"CIRCLE-2 MOUNTain Group"

Final Report

Project title
Assessment of **R**isks on transportation **N**etworks resulting from slope **I**nstability and **C**limate change in the **A**lps
ACRONYM
ARNICA

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A. Work progress

The general objective in the framework of ARNICA was to determine the potential impacts of future climate change on debris flows/landslides (DF) activity in the Alps. Moreover linear infrastructures are particularly vulnerable to such natural hazard. They are an essential component of the economic activity of these mountainous areas and transborder exchanges, which gives a highly strategic character to them. The vulnerability of the networks was also addressed in the project. To solve these points the project was organized in 5 WPs.

1- Define climate scenarios for the future periods

Firstly the aim was to derive localized scenarios of climate parameters triggering landslides and debris flows and to quantify their uncertainties. Localized and error corrected scenarios of heavy precipitation for three representative study regions (France, Switzerland, and Italy) have been generated by means of the methodology explained below and delivered to the project partners. Though the scenarios are subject to considerable uncertainty, they indicate increasing risk for heavy precipitation events in spring and autumn.

a) Ensemble of localized error corrected heavy precipitation climate change scenarios

As input for the analysis of future torrential activity within the ARNICA project local scenarios of heavy precipitation events are required. Since even high resolution Regional Climate Models (RCMs) are still too coarse for direct application in local climate change impact studies (Mearns et al., 2003), and since they are known to feature considerable errors, particularly regarding precipitation and their extremes (e.g., Suklitsch et al., 2010; Jacob et al. 2007), they need further processing before application. Within ARNICA localized climate scenarios of meteorological conditions triggering torrential disasters are produced based on 24 RCM runs taken from the EU-FP6 project ENSEMBLES (van der Linden and Mitchell, 2009) on a 25 km grid and from the reclip:century project (Loibl et al., 2011) on a 10 km grid. All simulations are based on the A1B emission scenario. An empirical-statistical downscaling and error-correction method (quantile mapping) as described in Themeßl et al. (2011; 2012) is applied to improve the skill of the RCMs in representing local climate at station scale. The simulations are available until 2050 for 24 RCMs and until 2100 for 17 RCMs. In the process of error correction tailored local observational data is used to improve the skill of the RCMs data in representing local climate. The observational data sets used as an input for quantile mapping are SAFRAN (Quintana-Seguí et al. 2008 and Vidal et al. 2010) in France and station data in Italy and Switzerland. SAFRAN is a mesoscale atmospheric analysis system for surface variables over France. Each data point used in ARNICA represents one massif, altitude and orientation of the French Alps. For the Italian study region, scenarios for 33 observational stations in South Tyrol were generated. Daily precipitation (6 stations) and temperature (2 stations) of Switzerland region were used to calibrate the error correction. The station data is available in daily time steps.

b) Details of uncertainty estimation in future trends of precipitation extremes

Uncertainty estimation and reliability of the scenarios of heavy precipitation frequency are developed using ensemble techniques. Uncertainty of the projected changes is quantified by different measures.

Here we adopted spreads of the ensemble distributions of climate change signals at each location. Statistics of the climate change signals are assessed to time horizon of mid (2050) and late (2100) century future periods. Results of this analysis are displayed in Section 2.

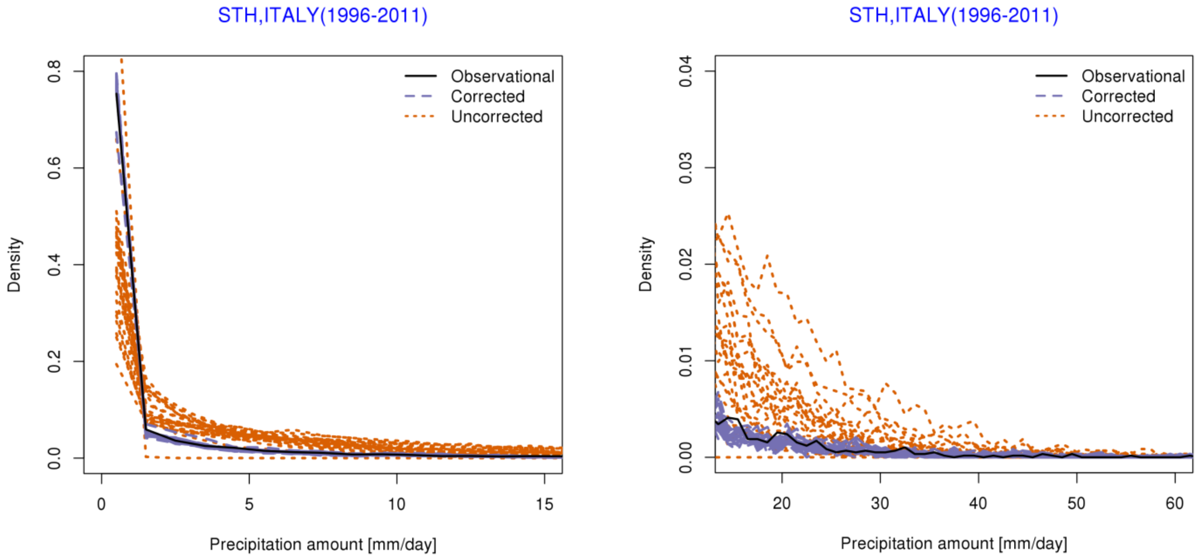
Developments and activities (described below) have only been partly funded from ARNICA. ARNICA also profits from work done in the Austrian Climate Research Program (ACRP) project "Deucalion" (Determining and Visualizing Impacts of the Greenhouse Climate Rainfall in the Alpine Watersheds on Torrential Disasters) and vice-versa.

Note the analyses have been finished for all study regions, but to keep this report short, this section is focused on the Italian study region (South Tyrol).

c) Evaluation of the error corrected RCMs time-series at point-scale.

An empirical-statistical error correction and downscaling method, quantile mapping (QM; Themeßl et al., (2011; 2012) is implemented for post processing and further downscaling the RCM results to the station scale. We evaluated the results in order to examine the quality of the generated point-scale time-series by a split sample approach, using independent evaluation and calibration periods. The calibration period is 1980-2011, whereas the data are validated in the independent period 1996-2011. This split-sample approach mimics the application to future climate scenarios, where observations of the past are used to calibrate the bias correction of future simulations. Distribution and frequency based evaluation procedures were carried out for all study regions.

The distribution-based evaluation regarding light and medium and heavy precipitation at the station St. Valent in der Haide, Italy is exemplarily displayed in Figure 1 (panel A, panel B, respectively) in order to give an overview of QM's mode of operation. Distributions of uncorrected model data, error-corrected model data and observations are shown. Error-corrected data (blue lines) match the observed distribution (black line) very well, regardless of the shape of the uncorrected distribution (orange lines). Most of the uncorrected models overestimate light precipitation frequency ("drizzling-effect"; e.g. Gutowski et al, 2003), which is well corrected by QM.



Panel A *Panel B*

Figure 1: Raw (orange) and corrected (blue) precipitation distributions at station St. Valent in der Haide. Left: Light and moderate precipitation; Right: Heavy precipitation.

The frequency-based evaluation has been carried out for various precipitation thresholds and all stations. As example, the results for precipitation events >30 mm/day at station St. Valent in der Haide are shown in Figure 2. The median bias is reduced in most cases and the annual variation of biases is strongly reduced in the error-corrected (blue) data sets compared to un-corrected (orange).

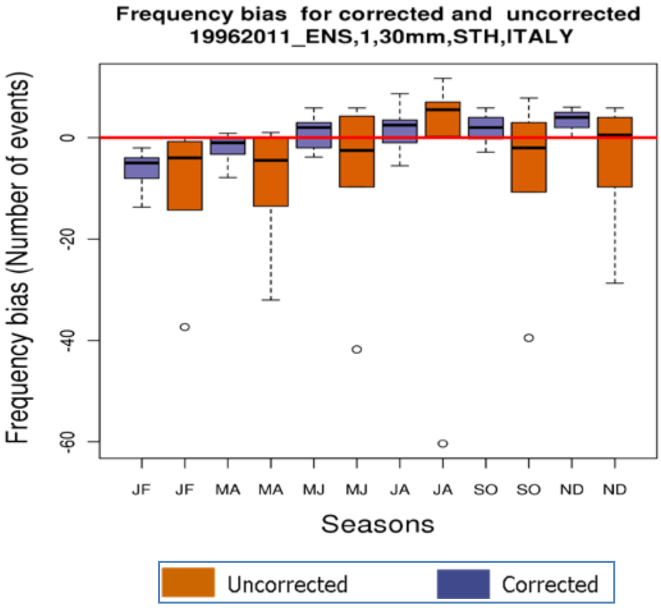


Figure 2: Biases in the frequency of days with more than 30 mm/day precipitation of raw (orange) and corrected (blue) RCM simulations at station St. Valent in der Haide, Italy. Box and whiskers indicate the variability of the frequency bias. Boxes indicate the first (q25) and the third (q75) quartile, the whiskers extend to q5 and q95, and the black horizontal line indicates the median.

Like other statistical downscaling methods, QM assumes stationarity of model error characteristics over time. That means QM assumes that the statistical relationship between observed climate and modeled climate in the calibration period applies to future periods. Application of QM methods works well under stationary conditions but non-stationarity leads to degradation of the bias correction results. This is particularly the case for extreme precipitation of >30 mm/day. For the time being, we suggest to consider results for higher thresholds than 30 mm/day with care. Nonetheless, there is a PhD, Satyanarayana Tani, currently working on that topic (also in conjunction with Deucalion).

d) The climate change signal

Climate change signal analysis was carried out all the stations in the 3 study regions. For this purpose, statistics of the frequency of heavy precipitation events (10 mm, 20 mm, 30 mm, 40 mm, 50 mm per day), are worked out for two 30-year scenario periods, namely 2021-2050 and 2070-2099. The reference period is 1961-1990. Two kinds of box plots are produced: One gives changes in absolute numbers of days and other shows relative change as factors. An example graph for relative change is given in Figure 3. They illustrate the multi-model analysis for the frequency of heavy precipitation events with respect to spread of the model ensemble at station Corvara im

Gadertal, Italy. The change of heavy precipitation events (>30mm/day) for the period 2021-2050 is shown. The box plots show the variation of the frequency in the analysed 24 RCMs. The bold line is the median, the box is the 25- and 75-percentile the whiskers are 95 and 5-percentiles. The numbers in the upper part of each of the graphs are the median number of events in the reference period. The single day event is counted as >30 mm in 1 day. The multi-day events are counted if each day has at least 5 mm and the total sum is above 30 mm (days with mean temperature ≤ 5°C are included; the 5°C threshold is used to differentiate liquid and solid precipitation in the debris flow source region).

The example of Corvara im Gadertal, shows that considerable increases of the frequency of extreme precipitation events (up to 25 % and more) can be expected in all seasons except summer. Only in July and August, a slight decreasing trend is indicated. However, the uncertainty in the climate simulations is large and the ensemble analysis shows that in each season positive and negative trends are possible.

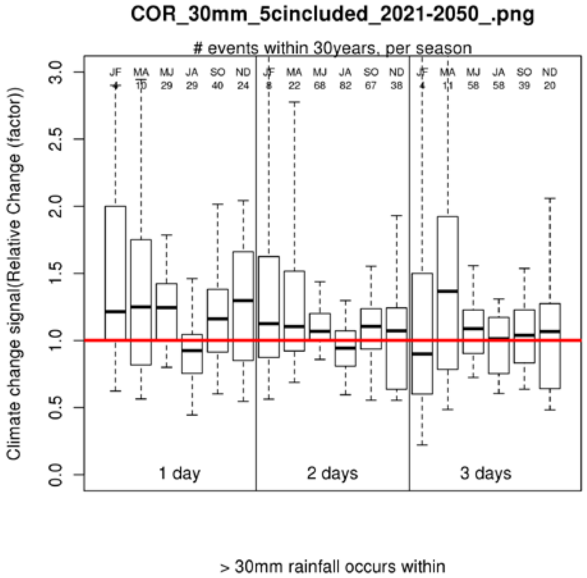
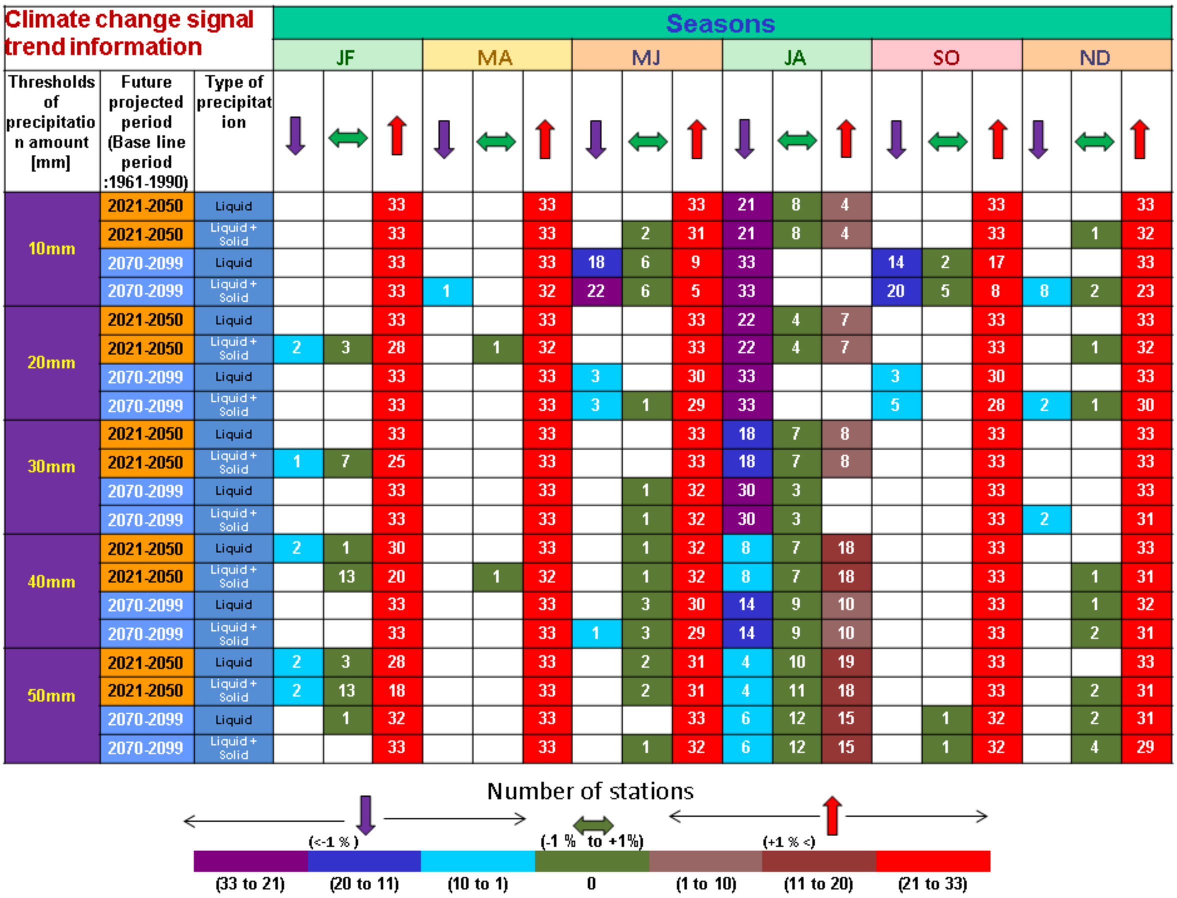


Figure 3: Climate change signal (relative) of the frequency of heavy precipitation events (>30 mm/day) of the scenario period 2021-2050 compared to 1961-1990.

The climate change signal for 33 stations in South Tyrol, Italy is summarized in Table 1. Climate change signals of single day events shows that potential triggering precipitation events are expected to become more frequent in most seasons and stations except July and August. This indication for more extreme precipitation events is most abundant in May, June, Sept., Oct., Nov., and Dec. However, also in the summer months July and August the frequency of very intense precipitation events (above 30 mm/day) often even increases. This illustrates that even under conditions with decreasing total precipitation sum and decreasing frequency of “mild extremes”, the frequency of very heavy precipitation extremes can increase.



Climate change signal trend information			Seasons																	
			JF			MA			MJ			JA			SO			ND		
Thresholds of precipitation amount [mm]	Future projected period (Base line period :1961-1990)	Type of precipitation	↓	↔	↑	↓	↔	↑	↓	↔	↑	↓	↔	↑	↓	↔	↑	↓	↔	↑
10mm	2021-2050	Liquid			33			33			33	21	8	4			33			33
	2021-2050	Liquid + Solid			33			33		2	31	21	8	4			33		1	32
	2070-2099	Liquid			33			33	18	6	9	33			14	2	17			33
	2070-2099	Liquid + Solid			33	1		32	22	6	5	33			20	5	8	8	2	23
20mm	2021-2050	Liquid			33			33			33	22	4	7			33			33
	2021-2050	Liquid + Solid	2	3	28		1	32			33	22	4	7			33		1	32
	2070-2099	Liquid			33			33	3		30	33			3		30			33
	2070-2099	Liquid + Solid			33			33	3	1	29	33			5		28	2	1	30
30mm	2021-2050	Liquid			33			33			33	18	7	8			33			33
	2021-2050	Liquid + Solid	1	7	25			33			33	18	7	8			33			33
	2070-2099	Liquid			33			33		1	32	30	3				33			33
	2070-2099	Liquid + Solid			33			33		1	32	30	3				33	2		31
40mm	2021-2050	Liquid	2	1	30			33		1	32	8	7	18			33			33
	2021-2050	Liquid + Solid		13	20		1	32		1	32	8	7	18			33		1	31
	2070-2099	Liquid			33			33		3	30	14	9	10			33		1	32
	2070-2099	Liquid + Solid			33			33	1	3	29	14	9	10			33		2	31
50mm	2021-2050	Liquid	2	3	28			33		2	31	4	10	19			33			33
	2021-2050	Liquid + Solid	2	13	18			33		2	31	4	11	18			33		2	31
	2070-2099	Liquid		1	32			33			33	6	12	15		1	32		2	31
	2070-2099	Liquid + Solid			33			33		1	32	6	12	15		1	32		4	29

Table 1: Summary of climate change signal information of the scenario period 2021-2050 & 2070-2099 compared to 1961-1990 for different precipitation types (Liquid, Liquid & Solid). The number of stations with increasing (arrow up), decreasing (arrow down), and no change (horizontal arrow (-1 % to +1 %)) for precipitation frequency of different thresholds is shown. Different colors represent the numbers of stations.

2. Impacts of changing climatic conditions on the frequency, magnitude and spread of debris flows and landslides

Before analyzing impacts of future climate change on slope processes we aimed to document current relationships between climate and periglacial processes. To this end we computed slope processes databases.

a) Database on past and contemporary debris-flow and landslide occurrences

In Switzerland, a database of 417 events (covering the period 1600 and today) has been elaborated in the Zermatt valley. The triggering of debris flows in the valley depends on a critical combination of available unconsolidated material and water supply. In the periglacial environments of the study region, debris flows are generally triggered by liquefaction of loose material in a channel, or by progressive erosion during a large release of water.

In terms of landslides, the work at Sachseln is currently being finalized in collaboration with University of Padova and WegCenter Graz, using detailed terrain data (LiDAR), land-use information, characteristics of past shallow landslides and statistically downscaled climate data to model the possible occurrence of future landslides in the area. The dendrolab of Bern is also working in the French Alps, The modeling is not planned, but work has focused on past and contemporary triggers of landslides. Past process activity on seven landslide bodies of the Riou Bourdoux catchment (southeastern French Alps) was reconstructed with an unusually large dataset of 3036 tree-ring series from 759 conifers affected by past landslide reactivations. Based on 996 growth anomalies identified in the cores, 61 landslide phases were identified since AD 1898.

In Italy, the University of Padova has developed an archive incorporating information on landslides and debris flows occurred in the period 2000-2010 in the Alta Adige area. The archive includes: triggering landslide points, deposition areas, sediment volumes, precipitation (at hourly time step) and soil moisture estimates based on a detailed hydrological model applied at the regional scale. The archive is based on a parallel data base developed by the Regional Office Repartition 30 and incorporating information on massmoves (landslides, debris flow, avalanches) recorded in the region over the same period. The archives were used to further test the local shallow landslide model and to establish precipitation thresholds for landslide triggering. These thresholds were re-assessed based on the precipitation database corresponding to the climate change scenario.

In France, LGP computed a debris flow database composed of 565 precisely dated DF events since the spring of 1970, (282 in the north of the French Alps (Savoie department) and 283 in the south of the French Alps (Hautes-Alpes and Alpes de Haute Provence departement) from 237 catchments (87 in the north and 150 in the south) during the period between May and October (Fig 4). The debris flow evolution shows however a significant difference in DF activity. Even though the number of events in both regions is nearly the same (57% of all events are in the north) there are significantly more catchments in the south and thus southern catchments are less active. However, major peaks in event numbers in both regions are nearly the same as in 1974, 1987, 1995 and 2005.

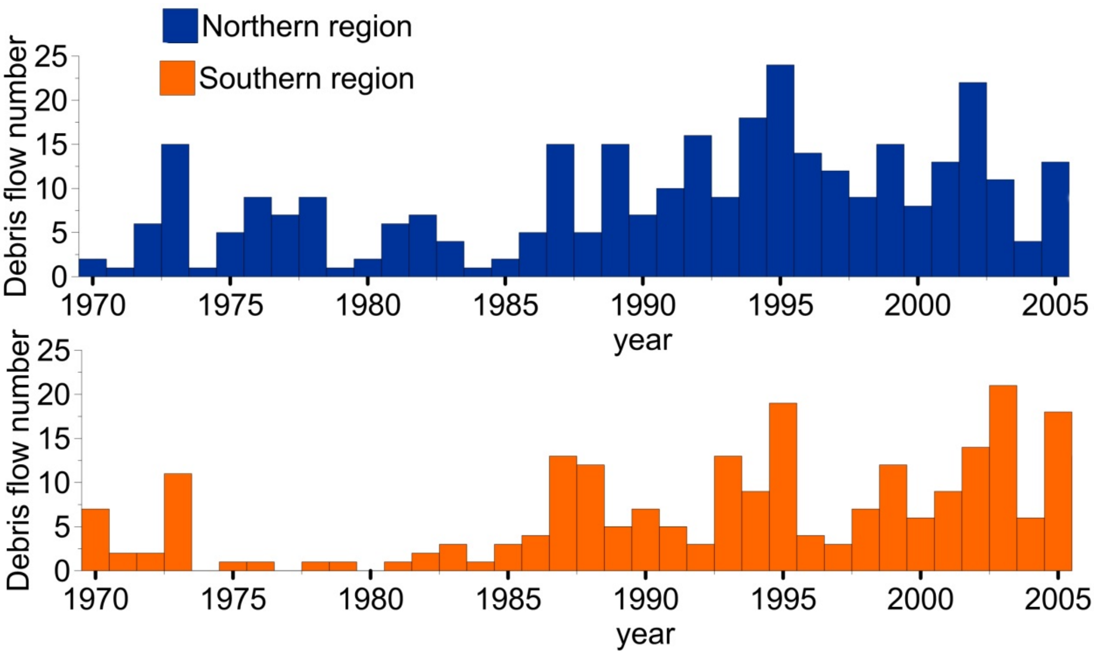


Figure 4. DF distribution since the 1970s in the northern (top) and southern (bottom) regions of French Alps

The database which started in the 1970s was split into two periods and revealed a significant change in the number of events in the two regions. A large increase in DF events has been observed after the mid-1980s. The significance of this change was proven by statistical T-tests.

b) Analysis of climatic conditions which were responsible for debris-flow and landslide occurrences

In Zermatt valley through the linkage of an unusually dense and highly resolved database on periglacial debris flows with meteorological records dating back to AD 1864, dendrolab.ch reconstructed 150 yr of rainstorms that triggered debris flows at high-elevation sites (source area elevations ranging from 2000 to 4545 m a.s.l.) in the Swiss Alps. Analysis was based on a tree ring-derived frequency series of debris flows from eight torrents, as well as on daily records from three meteorological stations and runoff data from four river gauging stations. Results show that the debris-flow season at these high-altitude sites now is much longer (May to October) than it used to be in the late nineteenth century when activity was limited to June–September. Debris flows early in the season are generally triggered by lower rainstorm totals (<20 mm/day) than those occurring later in the season because early season snowmelt adds considerable amounts of water to the system and therefore facilitates debris-flow formation. Debris flows in May, June, July, and August are triggered primarily by short-duration high-intensity rainstorms (local thunderstorms) whereas late season (September, October) debris flows are commonly related to longer-lasting advective rainstorms.
Logistic regressions and threshold analyses using monthly rainfall data and temperature anomalies indicate that landslides used to occur after wet winters with subsequent positive temperature anomalies in spring, and thereby point to the crucial role of snowmelt in landslide triggering at the catchment scale. Since the early 1990s, however, landslide activity in the Riou Bourdoux catchment shows an excessive and unprecedented increase in activity (12.5 events 10 yr^{-1}) favored by positive temperature anomalies in spring. From the data, we observe a shift from snowmelt induced landslides (controlled by winter precipitation) to instabilities controlled by spring temperatures and adds evidence to the hypothesis that climate change (and warmer springs) could further enhance landslide activity in the course of the 21st century.

In addition to the reconstruction of valley wide chronologies of debris, dendrolab.ch also investigated possibilities on how to improve reconstructed time series of debris flows at the level of individual fans. Identification of past debris-flow activity was often based on the presence of growth anomalies in trees, with a focus on scars, tilting, trunk burial or apex decapitation. Clear guidelines have been missing so far and the dating of events has only rarely been based on thresholds so as to distinguish signal from noise. In a similar way, the spatial distribution of affected trees has not normally been considered in mass movement reconstructions, and was at best used as a subjective exclusion factor. This study therefore aims at improving dating quality of and reducing noise in debris-flow time series. Based on a dataset of 803 increment cores (385 trees) affected by debris flows, we reconstruct event histories using (i) a classical experts’ approach, (ii) a weighted index (W_{it}) of responding trees as well as (iii) Moran’s I and Getis–Ord Local Gi indices. We identify similarities and differences in results and then investigate subsets of the tree-ring sample to define ideal sampling positions on debris-flow cones and guidelines for sample depth.

In Italy the analysis was based on Landsliding susceptibility which is the propensity of an area to generate landslides, i.e. the probability of spatial occurrence of known slope failures, given a set of geo-environmental conditions. Given the need to analyze the impact of varying climatic conditions on landsliding susceptibility, a process-based model has been developed for the task.

The model developed for the task at Padova University is able to cope with dynamic factors such as the variability of rainfall intensity and duration and yet maintains the simplicity of the index approach. Borga et al. (2002) developed a model of shallow landsliding which uses a quasi-dynamic wetness index to predict the spatial distribution of soil saturation in response to a rainfall of specified duration. The model is called Quasi-Dynamic Shallow Landsliding Model (QDSLaM). QDSLaM is based on the coupling of the soil saturation model with an infinite slope, Mohr-Coulomb failure model to describe the shallow landsliding process, and may predict duration and intensity of the rainfall necessary for landslide initiation to occur across the catchment. The QDSLaM model has been further generalized during the project in order to incorporate different hydraulic soil properties into the subsurface flow model and to accept different models describing the relationship between rainfall depth, duration and exceedance probability.

Since the model should be able to predict shallow landsliding susceptibility in different climatic conditions and with different land use conditions, an extended version of the model has been developed which could be applied to the three various sites considered in the project (Upper Adige basin (Italy), Malefosse and Rif Blanc (France) and Sachselns (Switzerland).

We extended the model to include the variability of soil depth into landslide susceptibility assessment. The dynamic topographic index is used to describe the transient lateral flow that is established at a hillslope element when the rainfall amount exceeds a threshold value allowing for (a) development of a perched water table above an impeding layer, and (b) hydrological connectivity between the hillslope element and its own upslope contributing area. A spatially variable soil depth is the main control of hydrological connectivity in the model. The hydrological model is coupled with the infinite slope stability model and with a scaling model for the rainfall frequency–duration relationship to determine the return period of the critical rainfall needed to cause instability on three catchments located in the Italian Alps, where a survey of soil depth spatial distribution is available. Comparisons with the standard QDSlAM show a better performance of the new model in predicting observed shallow landslides, implying that soil depth spatial variability and connectivity bear a significant control on shallow landsliding.

We also extended the model to represent anthopogenic disturbances like forest road networks and considered the impact of DTM resolution on the model performances.

The model has been successfully validated over eight different study sites, where detailed inventories of shallow landslides are available. Two study sites are located in France, another one is located in Switzerland, and four are located in the Italian Alps. The sites are characterized by different climates and by different duration of the landslide-triggering storms. Comparison with observed landslides shows that in all case studies the model provides a reasonably correct surrogate for failure initiation probability as a function of topography and climate. A comparison with the steady-state model (Montgomery and Dietrich, 1994) has also been carried out. Based on the results, the model presented here is seen to offer significant improvement over the steady-state model. The improvement is larger where shallow landsliding is triggered by rainfall durations which are short with respect to the length of time required for every point on a catchment to reach subsurface drainage equilibrium. Even though actual erosional intensity will reflect local conditions and variability in other important features (such as geology and vegetation) that cannot be resolved by the model, the model may offer specific insight on landsliding susceptibility in mountainous areas characterized by short and intense storms, like those prevailing in the Alpine and the Mediterrannean climate.

The project also included a field experiment (XPOL2012) aiming to examine the impact of fine precipitation estimation on the prediction of debris flows (Borga et al., 2013). The motivation for the field experiment was as follows. Mountain precipitation results from a multitude of processes such as mechanical lifting, enhancement, shadowing etc. Many of these processes are poorly understood, especially at small spatial and temporal scales. Consequently, this limits the predictive capability of debris flows models and our understanding of the majority of the precipitation-related natural hazards occurring in alpine terrain. This lack of knowledge is mainly due to the intrinsic limitations of our best measurement techniques: raingauges and weather radars. Raingauges provide relatively accurate but only point-like observations, while weather radars produce instantaneous spatially distributed rainfall maps but their operation over complex terrain creates a number of limitations, which make their estimates reliable in a limited space-time domain. A solution to this limitation might be the use of a number of cost-effective short-range X-band radars as complement to raingauges and conventional, large and expensive weather radars.The field experiment, called XPOL2012, has been carried in the period from August 2012 to November 2012, in collaboration with the HYMEX experiment (Anagnostou et al., 2013; Borga et al. 2013). The study focuses on a 64 km^2 mountainous basin located in Northern Italy. Rainfall observations from a dense network of raingauges located at different elevation, a C-band and an X-band polarimetric mobile unit are used to force a semi-distributed hydrologic model. A number of storm events were monitored and one major debris flow event was captured on the night between 25 and 26 August 2012. Events have been discriminated on the basis of rainfall intensity, snowfall limit and hydrological/debris flows response. Results reveal that in contrast with the other two rainfall sources, X-band observations offer an improved representation of orographic enhancement of precipitation, which turns to have a significant impact in predicting debris flows.

In France LGP approach consisted in modeling the links between the current climate and the occurrence of debris flows using a statistical model combining Safran data and the debris flow database described in the previous pages. We then developed a stochastic model using the simulated current climatic data and debris flow events by interchanging climate parameters from Safran data with those from climate models for the current and future periods. Finally, we compared the probabilities of the occurrence of debris flows in the current period and in the middle of the 21st century. As it is generally assumed that significant changes in DF activity are due to different climate conditions, one distinguished the northern humid French Alps from the southern dry French Alps. To link DF yearly activity with climate conditions in the French Alps, we used a logistic regression model.

Because the model only offers descriptions in binary response form (i.e. presence/absence), a certain number of annual debris flow events was chosen. Debris flows were classified in two groups of equal size (starting from a threshold of seven events in the northern French Alps and five in the southern French Alps) with years with fewer occurrences coded 0, and years with more occurrences coded 1. These numbers of DF events above/ below an annual threshold were chosen in order to keep an equal proportion of years with and without zero events. Several climate parameters calculated from Safran data were used as explanatory variables for the occurrence of debris flows such as precipitation sum (*Sum rr*); mean precipitation (*Mean rr*); number of rainy days (*Nrd*); number of rainy days with daily cumulated rainfall greater than 10, 15, 20, 30 40 and 50 mm/day (*Nrd>10….*); minimum, mean and maximum temperatures (*Tn, Tm and Tx*). Results of many tests revealed that the best model for the northern region was the annual number of rainy days (Nrd) and annual maximum temperature (*Tx*) during the period of debris flow activity (May-October). To check the quality of the model, several standard verification tests were computed for each logistic regression and then the relative weights of each variable were compared to select the most significant model result. Above all, the parameter was considered as significant if Chi^2 values differed from 0 and the corresponding p-value was less than the 0.05. The higher the absolute value of the parameter coefficient, the greater the weight of the corresponding variable.

Fig. 5 shows the best annual probability model (based on Safran data) of DF activity as a function of the number of rainy days (*Nrd*) per year and of the maximum annual temperature for the northern region as a function of the mean annual temperature between May and October (*Tm*) for the southern region. The probability of DF increased considerably when both parameters, i.e. the number of rainy days and the temperature, were positive. In the northern region, the probability of DF events >0.7 was positive when *Nrd* was >85 and *Tx* was >12 °C. The highest probability values in the south were for years in which *Tm* was >8.5 °C during the May-October period. Note the analyses have been finished for the southern French Alps, but to keep this report short, this section focused on the Northern part of the French Alps.

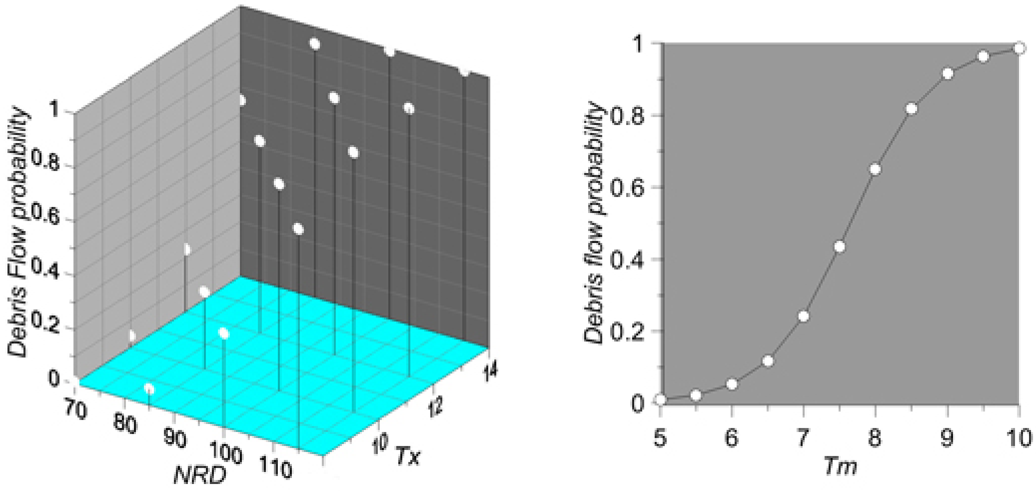


Figure 5. Annual probability of DF in the northern (left) and southern (right) French Alps. Nrd - number of days with precipitation per year; Tx/Tm – annual mean maximum/mean daily temperature from Safran data.

c) Susceptibility of the different regions to climatic changes and the related frequency and magnitude of debris flows and landslides

With this activity, UniPad analysed slope stability conditions for shallow landslides under an extreme precipitation regime with regard to present and future scenarios, in order to first study the effect of changes in precipitation on stability conditions, considering uncertainty in the model parameters, and second to evaluate which factors contribute the most to model output and uncertainty. The QDSlAM model has been used to study the hydrological control on shallow landslides in different precipitation regimes, with reference to the case study of the Upper Adige basin and of the Malefosse (France) and Sachselns (Switzerland) study sites.

The climate change scenarios developed by ARNICA were used as a reference. More specifically, we used the 17 RCMs available until 2100. All simulations are based on the A1B emission scenario. An empirical-statistical downscaling and error-correction method (Quantile Mapping) as described in Themeßl et al. (2012) is applied to improve the skill of the RCMs in representing local climate at 33 stations located in Southern Tyrol. The period 2070-2099 was considered as future scenario, compared to the current scenario (1961-1990). We used a weather generator to provide precipitation, temperature and radiation scenarios at the fine scale required for shallow landslide prediction. Weather generators are not, strictly speaking, downscaling techniques, but are often used to generate realistic temporal sequences of weather variables — precipitation, maximum and minimum temperature, solar radiation, relative humidity, etc (see Wilks, 2012, for a review) which are consistent with pre-fixed large scale climate scenarios. The temporal resolution of generated data can be substantially shorter than the one used in other downscaling techniques – for instance, hourly simulations are not uncommon (Ivanov et al., 2007). A number of weather generators (WG) have been considered for the study. For precipitation, they range from very simple series (e.g. Semenov et al., 1998) and Markov chain based models (Richardson, 1981) to sophisticated approaches based on the observed hierarchical organization of rainfall and on raincell space and time-clustering processes (e.g. Ivanov et al., 2007; Kilsby et al. 2007; Fatichi et al., 2012). For non-precipitation variables, that present a more convenient statistical behavior, simple autoregressive processes are usually applied (e.g. radiation, temperature, wind) (e.g. Wilks, 2012).

We used here a version of the weather generator developed by Fatichi et al. (2012), which showed good capability to capture the seasonality of the precipitation statistical structure as well as the interaction with the air temperature. This proved to be a critical step in the assessment of model sensitivity to climate change. This is because the analysis clearly showed that the most important change incorporated in the climate change scenarios is the more widespread occurrence of liquid precipitation even in the autumn season. This results in a step variation in the seasonality of the shallow landslides. These are concentrated in the summer season in the current climate and show a shift the autumn season with the changing climate.

We included a wide range of climatic settings, taking intensity, duration of the extreme events and two different antecedent precipitation conditions into account. In order to include the uncertainty in the soil parameters, we used a Monte Carlo approach and the probability of failure resulting from 1,000 different trials was calculated for each precipitation and temperature scenario, based also on earlier results reported by Melchiorre and Frattini (2012). A sensitivity analysis was carried out to understand how variations in input parameters influence the output of the selected model.

The results show that it is important to consider the relationship between temperature and precipitation when analysing the sensitivity of the landslide model to climate change scenarios. Without including the temperature effect, the sensitivity of the model is minimal, and cannot be distinguished given the overall parameter uncertainty. When considering the temperature effect and the resulting impact on the seasonality of the landslide-triggering precipitation, the climate change scenario can be recognized even considering the parametric uncertainty, with a significant increase of the portion of terrain predicted to fail with a low return time period. The effect of the initial conditions is important and it is part of the sensitivity to the climate change conditions.

In France, LGP conducted an innovative stochastic hierarchical analysis in order to estimate the

impacts of future changes on debris flow occurrence considering potential changes in land use as well as changes in geomorphological parameters. To this end we combined in a single analyze geomorphic and climatic parameters and quantified their respective influence on DF activity.
A hierarchical Bayesian annual logistic regression probability model of debris flow-triggering was fitted between the climate characteristics and the geomorphic catchment characteristics during the past 35 years. Individual catchment characteristics of DF events consisted of morphometric (the altitude of the area, exposure, the mean slope, and others) and qualitative (the dominant lithological type and dominant land use type) data. Annual regional meteorological parameters (such as the mean annual temperature and precipitation) were computed from mean values of the reanalysed Safran data. Several indices were then computed from a time-space general decomposition of a logit model such as a parameter explained by the geomorphological characteristics of the catchment, and another parameter explained by the annual climate variables.

Table 2 shows the analyses of variance for the global model. The regression that took into account both the geomorphological and meteorological components explains 0.83 of the total variance. 0.55 of this total variance is explained only by the geomorphological component while 0.28 is explained by the meteorological component. This trend confirms the 0.39 ratio between the temporal (climatic variables) and spatial regression components (geomorphological variables), indicating a clear domination of spatial influence in the total regression explanation. Another important index is the analogue of the coefficient of determination for spatial (geomorphological) and temporal (meteorological) components. It was calculated separately for the geomorphological component and the meteorological component. The selected geomorphological characteristics explain 0.9 of the variance in the spatial regression whereas the selected geomorphological characteristics explain 0.78 of the variance in the temporal regression.

Table 2. Variance for geomorphic and climatic parameters in the global model

Index	Coefficient Value
Total variance explained by both geomorphic and climate in total regression	0.838
Variance explained by geomorphic in total regression	0.552
Variance explained by climate component in total regression	0.286
R2 of geomorphic parameters explaining spatial component	0.889
R2 of climate parameters explaining temporal component	0.779

An interesting series of model outputs introduces the mean DF probability for an individual catchment during a certain period (1970-2005), i.e. the DF occurrence in an individual catchment tied to a spatial (geomorphological) component. The spatial component consisted of several geomorphological parameters among which two of them were significant, the surface area with a coefficient value of 0.5 and the possible presence of permafrost (2.05) (0.05 level) (Table 3).

Table 3. Coefficients of Spatial Regression Based on Geomorphological Parameters. In bold significant parameter (0.05 level).

Geomorphological Parameters	Coefficient Value
Mean Altitude	0.24
Area	**0.5**
Mean Slope	-0.31
Lithology	0.18
Grass	0.12
Forest	0.11
Rock	-0.17
Permafrost Presence	**2.05**
East	-0.22
South	-0.16
West	0.06

For the investigated region, the climatic component that explains 28% of the total variance (Table 2) is based on two explicative climatic variables i.e. the number of rainy days and the maximum daily temperature for the period between May and October. These two meteorological parameters (Nrd and Tm) explain 0.78 of the variance in the temporal regression. In this end the geomorphological parameters are the main factors controlling debris flow activity in these catchments.

In summary, the temporal component of the model is not the main driver of occurrence variability but is expected to change strongly in the context of climate change. On the other hand, the geomorphological parameters are very important but stable except the possible permafrost presence which is directly influenced by temperature which in turn should increase strongly in the future. Consequently the influence of future climate change on debris flows occurrence will be direct and indirect and should cause an increase in DF activity.

d) Impacts of debris flows activity at the local level on transportation corridors

The impacts of past debris flows and landslides on transportation corridors have been evaluated for the three regions. As example, we report the analysis conducted on Rif Blanc catchment area (fig. 6). A comparative analysis in normal and disturbed situation of the network was realized in terms of distance, time and cost considering different destinations. We also compared the accessibility in normal and disturbed situation due to an interruption on a road.

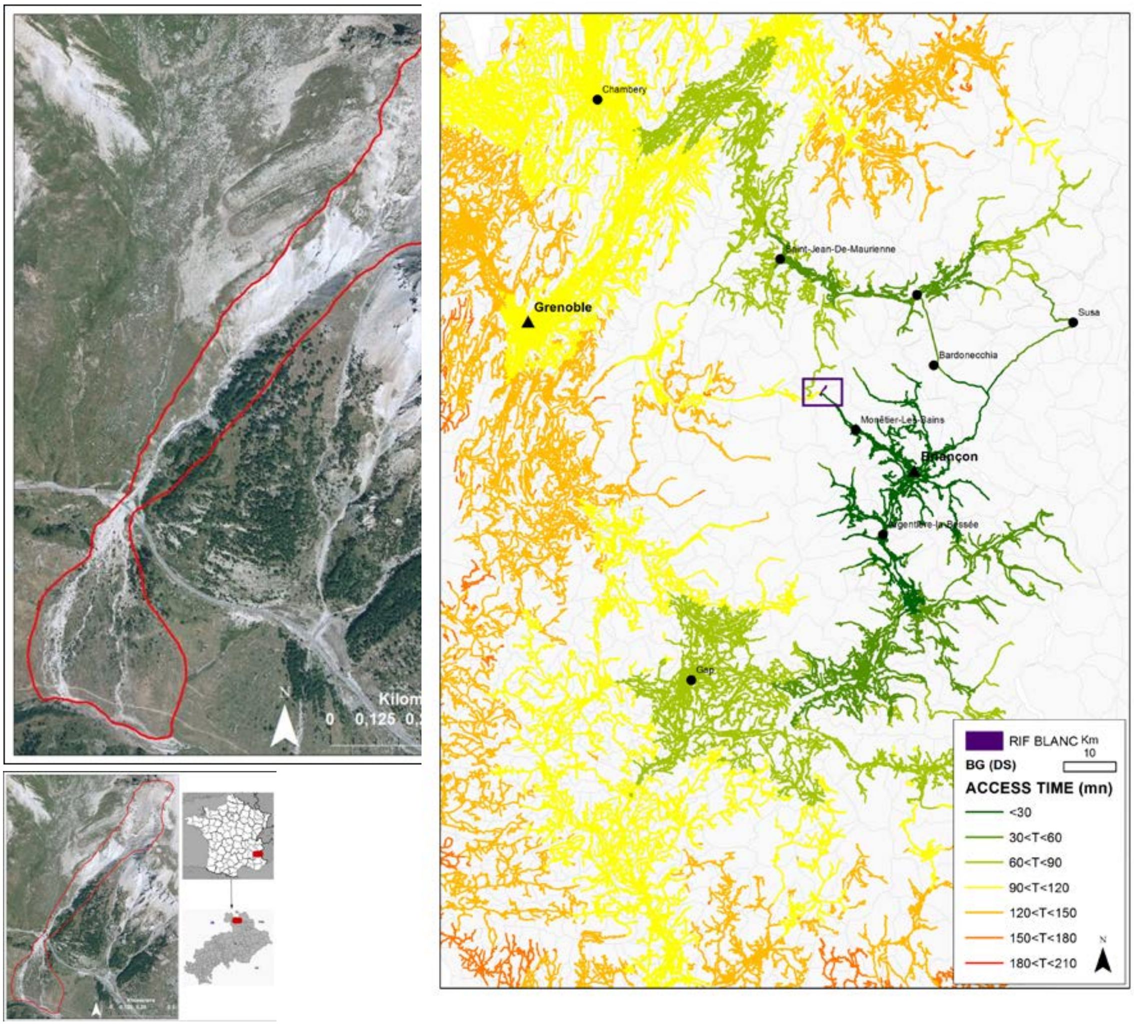


Figure 6. Territorial accessibility map considering a disturbed situation in the Rif Blanc catchment. The access time was divided into classes of 30 minutes on the territory.

Accessibility was measured considering the distance and the time of travel. The best travel time reflects the minimum value of the accessibility between a couple of places and reflects the optimal functioning of the transport chain in a given time interval.

The map is computed according to the characteristics of the network:

- the length and width of the road section.
- Axis administrative classification.
- Vehicles type used in the simulation (cars, all vehicles, long vehicles)
- Traffic direction.
- Road speed.

Figure 6 shows the loss of accessibility on the Grenoble-Briançon axis (French Alps) considering a debris flow event on the D1091 located at the torrent Rif Blanc. IT1 shows the main itinerary

Grenoble - Briançon via the RD1091 in a normal situation (via Guisane valley). In case of traffic disruption on the RD1091 on Grenoble-Briançon axis, three alternative itineraries are possible in this region:
- IT2. Grenoble - Briançon and Gap Argentière-la-Bessée via the RN85 and RN94 via Bayard Pass. Favored by CG05 for users.
- IT3. Grenoble - Briançon Gap, A51, D1075, D994, RN94 via Luce la Croix Haute Pass.
- IT4. Grenoble - Briançon by the department of Savoie and then by Italy: A41, A43 (via the Maurienne valley), Bardonecchia, RN94 in Montgenevre.

For the small vehicles category, the most appropriate alternative itinerary is IT2, recommended by the CG05 for Grenoble-Briançon axis. But the shortest itinerary in terms of time of transportation is IT4 using highways. The consequences of the disruption of the network lead to a lengthening of the access time of at least one hour for all replacements, and a surcharge of more than 70km to users. The cost shows the most significant changes in the data series.

The same approach was applied in the Italian and the Swiss Alps in collaboration with Unipad and Dendrolab. An example is given with the very famous Zermatt Valley. In this valley about 2 millions of tourists visit Zermatt village each summer using the single road or the rail way. In addition about 68 debris flows were recorded since 1921 which occurred in 6 debris flows catchments among which Ritigraben is the most active. About 17 debris flows events impacted the road and the rail way over the last decades. For example on the 26th of September 2000 a debris flow from Ritigraben catchment destroyed the road and the rail way to Zermatt isolating more than 500,000 people located in the different villages during 5 days. Figures 7 shows the consequences of a debris flow event occurring in Ritigraben that would damage road and rail way as already observed in the past (Fig.7). If a debris flow event would be triggered in the near future destroying road and railway about 2 million of people could not leave the valley during a couple of days.

Unipad focused on the development of a methodology integrating the assessment of the susceptibility of a transport system to rainfall-induced landslides within a general concept of road vulnerability assessment based on network analysis. The road vulnerability assessment concept has been developed in the context of the Alpine Space 2007-2013 PARAmount project (contractor: Geological Service of Bolzano Province, Bolzano, Italy); the work resulted in a collaboration between ARNICA and PARAmount projects. The assessment has been carried out considering the climate change scenarios described previously.
The proposed methodology is developed according to the following steps:
1. analysis of the hazard affecting the links of the road network;
2. vulnerability index computation for each link of the network;
3. computation of the exposure index for each link of the network;
4. ranking of the links based on the risk level.

The first step consists in the analysis of the investigated road network, accordingly with the method developed in PARAmount. The real network has been represented through a graph, thus requiring the functional classification of the network distinguishing main and secondary infrastructures. At each link of the network has been assigned a cost function that allows assigning the mobility demand to the network in order to compute links flows. Then, the vulnerability and exposure indexes have been computed for each link of the network in order to evaluate the risk for each investigated link and obtain a hierarchical rank of the links.

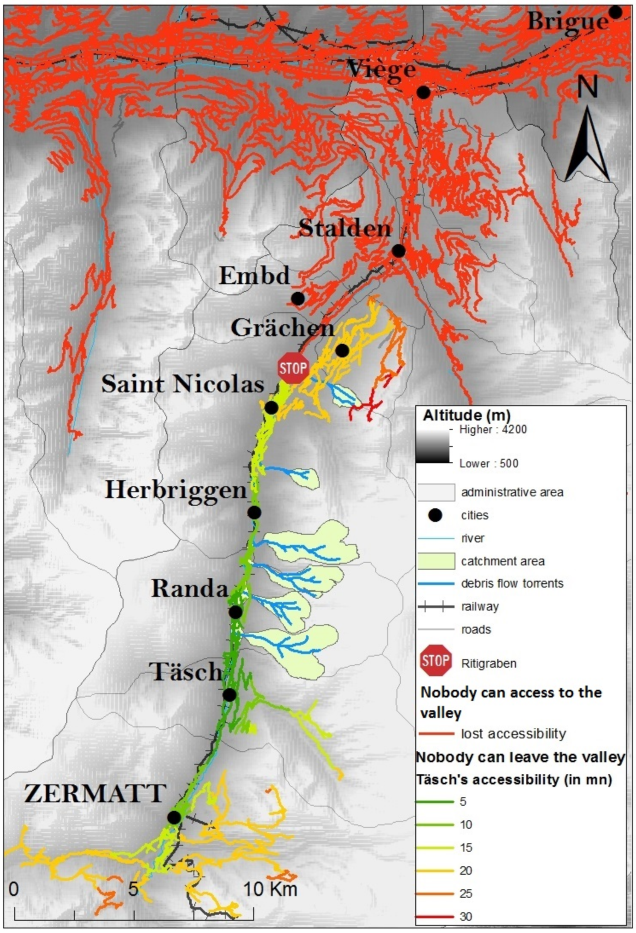


Figure 7. Map of lost accessibility induced by a debris flows in Zermatt Valley.

The hazard assessment at the scale of each link has been carried out by considering the contribution of the various catchments draining to the link. The response to rainfall of an individual catchment can be provided by a shallow landslide susceptibility model (see previous section); but, in order to predict the behaviour of a specific link which is receiving the contribution from various catchments, descriptions are required for i) the transport of the slide material to the vulnerable site, and ii) the combination of the hazard resulting from the multiple sites.

The QDSlAM model describe at session C has been extended to incorporate a transport model. When the amount of rainfall exceeds the critical rainfall in a grid cell, the landslide starts and debris begins moving downslope. Following the initial failure, unstable soil material is eroded. Landslide erosion follows the steepest descent and stops where the gradient falls below a certain slope angle and the transported material is deposited over a number of downslope grid cells. This permit to characterize the landslide (debris flow) hazard at the outlet of the specific catchment, i.e. the probability of exceeding a certain volume of sediment deposited at the assigned location.

While the previous steps concerns the status of the specific catchment, the effect of distributed rainfall on the reliability of a line transport system should be also considered. To this end, we have developed a failure model which is appropriate for the conditions under study. A railway/road system consists of a number of discrete sections, each of which may be up to several kilometers in length. Consider a system with a number *n* of small catchments crossing the line. A simple criterion for failure of an individual small catchment can be found based on the model described above. For a series system composed of a number of small catchments, system failure occurs when the catchments with minimum factor of safety is below a threshold. A mathematical model is given for the system failure and a statistical model is formulated for the joint distribution of rainfall on various small basins along the railway line. These are used to investigate the response of small basins along the railway/road link to current and future climate scenarios, including the effects of rainfall and snowfall on slope hydrology and stability.

The model has been applied to the highway and rail link on the Brenner pass, and more precisely at Fortezza (Figs. 8-9). This road and railway link is frequently subject to interruptions caused by debris flows and landslides. An extreme event occurred on 15.08.1998, when a debris flow buried two cars killing 5 persons. Fig. 9 shows also the system of small catchments crossing the link. The system includes 15 catchments, ranging in area from 0.2 km^2 to 6.6 km^2. The road network graph for the whole Province (including the study link) is reported in Fig. 10.

It is shown that, for the study case, the moisture profile at the regional level at the end of the summer months has a critical effect on system stability, both in terms of expected failure timing and probability of failure. Further, it is seen that, with changing climate, the system stability is likely to decrease due to the increased probability of liquid storms at high altitude during the fall season.

The susceptibility of the hazard (represented by the return time of the precipitation capable to trigger a landslide crossing the link) to climate change is represented, following the concepts already presented at section c, in Fig. 10.

Examination of Fig. 10 shows that the 90% percentile scenario of shallow landsliding susceptibility for the fall season is characterized by a step change in hazard, with a significant increase of the portion of terrain predicted to fail with a low return time period. This points to the relevance of changes to be expected in the fall season for the road system hazard in the Alto Adige Province.

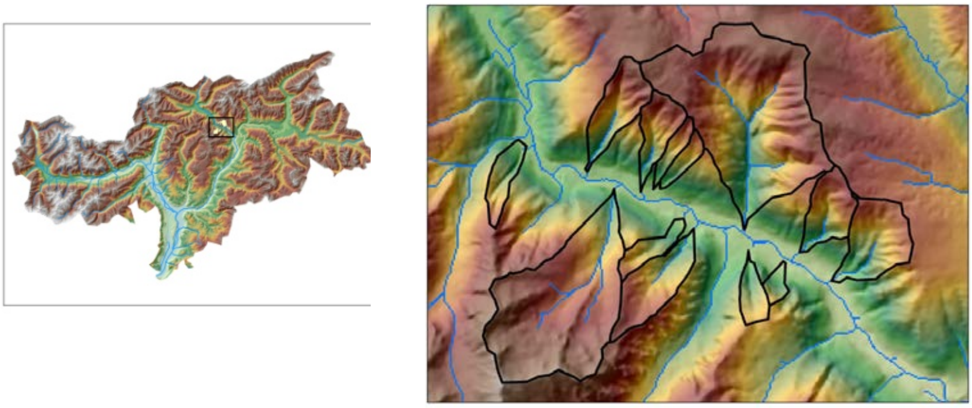


Fig.8: The system of catchments draining to the Upper Isarco road link in Southern Tyrol (insert shows location).

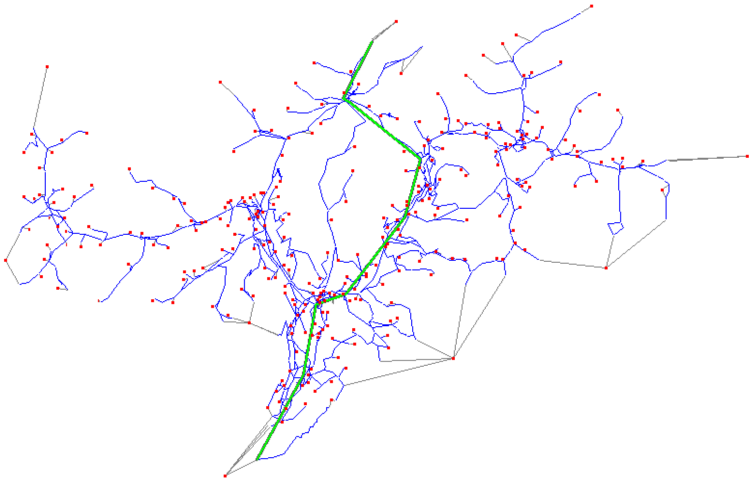


Fig. 9: Road network graph of the Autonomous Province of Bolzano

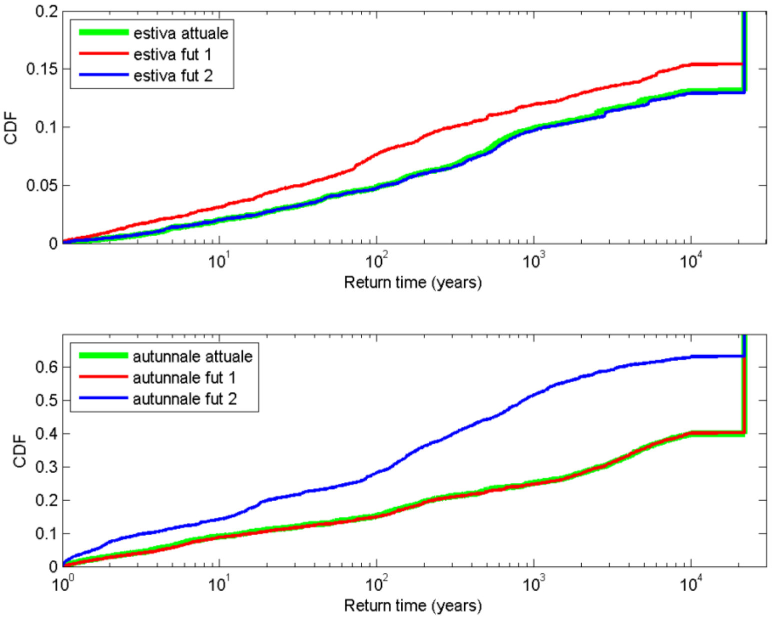


Figure 10: Cumulative distribution frequency (CDF) of critical rainfall return time for the catchment system on the Upper Isarco road link. SC: reference climate; s1: 10% percentile scenario; s2: 90% percentile scenario.

e) Identification and quantification of protection deficits through analysis of model results and discussions with local authorities

LGP conducted an analysis of sensibility of protection considering different volumes of debris flows on 3 watersheds selected for their high susceptibility using the model massvom2D. An example is given with the Rieu Sec (Savoie department). According to a report from an engineering agency ETRM (2008), the volumes of debris flows in the watershed affecting the road network are between 20 and 60 000 m^3. From measurements we made in September 2011, the height between the current surface level in the channel and the bridge is 4.5 m (Fig. 11). Therefore, we consider that the height of the flow must be equal or greater than this value to be able to impact the road network. The results show that volumes higher than 21 000 m^3 of materials are enough to impact the bridge on the road D1006 (Fig. 12) but does not impact the highway.However, a higher volume than 42 000 m^3 (return period <50 years) can impact the D1006 bridge and the highway (A43) roads causing physical damage to the structure along with a mains failure.

Figure 11a,b. Rieu Sec channel below the bridge of D1006 (11a) and highway from Grenoble to Turin A43 (11b).

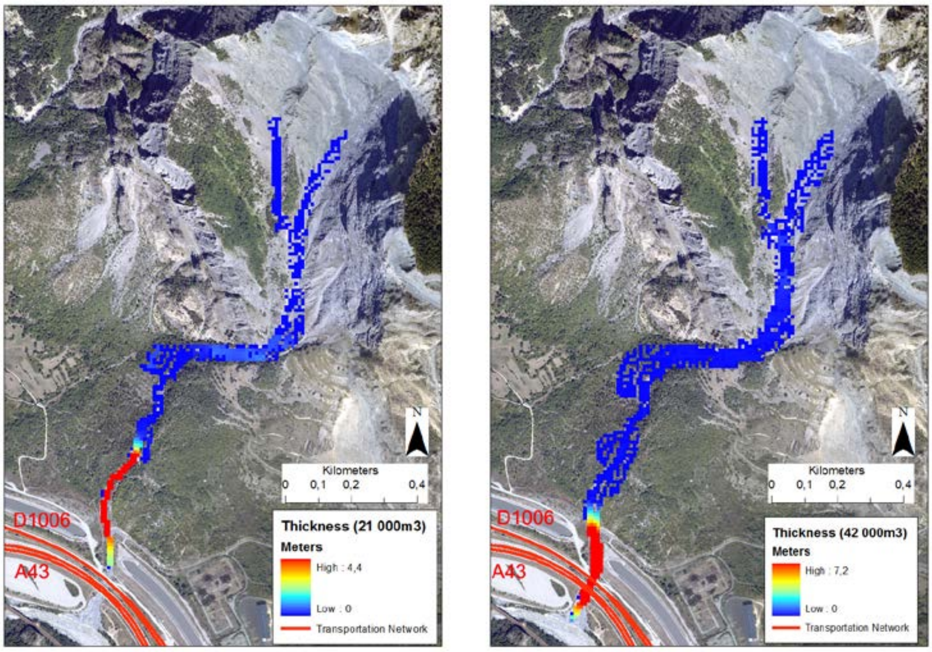


Figure 12a,b. Sensibility analysis on the Rieu Sec catchment (Savoie department French Alps) of debris flow volumes than impact the road network (21,000 m^3 (left) and 42,000 m^3 (right)).

f) Analysis of the impacts of potential future climate conditions on the occurrence and size of debris flows and landslides in the three study-site regions

Research also focused on climate change impacts on the frequency of debris flows. Results revealed different pattern of change. In Switzerland, based on point-based downscaled climate scenarios for meteorological stations located next to the catchments and for the periods 2001–2050 and 2051-2100, we study the evolution of temperature and rainfalls above specific thresholds (10, 20, 30, 40 and 50 mm) and durations (1, 2 or 3 days). We conclude that the drier conditions in future summers and the wetting of springs, falls and early winters are likely to have significant impacts on the behavior of debris flows. Based on the current understanding of debris-flow systems and their reaction to rainfall inputs, one might expect only slight changes in the overall frequency of events by the mid-21st century, but possibly an increase in the overall magnitude of debris flows due to larger amounts of sediment delivered to the channels and an increase in extreme precipitation events. In the second half of the 21st century, the overall absolute number of days with conditions favorable for the release of debris flows will likely decrease, especially in summer. The anticipated increase of liquid rainfalls during the shoulder seasons (March, April, November, December) is not expected to compensate for the decrease in future heavy summer rainfalls over 2 or 3 days in absolute terms, but with presumably increasing magnitudes.

In France, future annual debris flow probability was calculated based on climate parameters from the different RCMs for the northern region and the southern region (Fig. 13). Results show in the two regions a clear increase in future DF activity for the close and far future.

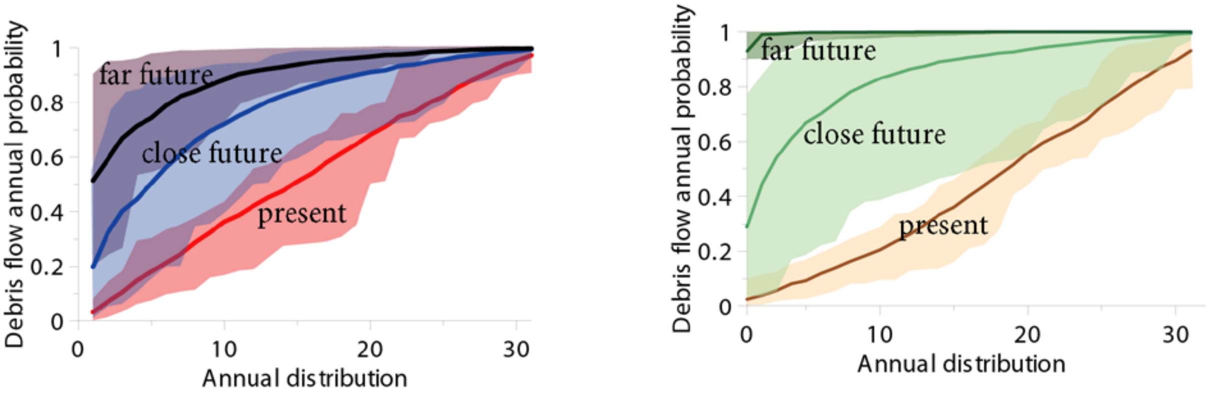


Figure 13. Future annual DF activity based on ensemble simulations for the northern (left) and southern (right) French Alps. Bold lines correspond to the mean probability from 24 RCMs for the close future and 17 RCMs for the far future based on A1B scenario.

In Italy the study was based on use of the output of the weather generator to estimate seasonal distribution of liquid precipitation for summer and fall season. Results are reported in Figure 14 (fall season), Figure 15 (summer season) and Figure 16 (summary of results) for the reference climate (1961-1990) and for the future scenario (2070-2099). The summary of the results (Figure 16) is reported for the three catchments considered in the investigation: Rio Cortina, Rio Fraviano, and Rio Pizzano, with an overall drainage surface of 7.5 km^2. We reported two quantiles (10th and 90th percentiles) from the ensemble of simulations, representing two extreme cases and highlighting the level of agreement between simulations as to the direction and magnitude of projected changes. The 10th (90th) percentile of the ensemble of results refers to the percentage change in the 100-year daily rainfall between the 1961-1990 reference period and the 2070-2099 future period. Examination of Figure 14 shows that the 90% percentile scenario of shallow landsliding susceptibility for the fall season is characterized by a step change in susceptibility, with a significant increase of the portion of terrain predicted to fail with a low return time period (see also Figure 16). This is due to the combined effect of the increase of percentage of liquid precipitation during the fall storms. The 10% percentile scenario shows minimal changes with respect to the reference scenario. A similar behavior is reported for the summer season (Figure 15), even though the changes are much less considerable.

Overall, the results show that considering the liquid precipitation is key for the analysis of projected changes in shallow landsliding susceptibility. Without considering the liquid versus solid precipitation, the sensitivity of the model is minimal, and cannot be distinguished given the overall parameter uncertainty.

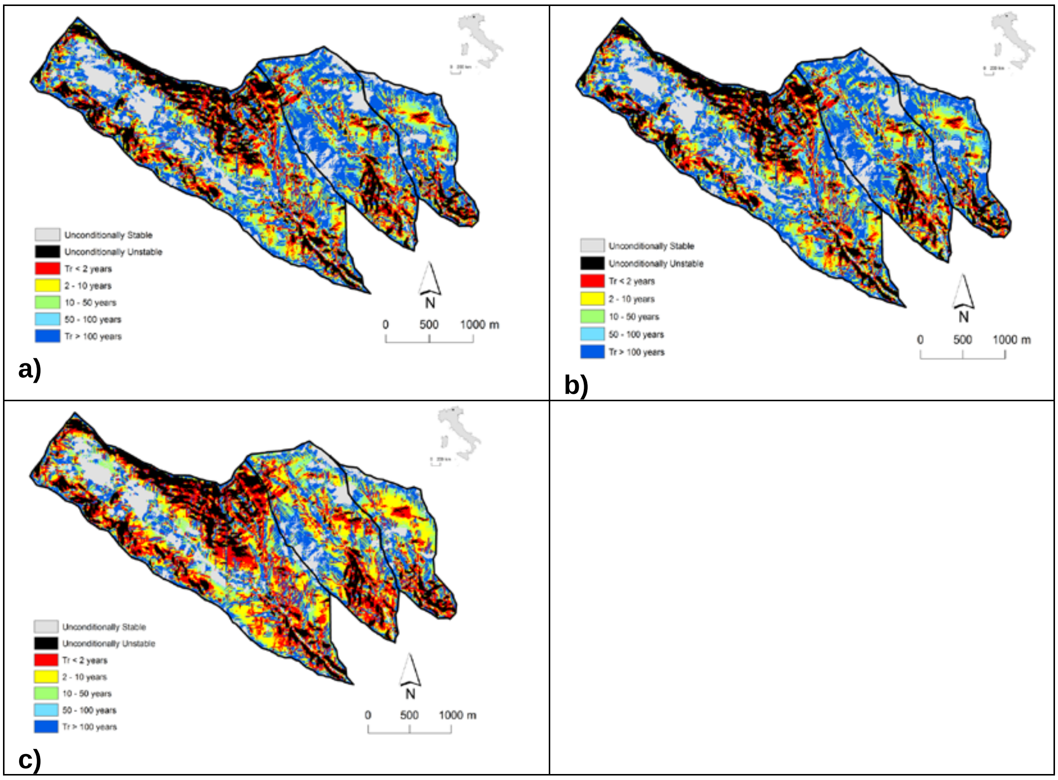


Figure 14: Scenarios of shallow landsliding susceptibility for fall season (SON): a) reference climate; b) future period, 10th percentile; c) future period, 90th percentile.

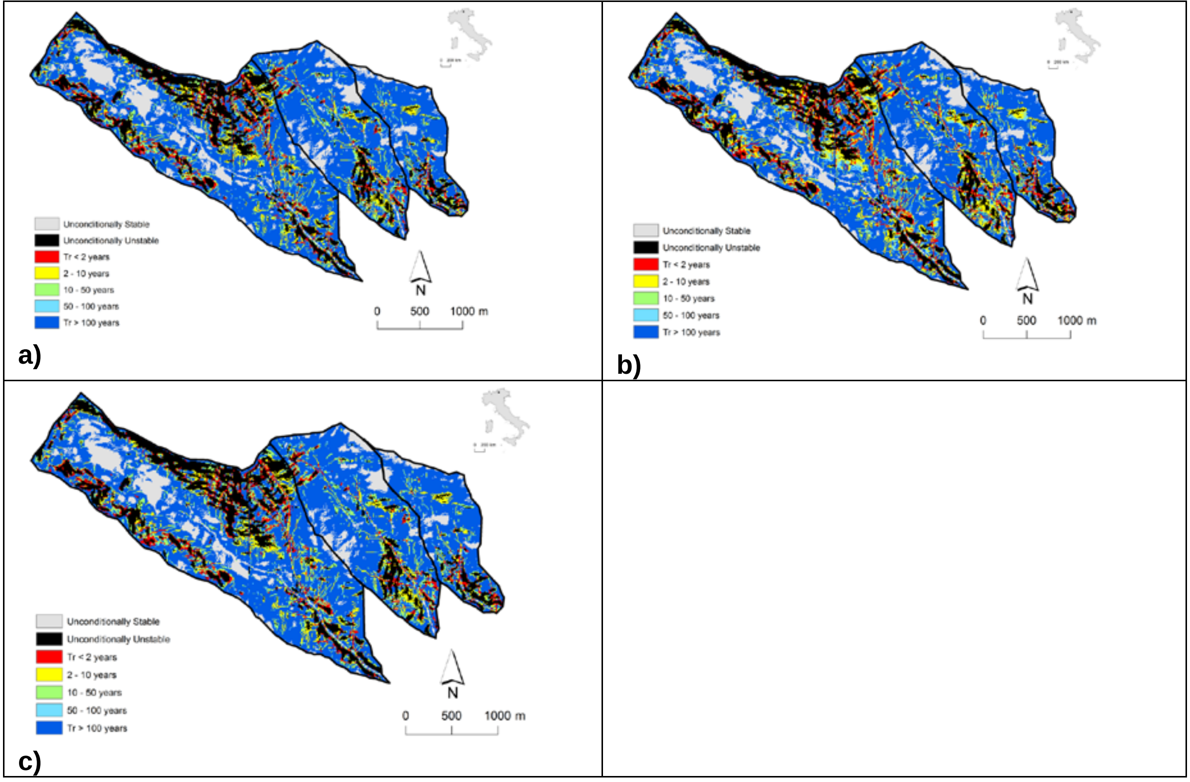


Figure 15: Scenarios of shallow landsliding susceptibility for summer season (MJA): a) reference climate; b) future period, 10th percentile; c) future period, 90th percentile.

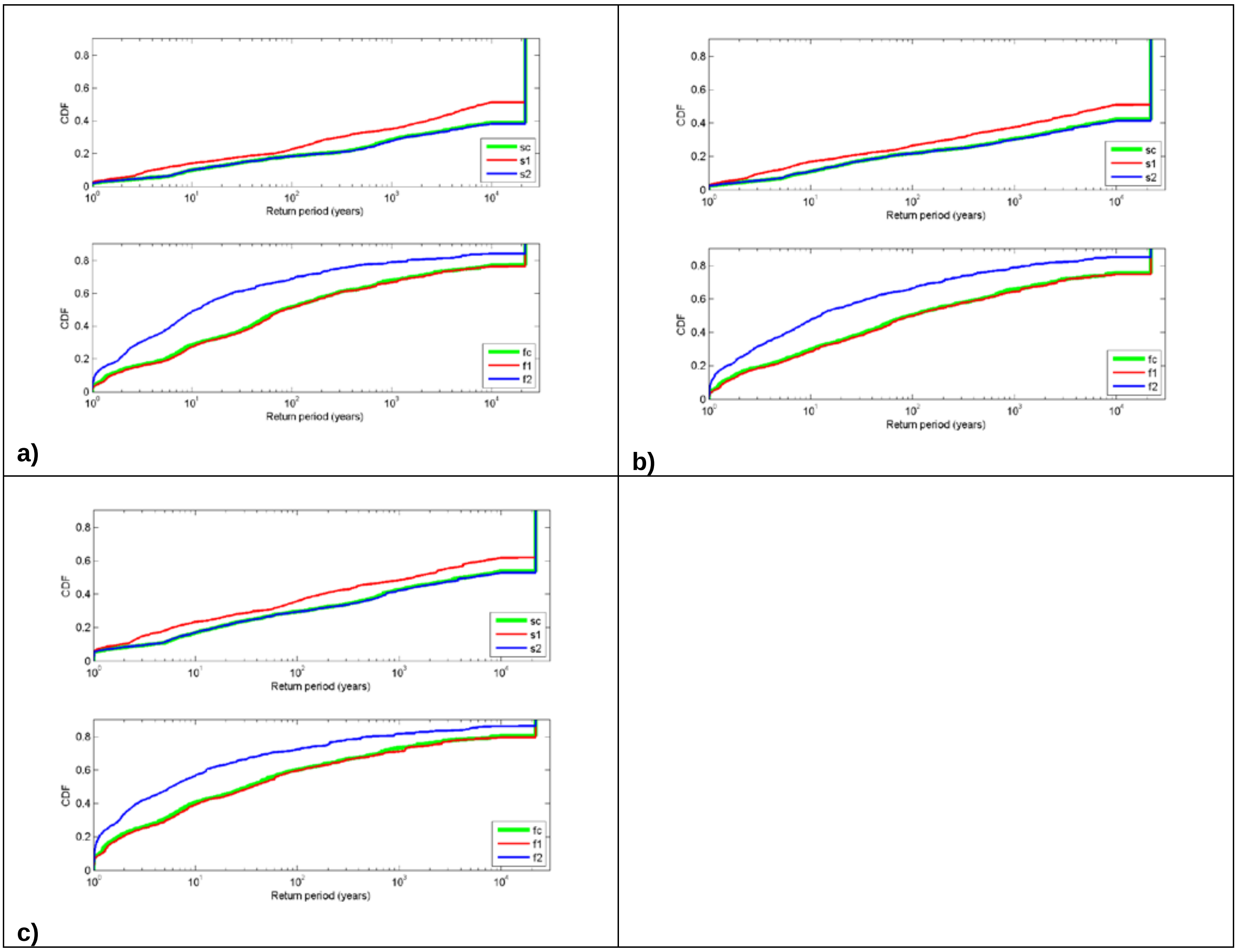


Figure 16: Cumulative distribution frequency (CDF) of critical rainfall return time for: a) Rio Cortina basin; b) Rio Fraviano basin; c) Rio Pizzano basin. SC: reference climate; s1: 10% percentile scenario; s2: 90% percentile scenario.

g) Definition of mitigation strategies and guidance document for implementation

LGP conducted a post crisis management analysis based on the event of Rif Blanc on 4th of June 2012 (Fig. 6 for location). A debris flow occurred in the Rif Blanc torrent following several rainy days in the valley and extreme precipitation events few hours before the triggering (35 mm during one hour). According to the road services, the debris flows was separated in two events at 5 in the morning and 10h in the morning respectively. Damages caused by DF were mainly due to the deposition of rock debris on roads and into the tunnel. Fieldwork observations allowed estimating the height of the deposit which reached 2m inside the tunnel and ranged from 2m to 7m on the road. The DF event has caused temporary breaks of the road traffic for several hours. A deviation procedure was decided by the General Councils of the Hautes-Alpes and Isère regions.

The post crisis management was analysed and revealed a very accurate process (Fig. 17). In the context of Arnica, we intentionally focused only on the difficulties but as said before our main opinion is that we noticed a very accurate crisis management. Despite a desire to develop trade and partnership between General Council of Hautes-Alpes with Councils of neighboring departments and especially with Italy, the issue of joint management across the Alps still poses problems in organization and communication. Trade is still very limited between managers county roads and national highways, i.e between the General Council and state management (eg DirMed). It seems that this communication is based more on an informal and sporadic network of technical services through seniority and exchanges between the agents before changes of administrative services. But conflicts of interest prevent the establishment of real collaborative process mainly due to fear of interference between services.

Similarly, there are many conflicts with tourism companies or of villages regarding the quality and flexibility of road service. In addition, communicating the natural hazards to the public may also be subject to controversy for the image of this Alpine territory, which mainly depends on tourism. Stakeholders are particularly worried about the bad publicity that could lead this type of information to their customers (Utasse et al in progress).

Finally, the role of the mayor as a central actor does not appear in the organizational crisis management. This is due to several reasons:

- the town only manages the municipal road network.
- In principle, the mayor's role is to declare “the natural disasters” said CatNat to implement the intervention and management of operations by the prefectural and communal services (a state intervention). However, this feature is rarely used for debris flows, unless a house is directly affected by an event.

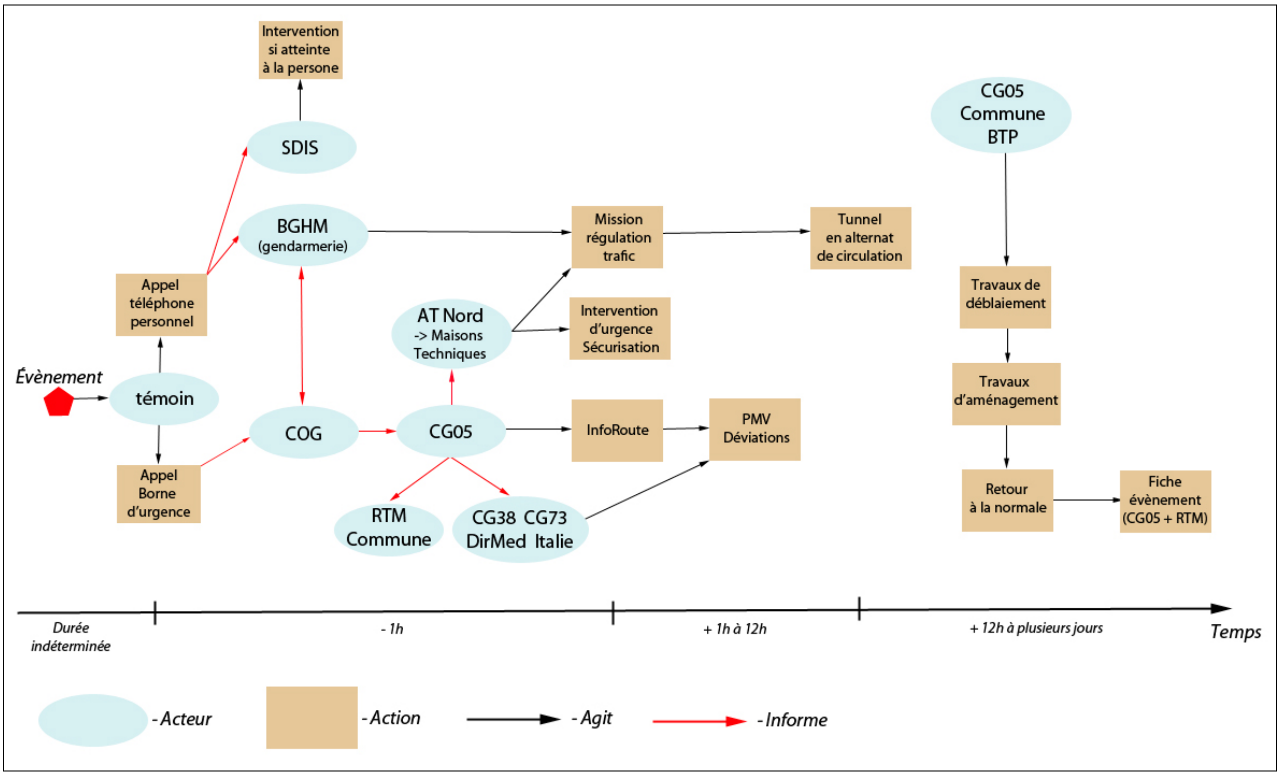


Figure 17. Crisis management in the French Alps.

In the Swiss case study, results on debris flow occurrence, frequency and reach of events have been used by stakeholders and decision makers for operational purposes. In particular, and in view of the imminent risks of debris flows in several of the torrents in the Zermatt valley (i.e. Dorfbach in 2009–2012, Geisstriftbach, Fallzug and Bielzug since spring 2013), dendrolab.ch has been invited to participate to discussions with the local communities, state agencies and Swiss Federal Government (Federal Office for the Environment) to perform cost-benefit analyses for the protection of the villages and the transportation network**.** Representatives of the main road, the railway line (Matterhorn Gotthard Bahn) as well as the owners of the power lines (Grande Dixence, Forces Motrices Valaisannes) have been involved in the discussions as well. As a result of the discussions with the stakeholders and decision-makers, the results of dendrolab.ch will indeed have consequences on future land-use planning as well as the operation of railway and road operations, and were used to develop and position structural and non-structural decisions with the best balance between prevention and rehabilitation in the current context of limited public funds. As a result, the data obtained within the Arnica project have clearly allowed contributing substantial knowledge on how debris flows occur in the Zermatt valley and on how to adapt and mitigate these processes in regions subjected to risk on roads and railway lines. As has been confirmed by the representatives of the Swiss government, the gathering of such a variety of stakeholders with government representatives and researchers can be seen as unique for Switzerland and the contribution of Arnica in terms of risk perception, risk communication and the demonstration on how these processes might change in a future greenhouse climate was certainly key for this success.

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