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Natural Hazards and Earth System Sciences

Spatial variability and potential impacts of climate change on flood and debris flow hazard zone mapping and implications for risk management

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Abstract. The main goals of this study were to identify the alpine torrent catchments that are sensitive to climatic changes and to assess the robustness of the methods for the elaboration of flood and debris flow hazard zone maps to specific effects of climate changes. In this study, a procedure for the identification and localization of torrent catchments in which the climate scenarios will modify the hazard situation was developed. In two case studies, the impacts of a potential increase of precipitation intensities to the delimited hazard zones were studied.

The identification and localization of the torrent and river catchments, where unfavourable changes in the hazard situation occur, could eliminate speculative and unnecessary measures against the impacts of climate changes like a general enlargement of hazard zones or a general over dimensioning of protection structures for the whole territory. The results showed a high spatial variability of the sensitivity of catchments to climate changes. In sensitive catchments, the sediment management in alpine torrents will meet future challenges due to a higher rate for sediment removal from retention basins. The case studies showed a remarkable increase of the areas affected by floods and debris flow when considering possible future precipitation intensities in hazard mapping. But, the calculated increase in extent of future hazard zones lay within the uncertainty of the methods used today for the delimitation of the hazard zones. Thus, the consideration of the uncertainties laying in the methods for the elaboration of hazard zone maps in the torrent and river catchments sensitive to climate changes would provide a useful instrument for the consideration of potential future climate conditions. The study demonstrated that weak points in protection structures in future will become more important in risk management activities.

1 Introduction

The assessment of dangerous processes and the delimitation of hazard zones is a fundamental task in risk analysis and risk management. In general, the assessment and evaluation of geomorphologic processes and hazards could be made using the reconstruction of historical processes (backward directed indication) or using simulation models (forward directed indication, Kienholz et al., 2004). In practice, both approaches mostly are combined. Usually, the hazard assessment is made for the actual state of the studied system (e.g. torrent catchment, landslide area, etc.). Natural hazards are described by the process intensity of a given design event with a certain reoccurrence interval (e.g. 30, 100, 300 years). The actual system status is described by the statistical system behaviour of the last decades.

Due to impacts of climate changes, slight changes in the future system could be assumed. Once changes in the environmental system occurred, the future geomorphologic processes must not occur exactly in the same way as in the past. E.g. shifts in altitude levels or system constellations never observer before could be expected. Thus, backward directed indication of natural hazards and the interpretation

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of the past geomorphologic processes also named as "silent witnesses" and statistical analyses of time series for assessing actual processes will increasingly be subjected to uncertainties. Past observation data (e.g. precipitation data series) could probably not represent the future system status. As a consequence, the statistically described natural hazard situation and the reoccurrence intervals of design flood discharges or design parameters for the planning of hydraulic protection structures could only partially be valid under future climate conditions (e.g. Caspary 1996, 2004, Caspary and Bardossy 1995, Bardossy and Pakosch 2005, Frei et al. 2006, Katzenberger 2004, Hennegriff et al. 2006).

But, most of the decisions made in risk prevention have to be made for a period of almost 30–50 years. E.g. hazard zone maps do influence land use planning over a long period. In Austria or in Switzerland, some of the hazard zone maps made in the 1980ies are still now valid documents for land use planning. Technical construction measures such as river dams or flood retention basins have an average lifespan of almost 50 years. In practice, today's decisions for long-term risk management activities such as the planning of technical protection measures do not consider the future system status but are reactions after damaging events.

Since a few years, the Autonomous Province of Bolzano – South Tyrol, Italy is beginning to elaborate hazard zone maps. Because of the high relevance of the elaborated hazard zone maps for land use planning and the planning of risk reduction measures, the institutions responsible for the elaboration of these decision bases are interested to know, if these documents will be valid also under future climate conditions. Thus, this study aims not at making a contribution to the quantitative assessment of the impacts of climate change to natural hazards. But, the main goal of this study was to assess the robustness or sensitivity of the commonly used procedures for the delimitation of flood and debris flow hazard zone maps to climatic changes. The question should be answered, if, where and how the practices for hazard mapping and risk management must be adapted to potential impacts of climatic changes.

The focus of this case study lied not on the exact representation of the environmental systems by means of detailed process and climate models but on the resulting differences of the hazard assessment representing different climate conditions. Thus, only the potential impacts of climate change to specific input parameters should be studied.

In this study, a procedure

- for identifying the alpine torrent catchments that are sensitive to climatic changes and
- for assessing the robustness of the methods for the elaboration of flood and debris flow hazard zone maps to specific effects of climate changes

should be developed.

The targeted time frame for the assessment of the potential effects of climate changes to the flood risk situation in the Autonomous Province of Bolzano - South Tyrol is the second half of the 21st century (2050–2100). The results of the procedure should lead to formulate recommendations for the adaptation of risk management practices to specific effects of climate changes.

Natural hazards are mostly defined as natural conditions or phenomena which cause undesired consequences for persons, settlements, infrastructures and goods. In some definitions, natural hazards are described as natural geomorphologic processes that are considered as hazards only in intersection with human activities. These processes are characterized as the probability of occurrence of a potentially damaging phenomenon (United Nations, 2004). The physical process itself is characterized by the parameters intensity/magnitude and occurrence probability. The risk resulting from natural hazards is defined as a quantifying function of the probability of occurrence of a dangerous process and the related degree of damage. The latter is specified by the damage potential and the vulnerability of the endangered object (Fuchs et al., 2007).

$$R_{i,j} = p_{Si} \cdot A_{Oj} \cdot p_{Oj,Si} \cdot v_{Oj,Si} \tag{1}$$

According to the definition of United Nations (2004), the specifications for the probability of the defined scenario (p_{Si}), the monetary value of the object affected by this scenario (A_{Oj}), the probability of exposure of object j to scenario i ($p_{Oj,Si}$), and the vulnerability of object j in dependence on scenario i ($v_{Oj,Si}$) are required for the quantification of risk ($R_{i,j}$).

The methods for the description and characterization of the natural hazards in the Alps are based on the intensity and frequency of events. Thus, the concept of the legally binding hazard maps is based on the return period and the intensity of processes. Usually, natural hazards are described in hazard maps by threshold classes of the process intensity for different design events with a given reoccurrence interval (e.g. 30, 100, 300 years, resp. 200 years for rivers with engineering measures). The relative consequences for the land use and the corresponding legally binding restrictions are also based on this concept. Risk analyses are made on the basis of this concept of hazard maps. Furthermore, the planning and design of permanent countermeasures are based on specific design events with a legally defined return period and the related process intensity.

The Autonomous Province Bolzano – South Tyrol adapted the methods for the elaboration of hazard maps of Heinimann et al. (1998) and combined this approach with the Italian national framework legislative of the laws no. 267 of 3 August 1998, no. 365 of 11 December 2000 and the D.P.C.M. of 29 September 1998 (Gius, 2005). The guidelines for the delimitation of hazard zone maps are described in Gius (2005), Stötter and Zischg (2007) and Autonome Provinz Bozen – Südtirol (2006).

Because of these practices in risk management, the deduction of the most critical factors for hazard assessment under changing environmental conditions is relatively obvious: At least for natural hazards related to precipitation, the most relevant changes in the environmental parameters due to climatic changes are to be expected in the intensity/frequency relation of precipitation events (rainfall, snowfall). Indirect effects are shifts in altitude levels due to rising temperatures, e.g. rising of the altitude of the limit between snowfall and rainfall or rising of the lower boundary of permafrost zones. Seasonal and regional changes in precipitation patterns are to be expected as follows: In Autumn, extreme values for daily precipitations are expected to increase by 10% in the Northern Alps and by 20% in the Southern Alps. In winter and spring, an increase between 0% and 20% is expected for both regions (KOHS, 2007). Brunetti et al. (2001) observed a trend for an increase in frequency of extreme precipitation events in Northeastern Italy. Under the most unfavourable conditions, a 100-year event of today could in the future become a 20-year event (Frei et al., 2006). Similar trends were calculated for the rivers Donau, Enz, Kocher and Alp in South West Germany (Caspary, 2004). Caspary (2004) underlines that the discharge regimes of these rivers show statistical instationarities in their time series because of the relative accumulation of extreme events since the 1990ies. E.g. a discharge event with a reoccurrence interval of 100 years in the reference period 1932–1976 of the river Enz at the gauge of Pforzheim equals a discharge event with a reoccurrence interval of 30 years in the reference period 1932–2002. Remarkably increases in runoff and discharge volumes were also computed for the Lavanttal region (Austria) when considering possible effects of climate changes (Regional Office of Carinthia, Department of Water Economy 2008).

An indirect effect of the increase of mean temperature is the rising altitude level for the limit between rainfall and snowfall. In areas of the Northern Alps below 1500 m a.s.l., an increase of flood peaks is expected in winter due to higher soil water contents, the rising of the rainfall/snowfall limit level and due to an increased liquid precipitation (KOHS, 2007). In the pre-Alpine regions, the increase of precipitation in winter and the rising of the snowfall limit will have consequences for the activities of landslides in winter and spring. The increase in saturation leads to an increase in landslide activity and to an increase in sediment load in alpine torrent catchments (Schädler et al., 2007). Due to the rising altitude level of glacier retreat and permafrost degradation, the sediment transport in the areas between approximately 2300 and 2800 m a.s.l. and with relevant bed load source areas in this altitude level is expected to increase (KOHS, 2007). Since in these areas more precipitation will fall in liquid form, this trend is expected to be remarkably.

Discussions with experts for hazard zone mapping in different workshops resulted, that the following climatological parameters used in the assessment of flood and debris flow hazards are at most sensitive to climate changes

- Intensity of precipitation
- Frequency of precipitation of a certain intensity/magnitude

Other parameters such as the altitude of snowfall limit, the altitude of snowmelt level, the antecedent precipitation, the retreating of glaciers or the degradation of permafrost are considered only in a generalized way in the common procedures for hazard zone mapping. Certain parameters needed for hazard mapping are assumed as worst case scenarios, e.g. the assumption that the altitude of the limit between snowfall and rainfall during extreme precipitation events is higher than the mountain crests and all precipitation contributes to runoff. Thus, in this study only the impacts of a potential increase in the intensities of extreme precipitation events (>50 mm/d) to the delimitation of hazard zones were analyzed. On the basis of a literature review, a possible increase in the precipitation intensity of at maximum of 20% for all design events as indicated by Frei et al. (2006) for the Southern Alps was assumed for this sensitivity analysis. The assumption is consistent with the observed trend in the reduction of the return period between extreme precipitation events in Northeastern Italy (Brunetti et al., 2001). Due to the main focus on the robustness of the procedures for hazard zone mapping, in this study no downscaling procedures from global and regional climate models to the local conditions were followed. It was assumed that the effects of an increase in precipitation intensity of less than 20% are laying within the uncertainties of the procedures for the delimitation of hazard zones. Therefore, it was expected that an increase of less than 20% will not show remarkably effects to the increase in the extent of the hazard zones.

2 Method

The study was made in three main steps. Firstly, the sensitivity of the alpine torrent catchments to climate changes was analysed qualitatively on the regional scale. Secondly, the possible effects of climate changes to the delimitation of flood hazard zones were analysed in a case study. In another case study, the possible effects of climate changes to the delimitation of debris flow hazard zones were analysed. Finally, conclusions and recommendations for the adaptation of the risk management practices have been elaborated on the basis of the results of the previous three steps.

2.1 Identification and localisation of alpine torrent and river catchments sensitive to climate changes

In this part of the study, the sensitivity of the alpine torrent catchments to climate changes was analysed on the regional scale. The focus of this study lied on the identification of the torrent catchments in which the future climate scenarios

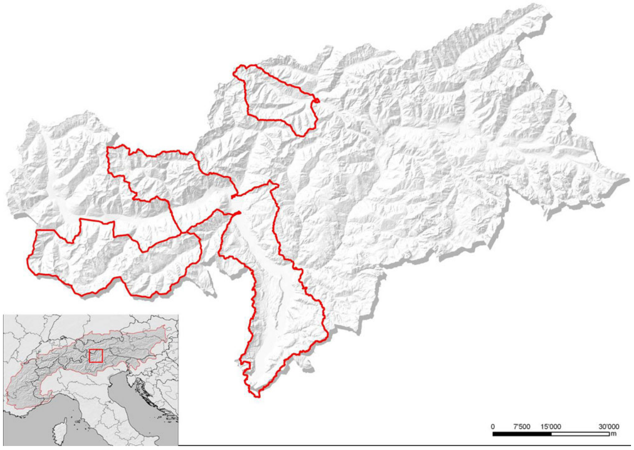


Fig. 1. Study area in the Autonomous Province of Bolzano South Tyrol, Italy.

described above will modify the hazard situation (flood and debris flows).

The first step of the procedure was to match the environmental parameters relevant for hazard assessment on the regional scale with the existing spatial datasets. On the basis of the identified parameters and the existing datasets, an approach for the classification of the torrent catchments of different dimensions and for the qualitative assessment of the sensitivity of the catchments to assumed climatic changes was developed. The catchments were classified into three catchment classes: mountain torrents, torrential rivers and alpine rivers (see Table 1). The results of the study were the delineated catchments classified by the sensitivity to the changes in the selected environmental parameters.

The activities of flood and debris flow processes in alpine torrents are mainly driven by the discharge, the sediment budget and the sediment transport capacity. The sediment transport capacity is influenced either by short precipitation events (thunderstorms) or by longer precipitation events. Because of the steepness of alpine torrent catchments, the hydrological characteristics in the runoff formation are less important. In torrential river catchments both the sediment budget and the hydrological characteristics in the runoff formation are important. In river catchments, the hydrological characteristics in the runoff formation are important. Because of the larger catchment area, the characteristics of the sediment budget are evened.

The sensitivity analysis was made in a pilot area of the Autonomous Province of Bolzano – South Tyrol (Fig. 1). The delimitation of the torrent and river catchments was made on the basis of the classification scheme for public watercourses of the Autonomous Province of Bolzano. The basic assumptions for potential future climate conditions were the following:

- The daily mean temperatures in summer and winter are increasing (Heimann and Sept, 2000; OcCC, 2007)
- The mean sum of precipitation in summer is decreasing or remains constant
- The mean sum of precipitation in winter is increasing (OcCC, 2007)
- The intensity and frequency of short extreme rainfall events in summer and autumn is increasing (Christensen and Christensen, 2003)

It was assumed that the following factors are varying spatially and are relevant for the sensitivity of the torrent catchments to climate changes:

- Percentage of areas located between 1000 and 2000 m a.s.l.: It is expected that the snow cover in these areas will be reduced and the frequency of combined snowmelt/rainfall events will increase (KOHS, 2006). A threshold value of 50% of these areas respective to the total catchment area was chosen. This information layer was extracted from the digital elevation model. The value for this parameter was found by a statistical analysis of the catchments assessed as sensitive to climatic changes by local experts.
- Characteristics of bed load source areas: Bed load source areas could be divided into recent and older deposits. Recent deposits are alimented by recent weathering and denudation processes. The quantity of mobilizeable sediment storages in torrents eroding recent deposits is depending on the intensity of the sediment delivery processes and the period between extreme discharge events transporting the weathered material downstream (Zimmermann et al. 1997). Older deposits were composed by relict geomorphologic deposition processes (e.g. glacial moraines, holocene alluvional sediments, landslides). The quantity of mobilizeable sediment storages in torrents eroding older deposits is mainly unlimited. If the percentage of areas with older deposits to the total bed load source area exceeds 30% of the total catchment area, the torrent catchments were classified as torrents eroding older deposits, otherwise as torrents eroding recent deposits. The value for this parameter was found by a statistical analysis of the catchments assessed as sensitive to climatic changes by local experts. Landslides do influence the quantity of mobilizeable sediment. An increase in precipitation could increase the activity of landslides, especially in winter and spring (Bader and Kunz 1998). If the percentage of landslide areas with respective to the total bed load source area exceeds 30%, the torrent catchments were classified as torrents mainly influenced by landslide activity. This information layer was extracted from the dataset of the hazard index map for debris

Table 1. Classification of alpine torrent catchments.

Torrent classification	Catchment area	Description
(a) mountain torrents	$<20\,\mathrm{km}^2$	torrents, torrential processes mainly driven by discharge and bed load transport processes
(b) torrential rivers	$20–100\,\mathrm{km}^2$	torrential rivers, processes mainly driven by hydrology and partially by bed load transport
(c) Alpine rivers	$100–1\,000\,\mathrm{km}^2$	rivers, processes mainly driven by runoff processes

flows and from the landslide inventory of the Geological Survey of the Autonomous Province of Bolzano (IFFI – Italian National Landslide Inventory).

- Available bed load source areas: The bed load sediment budget of alpine torrents depends on the quantity of bed load source areas available for sediment transport and the sediment transport capacity. The sensitivity of torrent activity against climate changes increases with a higher proportion of bed load source areas respective to the total catchment area. During the elaboration of the hazard index map for debris flow, the available bed load source areas were computed and weighted on the basis of the relevance for torrential processes (geo7 2006, Heinimann et al. 1998). For this analysis, a minimum threshold for the weighted bed load source areas per catchment was used for the identification of sensitive catchments. This information layer was extracted from the dataset of the hazard index map for debris flows.

- Permafrost degradation and glacier retreat areas: Permafrost influences the hydrology and stability of steep scree slopes, since ice-rich permafrost acts as a barrier to groundwater percolation and can imply local saturation within non-frozen debris (Zimmermann and Haeberli, 1992). Permafrost thawing in non-consolidated material leads to an increase of pore water pressure and a loss of cohesion (Harris et al., 2001). The disappearance of ground ice bodies in scree slopes leaves caverns and destabilizes parts of these disintegrated slope areas. With accelerated permafrost thawing, the susceptibility of these slope areas for landslide and debris flows and the triggered volumes is expected to rise (Zimmermann et al., 1997; Rebetez et al., 1997). Catchments were classified as sensitive, if more than 30% of the total catchment area is subjected to permafrost degradation. The value for this parameter was found by a statistical analysis of the catchments assessed as sensitive to climatic changes by local experts. This information layer was created by modelling the permafrost distribution of 1850, 1990 and 2100 (after Stötter, 1994; Zischg, 2007). The difference between the datasets of the permafrost distribution of 1850 and 2100 was classified as permafrost degradation areas. Because of a lack in multitemporal glacier datasets, glacier retreat areas were not considered in this study.

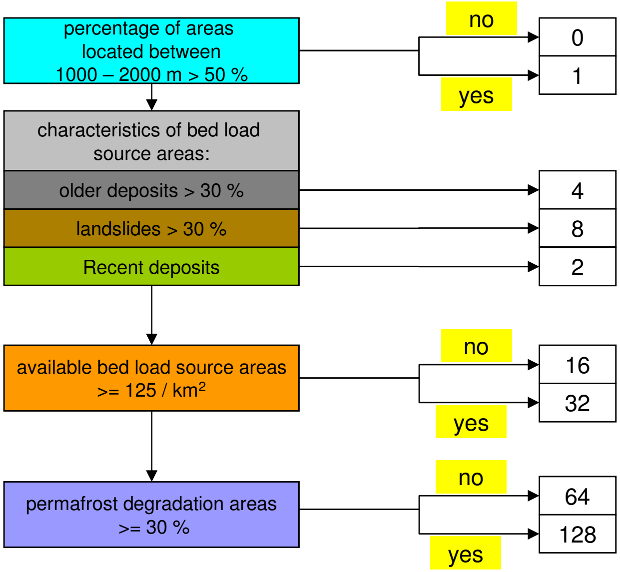


Fig. 2. Decision tree for the identification and localisation of alpine torrent catchments sensitive against climate changes.

- Areas with elevated surface runoff: Areas with reduced water storage capacities increase the surface runoff. The sensitivity of torrential rivers and rivers to climate changes increases with a higher proportion of areas with reduced water storage capacities respective to the total catchments area. This information layer was created by modelling the Topoindex after Beven et al. (1995) under consideration of the geological permeability. This index describes the susceptibility of areas for saturated surface runoff.

The delimitated torrent, torrential river and river catchment areas were classified by the combination of these factors influencing the sensitivity of mountain torrents and rivers to climate changes. The classification was made by means of a decision tree implemented into a GIS-based procedure (Figs. 2, 3, 4). The results of the classification procedure are different classes of torrent and river catchments reacting in different ways to potential climate changes (Figs. 5, 6, 7). The classification of the catchment types are shown in Tables A1–A3.

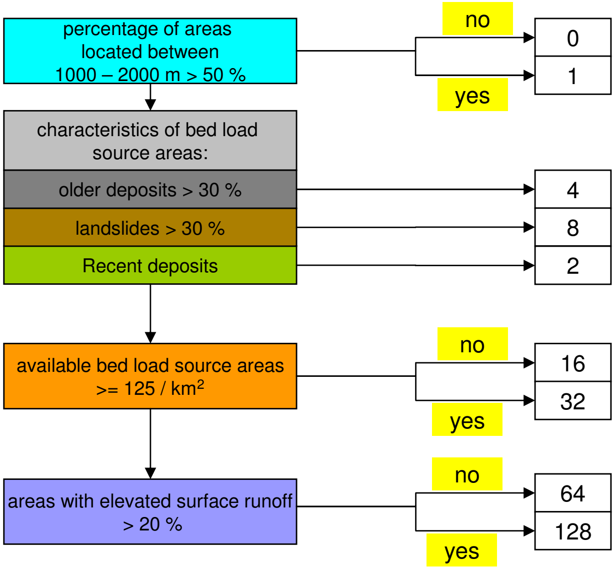


Fig. 3. Decision tree for the identification and localisation of torrential river catchments sensitive against climate changes.

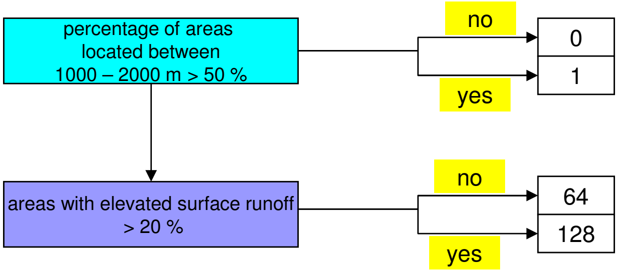
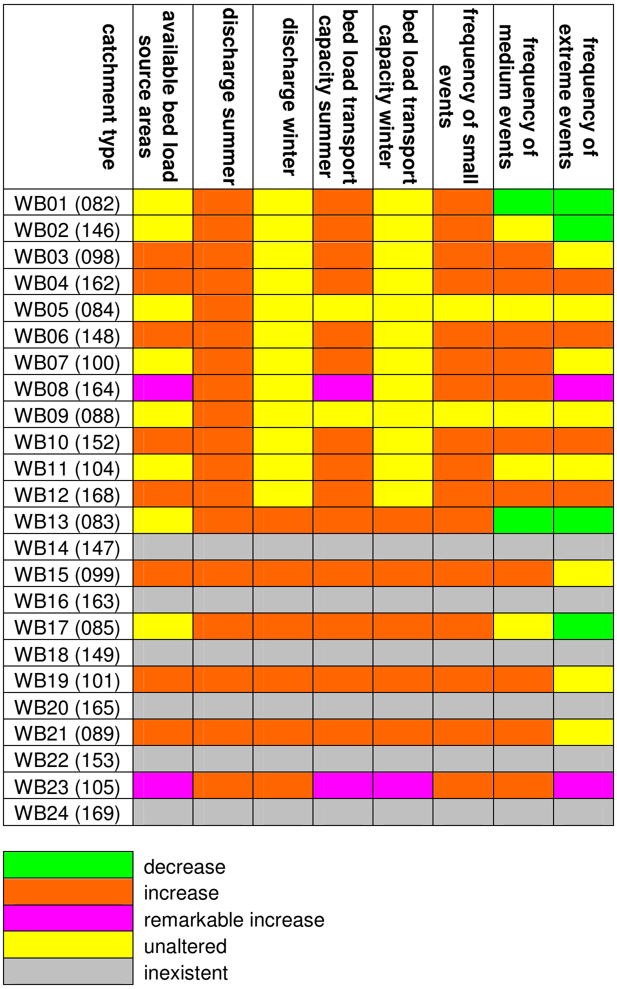


Fig. 4. Decision tree for the identification and localisation of alpine river catchments sensitive against climate changes.



catchment type	available bed load source areas	discharge summer	discharge winter	bed load transport capacity summer	bed load transport capacity winter	frequency of small events	frequency of medium events	frequency of extreme events
WB01 (082)	🟨	🟧	🟨	🟧	🟨	🟧	🟩	🟩
WB02 (146)	🟨	🟧	🟨	🟧	🟨	🟧	🟨	🟩
WB03 (098)	🟧	🟧	🟨	🟧	🟨	🟧	🟧	🟨
WB04 (162)	🟧	🟧	🟨	🟧	🟨	🟧	🟧	🟧
WB05 (084)	🟨	🟧	🟨	🟨	🟨	🟨	🟨	🟨
WB06 (148)	🟧	🟧	🟨	🟧	🟨	🟧	🟧	🟧
WB07 (100)	🟨	🟧	🟨	🟧	🟨	🟧	🟧	🟨
WB08 (164)	🟪	🟧	🟨	🟪	🟨	🟧	🟧	🟪
WB09 (088)	🟨	🟧	🟨	🟨	🟨	🟨	🟨	🟨
WB10 (152)	🟧	🟧	🟨	🟧	🟨	🟧	🟧	🟧
WB11 (104)	🟨	🟧	🟨	🟧	🟨	🟧	🟨	🟨
WB12 (168)	🟧	🟧	🟨	🟧	🟨	🟧	🟧	🟧
WB13 (083)	🟨	🟧	🟧	🟧	🟧	🟧	🟩	🟩
WB14 (147)	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
WB15 (099)	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟨
WB16 (163)	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
WB17 (085)	🟨	🟧	🟧	🟧	🟧	🟧	🟨	🟩
WB18 (149)	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
WB19 (101)	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟨
WB20 (165)	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
WB21 (089)	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟨
WB22 (153)	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
WB23 (105)	🟪	🟧	🟧	🟪	🟪	🟧	🟧	🟪
WB24 (169)	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜

🟩	decrease
🟧	increase
🟪	remarkable increase
🟨	unaltered
⬜	inexistent

Fig. 5. Synthesis of the considered potential impacts of climate changes to alpine torrent catchments (WB01 to WB24). The identification number of the torrent catchment type resulting from the decision tree is shown in the brackets

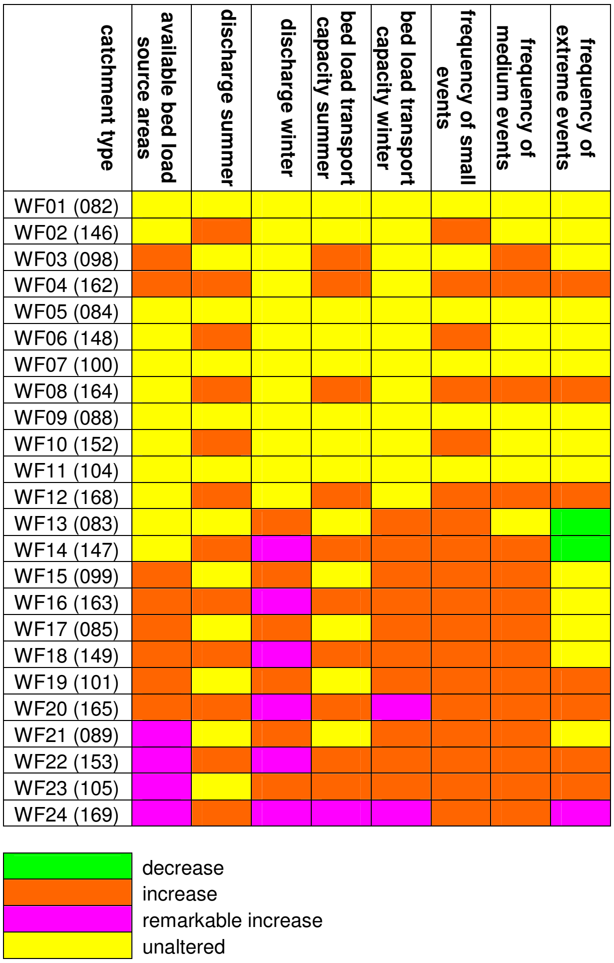
2.2 Potential impacts of climate changes to the delimitation of flood hazard zones, case study Rio Ridanna/Mareiter Bach

In this part of the study, the sensitivity of the common methods and procedures for the delimitation of flood hazard zone maps to climate changes was analysed. The focus of this case study lied not on the exact representation of the environmental systems by means of detailed process and climate models but on testing the robustness of the methods and procedures for hazard mapping to changes of the needed input parameters. On the basis of a literature review, a possible increase of 20% of the precipitation intensity for each design event (reoccurrence interval 30, 100, 200 years) was assumed for this sensitivity analysis. The hazard induced by bed load transport and overbank sedimentation was not considered.

The Rio Ridanna/Mareiter Bach basin lies in the north of the Autonomous Province of Bolzano – South Tyrol (Fig. 8). The river endangers parts of the Vipiteno/Sterzing Basin and the city of Vipiteno/Sterzing and confluences with the Isarco/Eisack River. The catchment area is 210 km^2. This study area is a representative example for an alpine river with hazard potential for settlements.

For the assessment of the present flood hazard situation of the Rio Ridanna/Mareiter Bach for the Vipiteno/Sterzing basin, this procedure was followed:

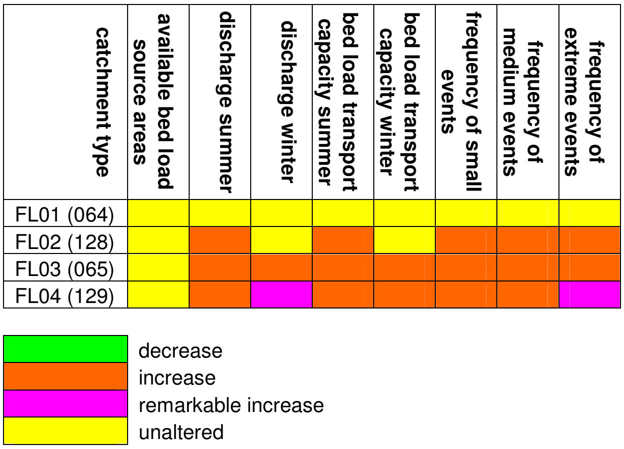
- statistical analyses of the precipitation time series of the measurement stations in the study area and calculation of the characteristics of precipitation events relevant for the hazard scenarios with a return period of 30, 100 and 200 years,
- preparation and calibration of the rainfall-runoff model,
- simulation of the inundation processes for each return period,



catchment type	available bed load source areas	discharge summer	discharge winter	bed load transport capacity summer	bed load transport capacity winter	frequency of small events	frequency of medium events	frequency of extreme events
WF01 (082)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
WF02 (146)	🟨	🟧	🟨	🟨	🟨	🟧	🟨	🟨
WF03 (098)	🟧	🟨	🟨	🟧	🟨	🟨	🟧	🟨
WF04 (162)	🟧	🟧	🟨	🟧	🟨	🟧	🟧	🟧
WF05 (084)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
WF06 (148)	🟨	🟧	🟨	🟨	🟨	🟧	🟨	🟨
WF07 (100)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
WF08 (164)	🟨	🟧	🟨	🟧	🟨	🟧	🟧	🟧
WF09 (088)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
WF10 (152)	🟨	🟧	🟨	🟨	🟨	🟧	🟨	🟨
WF11 (104)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
WF12 (168)	🟨	🟧	🟨	🟧	🟨	🟧	🟧	🟧
WF13 (083)	🟨	🟨	🟧	🟨	🟧	🟧	🟨	🟩
WF14 (147)	🟨	🟧	🟪	🟧	🟧	🟧	🟧	🟩
WF15 (099)	🟧	🟨	🟧	🟨	🟧	🟧	🟧	🟨
WF16 (163)	🟧	🟧	🟪	🟧	🟧	🟧	🟧	🟨
WF17 (085)	🟧	🟨	🟧	🟨	🟧	🟧	🟧	🟨
WF18 (149)	🟧	🟧	🟪	🟧	🟧	🟧	🟧	🟨
WF19 (101)	🟧	🟨	🟧	🟨	🟧	🟧	🟧	🟧
WF20 (165)	🟧	🟧	🟪	🟧	🟪	🟧	🟧	🟧
WF21 (089)	🟪	🟨	🟧	🟨	🟧	🟧	🟧	🟨
WF22 (153)	🟪	🟧	🟪	🟧	🟧	🟧	🟧	🟧
WF23 (105)	🟪	🟨	🟧	🟧	🟧	🟧	🟧	🟧
WF24 (169)	🟪	🟧	🟪	🟪	🟪	🟧	🟧	🟪

🟩 decrease
🟧 increase
🟪 remarkable increase
🟨 unaltered

Fig. 6. Synthesis of the considered potential impacts of climate changes to torrential river catchments (WF01 to WF24). The identification number of the torrential river catchment type resulting from the decision tree is shown in the brackets.



catchment type	available bed load source areas	discharge summer	discharge winter	bed load transport capacity summer	bed load transport capacity winter	frequency of small events	frequency of medium events	frequency of extreme events
FL01 (064)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
FL02 (128)	🟨	🟧	🟨	🟧	🟨	🟧	🟧	🟧
FL03 (065)	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧
FL04 (129)	🟨	🟧	🟪	🟧	🟧	🟧	🟧	🟪

🟩 decrease
🟧 increase
🟪 remarkable increase
🟨 unaltered

Fig. 7. Synthesis of the considered potential impacts of climate changes to alpine river catchments (FL01 to FL04). The identification number of the river catchment type resulting from the decision tree is shown in the brackets.

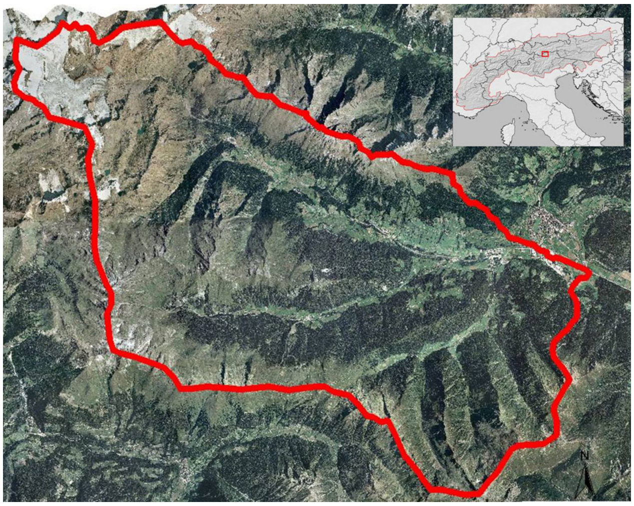


Fig. 8. Localisation and delimitation of the Rio Ridanna/Mareiter Bach catchment.

- delimitation of the hazard zone map,
- analysis of the exposed buildings.

The results of the procedures described above were the hazard maps describing the hazard situation on the basis of simplified assumptions representing present (scenario 2000) and future (2050–2100) climate conditions (scenario +20%). The main focus laid more on the comparison of the two hazard situations rather than on the single hazard assessment itself.

The statistical analysis of the precipitation time series was based on the measurement stations of Ridanna/Ridnaun (31 measurement years). In the analysis, precipitation events with a duration of 24 h were considered (Scherer and Mazzorana, 2007). The calculated precipitation values of a rainfall event with a duration of 24 hours representing reoccurrence intervals of 30, 100 and 200 years are shown in Table 2. For the representation of the design precipitation events under future climate conditions (scenario +20%) 20% of these calculated values were added (see Table 2). For the discharge prediction, the rainfall-runoff model Hec-HMS and the SCS-approach was used and adapted to the catchment characteristics of the Rio Ridanna/Mareiter Bach. The calibration of the model was made within the Interreg IIIB project "River Basin Agenda" (Scherer and Mazzorana, 2005a; Scherer and Mazzorana, 2005b). The model was calibrated with the precipitation events of 1996 and 1997. For the simulation of the inundation process, the simulation model SOBEK of WL Delft Hydraulics was used. The flood hazard zone map was made by following the guidelines for hazard zone mapping of the Autonomous Province of Bolzano – South Tyrol (Autonome Provinz Bozen – Südtirol, 2006) and Heinimann et

Table 2. Calculated rainfall and runoff values for relevant return periods and different climate conditions (Scherer and Mazzorana, 2007).

return period of a rainfall event, duration 24 h	N_{tot} (precipitation) [mm]		Q_{max} (discharge) at confluence [m^3/s]	
	scenario 2000	scenario +20%	scenario 2000	scenario +20%
30 years	106.6	127.9	212.5	299.6
100 years	125.7	150.8	272.6	383.9
200 years	136.6	164.0	333.3	431.8

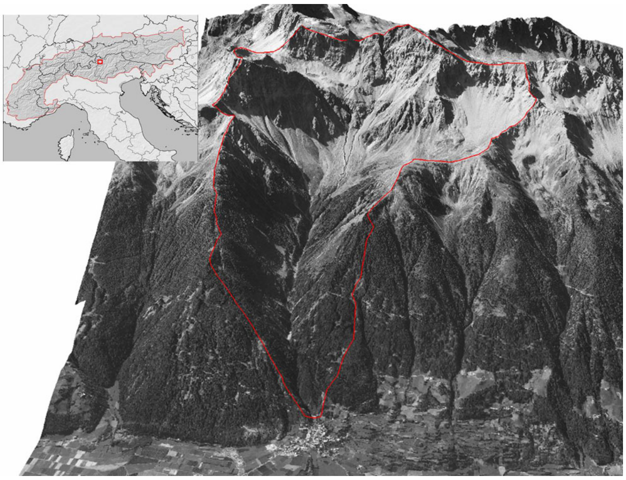


Fig. 9. Localisation and delimitation of the Rio Cengles/Tschenglser Bach catchment.

al. (1998). The resulting hazard maps were overlayed with the buildings in the settlement areas. Thus, the changes in the hazard situation were demonstrated by the changes in the extent of the hazard zones and by the changes in the number of the endangered buildings. The related damages were estimated by multiplying the number of endangered buildings with a mean value of expected losses per building. This value represents a combination of the terms A_{Oj} and $v_{Oj,Si}$ in Eq. 1. For residential buildings, a mean value of expected losses of about € 45 000 was used, and for industry buildings a mean value of expected losses of about € 80 000 was used for the estimation of the potential damages regarding flood events.

2.3 Potential impacts of climate changes to the delimitation of debris flow hazard zones, case study Rio Cengles/Tschenglser Bach

The Rio Cengles/Tschenglser Bach torrent lies in the western part of the Autonomous Province of Bolzano South Tyrol. The Rio Cengles/Tschenglser Bach torrent confluences with the river Adige/Etsch. The catchment area is 11 km^2. This study area is a representative example for systematized alpine torrents eroding older deposits in permafrost degradation areas (Fig. 9). The hazard potential of these kinds of torrents is mainly driven by the sediment mobilization and bedload transport capacity because of the unlimited sediment source areas. The sediment transport capacity is driven by the runoff and the discharge. The upper catchment area is characterized by the disappearance of a small glacier in the recent years and the erosion of oversteepened scree slopes supposed to permafrost degradation. The Rio Cengles/Tschenglser Bach is systematised by sediment retention basins and check dams.

For the assessment of the actual situation of debris flow hazards in the Rio Cengles/Tschenglser Bach catchment, the following procedure was followed (IPP 2007):

- characteristics of precipitation events relevant for the hazard scenarios with a return period of 30, 100 and 300 years,
- preparation and verification of the rainfall-runoff model,
- simulation of the bed load transport in the transit area and in the sediment retention basins,
- simulation of the debris flow processes in the deposition area for each return period,
- delimitation of the hazard zone map,
- analysis of the exposed buildings.

Since no meteorological station is located in the catchment area or in the neighbourhood of 20 km, the calculation of the rainfall characteristics representing the present climate conditions (scenario 2000) was made following the procedures of VAPI (Valutazione delle portate in Italia, Villi and Bacchi 2001). Villi and Bacchi (2001) made a regionalization of the precipitation intensities for given reoccurrence intervals. The results of the procedure were the needed input parameters for the hydrologic and hydraulic simulations representing precipitation events with reoccurrence intervals of 30, 100 and 300 years and a duration of 1 hour (scenario 2000, see Table 5). Because of the steepness of the catchment, intensive rainfall events with a duration of one hour are the most relevant precipitation scenarios. These values fit with the values of the precipitation time series of the meteorological station in Prato/Prad. For the representation of future climate conditions (scenario +20%), 20% of these precipitation values were added (IPP, 2007; Table 5). For the discharge prediction, the rainfall-runoff model Hec-HMS and the SCS-approach was used and adapted to the catchment characteristics of the Rio Cengles/Tschenglser Bach. The calibration of the model was made with well documented debris flow events (Gostner, 2002). For the simulation of the bed load transport in the transit area and in the sediment retention basins, the simulation model DAMBRK of the US National Weather Service was used. For the simulation of the debris flow processes in the runout area, the simulation model Flow-2D (O'Brian, 2001) was used. The flood hazard zone map was made following the guidelines for hazard zone mapping of the Autonomous Province of Bolzano – South Tyrol (Autonome Provinz Bozen – Südtirol, 2006) and Heinimann et al. (1998).

3 Results

3.1 Identification and localisation of alpine torrent and river catchments sensitive to climate changes

The main results of the procedure were the classification of the torrent catchments into different reaction typologies and the classification into different sensitivity typologies (Fig. 10). The datasets could be queried under different aspects. Figure 10 show a high spatial variability of the sensitivity of the torrent catchments to specific impacts of climatic changes. This underlines the observations made in the Ecrin massif (Jomelli et al., 2004; Jomelli et al., 2007). The procedure was made also for torrential river and river catchments. The results showed that the runoff of nearly all torrent catchments is expected to increase in summer (Fig. 10a). The runoff in winter is expected to increase only in torrent catchments having a high percentage of their total surface area below 2000 m (Fig. 10b). The bed load transport in summer is expected to increase in high mountain areas and is expected to decrease in catchments at submontane levels (Fig. 10c). In some catchments eroding younger deposits (weathered material), a decrease in extreme events is highlighted (Fig. 10f). This is consistent with the observations of Jomelli et al. (2004), Jomelli et al. (2007) and Stoffel and Beniston (2006). In some catchments eroding older deposits an increase in extreme events is pointed out (Fig. 10f). This seems consistent with the observations of Rebetez et al. (1997). The bed load transport in winter increases in a few mountain torrent catchments and does not change in the most catchments (Fig. 10d). The frequency of small scale debris flow and sediment transport processes is expected to increase in most of the torrent catchments (Fig. 10e).

Table 3. Number of buildings endangered by flood processes of the Rio Ridanna/Mareiter Bach and per hazard zones.

hazard zone	number of exposed buildings			
	scenario 2000		scenario + 20%	
	habitation	production	habitation	production
yellow	12	30	13	6
blue	3	7	9	35
red	0	1	2	2

3.2 Potential impacts of climate changes to the delimitation of flood hazard zones, case study Rio Ridanna/Mareiter Bach

By increasing the rainfall intensities for the design events describing the basic assumptions for the delimitation of the hazard zone maps by 20%, the parameters needed for hazard evaluation changed as shown in Table 2. Figure 11 show the spatial changes of the inundation processes. The modelling results (flow depth and flow velocity) were classified following the guidelines for hazard zone mapping of the Autonomous Province of Bolzano – South Tyrol (Autonome Provinz Bozen – Südtirol, 2006) and Heinimann et al. (1998). Figure 12 shows the impacts of climate changes to the delimitation of the compiled hazard zone maps (synthesis of all design events) by considering flow depth and flow velocity without further on-site investigations.

The study confirmed the results of prior analyses that the discharge capacity of the Rio Ridanna/Mareiter Bach in the Vipiteno/Sterzing basin is lower than the discharge of a design event with a return period of 30 years. Either considering the effects of climate changes to the hazard situation or not, this fact leads to the endangerment of parts of the Vipiteno/Sterzing basin also during relatively frequent events. The historical analyses of flooding events in the Vipiteno/Sterzing basin confirmed this fact (Zischg, 2005).

The analyses of the possible impacts of climate changes showed that the flooded areas of a design event with a return period of 30 years representing the assumed future climate conditions (scenario +20%) have a larger extent than the flooded areas of a design event with a return period of 100 years representing the actual climate conditions (scenario 2000). The hazard zones delimited and classified following the guidelines for hazard zone mappings show remarkable changes if considering the assumed changes in precipitation intensities due to climate changes. The hazard zones representing the assumed future climate conditions show a shift from the yellow zones to the blue zones. In this case study, the extent of the blue zones increased significantly. The changes in the extent of the hazard zones implicate changes in the number of exposed buildings (see Table 3). Under the assumptions made in this study, the buildings exposed to

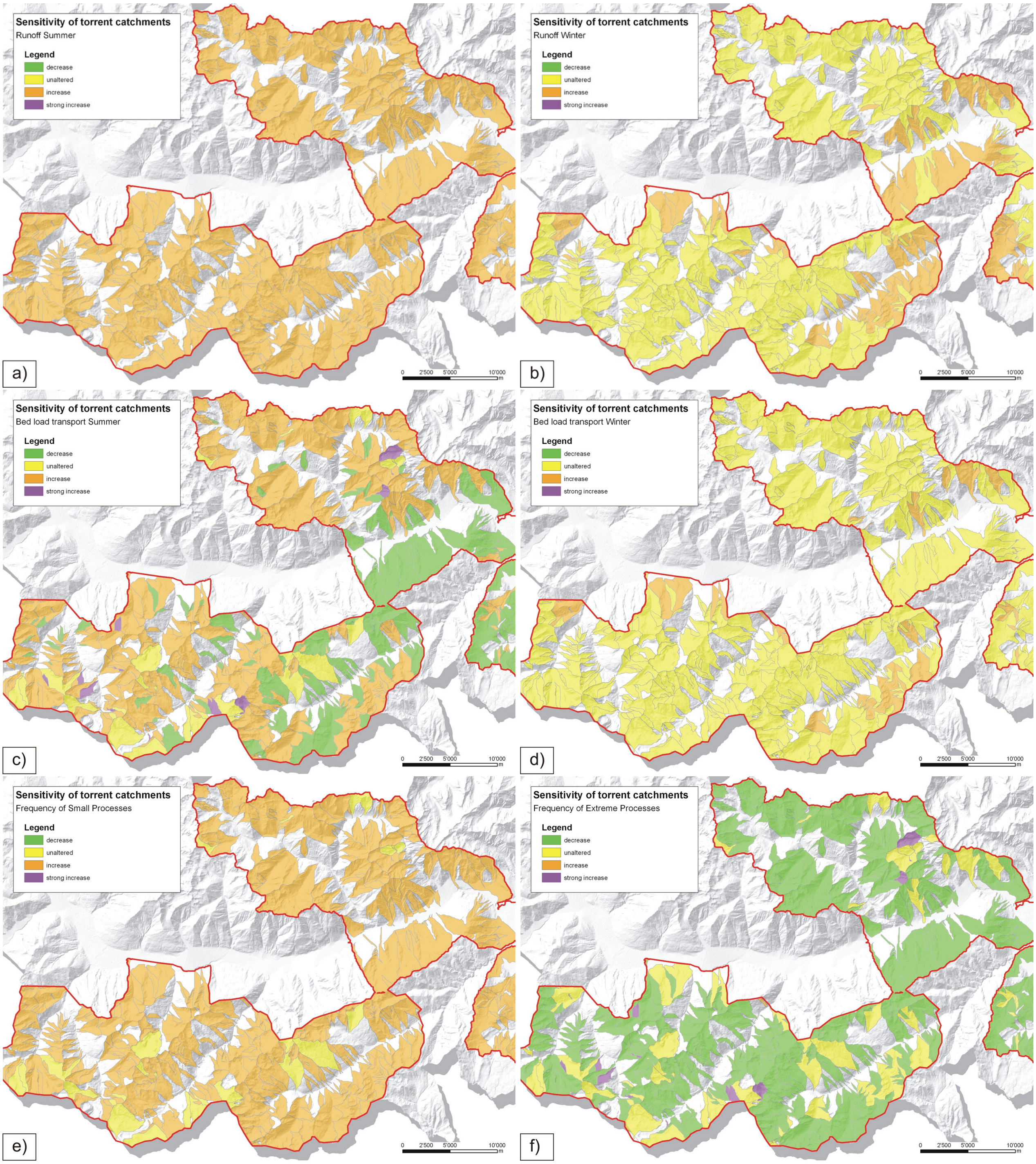


Fig. 10. Classified torrent catchments and their qualitative sensitivity to the assumed changes in the environmental parameters influencing the hazard situation. **(a)** Sensitivity of torrent catchments to climate changes: Runoff in summer. **(b)** Runoff in winter. **(c)** Bed load transport in summer. **(d)** Bed load transport in winter. **(e)** Frequency of small scale processes. **(f)** Frequency of extreme events.

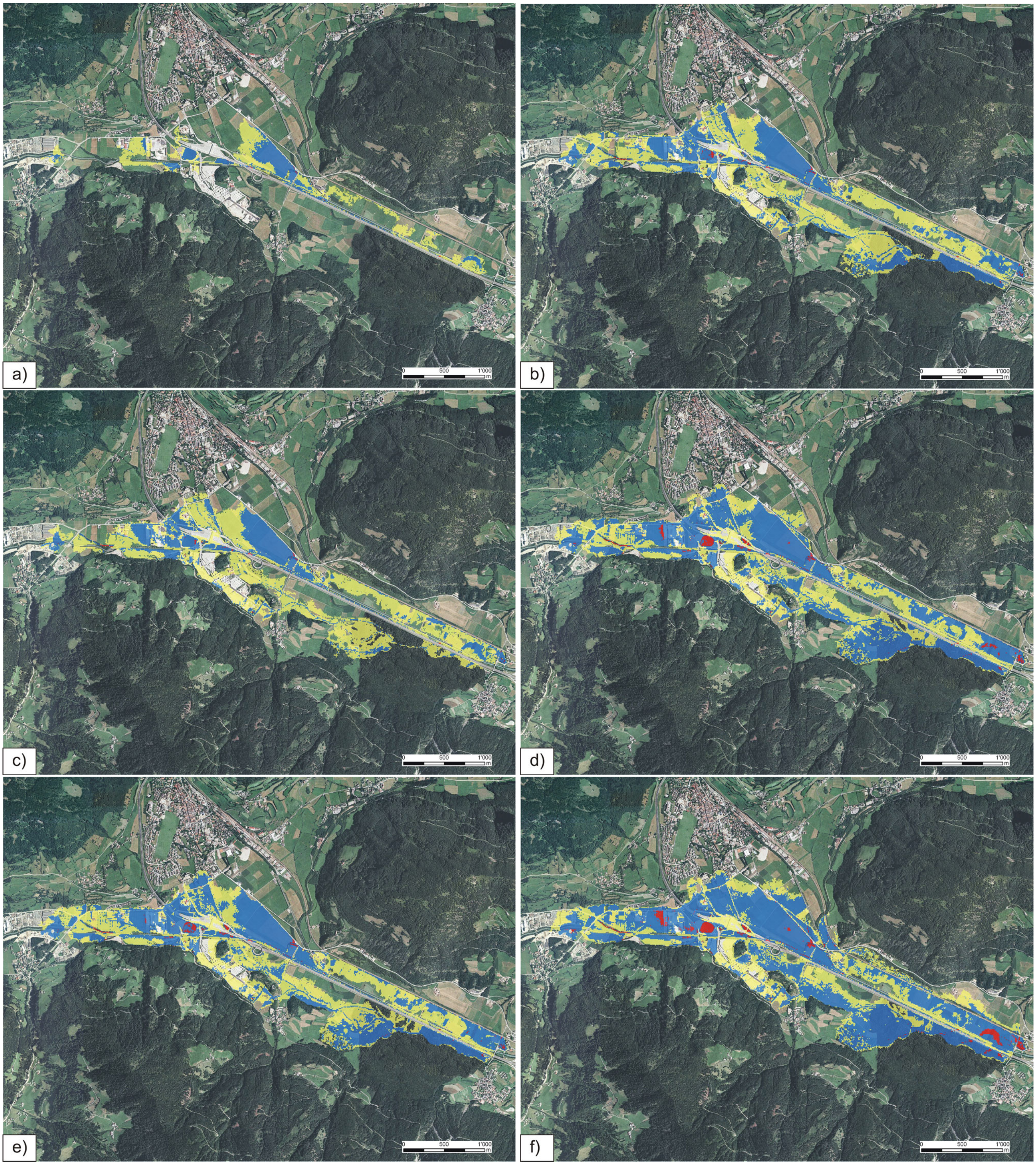


Fig. 11. Changes in flow depths and affected area of the inundation process in the Vipiteno/Sterzing basin. The maps show the classified flow depth. Flow depths from 0 to 0.5 m are shown in yellow, flow depths from 0.5 to 2 m are shown in blue, flow depths of more than 2 m are shown in red. **(a)** Flooded area of a discharge with a return period of 30 years (HQ30) representing scenario 2000. **(b)** Flooded area of a discharge with a return period of 30 years (HQ30) representing scenario +20%. **(c)** Flooded area of a discharge with a return period of 100 years (HQ100) representing scenario 2000. **(d)** Flooded area of a discharge with a return period of 1000 years (HQ100) representing scenario +20%. **(e)** Flooded area of a discharge with a return period of 200 years (HQ200) representing scenario 2000. **(f)** Flooded area of a discharge with a return period of 200 years (HQ200) representing scenario +20%.

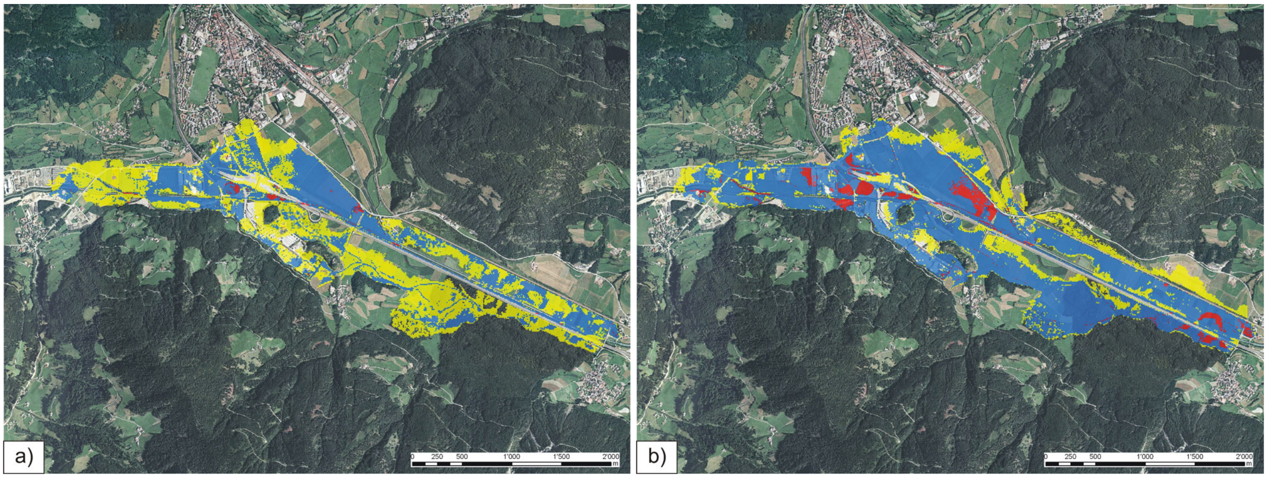


Fig. 12. Results of inundation modelling reclassified following the guidelines for hazard zone mapping (Autonome Provinz Bozen – Südtirol 2006; in red hazard zones, the construction of new buildings is restricted; in blue hazard zones, the construction of new buildings is regulated; in yellow hazard zones prevail hazards with low intensities). **(a)** Flood hazard map representing scenario 2000. **(b)** Flood hazard map representing scenario +20%.

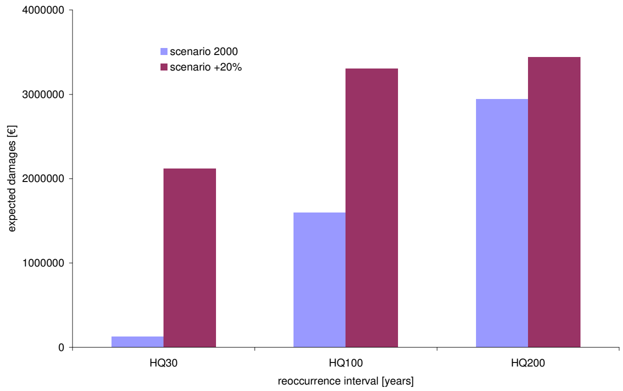


Fig. 13. Changes in expected damages due to flood events in the Vipiteno/Sterzing Basin for the scenario representing the present climate conditions and for the scenario representing possible future climate conditions.

flood hazards with a low intensity (yellow hazard zones) in future may be exposed to blue hazard zones. This is valid especially for the industrial buildings constructed during the last decade in the free spaces in the neighbourhood of the rivers, avoided for settlement in the decades before. The potential shifts from blue hazard zones to red hazard zones do not show significant consequences for buildings. The related risks increased for each scenario (Table 4 and Fig. 13). The expected damages of a flood event with a return period of 30 years (scenario +20%) increased up to 1700% (in comparison to the scenario 2000). The expected damages of a flood event with a return period of 100 years increased up to 207% and up to 117% for an event with a return period of 200 years.

3.3 Potential impacts of climate changes to the delimitation of debris flow hazard zones, case study Rio Cengles/Tschenglser Bach

By increasing the rainfall intensities for the design rainfall events for the delimitation of the hazard zone maps of 20%, the parameters needed for hazard evaluation changed as shown in Table 5. The assumed increase of 20% of the input parameter rainfall intensity for the design events (scenario +20%) lead to an increase of the water discharge of about 37% for a return period of 30 years, of about 45% for a return period of 100 years and of about 31% for a return period of 300 years. The transported volumes increased about 36% for a return period of 30 years, about 51% for a return period of 100 years and of about 43% for a return period of 300 years relative to the design events representing the actual climate conditions. The peak discharge of a design event with a return period of 30 years representing the assumed future climate conditions has nearly the same dimension as a design event with a return period of 100 years representing the actual climate conditions (Table 5). The areas affected by debris flows increases of about 4–30% if the assumed future climate conditions are considered in the simulation model (Fig. 14). The changes in the extent of the hazard zones do not have consequences for the settlements and do not influence the risk situation (if the case of an occlusion of the channel in the settlement area due to wood debris etc. and resulting overflow of the river banks is not considered).

Table 4. Number of buildings endangered by flood processes of the Rio Ridanna/Mareiter Bach and expected damages per design events.

reoccurrence interval	number of exposed buildings and related damages					
	scenario 2000			scenario +20%		
	habitation	production	damages [€]	habitation	production	damages [€]
30	1	1	125 000	8	22	2 120 000
100	7	16	1 595 000	13	34	3 305 000
200	12	30	2 940 000	16	34	3 440 000

Table 5. Calculated rainfall and runoff values and bed load transport in the Rio Cengles/Tschenglser Bach torrent for relevant return periods and different climate conditions (IPP, 2007).

return period of a rainfall event, duration 60 min	N_{tot} (precipitation) [mm]		Q_{max} (discharge) at confluence [m^3/s]		VB (volume of transported material) [m^3]	
	scenario 2000	scenario +20%	scenario 2000	scenario +20%	scenario 2000	scenario +20%
30 years	55.6	66.7	31.5	44.4	59 000	80 000
100 years	74.2	89.0	47.3	70.4	73 000	110 000
300 years	81.2	97.5	63.5	86.5	83 000	119 000

4 Conclusions

The results of the approach for assessing and classifying the sensitivity of mountain torrent and torrential river catchments against the assumed climate changes showed where the future scenarios of natural hazards are expected to occur more likely. The analyses pointed out that the impacts of climate changes to the hazard situation of torrential and river systems have a high spatial variability. The identification and localization of the torrent catchments, where unfavourable changes in the hazard situation occur could eliminate speculative and unnecessary measures against the impacts of climate changes like a general enlargement of hazard zones or a general over dimensioning of protection structures for the whole territory (e.g. as suggested by Hennegriff et al., 2006). Thus, the procedure could support the discussion about future strategies for adaptation to alternated climate conditions by providing the trends for the development of the hazard situation in a higher spatial resolution.

At the moment, the procedure for the identification and localization of torrent catchments does not consider quantitatively future climate scenarios (e.g. global and regional climate models). This weakness in fact could be eliminated in future, but the qualitative approach allows the transfer of the approach to other areas. The dataset about the classified torrent and torrential river catchments and their sensitivity to climate changes provides the basis for the identification and localization of settlement areas, where increases in the future risk potential have to be expected.

As an example for the use of the dataset, the hazard index map for debris flow processes (geo7, 2006; Zimmermann et al., 1997) was overlaid with the sensitive catchments and the settlement areas. The intersection of these two databases leads to the identification and localisation of potential debris flow processes starting in catchments that are sensitive to changes due to permafrost degradation. The settlement areas potentially affected by these debris flow processes were pointed out. The potential debris flow processes starting in catchments that are sensitive to permafrost degradation are endangering only insignificant parts of the settlements in the Autonomous Province of Bolzano. Thus, only these settlement areas are sensitive to this specific impact of climate change. But, the environmental changes in the starting areas of the debris flows endangering these sensitive areas must be observed and monitored.

The procedure for the identification and localisation of alpine torrent and torrential river catchments that are sensitive to climate changes provide an information basis for the identification of these cases, where the risk potential tends to increase. Because the impacts of climate changes to natural hazards show remarkably regional differences, the knowledge about where the expected changes in the natural hazard situation have consequences to the risk situation is crucial for the consideration of the impacts of climate change in land use planning and risk management. The presented procedure provides a further information basis for decision-making in land use planning and natural hazard and risk management with a long-term planning horizon. Furthermore, it provides a methodological framework for further refinement and enhancement of the consideration of the effects of climate changes in natural hazards and risk management.

The case study of the Rio Ridanna/Mareiter Bach river showed possible consequences of climate changes to the hazard situation of an alpine river. The study showed that the assumed increase of the precipitation intensities has

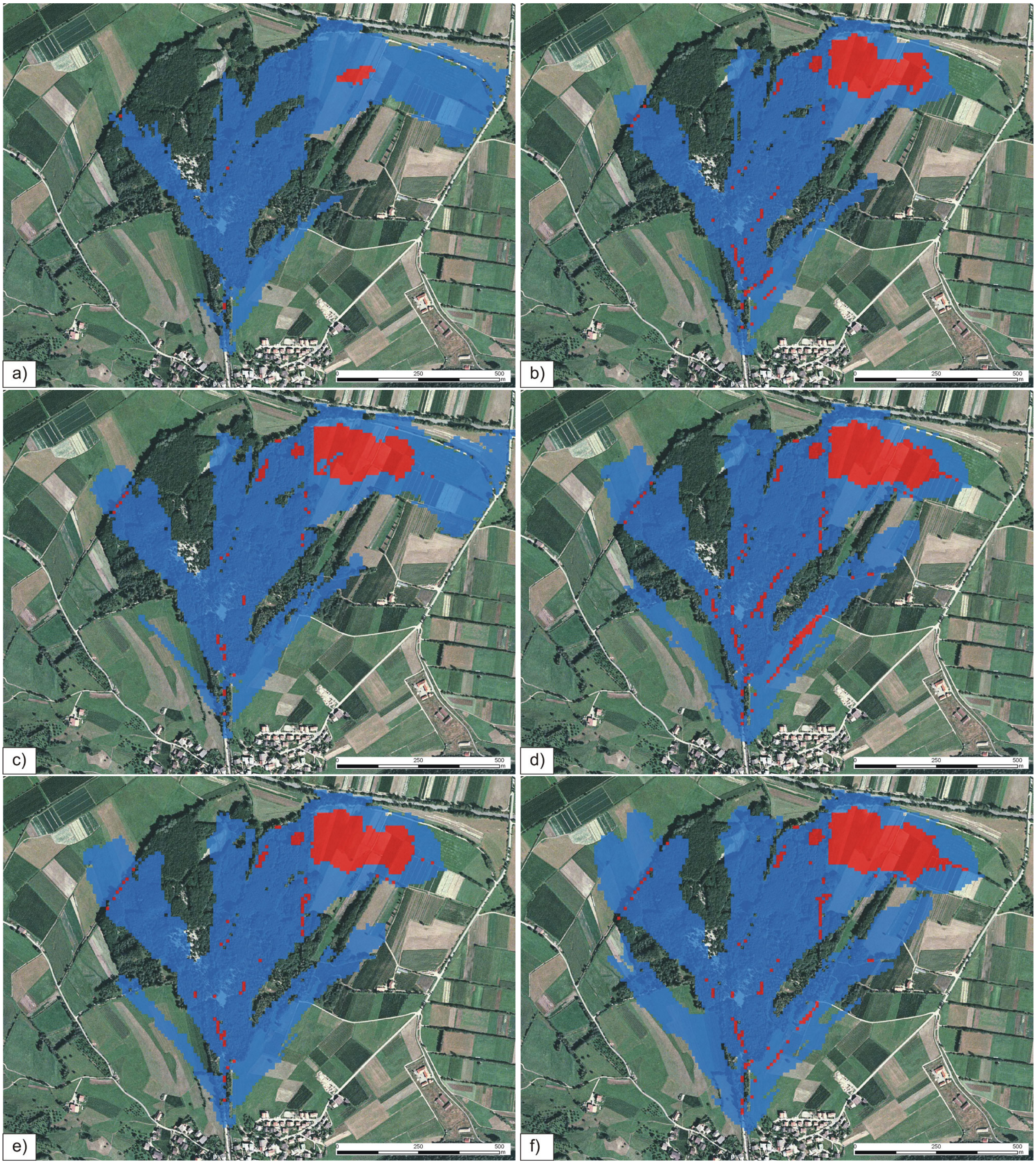


Fig. 14. Changes in flow depths and affected area of the debris flow processes of the Rio Cengles/Tschenglser Bach torrent. The maps show the classified flow depth following the guidelines for hazard zone mapping (Autonome Provinz Bozen – Südtirol, 2006). Flow depths from 0 to 1 m are shown in blue, flow depths greater than 1 m are shown in red. Critical shear stress parameter of 400 Pa. **(a)** Flow depths for a design event with a return period of 30 years (scenario 2000). **(b)** Flow depths for a design event with a return period of 30 years (scenario +20%). **(c)** Flow depths for a design event with a return period of 100 years (scenario 2000). **(d)** Flow depths for a design event with a return period of 100 years (scenario +20%). **(e)** Flow depths for a design event with a return period of 300 years (scenario 2000). **(f)** Flow depths for a design event with a return period of 300 years (scenario +20%).

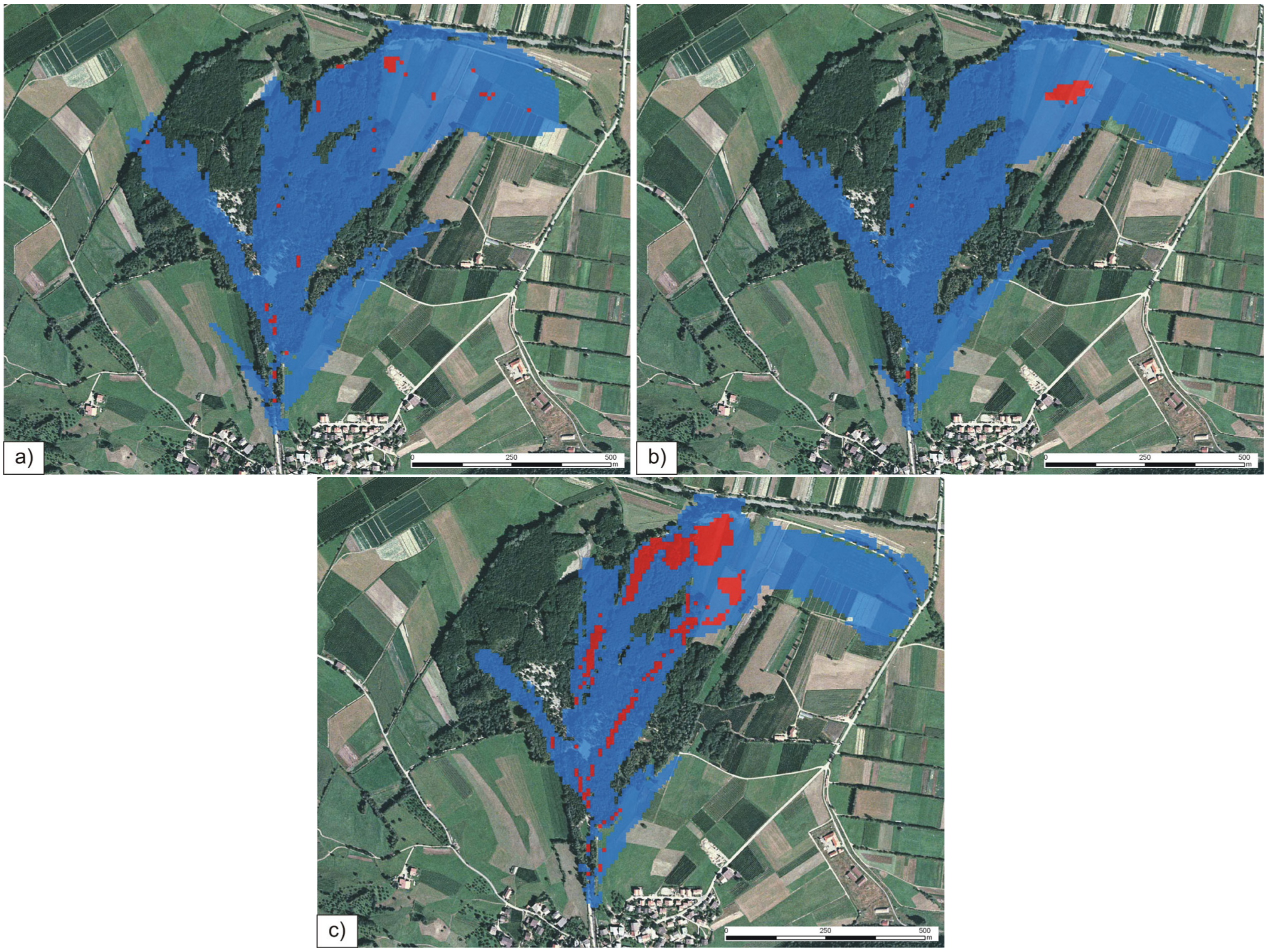


Fig. 15. Variations in flow depth and extent of a design event with a return period of 30 years (actual climate conditions) using different input parameters for the critical shear stress. **(a)** Flow depths for a design event with a return period of 30 years (scenario 2000). Critical shear stress parameter of 200 Pa. **(b)** Flow depths for a design event with a return period of 30 years (scenario 2000). Critical shear stress parameter of 400 Pa. **(c)** Flow depths for a design event with a return period of 30 years (scenario 2000). Critical shear stress parameter of 800 Pa.

remarkable impacts on the natural hazard situation (process intensities). The calculated increase of discharge due to the assumed increase in rainfall intensity showed a significant accentuation of the already existing weak points in the protection structures and the resulting hazard situation. The modelling results showed a remarkably increase in the flooded areas and an increase in flow depths. The hazard zones changed one "level" of hazard classification. Generally, the "yellow" zones delineated on the basis of the actual climate conditions tended to become "blue" zone. This could lead to significant restrictions for land use. The study demonstrated that already known weak points in risk reduction systems as protection structures in future will become more important in risk management activities. This means that the stress-strain behaviour of these weak points in cases of discharges exceeding the channel capacity must be studied. The knowledge about the behaviour of protection structures in loading case could provide a decision base for the elaboration of and the training of crisis management plans.

The potential effects of changed input parameters as the precipitation intensity to the extent of the hazard zones are not negligible for land use planning purposes. Usually, the hazard assessment of floods is based on the statistical analysis of relatively short data series for precipitation and discharge measurements. As shown in this case study, the analysis of the flood processes bases on a data series of about 31 years. Because of the curtness of the available data series, the calculated intensity values for the future design rainfall event (+20%) representing the future climate conditions (2050–2100) are laying within the 95% confidence interval of the data series representing the present climate conditions. Thus, the assumed future changes in the input parameter “precipitation intensity” lay within the uncertainty of the methods used today for the delimitation of the hazard zones. Thus, the consideration of the uncertainties laying in the methods used for the elaboration of hazard zone maps would provide a useful instrument for the consideration of potential future climate conditions in sensitive catchments.

The case study of the Rio Cengles/Tschenglser Bach torrent confirmed the hypothesis that the bed load transport capacity of torrents eroding older deposits increases with a potential increase in rainfall intensity. Due to the unlimited predisposition of mobilizeable material for debris flows, the process intensity of these torrents increases with the increase of bed load transport capacity because of higher discharges. The changes in process intensity in the deposition area of the debris flow are remarkable, but are lying within the uncertainties due to mostly poorly known process characteristics and models. The ranges of the modelling results due to changes in the input parameters of rheology and critical shear stresses of the debris flow simulation model exceed the ranges of the modelling results due to changes in the input parameter for rainfall intensity (Fig. 15).

The case study showed that possible effects of climate changes are not relevant for torrents that have been systemized with remarkably efforts and where the runout and deposition areas of the torrential processes have been kept free from settlements and infrastructures. Nevertheless, the analyses showed that an assumed increase of rainfall intensity lead to a nonlinear increase of the process intensities. Especially the volume transported by debris flows due to the increase in discharge and transport capacity increased remarkably when considering possible future climate conditions. This lead to the conclusion that the sediment management in alpine torrents will meet future challenges. In future, the costs for maintenance of existing protection structures will increase due to higher deposition volumes and a higher frequency of removal of debris flow deposits from sediment retention basins. Thus, cost-benefit analyses made within the planning of new protection structures must consider the future higher operating expenses.

The study showed that an increase in the intensity and frequency of flood and debris flow hazards has to be expected as a consequence of climate changes in sensitive catchments. But, the effects of these changes in the hazard situation to the risk situation depend also on other factors in the risk equation. The future changes in the extent of the damage potential and the vulnerability of endangered objects to natural hazard processes would also influence the future risk potential. Thus, the consideration of impacts of climate changes in natural hazard and risk management must be made using a holistic approach combining all the available instruments and possibilities from risk prevention to land use planning and crisis management activities.

The conceptional approach for assessing the impacts of climate changes on risks showed that especially the factor of the vulnerability mostly unconsidered in risk analyses points out the uncertainties in this assessment. But, the consideration of this risk factor opens new possibilities for risk reduction. With the reduction of the vulnerability of endangered buildings against the dangerous processes, a remarkable increase in the hazard potential as an impact of climate changes must not stringently conduct in an increase in risk.

Appendix A

Table A1. Types of Alpine torrent catchments.

catchment type	ID decision tree	Description
WB01	082	Higher located mountain torrent catchments with minor bed load source areas, mainly recent deposits.
WB02	146	Higher located mountain torrent catchments with minor bed load source areas, mainly recent deposits. Important areas affected by permafrost degradation or glacier retreat.
WB03	098	Higher located mountain torrent catchments with major bed load source areas, mainly recent deposits.
WB04	162	Higher located mountain torrent catchments with major bed load source areas, mainly recent deposits. Important areas affected by permafrost degradation or glacier retreat.
WB05	084	Higher located mountain torrent catchments with minor bed load source areas, manly older deposits.
WB06	148	Higher located mountain torrent catchments with minor bed load source areas, manly older deposits. Important areas affected by permafrost degradation or glacier retreat.
WB07	100	Higher located mountain torrent catchments with major bed load source areas, manly older deposits.
WB08	164	Higher located mountain torrent catchments with major bed load source areas, manly older deposits. Important areas affected by permafrost degradation or glacier retreat.
WB09	088	Higher located mountain torrent catchments with minor bed load source areas and active landslides.
WB10	152	Higher located mountain torrent catchments with minor bed load source areas and active landslides. Important areas affected by permafrost degradation or glacier retreat.
WB11	104	Higher located mountain torrent catchments with major bed load source areas and active landslides.
WB12	168	Higher located mountain torrent catchments with major bed load source areas and active landslides. Important areas affected by permafrost degradation or glacier retreat.
WB13	083	Lower located mountain torrent catchments with minor bed load source areas, mainly recent deposits.
WB14	147	Lower located mountain torrent catchments with minor bed load source areas, mainly recent deposits. Important areas affected by permafrost degradation or glacier retreat. Not existing!
WB15	099	Lower located mountain torrent catchments with major bed load source areas, mainly recent deposits.
WB16	163	Lower located mountain torrent catchments with major bed load source areas, mainly recent deposits. Important areas affected by permafrost degradation or glacier retreat. Not existing!
WB17	085	Lower located mountain torrent catchments with minor bed load source areas, manly older deposits.
WB18	149	Lower located mountain torrent catchments with minor bed load source areas, manly older deposits. Important areas affected by permafrost degradation or glacier retreat. Not existing!
WB19	101	Lower located mountain torrent catchments with major bed load source areas, manly older deposits.
WB20	165	Lower located mountain torrent catchments with major bed load source areas, manly older deposits. Important areas affected by permafrost degradation or glacier retreat. Not existing!
WB21	089	Lower located mountain torrent catchments with minor bed load source areas and active landslides.
WB22	153	Lower located mountain torrent catchments with minor bed load source areas and active landslides. Important areas affected by permafrost degradation or glacier retreat. Not existing!
WB23	105	Lower located mountain torrent catchments with major bed load source areas and active landslides.
WB24	169	Lower located mountain torrent catchments with major bed load source areas and active landslides. Important areas affected by permafrost degradation or glacier retreat. Not existing!

Table A2. Types of torrential river catchments.

catchment type	ID decision tree	Description
WF01	082	Higher located torrential river catchments with minor bed load source areas, mainly recent deposits. Limited susceptibility to surface runoff.
WF02	146	Higher located torrential river catchments with minor bed load source areas, mainly recent deposits. Increased susceptibility to surface runoff.
WF03	098	Higher located torrential river catchments with major bed load source areas, mainly recent deposits. Limited susceptibility to surface runoff
WF04	162	Higher located torrential river catchments with major bed load source areas, mainly recent deposits. Increased susceptibility to surface runoff.
WF05	084	Higher located torrential river catchments with minor bed load source areas, mainly older deposits. Limited susceptibility to surface runoff
WF06	148	Higher located torrential river catchments with minor bed load source areas, mainly older deposits. Increased susceptibility to surface runoff.
WF07	100	Higher located torrential river catchments with major bed load source areas, mainly older deposits. Limited susceptibility to surface runoff
WF08	164	Higher located torrential river catchments with major bed load source areas, mainly older deposits. Increased susceptibility to surface runoff.
WF09	088	Higher located torrential river catchments with minor bed load source areas and active landslides. Limited susceptibility to surface runoff
WF10	152	Higher located torrential river catchments with minor bed load source areas and active landslides. Increased susceptibility to surface runoff.
WF11	104	Higher located torrential river catchments with major bed load source areas and active landslides. Limited susceptibility to surface runoff
WF12	168	Higher located torrential river catchments with major bed load source areas and active landslides. Increased susceptibility to surface runoff.
WF13	083	Lower located torrential river catchments with minor bed load source areas, mainly recent deposits. Limited susceptibility to surface runoff.
WF14	147	Lower located torrential river catchments with minor bed load source areas, mainly recent deposits. Increased susceptibility to surface runoff.
WF15	099	Lower located torrential river catchments with major bed load source areas, mainly recent deposits. Limited susceptibility to surface runoff
WF16	163	Lower located torrential river catchments with major bed load source areas, mainly recent deposits. Increased susceptibility to surface runoff.
WF17	085	Lower located torrential river catchments with minor bed load source areas, mainly older deposits. Limited susceptibility to surface runoff
WF18	149	Lower located torrential river catchments with minor bed load source areas, mainly older deposits. Increased susceptibility to surface runoff.
WF19	101	Lower located torrential river catchments with major bed load source areas, mainly older deposits. Limited susceptibility to surface runoff
WF20	165	Lower located torrential river catchments with major bed load source areas, mainly older deposits. Increased susceptibility to surface runoff.
WF21	089	Lower located torrential river catchments with minor bed load source areas and active landslides. Limited susceptibility to surface runoff
WF22	153	Lower located torrential river catchments with minor bed load source areas and active landslides. Increased susceptibility to surface runoff.
WF23	105	Lower located torrential river catchments with major bed load source areas and active landslides. Limited susceptibility to surface runoff
WF24	169	Lower located torrential river catchments with major bed load source areas and active landslides. Increased susceptibility to surface runoff.

Table A3. Types of river catchments.

catchment type	ID decision tree	Description
FL01		Higher located alpine river catchments. Limited susceptibility to surface runoff.
FL02		Higher located alpine river catchments. Increased susceptibility to surface runoff.
FL04		Lower located alpine river catchments. Limited susceptibility to surface runoff.
FL02		Lower located alpine river catchments. Increased susceptibility to surface runoff.

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