the 10% of the landscape that are most prone to landsliding. For each class, the average landslide rate was computed m² year-1 km-2 based on the relationship from Figure 6. The landslide hazard maps are therefore provided for four categories of rates (Figure 8).

Table 6: **Landslide hazard categories**

Susceptibility classes	Average landslide hazard rate $m^2/year/km^2$
0-10% (highest susceptibility)	365
> 10- 30%	90
> 30-60%	18
> 60-100%	1

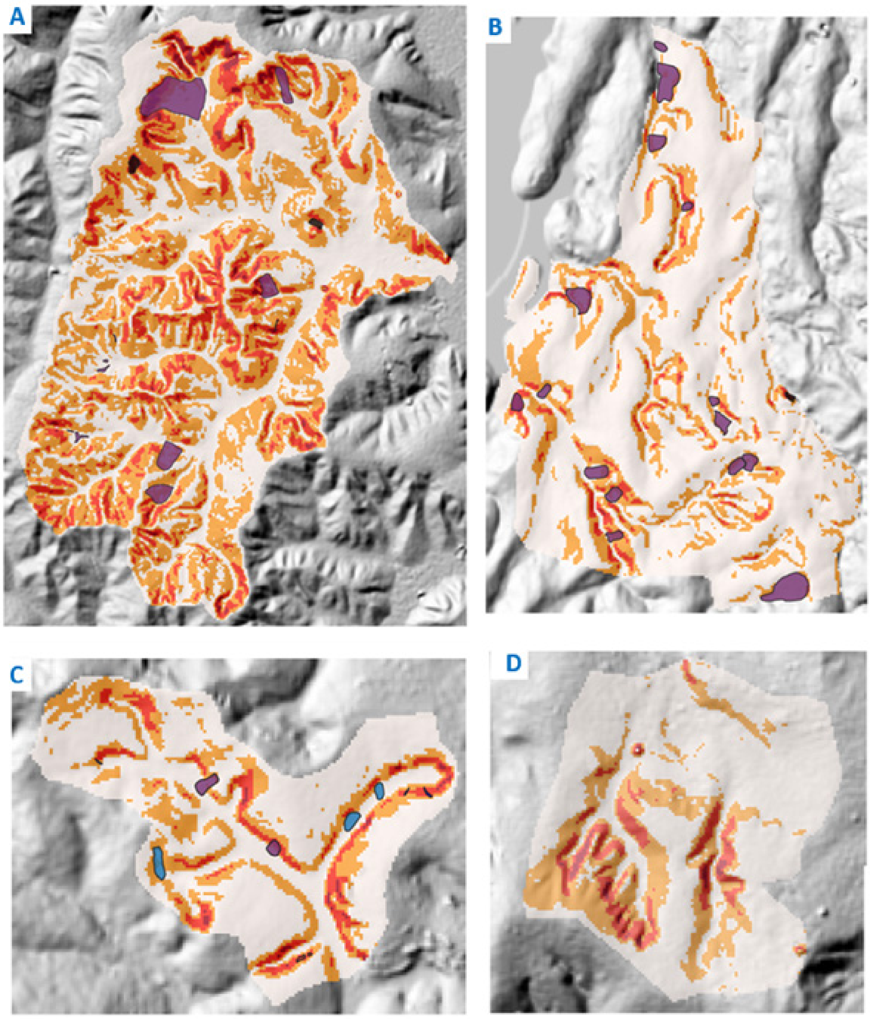

Figure 8: *Landslide hazard maps (purple and blue areas are inventoried landslides)*

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

2.5.3.2 How to read the hazard maps – what the hazard scenario means

When looking at the hazard map, the rate class (365 m² year-1 km-2) means that for an area of 1 km² (i.e. 106 m2) that belongs to the top 10% of the landscape that is the most susceptible to shallow landslide initiations in western Rwanda, 365 m² will be affected by the initiation of a slope failure every year. One can say that in ~2700 years; each pixel of this hazard area has the probability of being affected by the initiation of landslides. Note that this scenario is only here for the initiation of the landsides (i.e., the source area of the landslide) and does not consider the total area of the landslides (i.e. the source area + the impact zones – Figure 3 b). For every m² of new landslide initiation, 5 m² of landslide impacts are to be assumed (see description of inventory in Step 2).

We can therefore say that every year, for an area of 1 km2, 6*365 m² will be impacted by landslides. In other words, this represents 0.2 % of the area that are impacted every year. Knowing that it is based on an inventory from satellite images from which the identification of the landslides is always an underestimation (see earlier sections), we can fairly say that, overall, in the highest hazard class, every year about 1% of the land is impacted by the occurrence of new landslides.

Table 7: **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%

The hazard class of 365 m²/year/km2 that corresponds to the highest value in western Rwanda, corresponds to a very high hazard for the Lake Kivu region in general (Depicker et al., 2020a). When looking at the global scale, the highest hazard that we find in this study is relatively moderate (Larsen and Montgomery, 2010; Broeckx et al., 2020). However, such an assessment must be considered with care since environmental conditions of other regions can be highly different.

In Step 1, we explained that, in the Lake Kivu region, clusters of landslides (sometimes with thousands of slope failures) can occur and that their spatio-temporal distribution is random on a few years basis since they are associated with extreme convective rainfall events. This randomness must be kept in mind and an area that is not highlighted as hazard-prone can still be impacted by dramatic landslide events.

The model we provide shows trends and will never be able to tackle, at the local scale of these sub-catchments, the random processes associated with stochastic weather events. Together with the hazard assessment, we provide the inventory of the deep-seated landslides and highlight the susceptibility to ground deformations. Since we do not have measure of the ground deformation rates, we cannot provide a hazard scenario. However, as observed in other regions, and notably in the region of Bukavu in DRC that is close to Rwanda, ground deformations in such landslides can be pervasive (Nobile et al., 2018; Dille et al., 2021). As such, on a short time scale, independent of the weather conditions, disturbances due to existing deep-seated landslides are potentially higher. This needs further investigation.

2.6 Step 4: Exposure and vulnerability

2.6.1 Objectives

The goal of exposure and vulnerability assessment is to build an exposure database and assess the vulnerability of the elements at risk to landslides. Seeing we did not receive any vulnerability databases produced by other parties to assess the elements at risk based on previous landslides, we carried out a spatial overlap of hazard zonation and elements at risk. Such an approach using a simple exposure analysis is common in the literature as acquiring detailed vulnerability information remains generally a challenge, which would require significant research investment that is not compatible with the duration of this study (Glade et al., 2006; Corominas et al.,2014).

2.6.2 Results

Results were produced from a desktop exercise by spatially overlapping the hazard zonation (landslide rate) developed in Step 3 (Figure 8) with the different land use categories. Results are presented for two scenarios summarised in tables 8 and 9 below: -

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

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

Table 8: **Landslide exposure database for the current land use situation as per 2018 land use plans**

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

Table 9: **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	-	-

2.6.3 Comparative analysis of impacted land use categories

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 $m^2/year/km^2$ landslide hazard rate class only, which, as previously mentioned, corresponds to a very high hazard for the Lake Kivu region in general.

Land use categorisation in the projected land use masterplan (2050) is not the same as that of the 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.

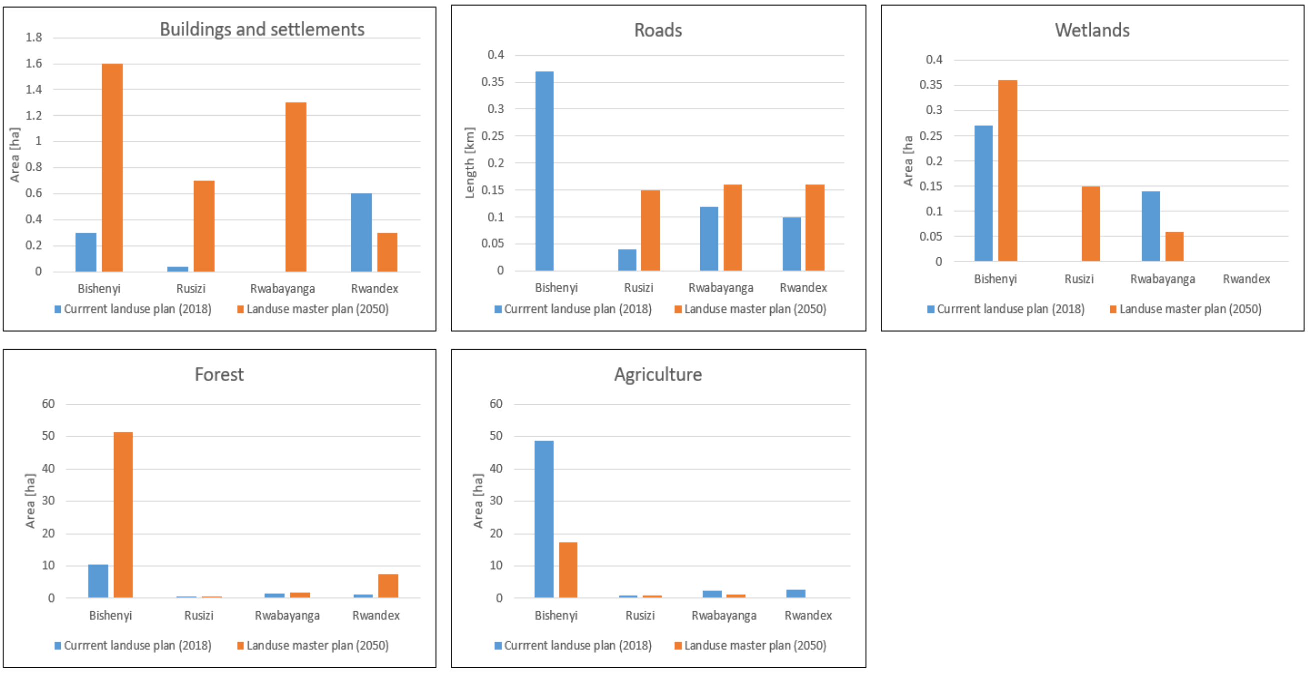

Figure 9: *Comparative analysis impacted land use categories – current and projected land use plans*

2.7 Step 5: Landslide risk assessment conclusion

2.7.1 Summary

This study has been undertaken to assess landslide risk in the sub-catchments of Rwandex-Magerwa, Bishenyi, Rwabayanga and Rusizi. The deliverable has been landslide risk maps for each watershed (refer to pdf maps accompanying report). Maps are classified in several classes.
The study has produced landslide risk maps in the form:

- Landslide inventories (step 1);
- Landslide susceptibility maps (step 2);
- Landslide hazard maps (step 3);
- Exposure databases (step 4)

2.7.2 Conclusion

The risk maps are here visual combinations of landslide process scenarios and land use categories. They allow to highlight the places where the risk could be the more problematic. Depending on the slope instability processes and the land use, the risk is different. For example, places where deep-seated landslides are located are areas where ground deformations are expected to be the larger (independently from soil creep, which is not discussed here, although highlighted in step 1). Such deformations can be very slow (a few centimetres per year or even less; e.g. Nobile et al., 2019; Dille et al., 2021) and therefore be not at all a problem for agricultural land. On the contrary, building a new road or heavy infrastructures on such areas could create problems (fractures, etc.) as most foundations cannot be deep enough to reach a stable bedrock below the surface of rupture of the landslides. While slow-moving deformations can have pervasive impacts difficult to mitigate, people are not in immediate dangers.

The hazard scenario we have computed here concerns shallow landslide processes. Their impacts will be much different from those of deep-seated processes. In terms of direct impacts, such shallow landslides can directly cover a road, but will not really damage it. Concerning big buildings with deep foundations, such landslides will also have minor impacts. However, shallow landslides can potentially remove a lot of soil and therefore have impacts of the fertility level of the agricultural land. Shallow landslides are in the region commonly associated with heavy rainfalls. They can occur very quickly and be responsible of fatalities.

When looking at such documents, we must be aware that further investigations are needed to really assess the problem, not only in terms of landslide process understanding (location, mechanism, deformation rate), but also in terms of vulnerability and direct and indirect impacts.

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2.9 Appendices

2.9.1 Appendix 1

<u>**Selection of the predictor variables for the shallow landslide susceptibility assessment**</u>

Checking for multicollinearity between the independent variables

Multicollinearity occurs when two or more predictor variables are strongly correlated with each other. In other words, multicollinearity occurs when one or more predictor variables can be accurately predicted by a linear combination of one or more of the other variables. Multicollinearity between predictor variables will not influence the accuracy or quality of the final landslide model. However, it can bias our interpretation of the variable importance. Hence, it is recommended to remove any strong multicollinearity between the predictor variables prior to constructing and analyzing the landslide model. Here we calculated two techniques to assess multicollinearity: the Variance Inflation Factor (VIF) and the Condition Indices (Cis).

The VIF for a predictor variable i is calculated as $\frac{1}{1 - R^2}$

Whereby the R2 is derived from a regression model that predicts variable i with the other variables as predictor. We consider a variable problematic (in terms of multicollinearity) when its VIF>4 (Belsley et al., 2005). For the variables used in our landslide susceptibility model, we observed no problematic VIF (Table 10).

Table 10: **Variance inflation factor for the continuous variables used in the landslide susceptibility model.**

Variable	VIF
Slope	1.04
Elevation	1.73
Profile curvature	1.17
Planar curvature	1.20
North exposure	1.00
East exposure	1.00
PGA	2.96
Distance to rivers	1.16
Distance to faults	3.46
Road (50m buffer)	1.00
Soil with >35% clay	1.06

Note that the morphological parameters were derived here from the 10 m resolution DEM.

The CIs are a second approach to check for multicollinearity (Belsley et al., 2005). A CI higher than 30 signals moderate to strong multicollinearity, while a CI<10 indicates weak multicollinearity. When two or more variables both have a very high variance decomposition proportion (>0.9) for the same CI, they are strongly correlated with each other. Within our data, the CIs indicated no problematic multicollinearity issues (Table 11).

Table 11: **Condition Indices (CIs), calculated for the continuous variables used in the landslide susceptibility model**

	Condition index	Slope	Elevation	Profile curvature	Planar curvature	North exposure	East exposure	PGA	Distance to rivers	Distance to faults	Road buffer	>35% Clay
1	**1.000**	0.007	0.002	0.000	0.000	0.000	0.000	0.004	0.010	0.012	0.006	0.013
2	**1.817**	0.000	0.000	0.319	0.311	0.000	0.000	0.000	0.000	0.000	0.004	0.000
3	**2.110**	0.000	0.000	0.000	0.000	0.521	0.452	0.000	0.000	0.000	0.013	0.000
4	**2.127**	0.000	0.000	0.000	0.000	0.465	0.539	0.000	0.000	0.000	0.000	0.000
5	**2.254**	0.004	0.000	0.007	0.000	0.011	0.007	0.001	0.001	0.000	0.927	0.003
6	**2.412**	0.006	0.000	0.001	0.000	0.000	0.001	0.000	0.779	0.012	0.000	0.022
7	**2.664**	0.000	0.000	0.670	0.687	0.001	0.000	0.000	0.002	0.000	0.003	0.000
8	**3.332**	0.075	0.005	0.001	0.001	0.001	0.000	0.033	0.023	0.312	0.012	0.216
9	**3.870**	0.004	0.002	0.000	0.000	0.000	0.001	0.001	0.003	0.459	0.011	0.728
10	**6.203**	0.755	0.020	0.001	0.000	0.000	0.000	0.301	0.084	0.001	0.025	0.016
11	**11.324**	0.149	**0.971**	0.000	0.000	0.000	0.000	0.661	0.097	0.204	0.000	0.001

No problematic multicollinearity was observed.
Note that the morphological parameters were derived here from the 10 m resolution DEM.

Reference

Belsley, D. A., Kuh, E., Welsch, R. E., 2005. Regression Diagnostics. Hoboken, New Jersey: John Wiley & Sons. doi:10.1002/0471725153

SECTION 2: PROPOSAL OF POTENTIAL LANDSLIDE MITIGATION MEASURES

3.1 Introduction

Because of the variety of the landsides processes, the nature of regolith and rock environments and landscapes in which they are found (Appendix 1), 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 in steps 1 to 5 as at risk and vulnerable to landslides. With the first paragraph in mind that any mitigation measures should be implemented based on data and information that we have not at this stage of our knowledge, one have to keep in mind that the purpose of this section is not to go beyond the sole role of the literature review. Further research and expertise actions are needed if one want to move towards the implementation of concrete mitigation measures. The measures presented here are therefore not catchment-specific, and to some extent not specific to a type of landslide in particular. The structure of the report is as follow: first, the mitigation measures are detailed. Along with criteria for the selection of the mitigation measures, details are provided on measures at the level of the hazard, the vulnerability, and the element at risk. The measures are then discussed in the context of the Catchment Restoration Opportunity Mapping Support System (CROM DSS). Together with the presentation of the mitigation measures, additional figures and appendixes explaining and illustrating key concepts are proposed to ease the understanding of the document. As a last note, a brief focus is provided on gully erosion. Although not landslide processes, problems of gullying have been identified in the study areas.

Figure 10 summarizes the framework for landslide risk management. This represents a framework widely used internationally (Fell et al., 2008). In this document on potential mitigation measures, we focus on one of the aspects of the whole risk management process.

Before starting presenting the potential mitigation measures that could be tested in the four study areas, it is important to provide an overview of the main findings of the first part of the analysis that concerned the landside risk and that are relevant for the mitigation focus. In this first part of the analysis were identified several slope failure processes:

- Deep-seated landslides. These processes are of the slide and earthflow types. Although it was not directly observed here in the field, these landslides are known to occur in all types of slope material, whether it is in highly weathered mobile regolith, or, at the other extreme of the weathering process, into fresh bedrock (Dille et al., 2019; Dewitte et al., 2021; Kubwimana et al., 2021).
- Shallow landslides. These landslides were not identified directly from the analysis of the Google Earth images in the four watersheds, but it is known that they can occur in the region at any time, especially during rainfall events. This is for these landslides that the landside hazard and risk analysis was carried out. In the region of western Rwanda, these landslides are commonly of the slide and avalanche types (Depicker et al., 2021). They mostly occur in regolith material and the degree of weathering of the material where they develop is variable (Kubwimana et al., 2021).
- In addition to these slope failures processes, soil creep is also known to occur on the hillslopes, affecting the regolith layer. This process can produce colluvium slopes where landslides can also take place.
- Gully erosion is also observed. Gully erosion is a process that is not due to gravity and it is not considered as a landslide process. Nevertheless, gully erosion is frequently associated with landsliding, either in cause or in consequence of it.

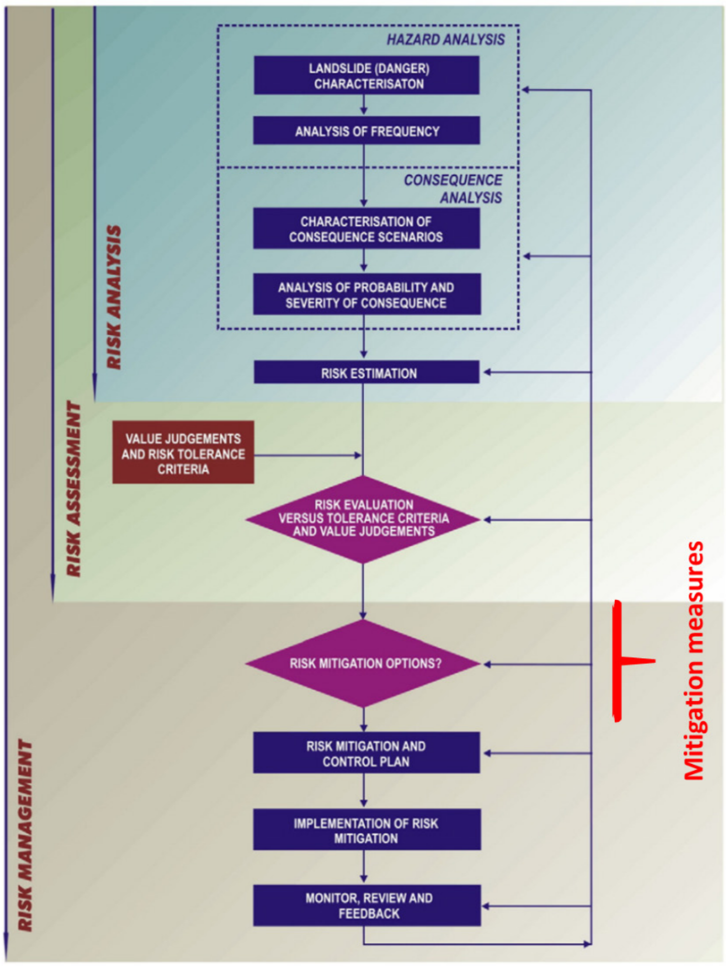

Figure 10: *Framework for landslide risk management. Adapted from Fell et al. (2008).*

To better understand the differences between the various landslide processes, visuals are provided in Figure Appendix 1.1. Landslide characteristics reflect the very diverse geologic, topographic, environmental, and climatic conditions (Figure Appendix 1.2) in which they can occur, resulting in a large diversity of landslide types and processes (Lu and Godt, 2013; Hungr et al., 2014; Sidle and Bogaard, 2016).

The four study areas are also inhabited, therefore presenting landscape alteration components that can have an influence on the landslide processes, essentially on the shallow landslides that are the most sensitive to the surface conditions such as the vegetation characteristics. The figure in Appendix 1.2 shows a general overview of the landslide predisposing factors (i.e. the ecosystem dynamics (ED) and the regolith/hillslope environment factors (RHE)) that may be altered by human actions. More specifically, here is a list of human actions in the landscapes that we have identified in the four study areas and that have the potential to alter the drivers of the landslides and therefore their distribution in space, in time, and in size:

- Deforestation and afforestation. Recent studies have evidenced that role on the shallow landslides in increasing landslide rates (Depicker et al., 2021). See Figure 11.A.
- Road construction. Recent studies in the region have also evidenced that role on the landslide occurrence (Dewitte et al., 2021; Kubwimana et al., 2021). See Figure 11.B.
- Agricultural practice. This included the implementation of agricultural terraces and irrigation.
- House/building constructions. These will change notably the surface water runoff conditions, as well as the load on the soil and, depending of the depth of the foundation, the groundwater conditions. See Figure 11.C.
- Mining/quarrying activities. These activities can locally have dramatic consequences where slope and sediment (rock, regolith) properties are changed (Dewitte et al., 2021). Recent work in the region of Bujumbura (Kubwimana et al., 2021) shows this.

<u>All the factors highlighted above, i.e. landslides types and landscape change characteristics, are parameters that must be taken into account in the mitigation of the landslide processes.</u>

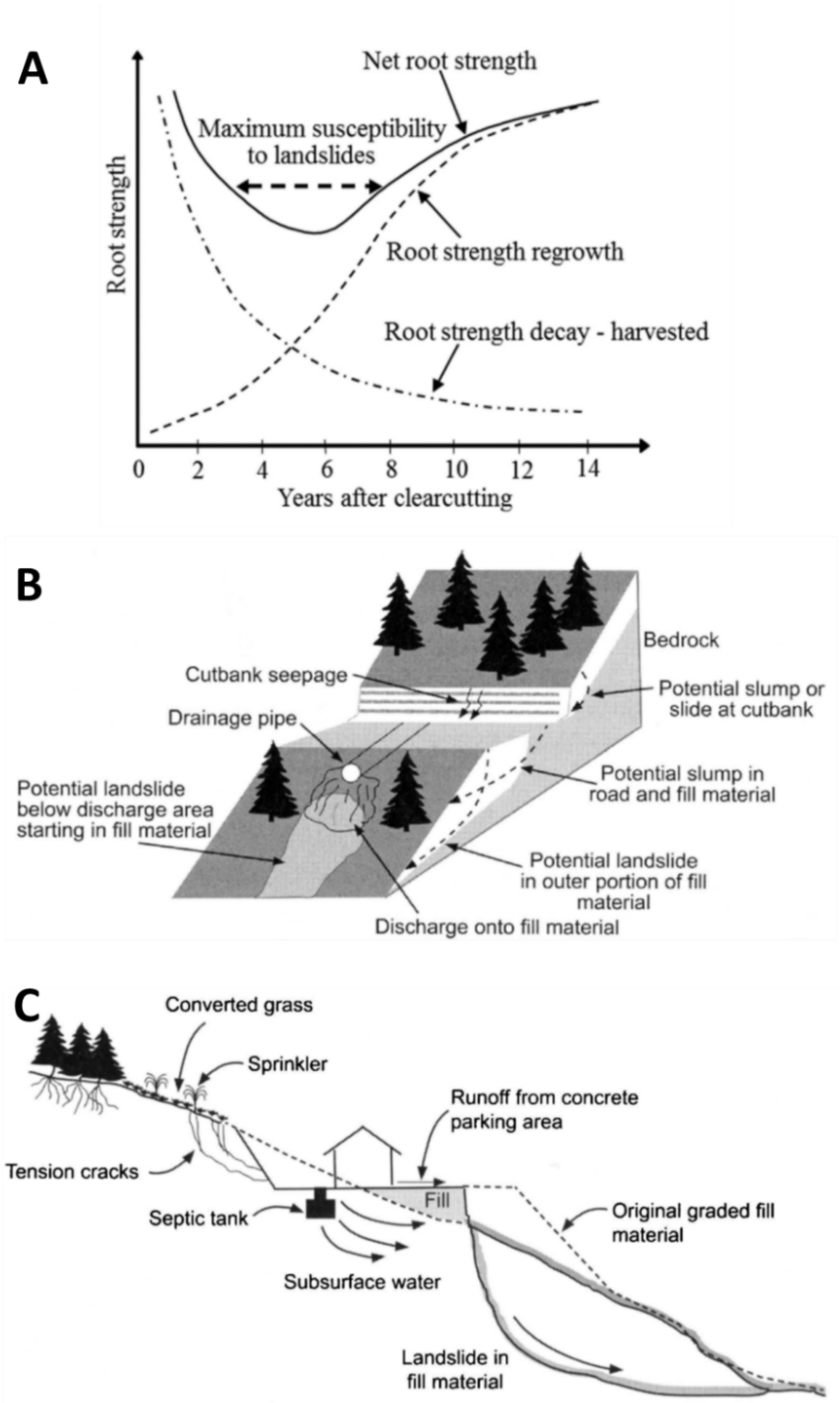

Figure 11: *A) Relative root strength following tree removal. Depending on tree species and site characteristics, the period of highest susceptibility for shallow landslides is between 3 to 15–20 after timber harvest; however, a rainfall event is still required to initiate a landslide, but with a lower threshold. Once regenerating tree roots fully establish, the risk of shallow landslides returns to pre-harvest conditions. Source: Sidle and Bogaard, 2016. B) Road effects on slope stability and drainage. Source: Sidle and Ochiai, 2006. C) Urban and residential influences on slope stability. Source: Sidle and Ochiai, 2006.*

3.2 Types of mitigation measures

Potential mitigation measures that could be implemented in the framework of this analysis are numerous (Turner and Schuster, 1996). Here we follow the classification proposed by the SafeLand project (https://www.ngi.no/eng/Projects/SafeLand); the SafeLand report (SafeLand, 2012) is attached as a supportive document. Table 12 shows that the Total Risk 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 12 makes the difference between structural and non-structural 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.

Table 12: **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

3.3 Criteria for selection of the mitigation measures

The selection of the most appropriate mitigation measures to be adopted in specific situations must take into account, according to Keaton and Beckwith (1996) and SafeLand (2012), the following aspects:

- Factors which determine the hazard, in terms of the type, rate, depth and the probability of occurrence of the movement or landslide, such as, for example:
  - The physical characteristics of the geosystem, including the stratigraphy and the mechanical characteristics of the materials, the hydrological (surface water) and the hydrogeological (groundwater) regime;
  - The morphology of the area;
  - The actual or potential causative processes affecting the geosystem, which can determine the occurrence of movement or landslides;
- Factors which affect the nature and quantification of risk for a given hazard, such as the presence and vulnerability of elements at risk, both in the potentially unsta ble area and in areas which may be affected by the run-out;
- Factors which affect the actual feasibility of specific mitigation measures, such as, for example:
  - The phase and rate of movement at the time of implementation;
  - The morphology of the area in relation to accessibility and safety of workers and the public;
  - Environmental constraints, such as the impact on the archaeological, historical and visual/landscape value of the locale;
  - Pre-existing structures and infrastructure that may be affected, directly or indirectly;
  - Design standards;
  - Balancing cut and fill;
  - Capital and operating cost, including maintenance.

Note that avoiding the landside problem is an excellent approach if it is considered during the planning phase. However, a large cost may be involved if a landslide problem is detected after the location has been selected and the design completed. With that respect of avoidance, the consideration of the inventory map of the old and recent deep-seated landslides that we have identified during the first phase of the project is important. This locates the places that are the most prone to be affected by ground deformations. Avoidance should also be kept as a potential mitigation measure for the area that we have identified has the most landside hazard prone.

3.4 Measures to reduce the hazard

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 of the landslide(s) which the specific measure is intended to address. This type of mitigation measures are sometimes referred to as “stabilization”.

The stability of any hillslope is decided by a balance of forces between stresses driving downward movement (shear stress) and stresses resisting to movement (shear strength) at the bottom interface between the landslide mass and the stable material, with gravity as the primary driving force (Lu and Godt, 2013). Thus, factors (or forcings) that affect the shear strength (e.g., weathering, vegetation, past movement, variation in pore-water pressure or changes in hydrologic conditions/properties) or the shear stress acting on the hillslope (e.g., mass redistribution, debuttressing at the toe, transient loading from earthquakes) are potential causes to landslide failure and/or acceleration (Sidle and Ochiai, 2006; Lu and Godt, 2013; Lacroix et al., 2020).

This mechanical balance between driving and resisting forces is mediated by the presence of water in the slope and quantified using the concept of effective stress (Lu and Godt, 2013). Water infiltration will lead to the build-up of pore-water pressure within the slope (generally depicted by the transient development of a perched water table), which will typically reduce the shear strength of the slope material (Sidle and Ochiai, 2006) and increase shear stress due to the weight of water (Lu and Godt, 2013). Besides, interactions between forcings – such as the combination of rainfalls with earthquake(s) – may affect the slope stability further than each forcing individually, illustrating the complexity of landslides mechanisms (Lacroix et al., 2020). It is to be noted that, when considering factors conditioning the hillslope stability, it is important to account that the forcings triggering initial failure (i.e., landslide occurrence) may be different from forcings controlling later motion (if any).

Independently of the causative processes and the complexity of the specific geosystem under consideration the factors which determine the triggering of movements are:

a) decrease in shear strength
b) increase in shear stress

The ratio between shear strength and shear stress forms the factor of safety (FS), i.e. an easy approach to discuss what drives the stability of a slope. This ratio may change over time in response to environmental changing conditions (Figure 12 and Figure in Appendix 1.2).

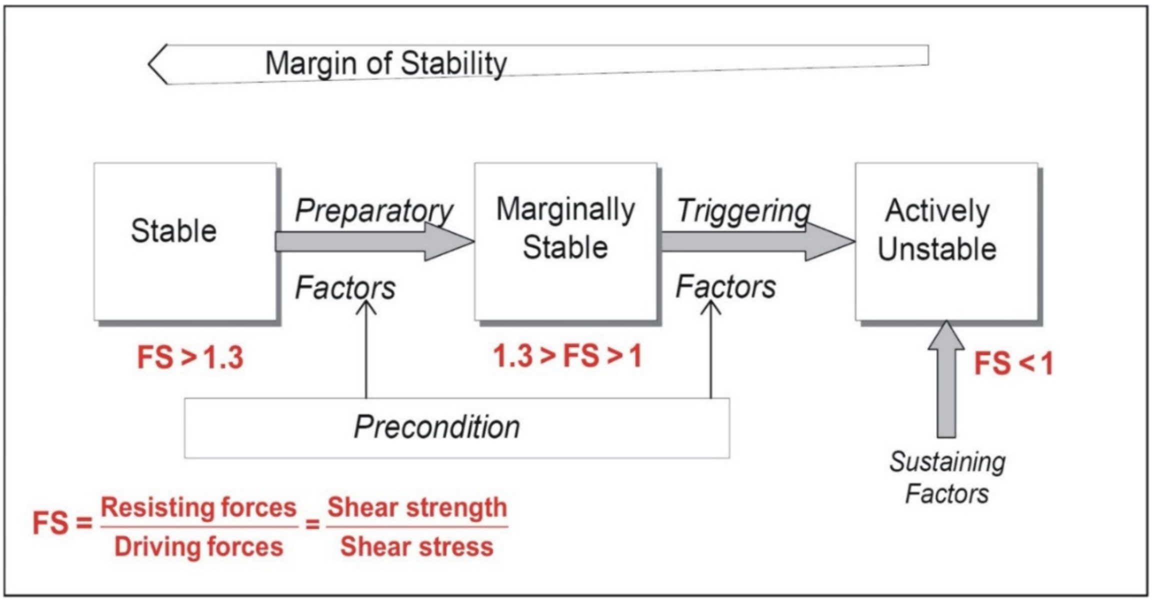

Figure 12: *Stability states and destabilising factors. Adapted from Glade and Crozier (2005). Landslides occur when the factor of safety (FS) is < 1.*

The most common causative processes that will have an impact of the changing characteristics of the factor of safety are listed in Table 13 and partly summarized in Figure 13. Combinations of (a) and (b) often act simultaneously as a direct result of external processes, as in the case of basal erosion or excavations, which can cause both an increase in shear stress through increased slope angle and/or height, or a decrease in shear strength, through a reduction in total and effective stress.

Table 13: **Triggering factors with examples of common causative/forcing processes. Adapted from Leroueil (2001) and Lu and Godt (2013).**

Triggering factor	Common causative/forcing processes
Decrease in shear strength	Infiltration due to rainfall, irrigation, leakage from utilities and the associated increase in pore-water presssures or changes in hydrolic conditions/properties Construction activities, e.g. pile diving Wheatering and cjnage is regolith or rock shear-strength properties Root decay (e.g. from forest removal)
Increase in shear stress	Weigth extra due to rianfall - weight of water Erosion or excavation at the toe Overloading at the top (e.g. by other mass movements or by placement of fill Mass redistribution (e.g. due to terracing) Transient loading from earthquake

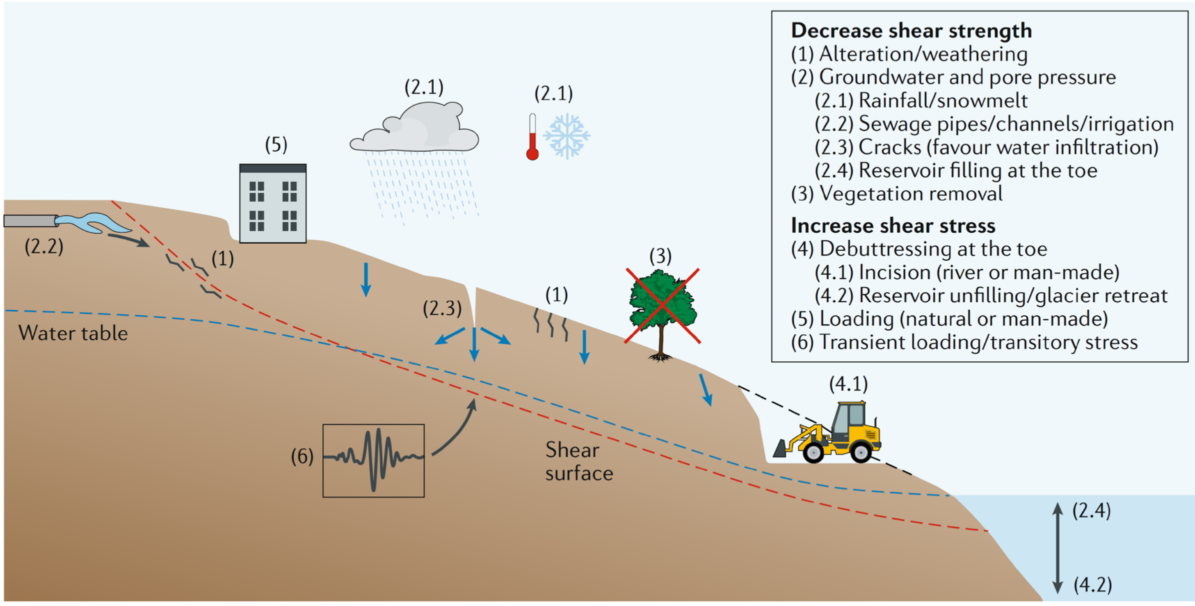

Figure 13: *Stability Schematic demonstrating the possible forcings of landslides. Source Lacroix et al., 2020.*

In order to reduce the probability of triggering, 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.

While this could provide a first step in the classification of this type of mitigation measures, it is more convenient to classify them on the basis of the physical process involved. In particular, it is here recommended to distinguish between the classes indicated in Table 14. In Appendix 2 we propose extra information on the mitigation approaches to reduce the hazard.

Retaining structures are used extensively and can be considered as an additional class of hazard mitigation measures, even though they are used as means to modify slope geometry and/or to transfer load to more competent strata, rather than to address a specific physical process.

Table 14: **Landslide Hazard Mitigation Measures (adapted from Popescu & Sasahara, 2009)**

Physical process	Brief description
Surface protection; control of surface erosion	• Vegetation (hydroseeding, turfing, trees/bushes) • Fascines/brush. • Geosynthetics. • Substitution; drainage blanket • beach replenishment; rip-rap. • Dentition
Modifying the geometry and/or mass distribution	• Removal of material from the area driving the landslide (with possible substitution by lightweight fill). • Addition of material to the area maintaining stability, with or without gravity, catilever, crib/cellular and/or reinforced soil walls. • Reduction of the general slope angle. • Scaling (removal of loose/unstable blocks/boulders).
Modifying surface water regime – surface drainage	• Diversion channels • Check dams • Surface drains (ditches, piping) to divert water from flowing onto the slide area. • Sealing tension cracks. • Impermeabilization. (*) • Vegetation. (*) 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 • Subhorizontal drains • 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 • Vertical medium diameter wells with gravity drainage through a base collector • Caissons (large diameter wells), with or without secondary subhorizontal drains and gravity drainage • 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 • Compaction • Deep mixing with lime and/or cement • Permeation or pressure grouting with cementitiuous or chemical binders • Jet grouting • Modification of the groundwater chemistry
Transfer of loads to more competent strata	• Shear keys: counterforts, piles; barrettes (diaphragm walls); caissons • Anchors: soil nails; dowels, rock bolts; multistrand anchors (with or without facing consisting of plates, nets, reinforced shotcrete) • Anchored walls (combination of anchors and shear keys)

3.5 Measures to reduce the vulnerability

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 (Figure 14 and Figure 15).
- 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.

Measures to reduce the vulnerability through the increase of structural resistance may be summarized as follows:

- Strengthening of shallow foundations and improved structural design to withstand predicted permanent ground displacements;
- Deep foundations properly designed to accommodate the landslide effect;
- Deep anchoring of foundation elements;
- Combination of the above three approaches.

Another important parameter affecting the strengthening approach is the fact that any approach is strongly case-depended, in the sense that the characteristics of the structure, its relative position within the landslide zone and the regolith-rock properties play an important role in any strengthening decision. This is why the relevant research and design practice is rather fragmented. Consequently it is practically impossible to define, in a general way, the improvement in the vulnerability (in quantitative terms) obtained by increasing the resistance of different parts of the structure, because de facto this is a case depended evaluation.

Measures to stop or to deviate the path of the landslide debris resistance relate to the following landslide types (Figure in Appendix 1.1):

a) Earth or debris flows of any type;
b) Toppling, rumbling or free falling rocks of various sizes.

They should be foreseen when the general stabilization of the landslide is not feasible from technical, environmental and financial point of view.

The basic idea of these measures is to intercept the sliding or falling material, or at least to deviate it, in order to protect existing elements at risk or points of particular interest located downslope of a potential landslide. Typical measures includes:

- Diversion channels;
- Re-modelling of the slope;
- Planting and vegetation on the slope;
- Catch trenches;
- Rockfall barriers;
- Rockfall nets (or Drapery)
- Rock sheds.

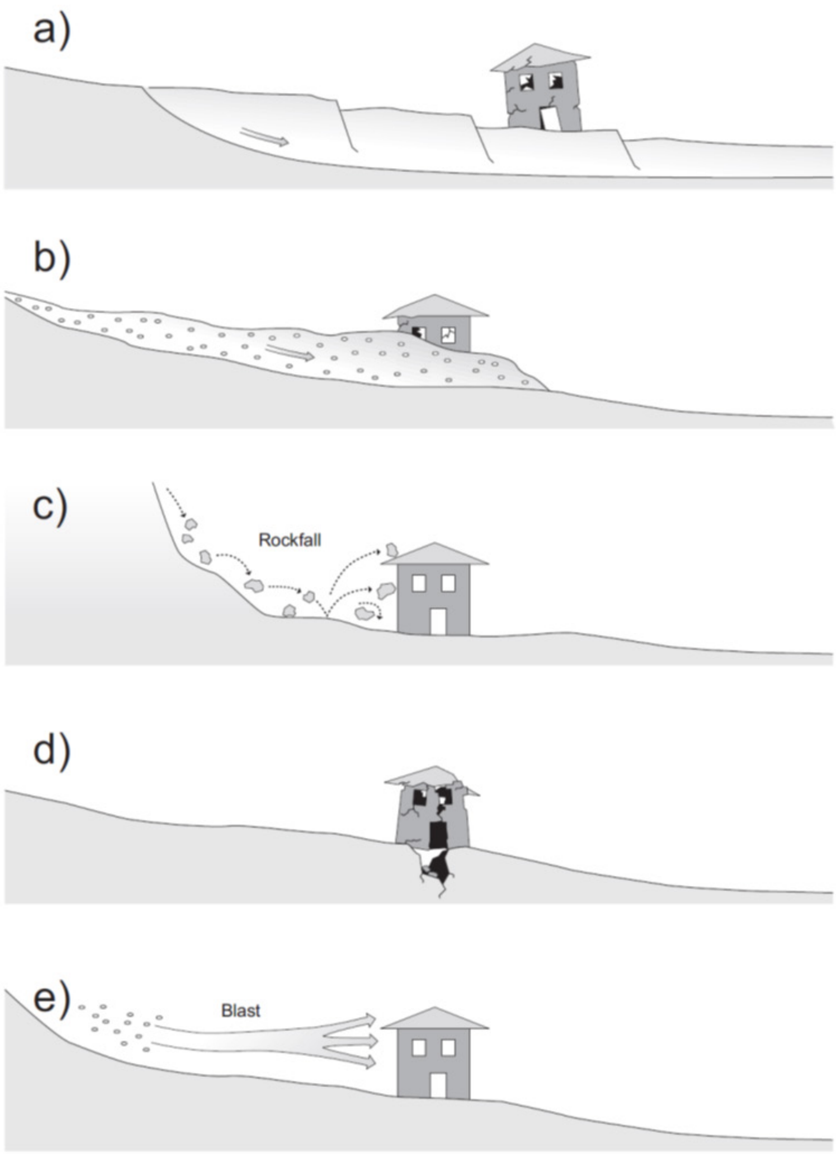

Figure 14: *Schematic representation of structural damage to buildings for different landslide types. Damage is assigned to slide and flow processes (a), to flows (b), to falls and topples (c), to subsidence (d), and to rock avalanches or large rock failures (e). Source: Glade and Crozier, 2005.*

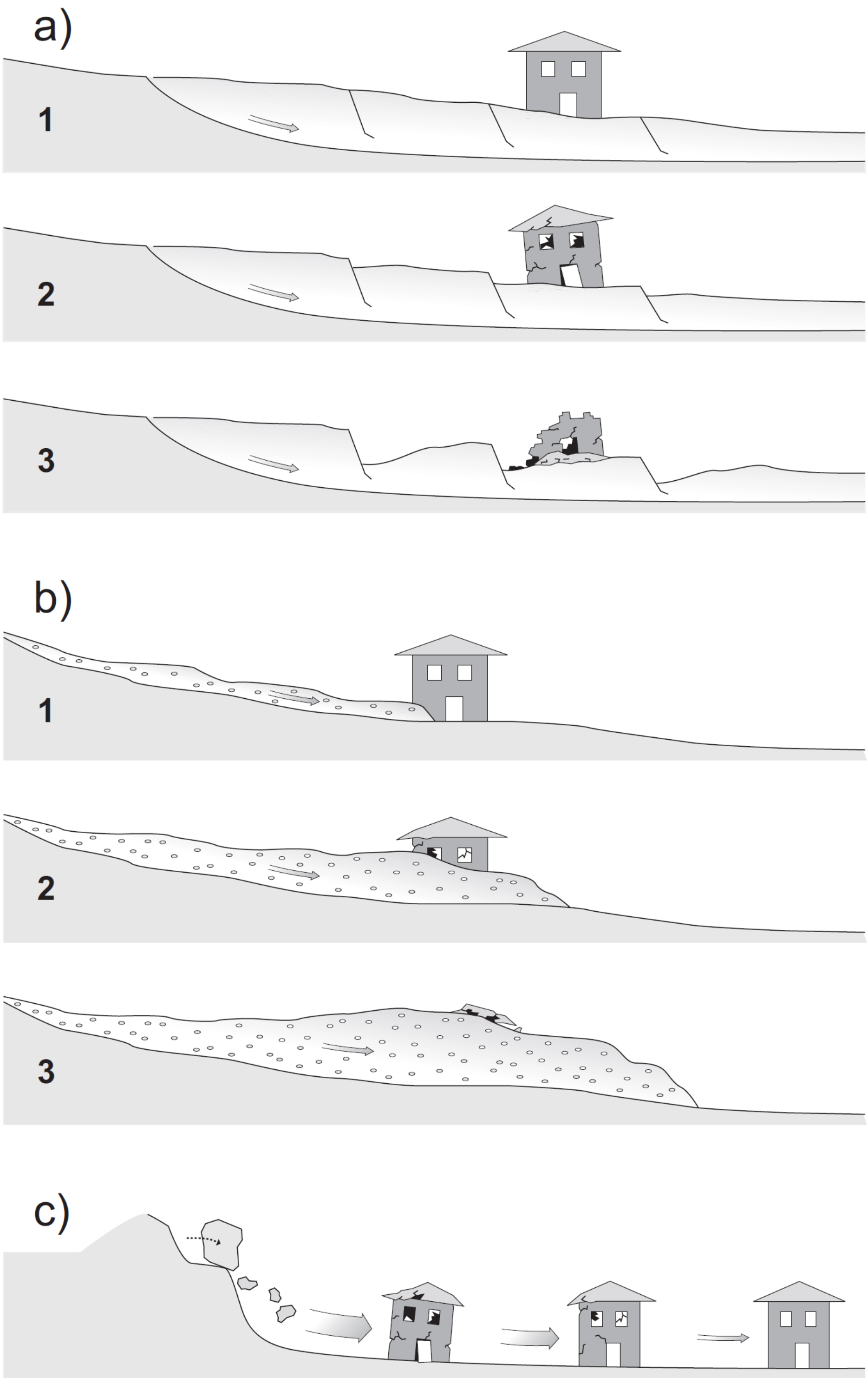

Figure 15: *Schematic consequences of different velocities of movement for different landslide types. A slide creeps (a.1) or fails suddenly (a.3). A debris flow progresses in low (b.1) or high velocities (b.3) with respective changes in flow height. A slow or fast moving rock fall damages, depending on the size and consequent momentum, elements at risk to a different degree (c). The degree depends on the distance between the process and the location of the element at risk. Source: Glade and Crozier, 2005.*

3.6 Measures to reduce the elements at risk

The temporary or permanent reduction of the number and/or value of the elements at risk is widely practiced and particularly cost effective, especially when the number of elements at risk is small in relation to the extent of the landslide and of the affected area and when it is achieved through the sustained implementation of appropriate long-term planning measures.

Ambrozic et al. (2009) and SafeLand (2012) distinguish between:

- Decreasing the number of vulnerable elements potentially affected by a landslide, for example by:
  - Zoning to prevent development in hazardous areas or removing existing development from hazardous areas (exclusionary zones);
  - Traffic restrictions (reduce number of vehicles).
- Decreasing the probability that vulnerable elements will both spatially and temporally intercept ground movements, e.g. by:
  - Moving non-stationary vulnerable elements to less hazardous locations;
  - Increasing awareness, detection and warning of hazards (either detected movement or trigger conditions) and subsequent avoidance (evacuation or temporary exclusion, followed by inspection before resuming normal use).

Each of these strategies can be implemented forcibly through standards and legislations or, less invasively, by means of incentives or disincentives introduced through planning. These actions could be:

- Relocation of existing facilities: Existing facilities can be completely eliminated or they can be reconverted to uses which imply a lower vulnerability to landslides;
- Reduction of specific value: The average number of people and/or the value of economic activities associated with a specific element at risk can be reduced, for example by limiting the range of end uses allowed through the planning instruments;
- Avoiding the construction of new facilities: The forced relocation of existing facilities is an extremely invasive measure, potentially applicable only in the most serious situations. A more practical approach in many cases may be the implementation of a long term strategy to prevent the location of new elements within hazardous areas, either by enforcing planning limits or through policies based on incentives or disincentives

A quote that presents landslide mitigation from a general perspective

To quote Highland an Bobrowsky (2008): "Vulnerability to landslide hazards is a function of a site's location (topography, geology, drainage), type of activity, and frequency of past landslides. The effects of landslides on people and structures can be lessened by total avoidance of landslide hazard areas or by restricting, prohibiting, or imposing conditions on hazard-zone activity. Local governments can accomplish this through land use policies and regulations. Individuals can reduce their exposure to hazards by educating themselves on the past hazard history of a desired site and by making inquiries to planning and engineering departments of local governments. They could also hire the professional services of a geotechnical engineer, a civil engineer, or an engineering geologist who can properly evaluate the hazard potential of a site, built or unbuilt."

3.7 Highlight on CROM DSS

The Catchment Restoration Opportunity Mapping Support System (CROM DSS) developed by W4G for the IWRM programme, a nationally-adopted tool for the mapping of soil erosion risk areas in Rwanda, proposes several land use options to mitigate the degradation of soil erosion by rainfall (e.g. agroforestry, progressive and bench terraces, forestation). This document is framed around a RUSLE soil erosion analysis, i.e. a physically plausible empirical method for predicting soil erosion (Renard et al., 1997). The RUSLE-based modelling approach provides estimates of the potential rates of soil displacement by water erosion (soil erosion). More specifically, the RUSLE modelling only predicts soil losses caused by sheet and rill erosion. In short this model does not handle at all other soil erosion processes such as gullying. In addition, gravity-driven processes such as landslides are not at all seized by this model. Therefore, what is suggested to managed soil erosion in CROM DSS must be considered with the highest care when mitigating the landslides. Indeed, reducing soil erosion, means reducing the runoff water. If the runoff is reduced, this means that the infiltration of the water is increased. If the infiltration is increased, this means that the soil/regolith water content is increased, hence creating conditions that are more favourable for landsliding (Sidle and Ochiai, 2006; Lu and Godt, 2013, Table 13, Figure 13).

A very striking feature in soil water conservation is that of agricultural terraces (Figure 16 – Figure Appendix 3.1); i.e. soil conservation practices that are commonly adapted in many regions of Rwanda e.g. the Ministry of Agriculture and Animal Resources (MINAGRI) set up the fourth Strategic Plan Agriculture Transformation for 2018 – 2024 where bench terraces are highlighted as a mean to fight against soil erosion).

Slopes in steep terrain are often converted into terraces. Terraces are structures that are built to divide a slope into short and gently sloping segments, as a measure to reduce the slope steepness. Terraces change the topography of slopes and thus hydrological pathways, for example by decreasing the runoff. Moreover, the surface roughness is altered, decreasing overland flow connectivity. These changes will reduce the runoff and improve water conservation, which will lead to a higher soil moisture and water holding capacity (Wei et al., 2016). Therefore, the mentioned factors will reduce (severe) soil erosion (e.g. sheet and rill erosion, gully formation) and benefit soil conservation (FAO, 2000). Worldwide, these structures are used to decrease runoff and combating soil erosion (Wei et al., 2016).

Within the tropics, however, very little is known about the impact of terracing on the occurrence of landslides. In South-East Asia, Sidle et al. (2006) argued that terraces allow for greater water infiltration and thus create conditions favourable for landslides. Turkelboom et al. (2008) observed an elevated landslide frequency on terraced slopes in northern Thailand. A similar perception is held by farmers in Eastern Uganda (Kitutu et al., 2011). It is to be expected that the impact of terraces on landslides is, to some extent, dependent on the terrace typology and management. However, this hypothesis still has to be tested in the tropics. The impact of terrace typology on land degradation processes has already been demonstrated in Rwanda where labour-intensive bench (radical) terraces appear to be more effective at controlling soil erosion compared to progressive terraces (i.e. terraces gradually made by local farmers – aka Fanya-juu terraces), yet landslides were not investigated in these studies (Fashaho et al., 2020; Rutebuka et al., 2021).

One of the key issues associated with terracing is their abandonment (Wei et al., 2016). Such abandonments generally equal to a total lack of maintenance, which in the long run can accelerate the formation of existed rills, interrills, gullies, gravitational erosion, piping and landslides on marginal slopes. Without adequate maintenance, various natural or other human-generated forces will gradually damage the structure and strength of terrace walls and risers, leading to a complete terrace failure. For example, Agnoletti et al. (2019) showed that abandoned terraces are particularly sensitive to slope failures, yet their study is situated in temperate regions.

Another agricultural activity that can lead to slope destabilization is irrigation, which can help increase water recharge in the upper soil layers. This process has been well documented in Indonesia, where the liquefaction of unconsolidated materials associated with the 2018 Palu earthquake was accentuated in irrigated areas, triggering translational landslides and lateral extension on relatively gentle slopes of less than a few degrees (Watkinson and Hall, 2019).

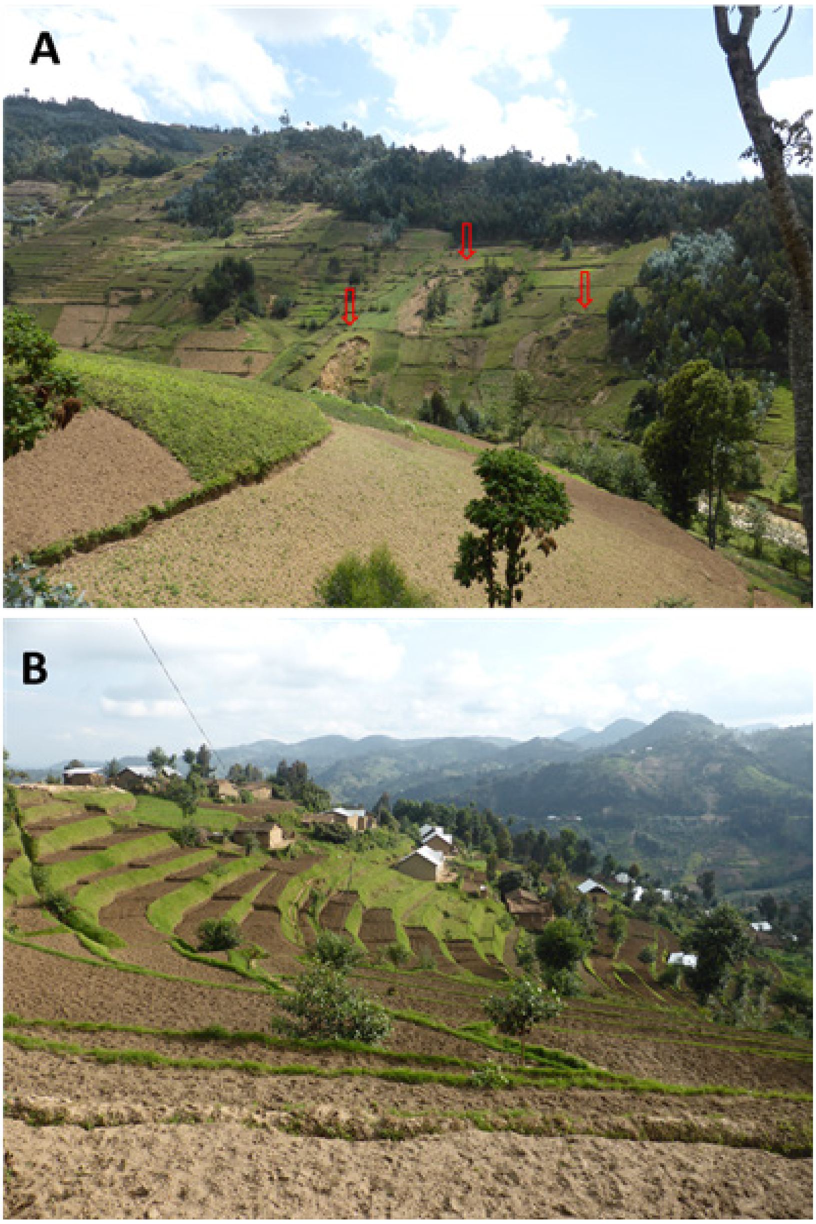

Figure 16: *A) Cropland and planted forest with different measures for soil conservation (contour ploughing & bund, terracing, etc.). Note also the presence of shallow landslides (red arrows). Photo taken in September 2018 in Kabaya (Ngororero district) in Rwanda. B) Photo of bench terraces. Photo taken in May 2021 in Karago (Nyabihu district) in Rwanda. Author of both photos: O. Dewitte.*

3.8 Gully erosion

Gully erosion is a major environmental problem, posing significant threats to sustainable development. However, insights on techniques to prevent and control gullying are scattered and incomplete, especially regarding failure rates and effectiveness. For an overview of the problem, we refer to the review paper recently published by Frankl et al. (2021) - https://onlinelibrary.wiley.com/doi/epdf/10.1002/esp.5033

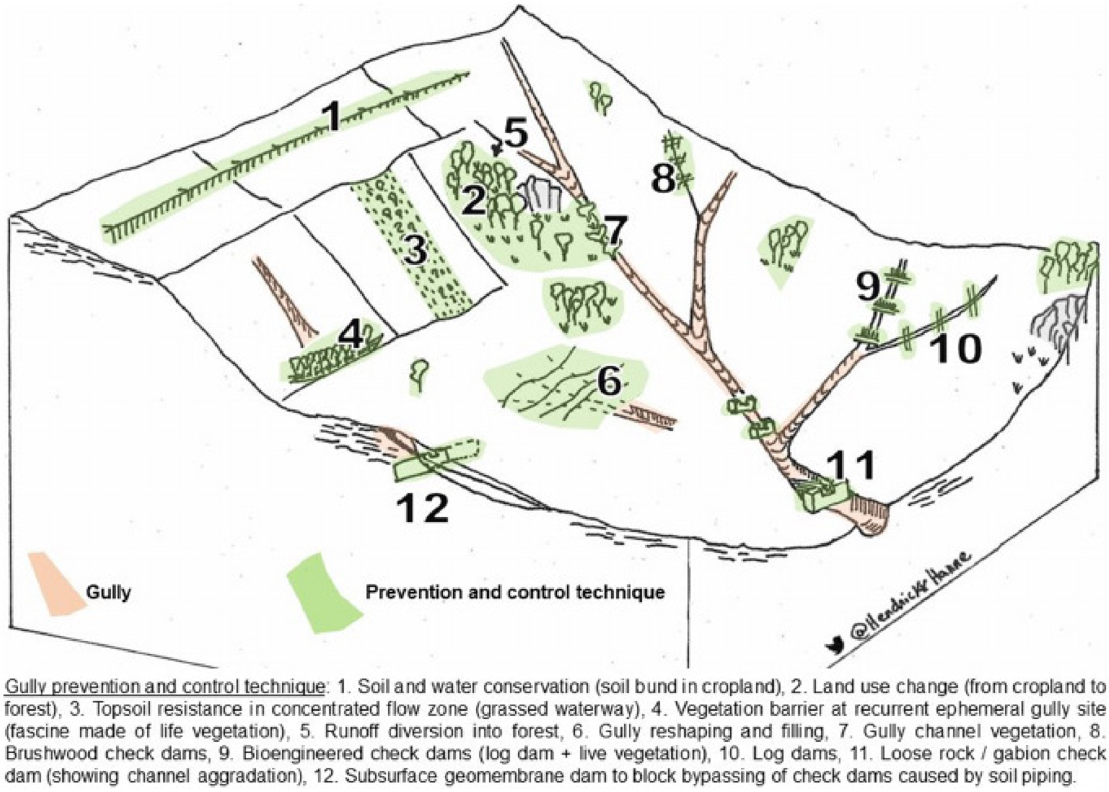

Figure 17: *Overview of gully prevention and control techniques discussed in this paper. Source: Frankl et al., 2021.*

The main outcomes of this paper, summarized by Figure 17, are:

- Preventing gully formation can be done through land use change, applying soil and water conservation techniques or by targeted measures in concentrated flowzones. The latter include measures that increase topsoil resistance and vegetation barriers. Vegetation barriers made of plant residues have the advantage of being immediately effective in protecting against erosion, but have a short life expectancy as compared to barriers made of living vegetation.
- Once deeply incised, the development of gullies may be controlled by diverting runoff away from the channel, but this comes at the risk of relocating the problem. Additional measures such as headcut filling, channel reshaping and headcut armouring can also be applied.
- To control gully channels, multiple studies report on the use of check dams and/or vegetation. Reasons for failures of these techniques depend on runoff and sedi ment characteristics and cross-sectional stability and micro-environment of the gully. In turn, these are controlled by external forcing factors that can be grouped into (i) geomorphology and topography, (ii) climate and (iii) the bio-physical environment.
- The impact of gully prevention and control techniques is addressed, especially regarding their effect on headcut retreat and network development, the trapping of sediment by check dams and reduction of catchment sediment yield. Overall, vegetation establishment in gully channels and catchments plays a key role in gully prevention and control. Once stabilized, gullies may turn into rehabilitated sites of lush vegetation or cropland, making the return on investment to prevent and control gullies high.

Overall, the strategy proposed by CROM DSS is well in line to tackle the problem of the mitigation of gully erosion.

3.9 Specific landslide mitigation measures for the study areas

3.9.1 Assumptions

This study has been carried based on literature review, satellite imagery review, and that no specific field measurements were taken; therefore the determination of landslide mitigation measures appropriate for each site has been based on assumptions. From these, cost estimates were produced.

The mitigation measures hereafter presented are proposed for areas in each sub-catchment with the highest susceptibility to landslides, i.e. landslide hazard classes of 365 m^2/year/km^2 and 90m^2/year/km^2. Section 1 provides details of the landslide risk assessment.

The total surface areas covered by the two landslides hazard classes are given in the table below.

Table 15: **Surface areas under the two highest landslide hazard classes**

Sub-catchment	Total surface area (ha)	Combined area under the landslide hazard classes of 365 m^2/year/km^2 and 90m^2/year/km^2
Bishenyi	4,686.8	666.7
Rwabayanga	809.0	68.4
Rwandex – Magerwa	979.3	63.9
Kamembe – Gihundwe	2,123.6	76.3

The following assumptions are made:

- Should landslides occur in the two aforementioned highest susceptibility zones, they would be shallow landslides that are likely to cause soil erosion;
- Given the assumption of shallow landslides, mitigation measures are designed to address the following physical processes:
    - o Surface protection and control of erosion;
    - o Modification of land geometry
    - o Modification of the surface water regime
- The mitigation measures proposed will not include elements that lead to an increase in surface water infiltration into the soil. It is has been discussed in the preceding section that any soil erosion control measure that leads to increased water infiltration (e.g. radical terraces) would lead to creation of conditions that are favourable to landslides;
- Within each area with the highest susceptibility to landslides, it is assumed that the total coverage of zones to be reforested is 30%. This assumption builds from the guidance of the Rwanda building code that stipulates a coverage of 30% for landscaping (trees, green spaces) in urban developments;
- For drainage trenches / ditches, a coverage of 500 m of channel per 3 ha is assumed.

3.9.2 Areas with the highest susceptibility to landslides

The maps below show the locations in each sub-catchment, which have the highest susceptibility to landslides, i.e. landslide hazard classes of 365 m^2/year/km^2 and 90m^2/year/km^2. Detailed maps are submitted together with this report.

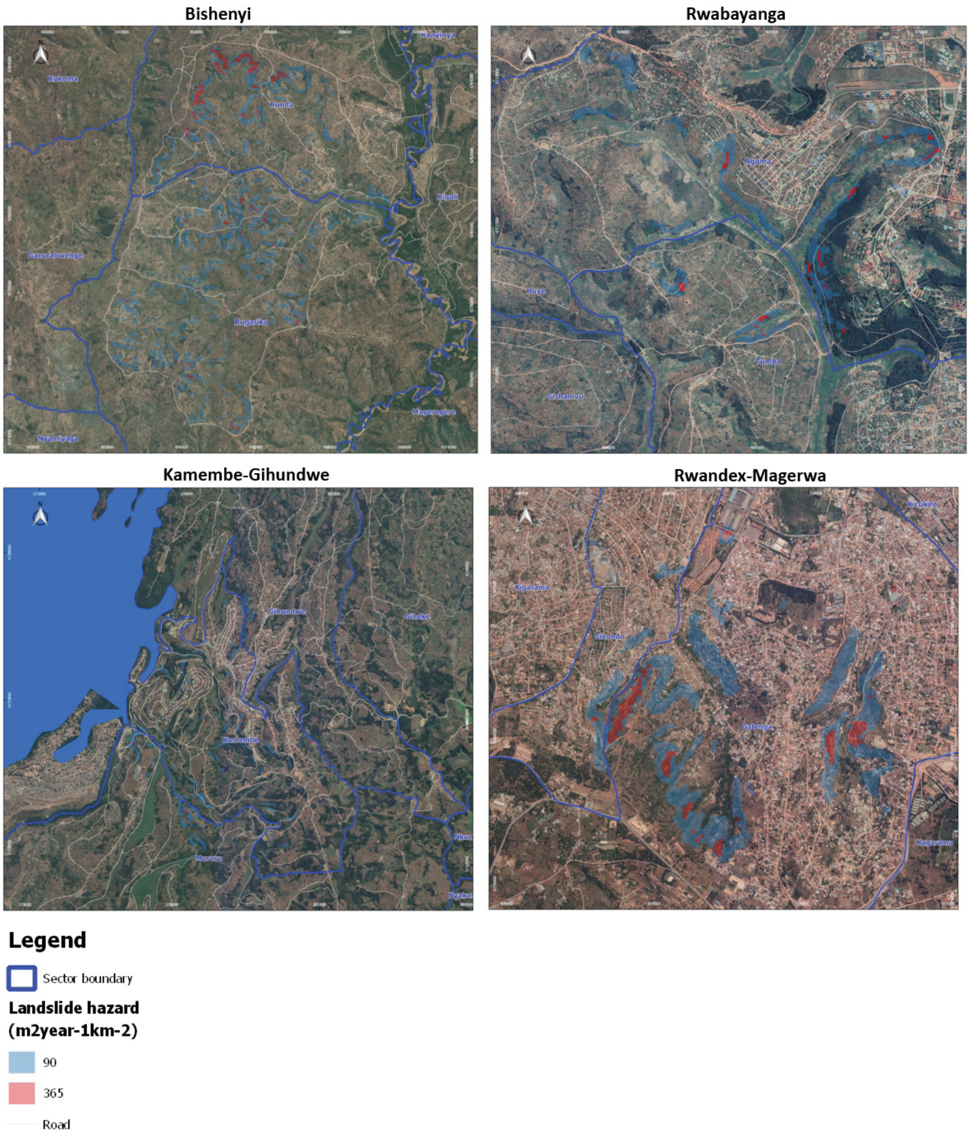

***Figure 18:** Areas with highest susceptibility to landslides in each of the sub-catchment*

Table 16 below presents the land uses in the at-risk zones:

Table 16: Existing land use in areas with the highest susceptibility to landslides

Sub-catchment	Existing land use in areas with highest susceptibility
Bishenyi	Mix of agricultural areas and forests with declining tree cover, few residential zones
Rwabayanga	Mix of agricultural areas and forests with declining tree cover
Kamembe-Gihundwe	Mix of agricultural areas and forests with declining tree cover
Rwandex-Magerwa	Mix of residential areas and forests with declining tree cover

3.9.3 Proposed mitigation measures

The mitigation measures proposed for the four study areas are informed by the Catchment Restoration Opportunity Mapping Support System (CROM DSS). The emphasis is here again placed on the assumption that, should landslides occur, these would be shallow landslides leading mostly to soil erosion. This assumption provides the rationale for the application of CROM DSS measures. The Catchment Restoration Opportunities Matrix presented in the Table 17 below summarizes the different erosion control measures according to the slopes, soil depth categories and geology.

Table 17: **CROM matrix of slope / soil depth classes and alternative land use options**

Soil depth Land slope	> 0.5 m	< 0.5 m
1: (0-6%)	**Class I** ▪ Agroforestry + contour ploughing + alley cropping with grass strips	**Class VI** ▪ Agroforestry + contour ploughing + alley cropping with grass strips ▪ Forestation where soil depth is too limited and unsuitable for crops. ▪ Perennial crops, coffee, tea, banana, fruit trees
2: (6 - 16%)	**Class II** ▪ Progressive terraces (reinforced by agroforestry hedges and grass strips) ▪ Perennial crops, coffee, tea, banana, fruit trees	**Class VII-a** ▪ Progressive terraces (reinforced by agroforestry hedges and grass strips) ▪ Perennial crops, coffee, tea, banana, fruit trees ▪ Forestation where soil depth is too limited and unsuitable for crops
3: (16 - 40%)	**Class III** ▪ Bench terraces (option only in case of suitable, stable parent material / geology; avoid introducing landslide risks) ▪ Progressive terraces (reinforced by agroforestry hedges and grass strips) ▪ Perennial crops, coffee, tea, banana, fruit trees	**Class VII-b** ▪ Progressive terraces (reinforced by agroforestry hedges and grass strips) ▪ Forestation where soil depth is too limited and unsuitable for crops ▪ Perennial crops, coffee, tea, banana, fruit trees
4: (40- 60%)	**Class IV** ▪ Narrow cut terraces (option only in case of suitable, stable parent material / geology; avoid introducing landslide risks) ▪ Progressive terraces (reinforced by agroforestry hedges and grass strips) ▪ Forestation (Biological measures) ▪ Perennial crops, coffee, tea, banana, fruit trees	**Class VIII-a** ▪ Forestation (Biological measures) + trenches / ditches
5: (> 60)	**Class V** ▪ Forestation (Biological measures) + trenches / ditches ▪ Perennial crops, coffee, tea, banana, fruit trees	**Class VIII-b** ▪ Natural vegetation

In line with the existing land use in each of the sub-catchments, the following mitigation measures are proposed:

Table 18: **Summary of proposed mitigation measures**

Sub-catchment	Existing land use in areas with highest susceptibility
Bishenyi	Agroforestry + progressive terraces, reforestation and trenches / ditches
Rwabayanga	Agroforestry + progressive terraces, reforestation, trenches / ditches and gully rehabilitation
Kamembe-Gihundwe	Agroforestry + progressive terraces, reforestation and trenches / ditches
Rwandex-Magerwa	Reforestation and trenches / ditches

A Bill of Quantities for the mitigation measures is provided below:

3.9.4 Bill of quantities

Sub-catchment	Mitigation measure	Unit	Coverage	Unit cost / RWF	Unit cost / USD	Total Cost / RWF	Total cost / USD
Bishenyi	Reforestation	ha	200.01				
	Agroforestry + progressive terraces	ha	466.69				
	Trenches / ditches	km	111.10				
					TOTAL		

Sub-catchment	Mitigation measure	Unit	Coverage	Unit cost / RWF	Unit cost / USD	Total Cost / RWF	Total cost / USD
Rwabayanga	Reforestation	ha	20.52				
	Agroforestry + progressive terraces	ha	47.88				
	Trenches / ditches	km	11.40				
	Gully rehabilitation + reforestation	ha	1.50				
					TOTAL		

Sub-catchment	Mitigation measure	Unit	Coverage	Unit cost / RWF	Unit cost / USD	Total Cost / RWF	Total cost / USD
Kamembe - Gihundwe	Reforestation	ha	22.89				
	Agroforestry + progressive terraces	ha	53.41				
	Trenches / ditches	km	12.70				
					TOTAL		

Sub-catchment	Mitigation measure	Unit	Coverage	Unit cost / RWF	Unit cost / USD	Total Cost / RWF	Total cost / USD
Rwandex-Magerwa	Reforestation	ha	44.73				
	Trenches / ditches	km	10.60				
					TOTAL		

3.10 Literature consulted for the landslide mitigation measures

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3.11 Appendices

3.11.1 Appendix 1– landslide types and processes

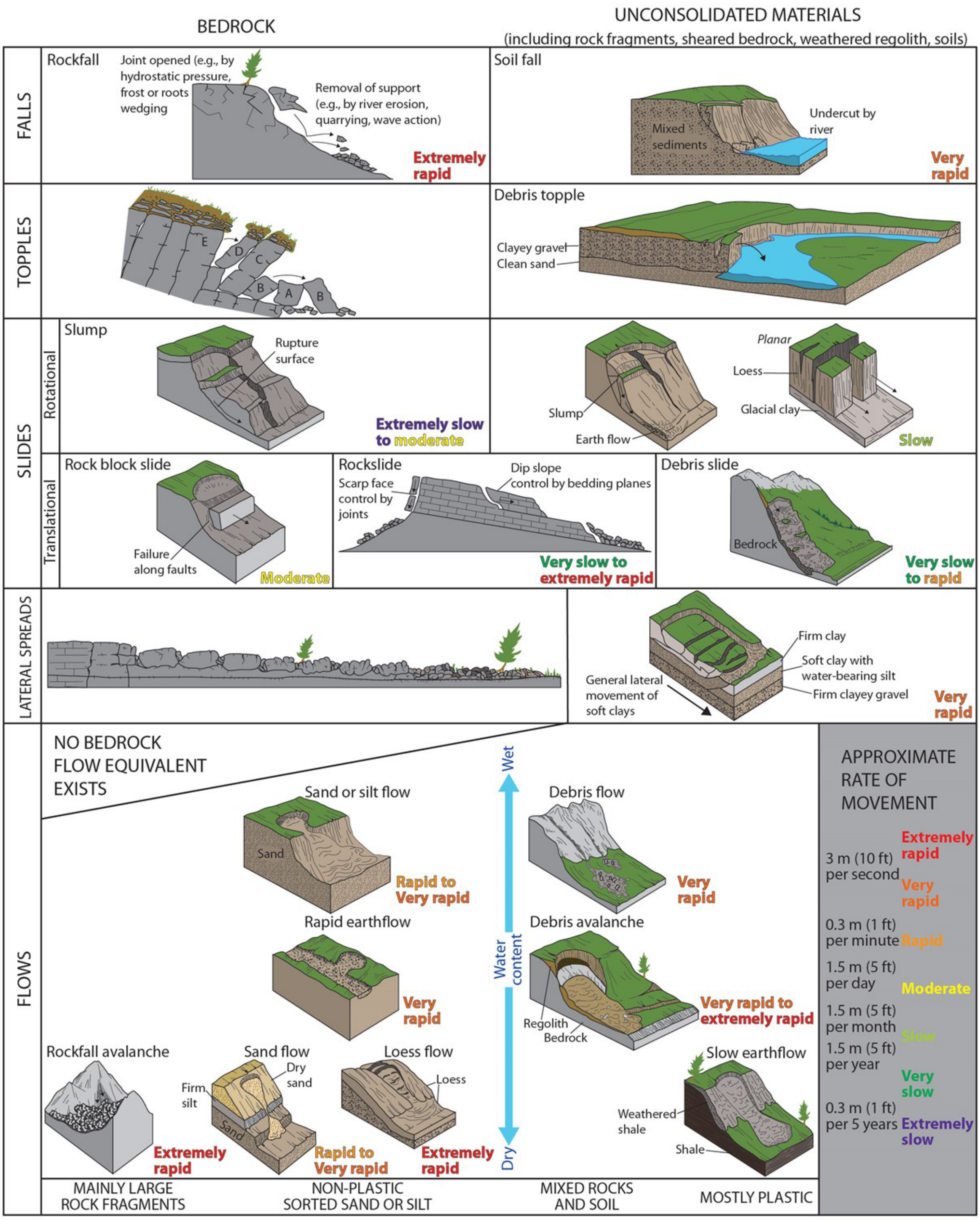

Figure Appendix 1.1. *Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Trista L. Thornberry-Ehrlich, Colorado State University modified from Varnes, D. J. 1978. Landslides: analysis and control. (https://www.nps.gov/subjects/geohazards/landslide-hazards.htm).*

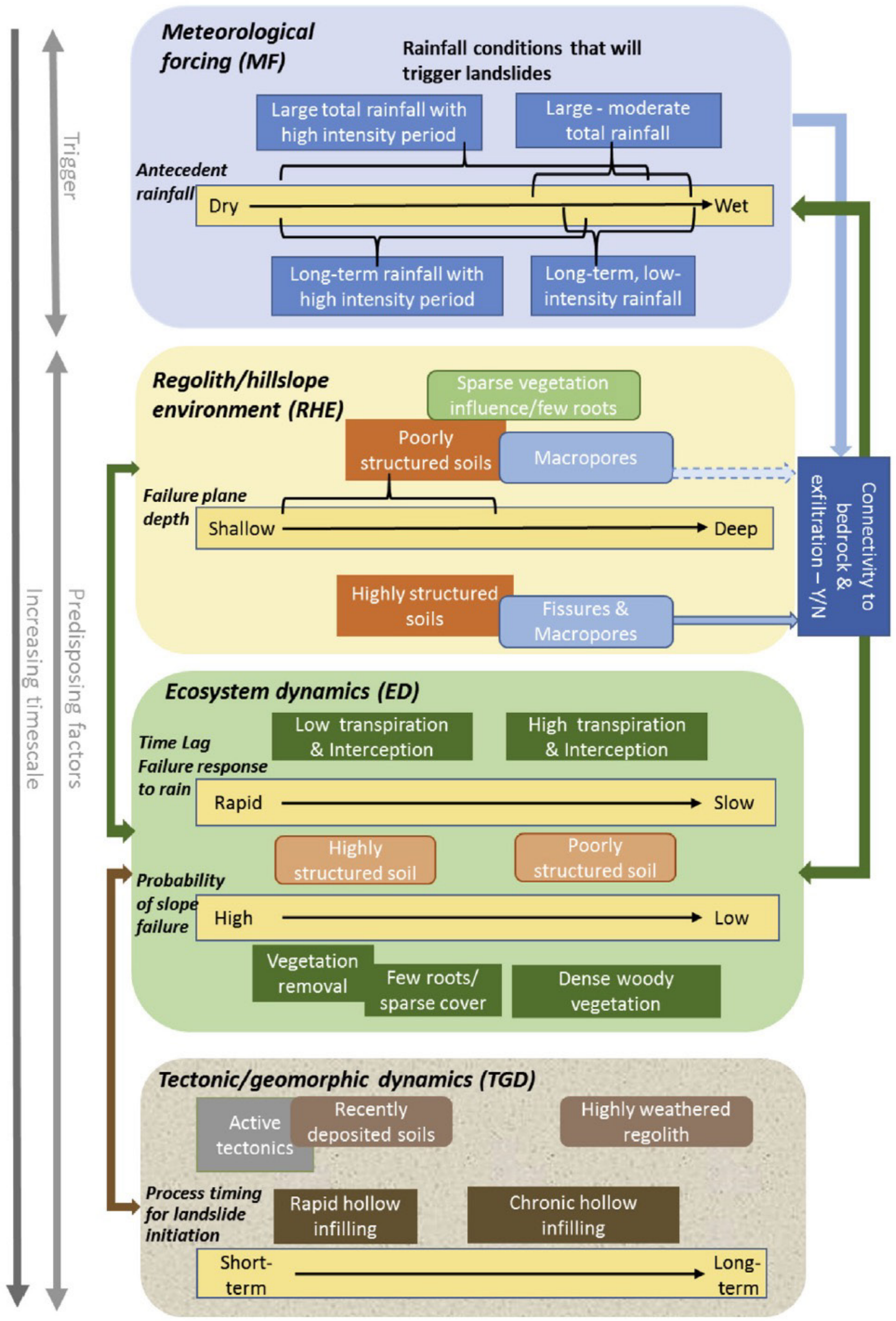

Figure Appendix 1.2. *Meteorological, hillslope, ecological and geomorphic factors that steer causal and triggering conditions, depth, probability, and timing of landslides. Bright colors are main processes within particular system, lighter colors show indirect or related processes in the considered sub-system. Arrows indicate linkages amongst processes or conditions that affect landslides (Source: Sidle and Bogaard, 2016). The ecosystem dynamics (ED) and the regolith/hillslope environment factors (RHE) are the two categories of predisposing factors that can be altered by human actions.*

3.11.2 Appendix 2 – mitigation approaches (extra information)

Table Appendix 2.1. Summary of mitigation approaches to potential slope stability problems is soil (mobile regolith). Source: Keaton and Beckwith, 1996.

Category	Procedure	Best Application	Limitations	Remarks
Avoid problem	Relocate facility	As an alternative anywhere	Has none if studied during planning phase; has large cost if location is selected and design is complete; also has large cost if reconstruction is required	Detailed studies of proposed relocation should ensure improved conditions
	Completely or partially remove unstable materials	Where small volumes of excavation are involved and where poor soils are encountered at shallow depths	May be costly to control excavation; may not be best alternative for large landslides; may not be feasible because of right-of-way requirements	Analytical studies must be performed; depth of excavation must be sufficient to ensure firm support
	Install bridge	At sidehill locations with shallow soil movements	May be costly and not provide adequate support capacity for lateral forces to restrain landslide mass	Analysis must be performed for anticipated loadings as well as structural capability
Reduce driving forces	Change line or grade	During preliminary design phase of project	Will affect sections of roadway adjacent to landslide area	—
	Drain surface	In any design scheme; must also be part of any remedial design	Will only correct surface infiltration or seepage due to surface infiltration	Slope vegetation should be considered in all cases
	Drain subsurface	On any slope where lowering of groundwater table will increase slope stability	Cannot be used effectively when sliding mass is impervious	Stability analysis should include consideration of seepage forces
	Reduce weight	At any existing or potential slide	Requires lightweight materials that may be costly or unavailable; excavation waste may create problems; requires right-of-way	Stability analysis must be performed to ensure proper placement of lightweight materials
Increase resisting forces				
Apply external force	Use buttress and counterweight fills; toe berms	At an existing landslide; in combination with other methods	May not be effective on deep-seated landslides; must be founded on a firm foundation; requires right-of-way	Consider reinforced steep slopes for limited right-of-way
	Use structural systems	To prevent movement before excavation; where right-of-way is limited	Will not stand large deformations; must penetrate well below sliding surface	Stability and soil-structure analyses are required
	Install anchors	Where right-of-way is limited	Requires ability of foundation soils to resist shear forces by anchor tension	Study must be made of in situ soil shear strength; economics of method depends on anchor capacity, depth, and frequency
Increase internal strength	Drain subsurface	At any landslide where water table is above shear surface	Requires experienced personnel to install and ensure effective operation	—
	Use reinforced backfill	On embankments and steep fill slopes; landslide reconstruction	Requires long-term durability of reinforcement	Must consider stresses imposed on reinforcement during construction
	Install in situ reinforcement	As temporary structures in stiff soils	Requires long-term durability of nails, anchors, and micropiles	Design methods not well established; requires thorough soils investigation and properties testing
	Use biotechnical stabilization	On soil slopes of modest heights	Climate; may require irrigation in dry seasons; longevity of selected plants	Design is by trial and error plus local experience
	Treat chemically	Where sliding surface is well defined and soil reacts positively to treatment	May be reversible; long-term effectiveness has not been evaluated; environmental stability unknown	Laboratory study of soil-chemical treatment must precede field installations; must consider environmental effects
	Use electroosmosis	To relieve excess pore pressures and increase shear strength at a desirable construction rate	Requires constant direct current power supply and maintenance	Used when nothing else works; emergency stabilization of landslides
	Treat thermally	To reduce sensitivity of clay soils to action of water	Requires expensive and carefully designed system to artificially dry or freeze subsoils	Methods are experimental and costly

3.11.3 Appendix 3 – Examples of terracing types

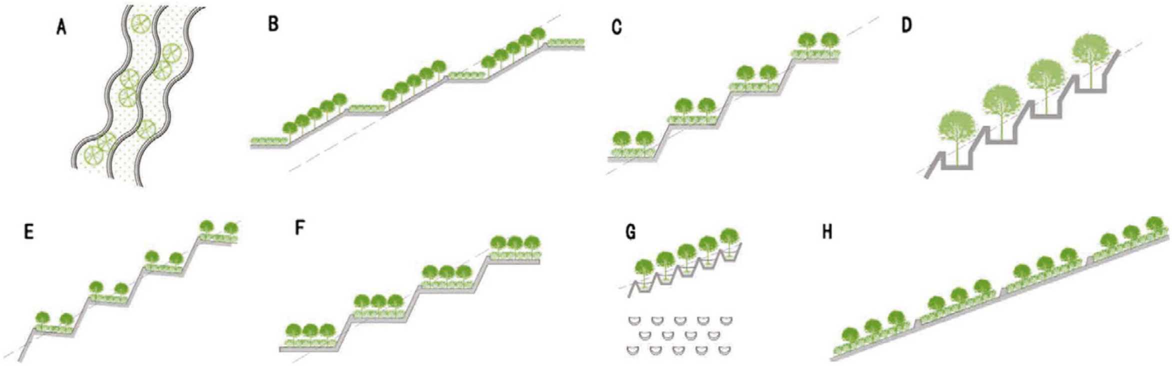

Figure Appendix 3.1. *Some typical terracing types based on the differences in structure and appearance. (Note: A:wave-like terraces; B: slope separated terraces; C: level benches/level terraces without embankments; D: level ditches; E: zig terraces; F: broad-based terraces with embankments; G: half-moon terraces/fish-scale pits; H: natural slope). Source: Wei et al., 2016.*

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