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Hydro-geological and meteorological behaviors of typical landslide prone hillslopes in North-western Rwanda

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Abstract

Landslide hazard prevention measures that include slope stabilization or an early warning system require an understanding of the hydro-geological and meteorological behaviors of the hillslopes prone to failures. This research aimed to understand the hydro-geological and meteorological processes and the relationship thereof using two typical hillslopes (Karago and Rwaza) that experienced slow moving rotational deformation. For each case study, geotechnical characterization and hydrological field and laboratory information was collected, i.e., saturated permeability measurements, soil moisture and groundwater monitoring. The surface displacements were also monitored and their linkage with hydrological processes was assessed. The geotechnical characterization indicated instability conditions ($Fs<1$) at the Karago hillslope and marginally stable conditions ($1<Fs<2$) at the Rwaza hillslope. The slope deformation and landslides occurred during the wettest conditions (i.e. soil moisture close to saturation and groundwater rises up to near surface). The surface displacements control points revealed the toe and head units to move faster than the intermediate units. The highest acceleration at the toe was attributed to the external incision agents like stream erosion while cracks and steeper failure plane were responsible for acceleration at the head units. The regression analysis indicated a strong correlation ($R^2=79\%$) between surface displacement and depth to groundwater and thus impactful for slope deformation and landslide initiation. The role of rainfall was also significant with long lasting low intensity rainfall being more important than short and high intensity rainfall.

***Keywords:** Hydro-geology, landslide, groundwater, soil moisture, surface displacement*

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Introduction

Landslides are well recognized global geomorphic hazards due to their considerable economic, social, and environmental impacts. Although, single landslide and or slope failures may be very local, and not as overwhelming as other hazards like earthquakes and floods, they occur more frequently and thus affect more people than any other natural hazard in mountainous areas of the world (Froude and Petley, 2018; Petley, 2012). In landslide prone hillslopes, much effort is put on the implementation of mitigation measures to control the most sensitive factors and stop or at least delay the slope failures. Slope stabilisation approaches are commonly used to control the slope failures (Mizal-Azzmi et al., 2011). However, in many places, stabilisation activities may be expensive in terms of financial and environmental limitations and hence early warning systems are adopted to timely inform the public and avoid the loss of human lives (Leinauer *et al.,* 2023). However, both reliable warning systems and sustainable slope stabilisation approaches require an understanding of the geotechnical and hydrological behaviours of the hillslopes prone to failures including the failure mechanism, potential predisposing and triggering conditions and their respective thresholds. A thorough understanding of the hillslope hydro-geological behaviours involves a knowledge of the appropriate equations defining the soil stresses and the nature of shearing resistance, the conceptual illustration of the hillslopes, the behaviour of groundwater, soil moisture changes and surface deformation relationships. The role of water, either as groundwater in saturated zone or as soil moisture in un saturated zone, on slope stability has been recognized for many years as highlighted in standard soil mechanics and hydrology books (Craig, 1997). Most slope failures can be induced by high intensity short lasting rainfall as well as low intensity long lasting rainfall. However, the timing of the initiation of slope displacement is controlled by the hydro-geological behaviour of the slope, the infiltration, temporarily storage and subsequent drainage in the slope (Bogaard and Greco, 2016). A thorough understanding of the slope failure mechanism involves therefore an understanding of the hillslope response to the dynamics of hydro-geological processes (i.e. groundwater and soil moisture). Since Rwanda hillslopes are recognized to be morphologically active landscapes (Depicker et al., 2021) strongly affected by changes in land use that modify the hydrological and geotechnical characteristics, this research aimed to make an understanding of these characteristics that could lead to the implementation of appropriate landslide prevention measures in Rwanda.

Materials and Methods

Study area

This study was conducted on two case studies of hillslopes that experienced slow moving rotational types of landslides located in North and western regions of Rwanda as shown in Figure 1.

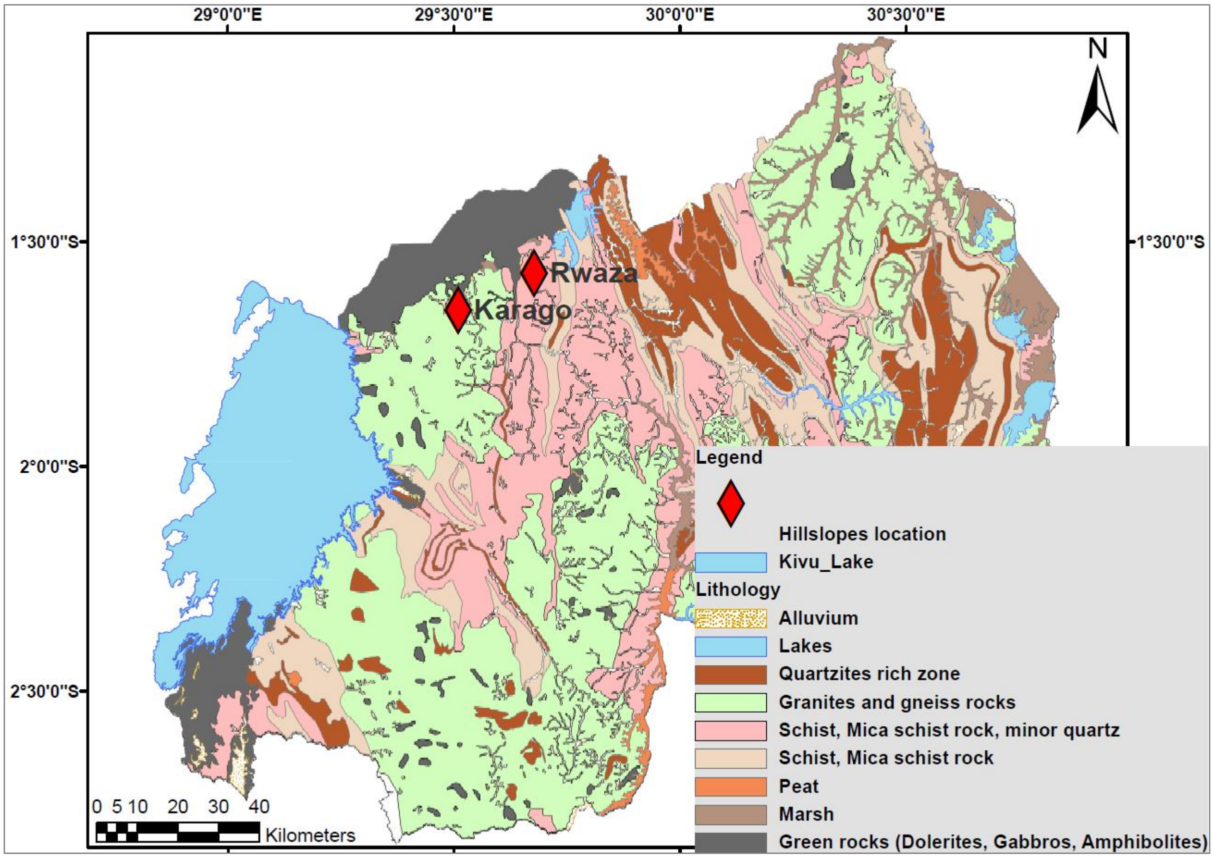


Figure 1. Location of the study hillslopes in the north-western region of Rwanda and lithological units

Karago hillslope

The western region of Rwanda has been identified as the most prone to landslide hazards. About 40% of its surface area is classified as high to very high susceptibility to landslide with more than 1 million of local population exposed to landslide risks (Nsengiyumva et al., 2018). The region receives abundant rainfall with a long-term mean annual rainfall of around 1500mm/yr and an estimated potential evaporation of about 900mm/yr. The Karago hillslope is geographically located at 1°39'3.3 S, 29°30'30.7 E in the western province, downslope of a paved road Mukamira-Ngororero. It is underlain by granite pegmatite geological unit and represents a landslide-prone zone with slow moving rotational landslides. The slope failure initiation occurred in April 2012 and completely failed at the end of March 2016 (Walraven, 2018). Before the slope failure, the area was under Eucalyptus trees that undergone a clear cut. Currently, there is a slow-moving landslide with clear rupture, cracks/fissures at the scarp (Figure 2). The scarp of the Karago landslide reveals three main layers, a sand layer, a clay layer and a rock layer, which have been further subdivided into 5 layers (Figure 2) based on visual observation and consistency of the soil materials. The first layer, made of light-colored sandy soil deposited from road excavation, contains no plant roots and extends from 0-4.8m. The second layer extending from 4.8-5.5m is made of the original terrain soil, some decaying roots with quite softer sand than the first layer. The third layer from 5.5-6.1m contains very hard yellowish sand with no plant roots. The fourth layer with hard light clay extends from 6.1 to 6.9m deep. The fifth layer, the failure plane of the landslide, is made of saturated soft clay at >6.9m deep. The landslide geometry is about 60m long, 40m wide, and 8m deep. The landslide body was divided into 3 separate units (Figure 2): head, main body and toe units for further analysis of the relationship between hydrological processes and slope displacement. On each unit, surface displacement control points were installed for weekly recording of surface displacement rates. Groundwater observation wells were installed on the landslide body as indicated by the letter M in Figure 2. Additionally, soil moisture monitoring tubes (T) and other groundwater observation wells (S) were installed along the hillslope for daily monitoring of groundwater and soil moisture. Downslope is a stream that undermines the landslide toe during the rainy season, causing secondary landslides.

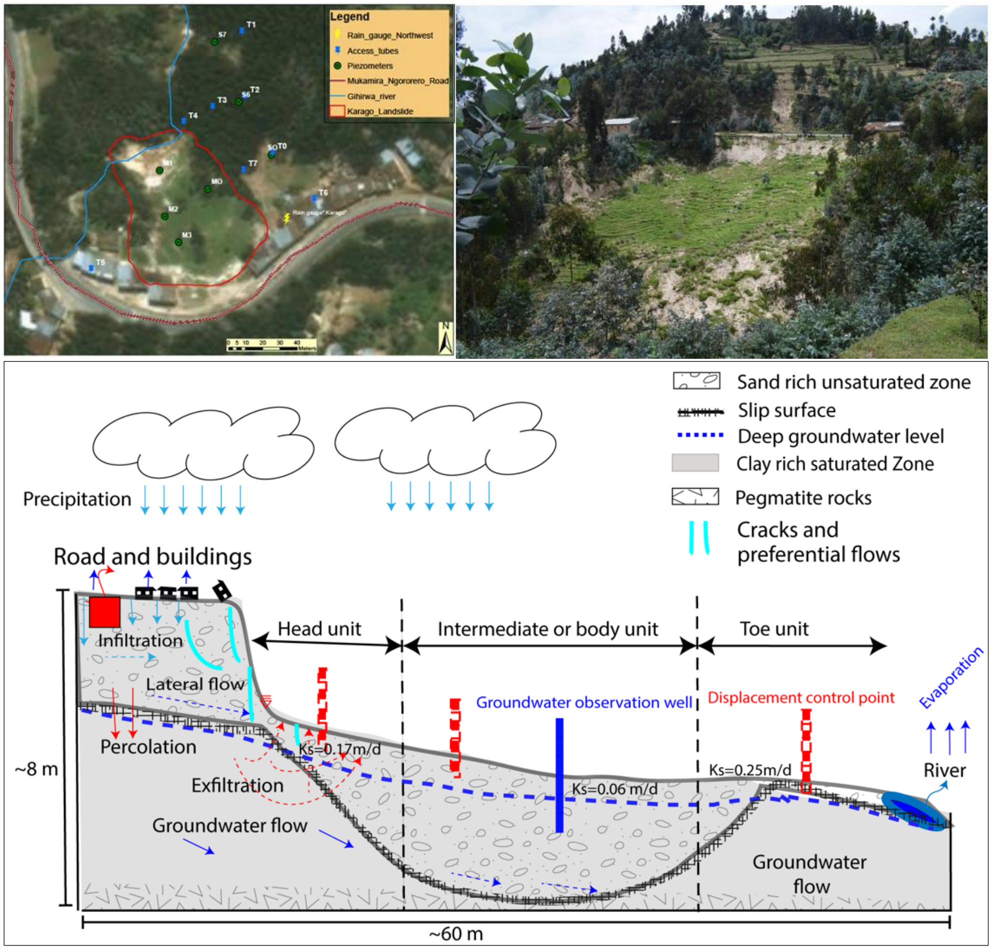


Figure 1. Conceptual illustration of Karago hillslope and the location of hydro-geological monitoring equipment along the hillslope: On the upper left image (Google imagery, 2022), T is the soil moisture access tubes; M and S are groundwater monitoring wells on the landslide body and the stable slope respectively; on the upper right is the photo of Karago hillslope taken in 2018; the conceptual illustration of Karago landslide and its different units, groundwater observation wells and surface displacement control points, Ks is the saturated hydraulic conductivity

Rwaza hillslope

The northern region has been also identified as susceptible to landslide hazards. About 23% of its total area is classified as high to very high susceptibility to landslide with more than 600,000 of local population exposed to landslide hazard risks (Nsengiyumva et al., 2018). The north region receives rainfall with a long-term mean annual rainfall of around 1200mm/yr and an estimated potential evaporation of about 800mm/yr. The Rwaza hillslope is geographically located at 29°40’39.9"E 1°34’6.7"S in northern province of Rwanda. The hillslope overlays the mica schists rock that represents a typical landslide prone zone with a slow-moving reactivating rotational landslide triggered by heavy rain of April 2017. The landslide is actively advancing downslope during the rainy season and thus exposing the local people to high risks. The slope length of the landslide is about 50m long, 15m wide, and an estimated depth of about 3m. The scarp reveals four layers (Figure 3). The first layer ranges from 0 to 0.80m with ploughed soft clay soil layer, plant roots and no stones. The second layer made of very compact clay layer extends from 0.8m to 1.6m with no roots and no stones. The third layer, from 1.6m to 2.8m, contains a mixture of clay soil and stones of about 10-25cm diameter. The fourth layer which is made of saturated clay layer with few stones, no roots, stands for the slope failure plane located at >2.8m.

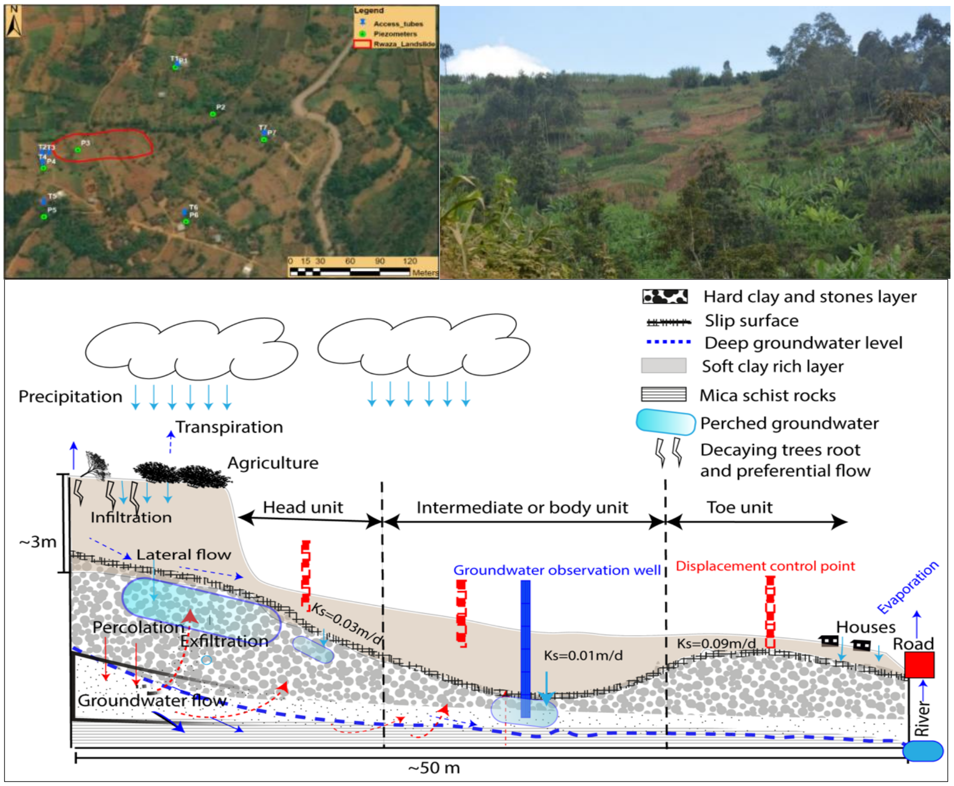


Figure 2. Conceptual illustration of Rwaza hillslope, hydro-geological and slope displacement monitoring equipment: On the upper left image (Google imagery, 2022), letter T represent the soil moisture access tubes; P (Piezome- ter) represent the groundwater monitoring wells, the upper right is the photo of Rwaza hillslope taken in 2018; the conceptual illustration of Rwaza landslide and its different units, groundwater observation wells and sur- face displacement control points, Ks is the saturated hydraulic conductivity

Geotechnical analysis

For each hillslope, soil samples were collected from distinct soil layers along the land- slide scarp. Geotechnical properties such as soil texture (% sand, % silt and % clay), soil density, Atterberg limits, and shear strength parameters were tested. The soil texture was tested using sieving and sedimentation methods and classified according to the unified soil classification system (USCS) (Casagrande, 1948). The bulk density (ρd) was tested using the core method and was used to compute the unit weight of soil (γ). The cohesion (C) and angle of internal friction (φ) were derived from direct shear tests. In-situ and laboratory measurement of saturated hydraulic conductivity (Ks) was undertaken on each soil layer and at different landslide units (head, body, and toe) using the inverse auger hole and bottomless bucket methods (Mirus and Perkins, 2012). The results of these geotechnical parameters and the mean groundwater level were used for the slope stability (factor of safety Fs) analysis using the SLIP5EX model developed by Van Beek and Van Asch, (2004); Greenwood et al., (2004). SLIP5EX has been developed to facilitate comparison of various slope stability analyses methods particularly the Infinite slope method (ISM) and Felenius method (FM) given the slope geometry and geotechnical parameterization.

Hydro-meteorological processes and landslide occurrence

The monitoring of hydro-geological processes was conducted from September 2018 to June 2020 at the Karago hillslope and from April 2019 to June 2020 at the Rwaza hillslope. We installed different hydrological and meteorological monitoring equipment to have an overview of the soil moisture dynamics, groundwater fluctuation and rainfall with respect to the slope failure and landslide occurrence. For the Karago hillslope, we used meteorological data recorded from the installed rain gauge at the hillslope. Data from Ruhengeri meteorological station, located around 5km, were used for the Rwaza hillslope analysis. The soil moisture was monitored through installed soil moisture monitoring tubes using Delta-T, PR2/6 and PR1/6 soil moisture profile probes. At both hillslopes, we installed eight soil moisture monitoring tubes distributed in different land use spots to ensure for the entire hillslope representability. Both hillslopes are covered by spots of eucalyptus trees, agricultural crops, and built-up areas. In each land use, two soil moisture monitoring tubes were installed as indicated by the letters T in Figure 2 and Figure 3. The soil moisture was recorded daily using a disturbed soil moisture profile probe measuring at six depth: 10, 20, 30, 40, 60 and 100cm. We installed also eight groundwater monitoring wells (S and P) in the close proximity of the soil moisture monitoring tubes as shown in Figure 2 and Figure 3. Additional groundwater monitoring wells were installed on the moving landslide bodies to monitor changes in groundwater levels and their effect on surface displacement. Since the studied landslides occurred before the start of the monitoring period, we referred to another landslide that occurred during the monitoring period to have an insight on the impact of the observed hydrological processes on slope deformation.

Surface displacement and Slope response to hydro-meteorological processes

The measurements of surface displacements have been undertaken to identify the most influential hydro-geological and meteorological factors. On each landslide body, one line transects of seven displacement control points P1 - P7 were installed at different landslide units from the head, main body to the toe as shown in Figure 2 and Figure 3. A stable reference control point P0 was installed at a stable upslope and was used as a benchmark for weekly measurement of the relative distance between the control points and reference point using a measuring tape. The GPS receiver was also used for weekly records of the location of each control points in x, y coordinates which were used for computation of the surface displacement rates with Equation 1.

$$D = \sqrt{(X_i - X_{i-1})^2 + (Y_i - Y_{i-1})^2} \qquad (1)$$

With D the surface displacement rate (mm week-1), Xt and Yt are the weekly measured locations of the control points (mm) while Xt−1 and Yt−1 are prior measurements (mm). The weekly records of the locations of the displacement control points were carried out from 3rd April 2019 to 27th May 2020 at the Karago hillslope and from 6th April 2019 to 30th June 2020 at the Rwaza hillslope. A simple regression analysis was used to test the relation between the hydro-meteorological parameters and surface displacement rates.

Results and discussions

Geotechnical characteristics

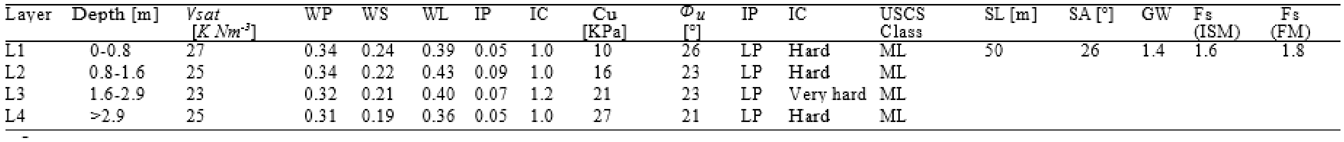
The results of the geotechnical parameters are summarized in Table 1 and Table 2 for the Karago and Rwaza hillslopes respectively. Based on the results of soil texture, Atterberg limits and according to the unified soil classification system (USCS), the soil of the Karago hillslope is classified as a well graded sand (SW) except the failure plane with poorly graded sand (SP). The soil of the Rwaza hillslope is classified as a low plastic silt (ML). However, referring to the results of texture analysis, some values of the angle of internal friction (φ) and cohesion (C) derived from the peak stresses at the failure envelope are likely overestimated (Table 1). The overestimation of C was attributed to the additional resistance required to overcome the interlocking and rearranging the soil particles especially in the upper most layer that have undergone artificial consolidation at Karago. It may also due to the size of the coarse-grained soil with some proportion of large soil particles which causes the shearing of individual grains instead of the core soil sample and thus yielding higher values of C (Kim and Ha, 2014). Despite that however, by using the tested soil strength parameters C and φ, the unit weight γ from each soil layer, the measured mean depth to groundwater, and landslide geometry, the Fellenius method of stability analysis indicated unstable state of the Karago hillslope with a safety factor Fs < 1. Further sliding and displacement processes are therefore expected which may affect the neighboring infrastructures and communities due to the instability of the scarp and the linked retrogressive, enlargement and advancing reactivation processes. Based on both infinite slope and Fellenius methods, existing conditions of the perched groundwater level (1.4m), geotechnical parameters, and landslide geometry, the scarp of Rwaza shows marginally stable conditions with 1<Fs<2. This indicates no current retrogression but there is a rather advancing reactivation and thus exposing the downslope local population at high risks.

Table 1. *Geotechnical parameters and USCS classification of Karago landslide*[a]

Layer	Depth [m]	Γ_{sat} [KNm^{-3}]	CU	CC	C [KPa]	Φ [°]	USCS Class	SL [m]	SA [°]	GW [m]	Fs (ISM)	Fs (FM)
L1	0-4.8	23.6	13	2	18	28	SW					
L2	4.8-5.5	21.6	14	1	0	35	SW					
L3	5.5-6.1	20.6	12	2	0	40	SW	60	26	0.20	1.12	0.90
L4	6.1-6.9	20.7	11	2	0	50	SW					
L5	>6.9	20.7	17	1	11	40	SP					

[a] *Moist bulk unity weight γ; Saturated bulk unity weight γsat ; Groundwater GW (m below surface); Coefficient of uniformity CU; Coefficient of curvature CC; Factor of safety FS; Slope length SL; Slope angle SA; Well graded sand SW; Infinite slope method ISM; Felenius method FM*

Table 2. *Geotechnical parameters and USCS classification of Rwaza hillslope* [b]



Layer	Depth [m]	γ_{sat} [KNm^{-3}]	WP	WS	WL	IP	IC	Cu [KPa]	Φ_u [°]	IP	IC	USCS Class	SL [m]	SA [°]	GW	Fs (ISM)	Fs (FM)
L1	0-0.8	27	0.34	0.24	0.39	0.05	1.0	10	26	LP	Hard	ML	50	26	1.4	1.6	1.8
L2	0.8-1.6	25	0.34	0.22	0.43	0.09	1.0	16	23	LP	Hard	ML					
L3	1.6-2.9	23	0.32	0.21	0.40	0.07	1.2	21	23	LP	Very hard	ML					
L4	>2.9	25	0.31	0.19	0.36	0.05	1.0	27	21	LP	Hard	ML					

[b] *Plastic limit WP; Shrinkage limit WS ; Liquid limit WL; Plasticity index IP; Consistency index IC; Water content WP; Low plasticity LP; Low plastic silt ML; Groundwater GW (m below surface)*

Soil moisture dynamics and landslide occurrence

The dynamics of soil moisture at the Karago and Rwaza hillslopes are summarized in Figure 4 and Figure 5. The highest soil moisture content at the Karago hillslope was recorded in deep layers from 40-100cm resulting from water exchange between groundwater and unsaturated zone. Contrarily, at the Rwaza hillslope, the highest soil moisture content was recorded in shallow layers, 0-40cm, indicating a very low permeable or impediment layer at around 40cm depth. The soil moisture response time to rainfall was quite similar in all soil profile layers at the Karago hillslope while at the Rwaza hillslope, shallow layers respond faster than deep layers due to the high clay content that slows down the infiltration rate and the wetting process. Figure 4 and Figure 5 show that landslide occurred at the peak soil moisture in deep layers at Karago and shallow layers at Rwaza. Furthermore, the effect of different land uses on soil moisture response was noticed. The soil moisture in deep layers of the built-up and fully grown eucalyptus was frequently lower (< 0.5 m3m-3) than other land uses due to the low infiltration rate in built up area and high rainfall interception by trees canopy and transpiration in fully grown trees. The high soil moisture recorded in agricultural land implies the loss of soil strength not only due to the lack of additional strength provided by trees' roots but also the built up of high pore water pressure, lack of pressure dissipation processes like transpiration and thus frequent slope failures. While the influence of groundwater is obvious on shear strength and the factor of safety, the soil moisture content also influences the shear strength through changes in suction forces and the saturation index. This role of soil moisture on suction force and soil strength is not frequently considered probably due to the fact that the main soil strength parameters (c′, φ′) are not directly affected. Talebi et al., (2007) studied the role of soil moisture by considering the total cohesion Ct, the moist unit weight γm, degree of saturation and matric suction on slope stability conditions but found no significant effect on the factor of safety Fs.

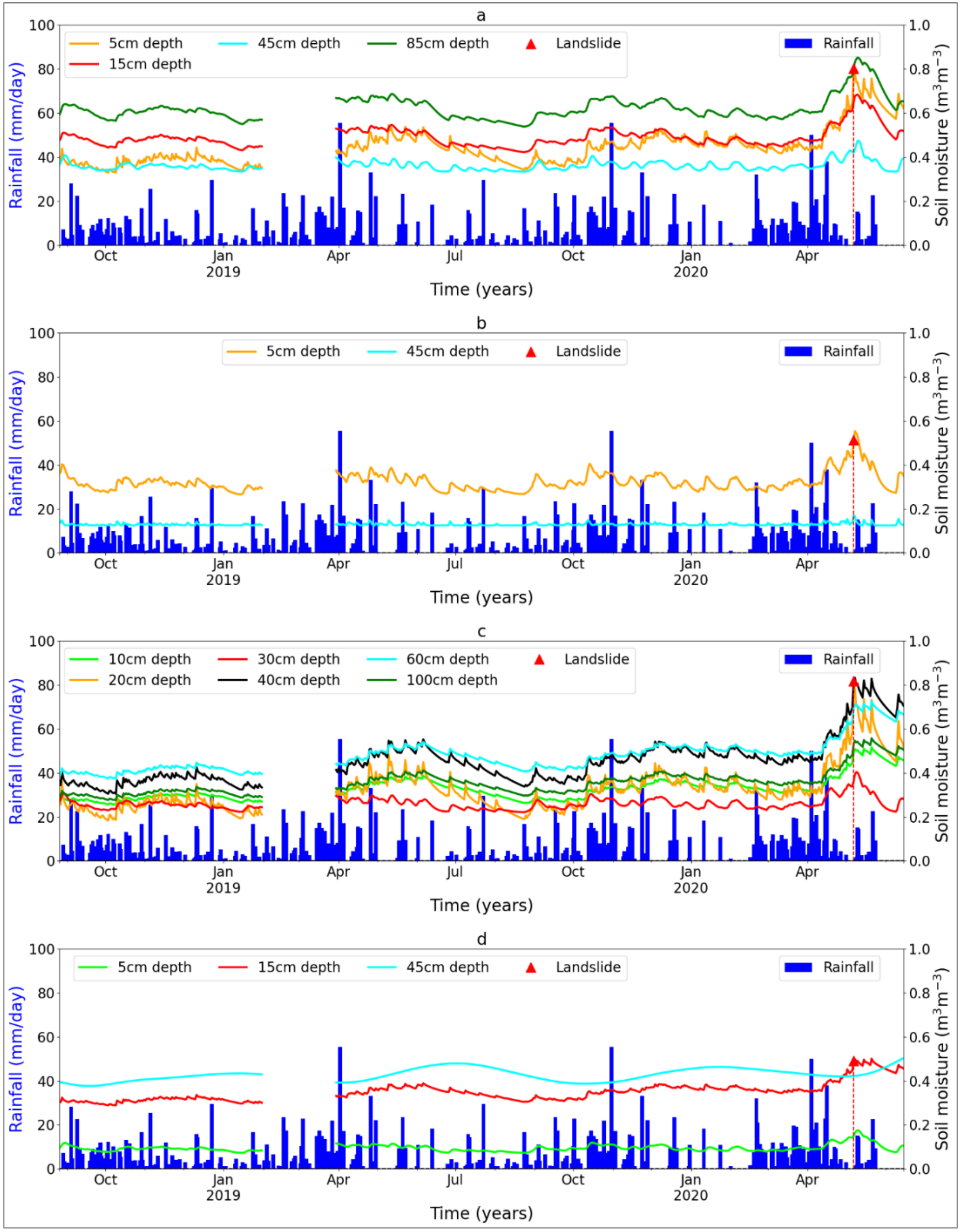


Figure 4. Soil moisture content, rainfall and landslide occurrence at Karago hillslope a) agricultural land, b) built up land c) Eucalyptus coppices, d) fully grown Eucalyptus

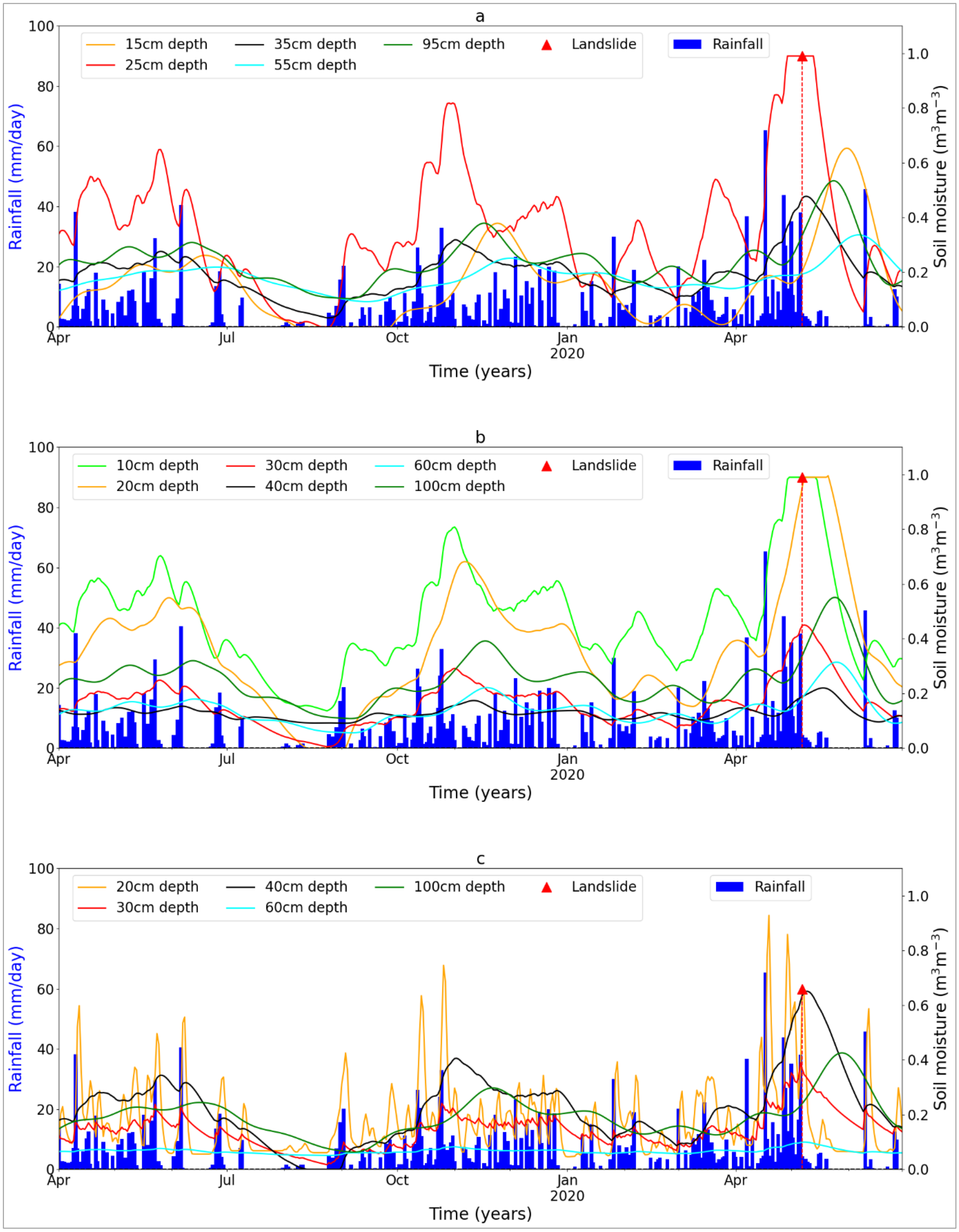


Figure 5. Soil moisture content, rainfall and landslide occurrence at Rwaza hillslope a) agricultural land b) built-up land c) Eucalyptus forest land

Groundwater fluctuations and landslide occurrence

Groundwater levels at the Karago hillslope were monitored from three groundwater observation wells located in three land use spots: agricultural land S0, eucalyptus coppices S6 and fully grown eucalyptus trees S7 as presented in Figure 6. At the Rwaza hillslope, the groundwater levels were measured under three land use spots: Agriculture P1, Built-up P2 and Built-up P7 as depicted in Figure 7. The groundwater observation wells installed in built-up land at Karago and in Eucalyptus trees at Rwaza were dry during the entire monitoring period and are not presented here. The results of groundwater levels in different observation wells are plotted in Figure 6 and Figure 7 for both Karago and Rwaza respectively. The groundwater information indicated shallower and slow responding groundwater levels in agricultural land as compared to other land use. The built-up and forest lands respond very fast to the drying conditions as compared to agricultural lands. This can be explained by the high level of surface evaporation and overland flow in built-up areas and high level of rainfall interception and transpiration in forest areas and thus less groundwater inputs compared to outputs. The landslide occurred at the peak groundwater level and after the long-lasting rainfall. The impact of groundwater levels on shear strength (saturated soil) is caused by the increase in pore water pressure that increases shear stress, reduces the effective normal stress and thus soil strength and the factor of safety. Even though the fluctuations of groundwater levels may have been affected by land use type and the linked hydrological processes such as evaporation, transpiration, and interception, these processes are beyond the scope of this study. Furthermore, the impact of tensile strength of roots either from forest trees or crops have not been tested to confirm their effect on soil stresses and strength parameters.

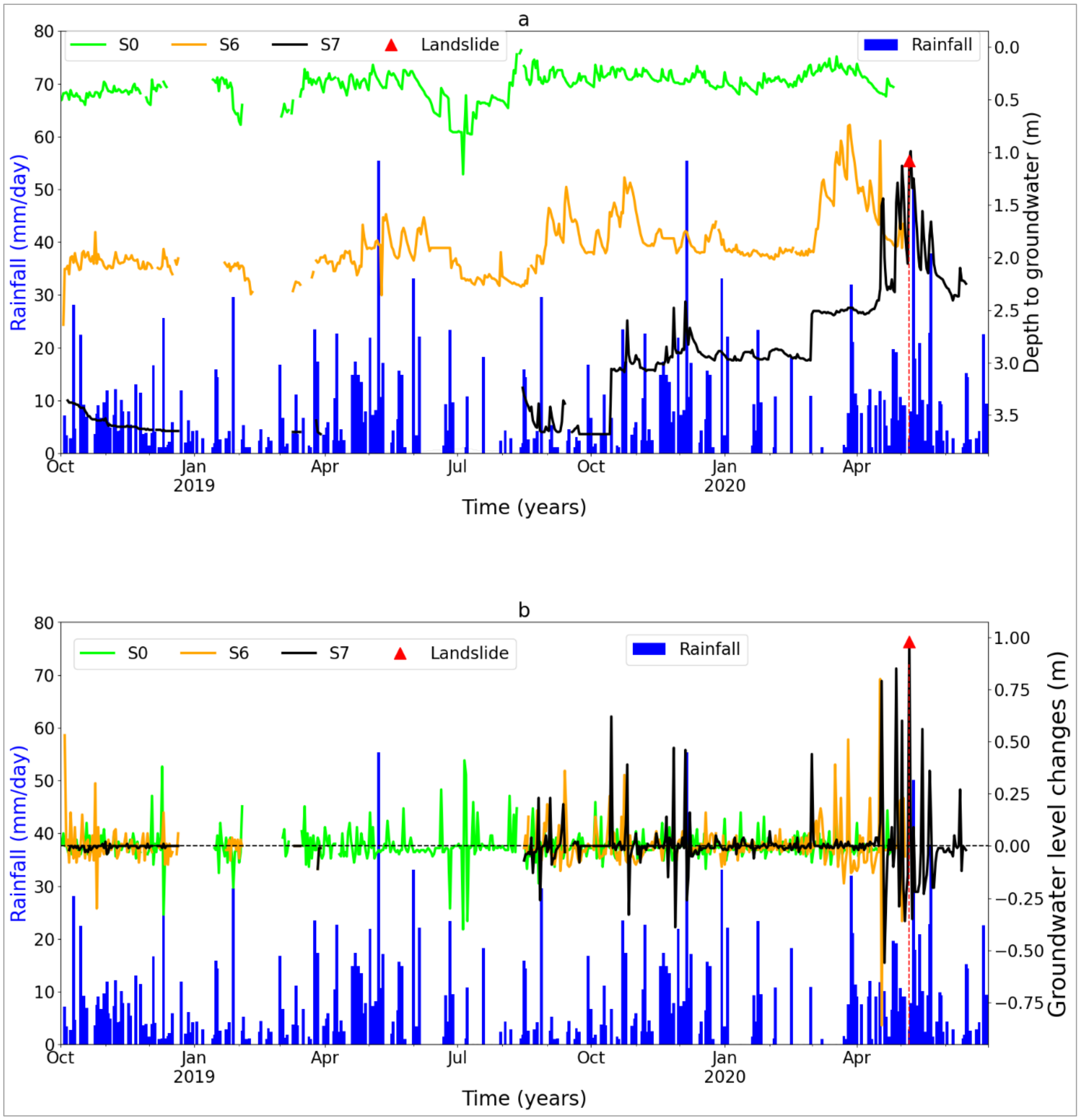


Figure 6. Groundwater information from different groundwater observation wells installed in agricultural land (S0), in Eucalyptus coppices (S6) and fully grown eucalyptus (S7) and landslide occurrence at the Karago hillslope: a) depth to groundwater (m below surface) and landslide b) groundwater level changes (m/day) and landslide

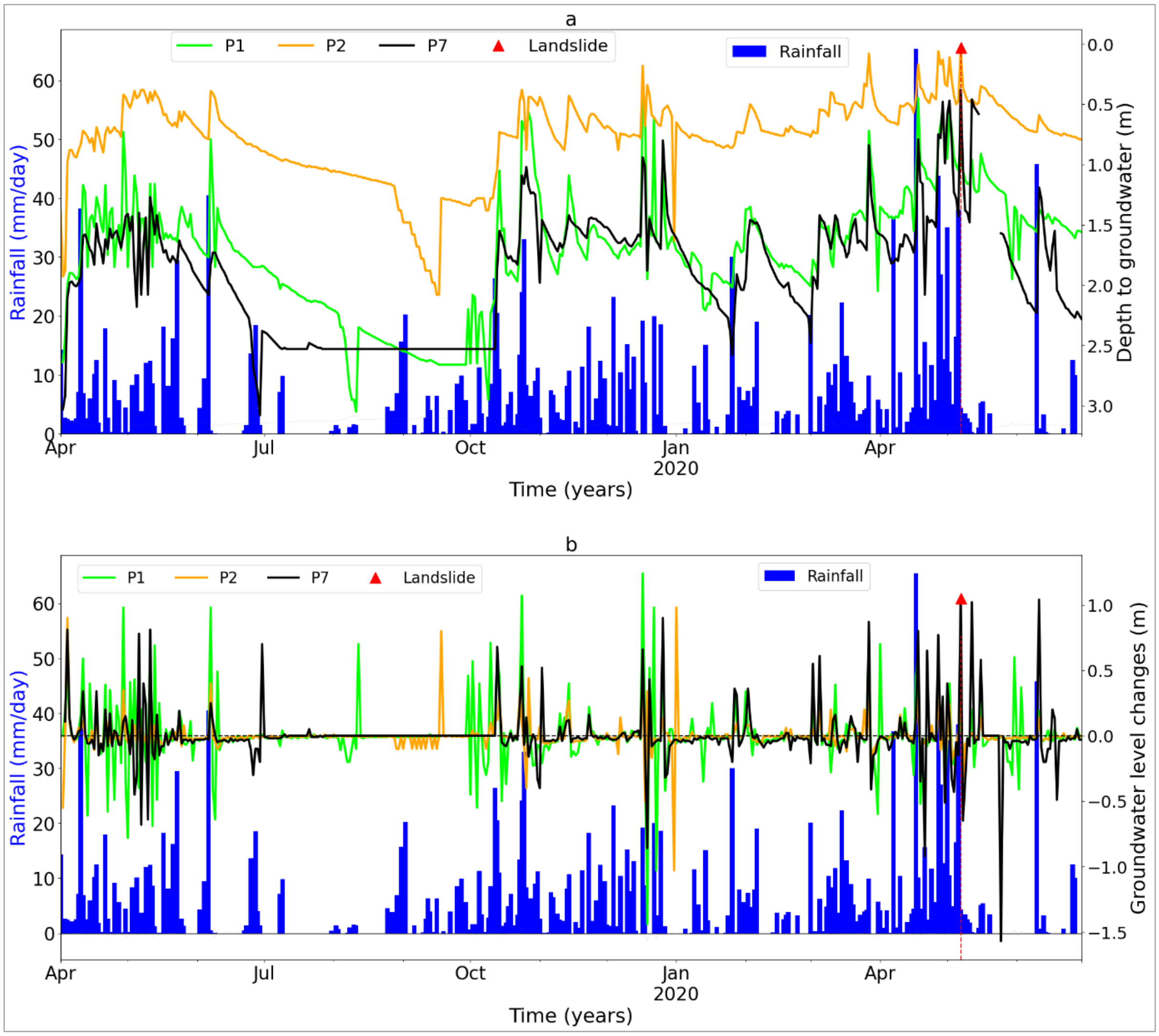


Figure 7. Groundwater information from different groundwater observation wells installed in agricultural land (P1), in built-up 1 (P2) and built-up 2 (P7) and landslide occurrence at the Rwaza hillslope: a) depth to groundwater (m below surface) and landslide b) groundwater level changes (m/day) and landslide occurrence

Surface displacement and slope response to hydro-meteorological processes

Figure 8 indicates that both the Karago and Rwaza hillslopes undergone obvious surface displacement. The mean horizontal cumulative displacements of the landslide bodies were 340mm and 176mm with a mean weekly displacement rate of about 6.4mm week^{-1} and 2.7mm week^{-1}, equivalent to about 330mm year^{-1} and 140mm year^{-1} at Karago and Rwaza, respectively. The measurements of displacements show that the landslide body movements have never completely stopped since the start of the continuous monitoring, although the rates reduced significantly during the dry periods from July to August and from January to March as shown by the white background in Figure 8. Even though the landslide bodies move quite synchronically, the fastest displacement rates for both hillslopes were generally observed in control points P3 and P1 located at the toe unit of the landslides with cumulative displacement of about

540mm and 385mm for the Karago and Rwaza hillslopes, respectively. Note that the control point P1, located at the toe of the Karago landslide, was quickly displaced and lost at the very beginning of the monitoring period. The control points located at the head of the landslide also exhibited faster displacement as compared to the control points located in the intermediate units of the landslide body (P4, P5). This indicates that the intermediate units of landslides are less active as compared to other parts. The intermediate units are quite stable probably due to the new equilibrium created by the reverse slope at the arc shaped failure plane. The fastest displacement rates at the toe of Karago landslides are accelerated by a stream that undercuts the landslide toe during the rainy season, causing secondary slides. When the destabilized soil materials are removed from the edge of the toe unit, the materials in the intermediate unit starts moving at a distance that depends on the velocity of the destabilized materials, the strength, the angle and the resistance along its path.

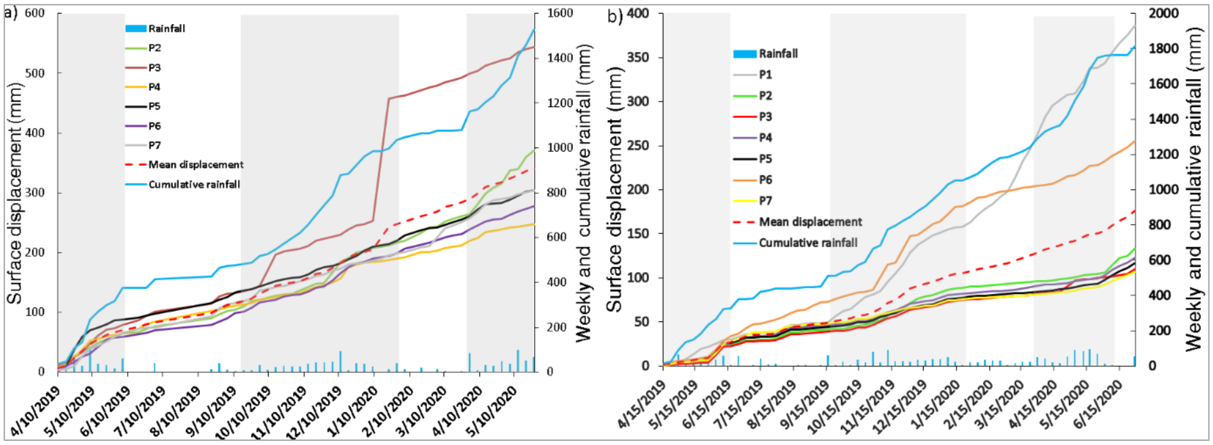


Figure 8. Cumulative surface displacement and rainfall at a) Karago and b) Rwaza hillslopes

The recorded surface displacements rates were separated into two classes to facilitate the regression analysis. The values of 10mm/week and 5mm/week were subjectively found as separating lines between the two classes. The first class with displacement rates <10mm/week and <5mm/week were hypothesized to be small and referred to as "minor displacements" while the class with >10mm/week and 5mm/week were hypothesized to be significant and referred to as "major displacements". The relationships between the tested hydrological processes and the defined classes of surface displacement are shown in Figure 9 and Figure 10. At the Karago hillslope, the regression analysis (Figure 9) indicated a strong negative correlation (R^2=0.79) between groundwater levels and major displacement rates. The regression model express that 79% of the proportion of the major displacements could be explained by the depth to groundwater. The model indicates that the major displacement rates decrease with increasing depth to groundwater and that the former could be easily predicted using the latter. Contrarily, there was no correlation between minor displacements and groundwater. However, it is generally observed that the majority of the minor displacements occur when the groundwater rises to near surface while the major displacements frequently occur during the groundwater drawdown phase at Karago hillslope. A negative correlation was also found between rainfall and displacement rates. It indicated that only about 50% ($R^2=0.50$) of the variance in major displacement could be explained by the rainfall information. Most of the displacement either major or minor occurred at low long-lasting rainfall intensities between 20-60mm/week. This explains that the long-lasting low rainfall intensity have sufficient time to infiltrate and rise up the groundwater and pore water pressure and thus inducing more surface displacement as compared to short and high intensity rainfall with frequent overland flow than infiltration. The soil moisture information in the unsaturated zones showed no significant impact on surface displacement at the Karago hillslope. This suggests that the movement of deep-seated landslides in sand rich soils like Karago (>6.9m) are more linked to groundwater rather than rainfall and soil moisture. The groundwater induced displacement frequently occurs in a considerable time after rainfall as function of the rainfall infiltration time, the distance between the surface and the ground water table, the hydraulic properties of the soil materials and the depth of the slip plane. Contrarily, at the Rwaza hillslope whose slip plane is shallow (2.8m) with clay dominated soil texture, the major displacement occurred at higher soil moisture > $0.25m^3m^{-3}$. This suggests that in clay dominated soil textures, shallow landslides are likely due to the above normal soil moisture or rainfall. Similar findings were noted by Bordoni et al., (2015), who indicated that shallow landslides with < 2m thickness are easily induced by rainfall due to the progressive infiltration of the rainwater up to the hard layer while deep seated landslide are frequently induced by groundwater fluctuations. Despite the role of hydro-meteorological processes as accelerators, it has to be noted that the minor surface displacements frequently occur due to gravity force in sloppy areas.

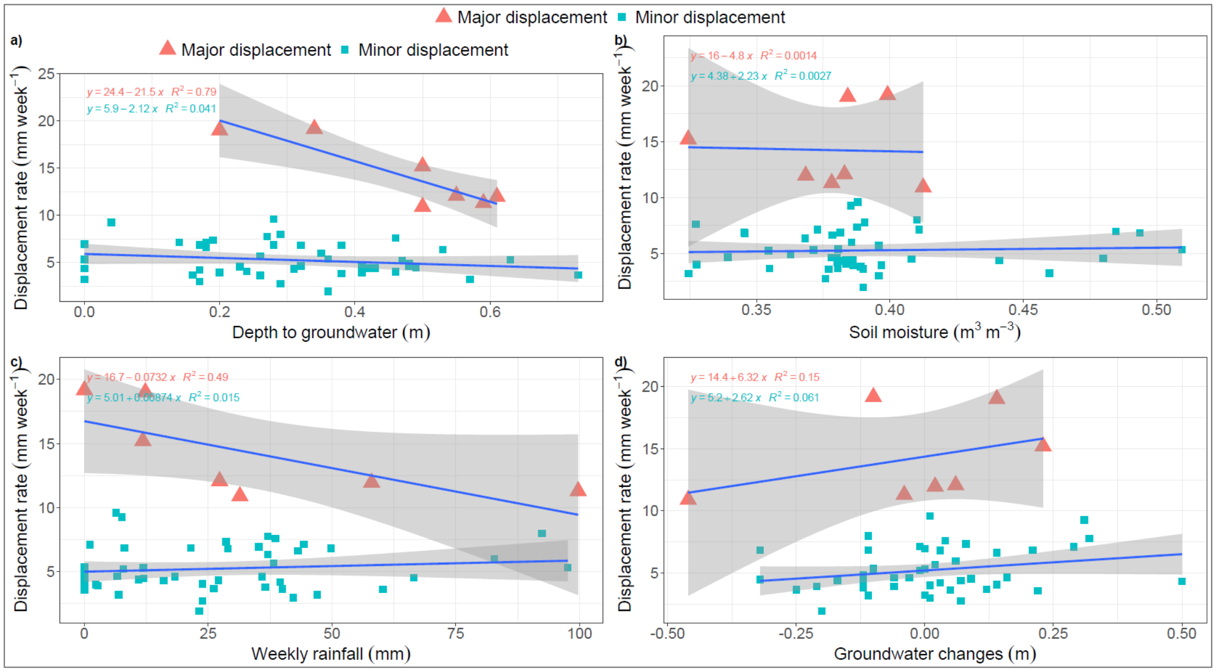


Figure 9. Karago hillslope: Regression analysis between hydro-meteorological processes and slope displacement

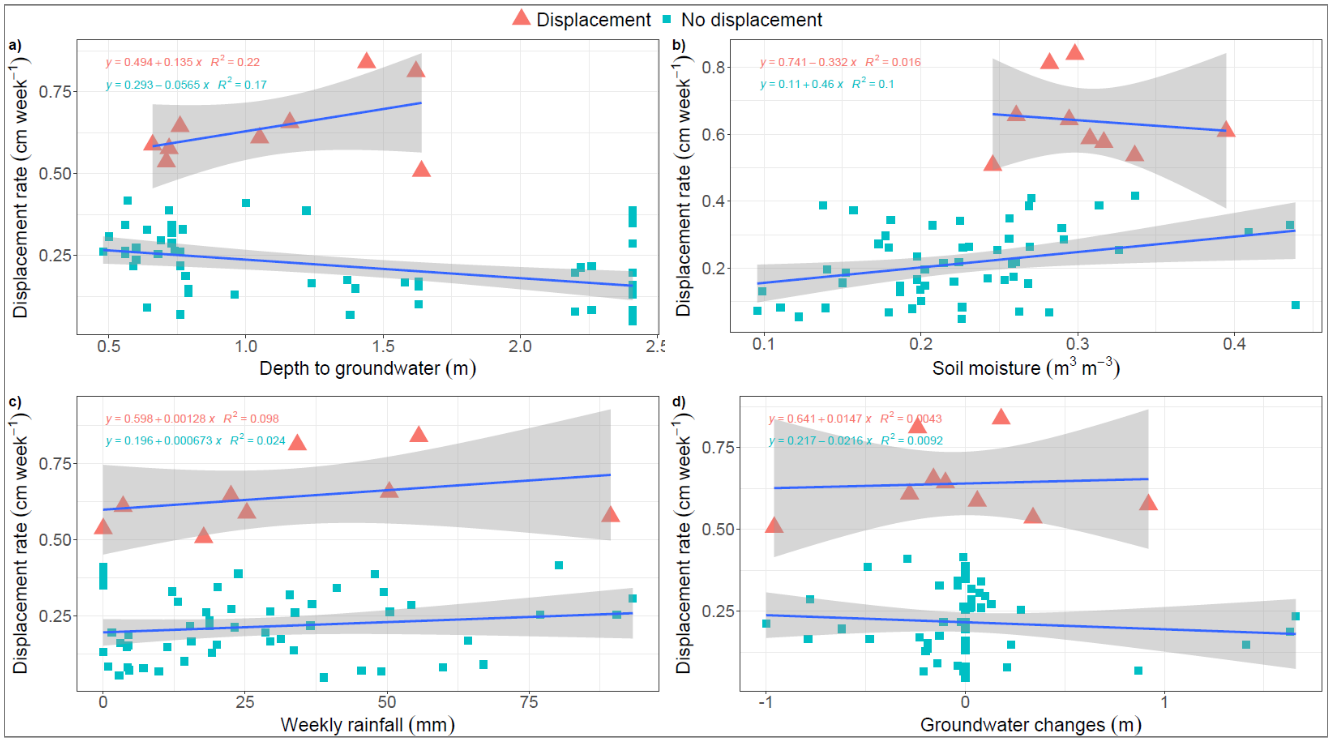


Figure 10. Rwaza hillslope: Regression analysis between hydro-meteorological processes and slope displacement

Conclusion

This research aimed to understand the hydro-geological and meteorological processes and the relationship thereof using two typical hillslopes (Karago and Rwaza) prone to landslides in northwestern Rwanda. The geotechnical characterization indicated instability conditions at the Karago hillslope and marginally stable conditions at the Rwaza hillslope. It was observed that landslides occur during the wettest period (i.e. soil moisture close to saturation and groundwater rises to near surface). Even though, the landslide body masses moved quite synchronically, the surface displacements control points revealed the toe and head units to move faster than the intermediate units. The highest acceleration at the toe was attributed to the external incision agents like stream erosion while cracks and steeper failure plane are responsible for acceleration at the head unit. The regression analysis indicated a strong correlation between surface displacements and depth to groundwater at Karago and thus important for landslide initiation thresholds definition. The role of rainfall was also significant with long lasting low intensity rainfall being more impactful than short and high intensity rainfall.

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