Chapter

Influence of Canopy Disturbances on Runoff and Landslide Disposition after Heavy Rainfall Events

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Abstract

As protective forests have a major control function on runoff and erosion, they directly affect the risk from hydrogeomorphic processes such as sediment transport processes or debris flows. In this context, future scenarios of climate-related canopy disturbances and their influence on the protective effect remain, however, an unsolved problem. With the individual-based forest landscape and disturbance model iLand, an ensemble of forest landscape simulations was carried out and the effects of future changes in natural disturbance regimes were evaluated. To determine peak runoff, hydrological simulations have been conducted, using the conceptual hydrological model ZEMOKOST as well as the deterministic model GEOtop. Effects of forest disturbances on hillslope stability were investigated, based on a modified Coulomb landslide model. Our results suggest no influence of the disturbance regime on the runoff. The climate-related increase in the frequency of disturbances is not reflected in increased runoff during the period under consideration. Contrary, slope stability analyses indicate that the availability of shallow landslides in steep forested torrent catchments might be decreased by the occurrence of disturbances – especially for a warm and dry climate projection. Canopy disturbances seem to accelerate the adaptation of tree species to future climate conditions, which is likely to be accompanied by a change in root systems away from flat roots that currently predominate in torrential catchments. In terms of managing the protective effect of forests against shallow landslides, such natural disturbances can thus be considered as positive interventions in the existing forest ecosystem by promoting natural succession.

Keywords: canopy disturbance, runoff, hillslope stability, torrential catchment, protective forest

1. Introduction

Quantitative risk assessment of natural hazards serves nowadays as the basis for a targeted risk management, respectively allows a risk-based classification and communication of the considered hazardous event in society [1, 2] (see also chapter [3] of this book). One of the most important and pervasive problems in this context concerns the investigation of time-scale properties and complex relationships between process activity, social development (exposure, protective measures, land use, etc.) and climate change. The correct understanding of the correlation structures governing observational time series might provide useful information on the dynamical features of natural hazard processes and on the dynamical mechanisms involved [4].

Steep headwater catchments typically provide the setting for such natural hazardous events because they are, besides being a drainage area for precipitation (see chapter [5] of this book), also sediment source zones of river systems, delivering significant volumes of sediment to the valley floor in highly dissected and coupled landscapes. As stated by [6], headwater catchments differ from down-stream reaches by their close coupling to hillslope processes, more temporal and spatial variation, and their need for different means of protection from land use. Especially processes, which are capable to relocate a considerable quantity of sediments, like bedload transport processes, debris floods or debris flows, often have tragic consequences on human settlements and infrastructures. Thus, for such hydrogeomorphic hazards the probability of occurrence and magnitude is beside the occurrence of critical rainfall events essentially a function of runoff and erosion which is, however, directly coupled to the protective effects of forested landscapes. In connection with frequently occurring natural hazard processes, protective forests, even if they currently only fulfill indirect protective effects, represent an essential factor in the risk reduction of natural hazard processes over long periods of time – on large potential natural hazard disposition areas. Today, about 30% of the forest area in Austria is assigned a protective function to avoid serious natural hazards, and according to the interim evaluation of the Austrian Forest Inventory, this share is increasing [7]. However, the same inventory data show that only half of such classified protective forests have a stable structure. The reasons for this are a significant aging of the Austrian protective forest stands due to a lack of natural regeneration and a lack of resistance to natural disturbances. This concerns climate-related forest disturbances such as forest fires, wind, and insect outbreaks, which will likely increase in the coming decades. Here, climate change can alter the frequency, intensity, duration and timing of such natural disturbances [8, 9]. Based on data of more than 10,000 torrent catchment areas in Austria [10], showed that natural disturbances increased the probability of torrential events in the last 32 years. With the expected increase of the global average surface temperature of 3–5°C by 2100, compared to the first decade of the 20th century, the spatial and temporal impact of climate change on forests represents an additional threat to the desired protective forest structures and thus to natural hazard management.

The aim of this research was to investigate the effects of climate-induced natural disturbance regimes (bark beetle or storm damage) on hydrogeological processes in forested alpine torrent catchments. Combining methods from forestry, hydrology and geotechnical engineering, an integral approach was chosen to analyze possible effects of natural disturbances on hydrogeomorphic hazards in the perspective of future protective forest developments. This work was carried out in the course of the project “PROTECTED” funded by the Austrian Climate Research Program. The chapter presents hydrological findings as well as a brief summary of geotechnical findings as described in [11].

2. Runoff and landslide simulations in forested headwater catchments affected by canopy disturbances

To analyze the impact of future change, an ensemble of forest landscape simulations has been conducted in two steep headwater catchments located in the Stubai valley, Tyrol, Austria. With the "Innerer Lehnertalbach" (IL) and the "Äußere Lehnertalbach" (AL) two typical torrential catchments with high relief energy (Melton ratio for IL = 1.3; Melton ratio for AL = 1.2, cf. [12]) have been chosen. Both catchments are situated in ecoregion 1.2 (Subkontinentale Innenalpen-West), dominated by metamorphic lithologies (mainly Gneiss). They are a typical example of mountain forest ecosystems of the central Alps, dominated by Norway spruce (*Picea abies* (L.) Karst.), European larch (*Larix decidua* L.) and Swiss stone pine (*Pinus cembra* L.). An overview of the catchment area characteristics is shown in **Table 1**.

2.1 Climate and precipitation scenarios

In order to cover the widest possible range of future climate scenarios, four different climate forecasts have been selected, based on three global models from the Irish Center for High-End Computing (ichec), the Pierre Simon Laplace Institute (ipsl) and the MetOffice Hadley Center (mohc). All three global models (ichec, ipsl, mohc) have been operated with the RCP 8.5 scenario – assuming a very high gain of energy (8.5 W/m^2) caused by future climate change. The global model ichec, however, was additionally operated with a moderate, RCP 4.5, climate perspective (4.5 W/m^2). The temperature and precipitation differences of the Eur-11 dataset for the period 2071–2100 compared to 1981–2010 are shown in **Figure 1**. All mean air temperatures increase in comparison to 1981–2010. Of the climate predictions used, only mohc8.5 shows negative precipitation trends. In addition to the climate forecast scenarios, forest landscape simulations are further driven by assuming no climate change and a future climate development aligned with historic climate data. This climate scenario is denoted as historic and results for the period from 1961 to 2015 from combined 1x1 km INCA and SPARTACUS, grid data of the Central Institute for Meteorology and Geodynamics (ZAMG) and observation series of ZAMG weather stations, as well as locally installed monitoring stations.

For each of the climate forecast scenarios, forest landscape development was simulated for 200 years with the individual-based forest landscape and disturbance model (iLand) [13]. Disturbance events have been stochastically considered based on 20 replicates, while we considered the non-disturbance landscape to be based on one replicate. Further, all iLand simulations were additionally conducted with and without considering forest management activities. Thus, in total 210 landscape simulations have been performed.

Parameters	"Innerer Lehnertalbach"	"Äußerer Lehnertalbach"
Area [km^2]	4.8	1.3
Min. elevation [m a.s.l]	1,043	1,037
Max. elevation [m a.s.l]	2,094	2,480
Mean slope gradient [°]	34	36
Forest cover [%]	83	36

Table 1.
Catchment area characteristics of the "Innere-" and "Äußere Lehnertalbach".

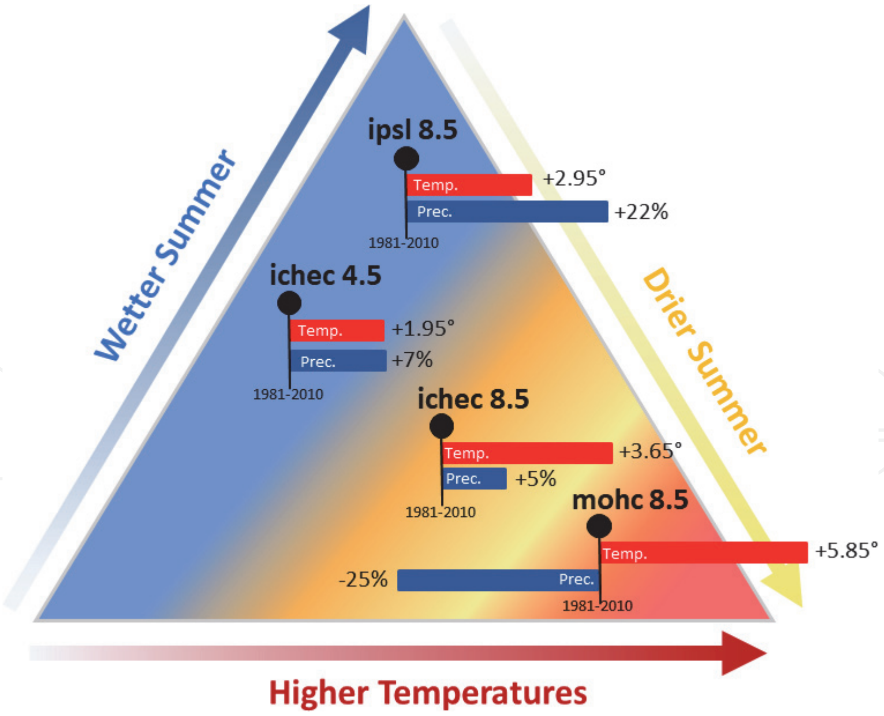

Figure 1.
Used climate forecasts based on the EUR-11 dataset as average temperature and precipitation difference of the period 2071–2100 compared to 1981–2010 (summer).

Duration [min]	Precipitation intensities [mm/h]	
	"Innerer Lehnertalbach"	"Äußerer Lehnertalbach"
60	88.85	94.65
240	130.10	138.39
720	178.56	180.26

Table 2.
eHYD design precipitation values based on a 100-year recurrence interval for the selected catchments.

Three precipitation events of varying duration (60 min, 240 min and 720 min) with a recurrence interval of 100 years have been defined, covering a wide range of information about the hydrological response of disturbances in forests. The design precipitation events result from the area-averaged, maximized precipitation (MaxModN, eHYD) of grid points close to the selected torrential catchments. Design precipitation probabilities of MaxMod are based on a simulation model calibrated with measured data and accounting for the topography. MaxModN gives precipitation values that are usually higher than those observed (**Table 2**).

2.2 Runoff simulations

The runoff simulations in the study area were performed with two, conceptually different, hydrological modeling approaches.

For the selected torrential catchments, like for nearly 96% of all torrential catchments in Austria, no information about past rainfall-runoff events exists. This is mainly because of the lack of continuous discharge measurements devices (water gauges). For this reason, runoff simulations have been performed with the precipitation/runoff (P/R) model ZEMOKOST [14] – an easy to apply event-based concept-model, specially developed for the application in small to medium-sized (< 100 km^2) ungauged torrential catchments. The semi distributed model is based on a two-layer concept with a surface and a subsurface runoff module. ZEMOKOST needs the portions of surface runoff classes (RC_{const}) and surface roughness (c) classes for each sub-catchment (see chapter [5] of this book). The main parameters, runoff coefficient (RC_{const}) and surface roughness (c), have been investigated, following the code of practice developed by [15]. Actual site characteristics (vegetation, soil) were mapped in the field to ensure realistic assessment of runoff characteristics. In this context, vegetation in ZEMOKOST is primarily considered on the basis of its hydrologic vegetation characteristics, i.e., forest vegetation and dwarf shrub cover versus woody free vegetation. ZEMOKOST was then calibrated and checked for plausibility for the test-catchments using the existing precipitation and discharge time series and data from historic events.

Runoff simulations have additionally been carried out with the physically based, grid-distributed hydrological program GEOtop 2.1. Such models account beside surface flow also for subsurface (or inter) flow and groundwater related effects, important phenomena when simulating soil erosion activity. In GEOtop, land use is made up of vegetation classes consisting of a non-arable and differently forested groups. The individual groups do not represent any particular tree species, but result from units of similar vegetation height, leaf area, canopy coverage and root depth, directly determined by iLand simulations. Surface runoff in the channel and along the hillslopes are determined by Manning's empirical hydraulic approach. Since the runoff regime in forests is determined primarily by forest soil conditions, the interaction with the lithosphere is of high importance, described by soil physical parameters. In addition to the topographical data, pedological data add differences in depth, so-called horizons. Each type of soil consists of different soil horizons. Each soil horizon is characterized by its physical properties (soil texture data). The storage and conductivity of the individual horizons is given by the water content at wilting point, field capacity and saturation, as well as the conductivity at saturation and determined by means of pedotransfer functions proposed by [16] on their sand and clay content. The conductivity in the unsaturated soil matrix is calculated by van Genuchten values (α, n). Those values can be determined according to [17] by classifying the soil texture according to United States Department of Agriculture (USDA).

Finally, GEOtop runoff results have been validated with the runoff results proposed by ZEMOKOST, where it has been found that the drainage roughness has a significant impact. **Figure 2** shows a calibration example of the "Äußere Lehnertalbach" for GEOtop simulations based on a sensitivity analyses of varying hydraulic roughness parameters (40 simulations), compared to ZEMOKOST simulations for a 100-year precipitation event of the duration levels 60, 240 and 720 min. The solid line corresponds to the calibrated GEOtop simulation.

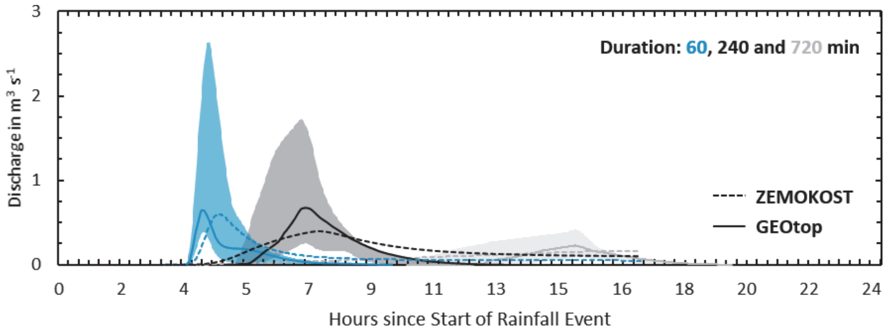

Figure 2.
Validation of GEOtop based on ZEMOKOST simulations for a 100-year precipitation event of the duration levels 60, 240 and 720 min at the "Äußere Lehnertalbach". While the shaded area contains all simulated hydrographs, the solid line represents the hydrograph of the calibrated model.

For future runoff predictions of peak discharges, simulated with both hydrological models, varying land use conditions were provided by the pre-conducted number of iLand simulations of the selected catchments – resulting in multiple runoff simulation scenarios.

For future ZEMOKOST simulations the parameters RC_{const} and c are calculated from iLand outputs. In order to derive RC_{const}, pedohydrological reaction units were mapped in the field. Six different units have been characterized. Considering the iLand outputs canopy cover, ground cover and soil water content, RC_{const} is given as an output for the different reaction units. Each c value is assigned a range of iLand output values per parameter on basis of [15]. For an iLand output parameter set the best fit c value is selected.

GEOtop simulations have been based on the biosphere mapped via land use parameters. The land use is formed by vegetation classes, consisting of non-vegetated and differently forested groups. The individual groups do not represent a specific tree species, but result from units of similar vegetation height, soil roughness, leaf area, canopy cover and root depth, which were determined via iLand.

2.3 Slope stability simulations

Simulations of the effect of forest disturbances on hillslope erosion processes are based on the results from the distributed runoff simulations of GEOtop in combination with an extended version of the Mohr-Coulomb soil stability model. The stability of each soil column – 1 m in depth with an area of 100 m^2 – i.e. each cell in the study area, was subsequently estimated for each layer l for simulation i at time t according to Eq. (1).

$$FS_i(l,t) = \frac{B + \left(A - \sum_{k=1}^{l} h(k) * m_i(k,t)\right) * \frac{tan\,(\phi(l))}{tan\,(\beta)}}{A} \tag{1}$$

where $FS_i(l,t)$ is the factor of safety for a specific soil column in the study area under simulation i for its layer l, with values below 1 indicating that the soil column is instable at the depth of layer l and time t. $h(k)$ is the depth of layer k, $m_i(k,t)$ the saturation of layer k at time t, as given by Eq. (3), $\phi(l)$ is the internal angle of friction of layer l in rad and β is the slope angle of the soil column in rad. In Eq. (1), A equals to the normal stress resulting from the soil and plant weight reduced by the pore water pressure and was derived by means of Eq. (2).

$$A = \gamma_w^{-1} * \left(q_i + \sum_{k=1}^{l} h(k) * [m_i(k,t) * (\gamma_{sat}(k) - \gamma(k)) + \gamma(k)]\right) \tag{2}$$

where γ_w is the specific weight of water in kNm^{-3}, q_i is the additional pressure due to the weight of the vegetation in Pa, $h(k)$ is the depth of layer k in m, $m_i(k,t)$ is the saturation of layer k for simulation i given by Eq. (3):

$$m_i(k,t) = \frac{\theta_i(k,t)}{\theta_{sat}(k)} \tag{3}$$

where $\theta_i(k,t)$ is the soil water content of layer k at the time t for simulation i and $\theta(k)$ is the saturated water content of layer k, $\gamma_{sat}(k)$ is the specific weight of the saturated soil of layer k in kNm^{-3}, $\gamma(k)$ and is the specific weight of the dry soil of layer k in kNm^{-3}.

The cohesion component of the resisting forces was estimated according to Eq. (4).

$$B = \frac{2 * (C_s(l) + C_{r,i}(l))}{\gamma_w \, sin\,(2\beta)} \tag{4}$$

where $C_s(l)$ is the soil cohesion of layer l in Pa, $C_{r,i}(l)$ is the root cohesion of layer l for simulation i in Pa, γ_w is the specific weight of water in kNm^{-3} and β is the slope angle of the soil column in rad.

A detailed description of the geotechnical parameterization as well as the parametrization of root cohesion and vegetation weight can be found in [11].

3. Future possible tendencies of canopy disturbances show no significant influence on runoff after heavy rainfall events

The variability of the peak discharge, resulting from the presence of natural disturbances within the forested area, is given by the relative peak discharge change $\Delta Q_j(t, d)$ for each climate scenario j, with specific precipitation duration d and time frame t. Accounting for disturbance effects per applied climate scenario, $\Delta Q_{j,i}(t, d)$ is estimated based on the ratio between the peak discharge of the i-th replicant of the climate change scenario j considering disturbance effects $Q^1_{j,i}(t, d)$, with the

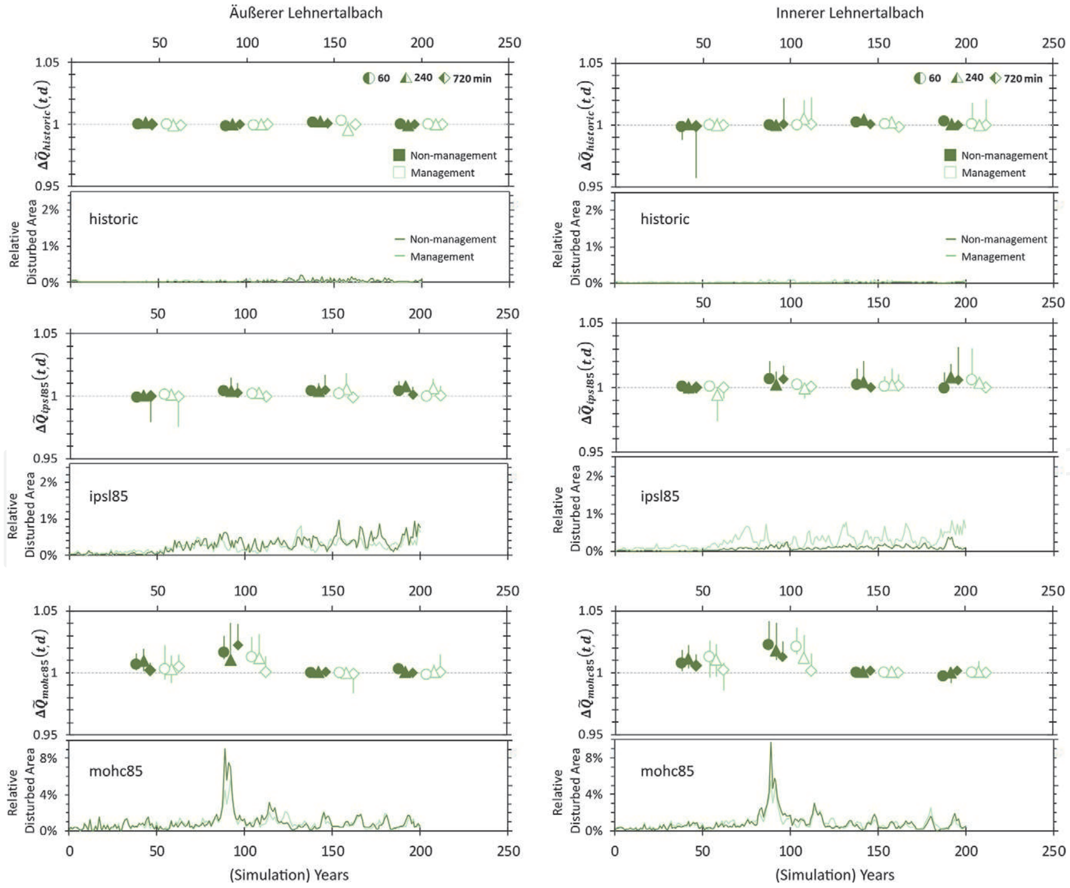

Figure 3.
In each figure, the upper panel shows the change in peak discharge relative to the peak discharge without disturbances stratified by management and no management for 50, 100, 150 and 200 years after simulation begin. All discharge values are based on the pooled model results (ZEMOKOST and GEOtop). The symbol is located at the median, while the lower and upper end of the bar represent the 25. And 75. Percentile estimated from 20 repetitions. The lower panel shows the disturbed area relative to the total area occupied by forest for each year.

peak discharge of the climate change scenario j without considering disturbance effects $Q_j^0(t,d)$, for each precipitation duration and time slice.

$$\Delta Q_{\,j,i}(t,d) = \frac{Q^1_{\,j,i}(t,d)}{Q_j^0(t,d)} \tag{5}$$

From the 20 relative peak discharge change observations per climate scenarios, precipitation duration and time slices, the median $\Delta\tilde{Q}_j(t,d)$ is derived, and the 95% confidence interval is estimated based on 2,500 bootstrap samples. To account for epistemic uncertainty, $\Delta Q_{\,j,i}(t,d)$ values are based on the pooled model results (ZEMOKOST and GEOtop).

Figure 3 shows the relative peak discharge change for 50, 100, 150 and 200 years after simulation begin – stratified by the selected torrential catchments, historical based –, wettest (ipsl85) –, and driest (mohc85) climate scenarios as well as management and no management.

The results (**Figure 3**) do not permit any significant influence of natural disturbances on the runoff behavior in torrent catchment areas. Neither could a significant change in soil water content be observed for any of the future climate scenarios and disturbance induced simulated landscapes (c.f. **Figure 4**). However, positive trends describing an increase in runoff due to an increase in the disturbed forest area cannot be completely ruled out visually, i.e.: times with a high number of disturbances (supposing a critical size of disturbed area) apparently also cause an increase in runoff behavior during heavy precipitation events.

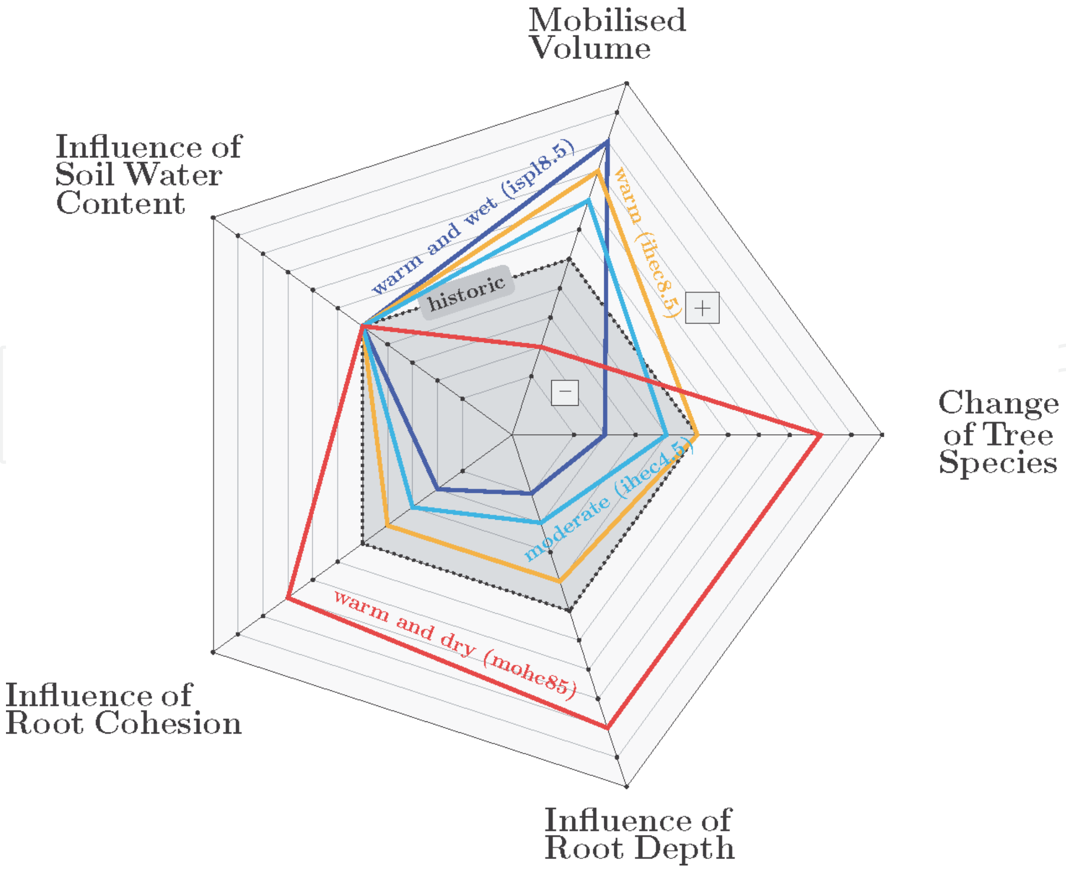

Figure 4.
The influence on climate change scenarios on modeled slope stability criteria and the corresponding mobilized volume. Canopy disturbances influence the development of tree species and thus the existing apparent cohesion through the root system.

4. Climate change and climate-driven development of canopy disturbances are directly related to the disposition of landslides

The results given refer to the mobilized volume, which is calculated for each cell and all climate scenarios individually as the cell-area times the unstable soil depth. The latter is defined as the height from the surface, of the considered cell, to the first soil layer whose factor of safety (FS_i, eq.1) is simulated below one. A detailed presentation and discussion of all results can be found in [11]. However, this chapter provides a brief summary of the main findings that summarize the influence of natural disturbances on slope stability criteria (amount of mobilized volume) by i) the influence of soil water content, ii) the influence of root cohesion, iii) the influence of rooting depth, and iv) the change in tree species (**Figure 4**). While under historical conditions the mobilized volume is constant over time, the mobilized volume increases for the moderate (ihec4.5) and warm (ihec8.5) to the warm and wet (ispl8.5) climate scenarios (**Figure 4**). A considerable decrease of the mobilized volume was, however, found for the warm and dry climate scenario (mohc8.5). Beside these trends the mobilized volume is for all climate scenarios and time periods constantly less for forest stands influenced by canopy disturbances. These conclusions are also preserved if the duration is changed from 240 minutes to 60 or 720 minutes, with the only difference that for the 60-minute scenario less volume and for the 720-minute scenario more volume is mobilized compared to the 240-minute scenario.

The lower landslide disposition for the warm and dry climate scenario (mohc8.5) may initially be contra-intuitive but can be explained by a closer look at the structural change of the forest stands. Regardless of the climate scenario or the time period, the share of heart and taproot systems is higher for forest stands with natural disturbances. While for the climate scenarios ihec4.5, ihec8.5 and ispl8.5 the share of trees with sinker root system increases over time, the share of trees with sinker root system decreases in the mohc8.5 scenario. This leads to an increase in slope stability due to a higher rooting depth and increased root cohesion. The results suggest that on steep slopes, stability due to disturbances can occur through a more rapid change in natural succession – especially when a change in climate leads to a change in tree species with a higher root cohesion capacity.

5. Conclusion

Forest disturbances which have a possible influence on natural hazard processes are understood to refer primarily to large-scale disturbances, i.e. disturbances which cause large-scale deforestation. After such large-scale disturbances, technical protection structures are very often installed as immediate measures to compensate for the loss of forest’s protective effects. Frequently recurring disturbances are often much smaller in relation to “catastrophic” large-scale disturbances and thus less in the awareness of natural hazard experts, but very much in the attention of forest experts. The canopy disturbance intensities modeled in this study affected less than 20% of the forested area of the considered catchments – somehow a critical size of disturbances regarding change in runoff regimes [18–20]. Although the runoff simulations do not permit clear quantifiable statements, it must be noted that such critical size of the natural disturbance is more likely to be reached in steep and small torrent basins especially in causing a change in runoff behavior. However, future research questions will most certainly address quantifying the size of a critical disturbance area, i.e., determining the area above which a significant impact on the hydrologic regime in steep torrent catchments would be evident. The influence of critical disturbances on slope stability showed, in a first moment, contra intuitive results, especially for the smallest and most densely forested investigation area. Here we have noticed an increase in slope stability with an increase in the disturbed area, significantly for the climate scenario with high temperatures in combination with lower precipitation (mohc 8.5). As trees exert a kind of cohesion on the soil layer due to their roots, the formation of the root system plays an important role regarding slope stability. However, the shape of the root system depends mainly on the tree species and the age. Both are subject to significant changes due to the influence of climate and the occurrence of natural disturbances and thus influence stability on steep forested slopes. In the Alpine region, the treatment of protective forests faces more than ever the challenges of sustainable and proactive management. While it is still too early to define general management strategies to maintain or improve the protective effect of forests in relation to runoff formation in the context of disturbances, it can be stated that scenarios of future climate projections suggest the targeted promotion of tree species with deep-root or heart-root systems as necessary, especially on landslide-prone sites.

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Conflict of interest

The authors declare no conflict of interest.

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