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NATURAL HAZARDS REPORT

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CHAPTER 1

ASSESMENT OF HISTORICAL PROCESSES INVOLVING NATURAL HAZARDS

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1. FLOODS – HISTORICAL PROCESSES REGARDING CLIMATE ISSUES

1.1 Data concerning floods in the Alps

Floods are relatively well observed in both time and space. Monitoring and observation networks are implemented along most of the alpine and peri-alpine rivers. The Alps represent an important part of the big European rivers catchment's area. Indeed, 20% of the Rhône waters and 67% of the Rhine waters originate in the alpine area. Rivers like the Rhône and the Rhine have quite long flow measure chronicles. Furthermore, historic reconstructions (like the one of Pfister in Switzerland) can give an idea of the past activity for the period preceding instrumental records.

1.2 Flood sensitivity and links with climate

The link between climatic parameters and river floods is obscured by many human factors (this is even more perceptible than for torrential events). Land-use changes greatly modify the surface flows and the stream. One can say that today there are no more catchment's areas in the Alps with "natural" flow processes.

The water used for agriculture also represents an important part in the flow balance. Hydraulic works can also have strong influences on river characteristics. Dams radically change the flow patterns, whilst protective buildings and the micro power plants represent "noises" in frequency and intensity analyses.Moreover, "hazard-reducing" measures (dikes, protection forests, etc.) were implemented in the first half of the 20th century, while "hazard-aggrieving" measures (ground waterproofing, concrete banks, etc.) have generally increased in the second half of the 20th century.

The following is the hypothesis generally proposed: in a warmer climate, the situations that could lead to floods would increase (with the postulate that with more energy in the climatic system, the water cycle would be enhanced).

The assumption that precipitation would increase for some part of the year and decrease for other parts of the year is based on the same hypothesis. The hypotheses for floods propose that their evolution should follow the evolution of precipitation. These suppositions do not take into account buffer effects (*e.g.* snow and vegetation cover, dams…) which attenuate the effects of precipitation in large catchment's areas. These buffer effects are far more limited in regards to torrents and their reaction to precipitations (and their evolution) is faster.

1.3 Observed impacts of climate change on floods

Flood intensity: On the world scale, around 70% of rivers flows do not show any significant trends related to climate change. When these trends are significant, they are divided equally between the increase and decrease of flood volume. In France, different studies converge on the fact that there are no significant trends concerning the flood volumes since the mid 20th century. These findings are also valid for Central Europe (Elb and Oder rivers).

Data and study results concerning the other countries of the Alps have not been integrated in the database because they were not available in literature. However, in Southern Germany, the examined runoff time series demonstrate regional increase in floods runoff for some stations in the last 30-40 years; but no significant changes were detected when examining the annual series for 70 to 150 years time series duration.

Flood frequency: An increase in the frequency of « extreme » floods has been observed over the past 20 years in the Alps, compared to the 20th century mean. For example, significant floods hit Switzerland in August 1987, September 1993 and October 2000, the Ticino in 1978, 1987, 1993 and 1994. But this flood increase seems to remain within the natural range of variability. The same kinds of conclusion have been proposed for floods in Central Europe (Oder and Elbe). In France, statistical studies do not show any significant flood frequency increase. In Southern Germany, the KLIWA project stated that the winter floods frequency increased since the 1970s with the exception of Southern Bavaria (*i.e.* North edge of Alps).

Flood intensity/frequency and seasonality: An increase of summer flow for rivers fed by glaciers, due to increased glacier melting, has been observed in the Alps, with favourable impact (on short time scale) on low waters, but no direct impact on floods. In Southern Bavaria, the KLIWA project stated that monthly runoffs during winter time are higher since the 1970s (compared to preceding values, available since 1931).

2. DEBRIS FLOWS AND TORRENTIAL FLOODS – HISTORICAL PROCESSES REGARDING CLIMATIC ISSUES

2.1 Data concerning torrential events

Debris flows and other torrential events are relatively difficult to observe. The same is true of the predisposition, triggering and aggrieving factors of the torrential events. There are insufficiencies in the rain cover network, i.e. a precipitation measure network that is adapted to the torrential phenomenon. With the exception of some experimental basin catchment’s areas, the measure stations are rarely located in the close vicinity of the hazard zones and the data have to be extrapolated from distant stations.

The precipitation data provided by the meteorological stations also have limits when trying to assess the link between torrential events and climatic parameters. Indeed, the significant precipitation gradient on the mountainous relief makes the data from permanent measure stations located at the piedmont or valley floor unusable. For example, during the August 2005 floods in the Belledonne massif (France), 278 mm of rain was been recorded in 48 hours at the La Pra refuge (2100 m a.s.l) whilst only 32 mm was recorded at the Versoud automatic station (220 m a.s.l).

To correctly assess the meteorological situations associated with the triggering of torrential events in a particular location, it would be necessary to have measure stations in these locations or at least to have a network representing the massif with a good altitudinal distribution.

The implementation of automatic flow monitoring station is not really possible as these installations would most likely be carried away during each torrential flood. Even direct observation during the events is difficult as it is hard to correctly estimate torrent flow during a flood. However it is easier to evaluate the carried materials volume, especially coarse debris (*e.g.* those exceeding 1 meter in diameter). Automatic monitoring systems exist in Switzerland but they are used to give the alert and cannot provide instrumental data that could be used for studying the events.

The torrents have a very punctual observation. In France, these observations are realised on the field by the RTM service (Special Office for the Restoration of Mountain Soils) in the Alps and the Pyrénées. These specific studies of some torrential catchment areas usually provide long event chronicles but with the difficulties mentioned above, especially the concerning volume estimation.

This does not mean that no data exists for torrents and associated natural phenomena, but the data are too heterogeneous or too rarely synthesised at the regional scale to propose a complete analysis of the evolution of torrential events.

2.2 Debris flow sensitivity to climate

Fluctuations in precipitation amount can have an influence on torrential events. Debris flows are triggered above all by violent water release on areas where materials are available that will potentially be carried away by the rush of water. The threshold values for the triggering of debris flows can be very different from one massif to another, and even between two hazard areas within the same massif. This violent release of water can be characterised as follows:

- Spring / beginning summer thunderstorms (May, June and July) with very confined and short (1 to 4 hours duration) events but at a period when the mountainous catchment's areas are still moist from the recent snow melting.
- Generalised autumn events (end August, September, October) when the water is falling on drier ground, but with much intensity, longer duration (6 to 18 hours) and wider area. The autumn events show more intensity due to their origin, the Mediterranean Sea is warmer during this period of the year.

At Ritigraben (Wallis, Switzerland), it has bee observed that the precipitation events that can lead to debris flows have increased during the last three decades. However, the precipitation data available are at the daily scale while for a more precise assessment, hourly precipitation data would be required. Indeed, hourly precipitation intensity is an important parameter, and for a given daily precipitation value, the hourly precipitation distribution can vary greatly.

If the heavy precipitation occurrence is a decisive factor in the triggering of debris flows, the material availability is another. These two parameters are the main debris flow factors that could be influenced by new climatic conditions. In some rare cases, glacial events with liquid water release (glacial lake outburst flooding, glacial water pocket, and even sérac falls) can also trigger debris flows with significant volumes.

Many hypotheses propose links between permafrost degradation and an increase in debris flows intensity and frequency. The degradation of frozen grounds concerns the periglacial area[1] in its entirety. Permafrost thawing diminishes the cohesion inside already unstable or metastable structures and could potentially increase the future material availability for debris flows. Glacier retreat also exposes large amount of freshly exposed materials presenting very low cohesion.

All these phenomena that could lead to debris flows are potentially influenced by climate change, through changes in the freezing/defreezing cycles, changes in the heavy precipitation seasonality and frequency, changes in glaciers patterns and through changes in the available materials for debris flows triggering.

Debris flows and mud flows are phenomena characterised by very significant spatial and time variability. This significant variability leads to difficulties in assessing the impact of climate change on these natural events.

2.3 Observed impacts of climate change on debris flows

Debris flow intensity / frequency: Despite the important number of hypotheses proposing an increase in debris flow intensity with climate change, no trends have been observed or modelled. The available studies mention a decrease in the occurrence of debris flows. Thus, the debris flow frequency in the Swiss Wallis seems to be the lowest for the last 300 years and a significant decrease in the number of debris flows has also been observed since the mid 1970s in the Écrins and Dévoluy massifs (France).

The evaluation of events considered as «extreme» when they occurred (this is especially true concerning the Ritigraben torrent in Switzerland in 1987 and 1993) has been moderated by recent publications. Early analyses which interpretated these events as the first signs of climate change incidence have been attenuated because further investigations on the site showed that such intense events occurred with the same frequency in the past.

Debris flow seasonality: Debris flows mainly occur during summer time, generally between June and October. A seasonal shift has been observed at Ritigraben where the debris flow season shifted from June/July/August to August/September. The authors interpret this seasonal

[1] Area where freezing/defreezing and snow cover alternation play a predominant role

change as a consequence of the temperature increase at high altitude and of permafrost degradation (to be confirmed).

Debris flow localisation: An altitude increase has been observed in the triggering area of debris flows for some massifs, such as the Ecrins (France), where their altitude rose by more than 100 m between 1952 and 2000. The triggering areas located under 1800m a.s.l. have remained inactive since 1976. But no variations have been observed above 2200 m a.s.l. The temperature increase and the decrease in freezing days are supposed to explain these altitudinal shifts. Another study at the Mont Rose, also mentioning a spatial shift proposes glacier retreat as an explanation.

Nevertheless today, no changes in debris flow activity directly caused by changes in the available materials volume in these areas have been detected. However, regarding the limited number of studied sites, and the fact that studies do not focus on the material availability, this does not mean that no changes have yet occurred.

3. AVALANCHES– HISTORICAL PROCESSES REGARDING CLIMATE ISSUES

3.1 Data concerning avalanches in the Alps

Past avalanche activity reconstructions are realised by using historical documents reporting damages to buildings and inhabitants, some of these chronicles date back to the 16th century. However this kind of analysis cannot be used to assess the evolution of natural events because only catastrophic events, which led to damages, are reported and detailed. Some dendrochronology and lichenometry techniques have also been used to characterise past avalanche activity in a very precise location. These techniques are still being developed and many limits still exist; the limited number of available studies hinders a critical view of the method used. Some problems concerning the time calibration can also be found.

Furthermore, even if avalanche activity can be reconstructed for a precise location using these techniques, the link with climatic parameters is not easy to discern. Even if it is possible to assess the link scientifically, the researcher must extrapolate data from meteorological stations often located quite far from the observation site.

Avalanche observation is compiled in avalanche atlases, data bases which are often maintained by the forest services or their equivalent in the alpine arc. This observation work is done from identified avalanche locations on maps.

The technicians observe the events and describe the characteristics using a data form; all these data forms represent a data base describing the avalanche activity for the monitored avalanche area.

Some cooperation networks with ski resorts provide information about avalanche activity in the ski resort area or in its vicinity. The data analysis is not able to propose a clear evolution of the avalanche hazard and even less to provide links between avalanches and climatic parameters.

3.2 Avalanche data in France

The « Enquête Permanente sur les Avalanches » (EPA) started around 1900 in Savoy and has been carried out systematically on the French mountain ranges since 1965, leading to a data base which now includes over 70 000 events. For a long period, this monitoring was dependent on the initiative and good will of the ONF (National Office of Forestry) personnel and particularly the RTM services.

Since 2002, the « Ministère de l'Écologie et du Développement Durable » (today MEDAD) has been willing give an official frame for this action (following one recommendation of the back analysis commission set up after the catastrophic avalanche of Montroc in 1999). A protocol has been developed so that the information is homogenous for all the sites: the observation is always conducted from the same location, indications on the map help the observer to estimate the event's magnitude and the periods without avalanche activity are also detailed not to be considered as period without observation. All theses recommendations are detailed in an instruction book.

The Snow-Meteorological Network was implemented in the 1980s through cooperation with Météo-France. This network provides daily information on avalanche activity in ski resort areas and their vicinity during the tourism period. These data are not exhaustive in terms of area covered or in terms of time covered. They are of very poor quality when the meteorological conditions do not enable the personnel to make direct observations (*e.g.* because of fog).

Despite the importance of the data collected and its compilation within a homogeneous data base, it does not represent a systematic and instrumental chronicle of avalanche activity. The information is limited to certain areas and even to particular periods of time.

3.3 Avalanche sensitivity and links with the climate

No complete model exists today to assess the predisposition, the triggering and the flow of avalanches, but some partial models have been developed. In France, software have been developed by Météo-France to estimate the snow cover (including wind transport and metamorphosis) and its stability on a slope and by the Cemagref to calculate the avalanche flow and limits of propagation.

Avalanche characteristics (stopping distance, volume in movement, etc.) depend not only of the quantity of available snow pack, but also of the snow, conditioning different types of avalanches. Fresh snow avalanches (aerosol) are almost independent of the local topography during their propagation, contrary to wet-snow or snow-slab avalanches that are extremely sensitive to relief details. Vegetation cover also plays a role for the triggering of slab avalanches. Nevertheless, all avalanches are linked to the existence of snow and a possible reduction in snow cover (both in height and duration) or the elevation of the snow/rain limit will have direct consequences on avalanche activity. However, the mean climatic trends which are based on the most efficient climate model currently available are not sufficient to predict the future evolution of avalanche activity.

Indeed, an avalanche often results from the combination of an extreme meteorological situation (massive snow falls, intense melting) and of an already significant existing snow cover. It is therefore necessary to know the evolution of such extreme meteorological situations to be able to assess the evolution of avalanche activity.

But the understanding and integration of extreme meteorological events into the climatic model is still in process. Furthermore, trends for each altitude have to be characterised since avalanches often concern a wide range of altitudes. Thus it is very important to identify the trends for the triggering area, for the flow area and for the stopping area.

All these factors are obstacles to providing a direct link between avalanche activity and climatic parameters on one hand and between avalanche activity and snow cover on the other.

Even with good snow cover observations showing clear trends for its evolution and the existence of good modelling of snow cover evolution in a warmer climate, this information would not be sufficient to assess potential avalanche activity evolution. Some hypotheses can be proposed but they encounter the limits mentioned above.

Some publications have also studied the possible link between avalanche activity and large scale climatic circulations such as the North Atlantic Oscillation, but no links have been found.

Considering the land use changes and the avalanche protection policy, it is very likely that any change in forest cover, or the implementation of active and passive protection measures would have a far greater impact than the one potentially produced by climate change. Similarly to floods, avalanches are highly monitored (in the critical area) and many prevention/protection measures exist. All theses measures represent “noise” in the signal of the natural event itself, making its interpretation more difficult.

Avalanches are chiefly governed by short-term meteorological situations (periods of a few days), while climatic studies are more concerned with long-term trends and mean values. Furthermore, the data samples for avalanches are not prolonged enough to observe a statistically significant evolution of the natural event. Indeed, contrary to floods, avalanches are very punctual events, both in terms of time and space. The data are not available every year and for every avalanche location.

The data deficit is a crucial problem for the question of avalanche evolution. Methods aiming to account for these insufficiencies (using automatic monitoring with seismic captors or satellite data for example) are currently under development or test.

3.4 Observed impacts of climate change on avalanches

The climate does not seem to have evolved enough yet to really have consequences on the avalanche activity. Indeed, no trends have been observed considering the frequency, the intensity, the seasonality or the localisation of the avalanche in the Alps.

The catastrophic avalanche situations, such as the one that hit the Alps in 1999, are the consequences of extreme snow falls. Such situations are encountered around once each ten years and no changes concerning this kind of situations have been detected so far.

4. MASS MOVEMENTS– HISTORICAL PROCESSES REGARDING CLIMATIC ISSUES

4.1 Data concerning mass movements

There are many data base in the Alps that inventory mass movement. In France, there are two main databases. One is the BDMvt, held by the BRGM (Office for geologic and mining risks). In this data base, the mass movement (landslides, rock falls, mudflows, etc.) characteristics are recorded. For each movement data form, the precise location (both geographic and administrative data), the date, the volume, the width and the possible damages are detailed. However, all the parameters that could lead to these movements (geologic, precipitation, chemical, etc.) are not recorded. The second database is the RTM service data base, that is filled by the observations of forestry agents working on estate, communal or State lands.

In these data base, only the events leading to damages are generally recorded, contrary to systematic instrumental inventory (*e.g.* seismic monitoring data network). These data base are strongly influenced by the vulnerability evolution and thus need to be used with high caution in order to evaluate the natural event evolution.

These precise kinds of information are only available for experimental sites (“observatories”), monitored by laboratories or observatories. These sites have a good time cover but are limited geographically. An extrapolation based on these data for wider territories is not really possible as each movement is strongly conditioned by local parameters.

Radiocarbon dating methods enable the scientists to re-construct the temporal distribution of landslides for various locations in Europe during the Holocene. Some dendromorphology methods are also used to reconstruct the past rock fall activity by studying the impacts done by rock falls on trees. This kind of process is still under development and many limits still exist: the rock falling can impact only one tree, several trees or not at all. As it is impossible to determine, the scientists take the postulate that "each impact corresponds to a rock fall event". The impacts can make scars or "traumatisms" in the resin duct, but these signs are not easy to study.

Furthermore, the correlation test with climatic parameter are based on measures from very far meteorological stations (from some km to dozen of km). The limits are numerous and the proposed results have to be carefully considered.

4.2 Mass movements / Shallow landslides– historical processes regarding climatic issues

4.2.1 Shallow landslides sensitivity and links with the climate

Intense precipitation increase could lead to shallow landslides increase. The increasing number of landslides in the "Romandie" and Ticino canton (Switzerland) seems to be linked with the precipitation increases observed for two decades on these territories. The shallow landslides can also be impacted indirectly by climate change, trough the impacts on glaciers, permafrosts or forest fires. The glacier retreat and the permafrost degradation would lead to large area of slopes in unstable conditions (especially because of the cohesion loss due to the melting of ice particles in theses slopes). These voluminous material amounts could potentially become debris flows at high altitudes; this is even truer for the very steep slopes.

With a temperature increase, some hypotheses are also proposed concerning a possible re-colonisation of scree slopes because of longer vegetative period. The re-vegetation would enhance the slope cohesion. This stabilisation as a result of vegetation cover could also be limited by the appearance of acidifying species (such as Ericaceae s.l. on grassland) limiting the growing of plants with a wider roots system. The vegetation conditions can also be very harsh at high altitude and the re-vegetation in this case will be quite slow.

After forest fire event, the ground looses a great part of its protection that was previously provided by the vegetation cover. Furthermore, the fact they are very small particles (such as ash and coal) can play the rule of lubricant and would favour the surface erosion. All these conditions are aggrieving the aggressive effects of intense precipitation and could lead to more superficial mudflows. The forest fire multiplication (plausible in a climate change context) is a supplementary aggrieving factor for shallow landslide increase. This type of aggrieving circumstances has been observed after the forest fire in the Chamatte massif, the 6th of July 1982 (Alpes-de-Haute-Provence, France). The 18th of July, a thunderstorm occurred and reactivated slopes (considered as non active) leading to mudflows on the Angle village. However these ground conditions degradation is only temporary and after some years, the vegetation recolonises these slopes and provides again its protection effect. Similar features can also be observed after heavy storms, when wide parts of the forest cover are destroyed.

4.2.2 Observed impacts of climate change on shallow landslides

No observed direct impacts of climate change on shallow landslides are currently available in the referenced literature. However, indirect impacts via forest fires and storms might are often mentioned or locally observed, but the observations are limited both in terms of time series and geographical extent. Thus, despite the lack of significant trend, these indirect impacts have to be considered as potential emerging risks.

4.3 Mass movements / Deep landslides– historical processes regarding climatic issues

4.3.1 Deep landslides sensitivity and links with the climate

Deep landslides often occur on "dormant" landslides (e.g. Val Pola 1987). The assessment of such old inactive features as well as of slow creeping slopes is possible with geomorphological studies, but the forecasting of their reactivation is difficult to assess.

The annual precipitations and even pluri-annual means are proposed by different scientists as the key-parameter for the deep landslides, trough the influence of deep infiltrating waters and underground waters. Thus, any marked change in the precipitation pattern may have consequences on the deep landslide activity. Particular case: the slopes with stability controlled by foot erosion would be more sensitive to surface water runoffs linked with intense precipitation.

On the very long term, a dendrochonologic study has highlighted a link between climate and landslides activity in the Fribourg Pre-Alps (*e.g.* Hohberg and Falli-Hölli sites) where warm periods led to deep landslide activity increase in the Flysch area under 1500m a.s.l. This re-activation seems to be linked with the 0°C isotherm position. But these links between warm periods and deep landslides activity increase can not be extrapolated for the Alps.

4.3.2 Observed impacts of climate change on deep landslides

No observed impacts of climate change on deep landslides are currently available in the referenced literature.

4.4 Mass movements / Rock fall – historical processes regarding climatic issues

4.4.1 Rock fall sensitivity and links with the climate

Positive correlations between rock falls and the days with freezing/defreezing have been highlighted. But the link with precipitation has not been established. In France, a study on 46 rock falls in the Chartreuse and Vercors massifs has shown no correlation between rock falls activity and precipitation; but a correlation has been shown for the day with freezing/defreezing cycles. This link is valid for small to medium scale rock fall. For very large events (millions of cubic meters, e.g. Randa 1991), the importance of climatic factors becomes negligible in comparison geological patterns.

During the 2003 summer, many rock falls have been observed in mountainous area. This rock fall activity increase could be the consequence of permafrost degradation induced by very high summer temperature. The permafrost thaw depth reached values 10 to 50 cm deeper than the mean for the precedent 20 years. It is interesting to note that these instabilities occurred between June and August, *i.e.* not when the thawing phenomenon was at its deepest point but when the heat flow in the superficial layer was at its maximum. Many studies propose the hypothesis of a link between permafrost degradation and rock fall activity. This permafrost degradation may have consequences on the intensity, the frequency, the seasonality and the localisation of the natural event.

After the immediate response of the superficial permafrost layer to increased temperature, the lower limit of permafrost may rise in altitude and several instabilities may develop at high altitude where there are usually no freezing/defreezing actions. The penetration of freezing front in previously thawed materials may lead to important constraints trough the ice formation in cracks.

The forest and vegetation cover disappearing following forest fires would have potential consequences for the rock falls triggering and the rock stopping distance (forest protection effect): a forest fires multiplication (likely to happen in a climate change context) may be an aggrieving factor for the rock falls evolution. These negative consequences have been observed after the fire at Argentière-la-Bessée in 2003 (Hautes Alpes, France) and at the Néron, also in 2003 (Isère, France).

4.4.2 Observed impacts of climate change on rock falls

Rock fall intensity: A study using dendromorphology technique in the Swiss Pre-Alps did not show any intensity evolution for the rock fall activity in the studied area in the last decades.

Rock fall frequency: The rock falls frequency seems to have increased in the Swiss pre-Alps. Many rock falls events have been observed during the 2003 summer. But because of observation lacks, it is hard to determine if the rock falls during this scorching summer was higher than during a “normal” summer. A statistical study proposed that the occurrence probability of rock falls events is 2.5 higher for the days with freezing/defreezing effects than for the days without theses influences (evaluation for the Chartreuse and Vercors massif, France).

Rock fall localisation: During the 2003 heat wave, numerous rock falls have been observed in the north face in the alpine mountains. This increase frequency may be explained by more important permafrost surface in the north faces. A study on the Monte Rosa (Swiss Wallis) observed an altitudinal rise of the triggering area. This spatial shift has been explained (as for the debris flows) by glacier retreat.

5. GLACIAL HAZARDS – HISTORICAL PROCESSES REGARDING CLIMATIC ISSUES

The following parts are mainly based on the comment of C. Vincent from the Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE, Université Joseph Fourier, Grenoble), information collected in the GLACIORISK project and experience.

5.1 Data concerning glacial hazards

The last catastrophe due to a glacier in the Alps occurred in 1965, in Switzerland. The terminal part of the Allallin glacier tongue broke off and devastated the Mattmark dam building site (Swiss Wallis). As few glacier catastrophes occurred during the second half of the 20th century, the attention given to this hazard has decreased.

However, some potentially dangerous situations have existed in the Alps during the last few years, such as the pro-glacial Arsine lake (Hautes Alpes, France), the supra-glacial lake on the Rochemelon glacier (Savoie, France) or the Laggo Effimero on the Belvedere glacier (Piemonte, Italy).

The GLACIORISK program (2001-2003) aimed to propose a homogeneous data base concerning glacial hazards in Europe. This data base provides data forms for 166 alpine glaciers considered as "hazardous" and located in France, Switzerland, Austria and Italy.

The glaciers characteristics (length, altitude, type, surface, slope, orientation and localisation) are detailed as well as known glacial events that occurred in the past. But all the glacial events are not reported and the data quality is not homogeneous for all the events; some have been provided by technical services observers, other are quite old and based on various historical documents. Therefore, this data base, a unique piece regarding glacial hazards, does not allow glacial hazards evolution assessment.

Glacial water pockets are up to now impossible to observe and despite some attempts using teledetection, there are no data for this class of glacial hazard. Glacial lakes and séracs falls are observed punctually by research institutes (e.g. the French LGGE or the Swiss VAW - Versuchsanstalt für Wasserbau, hydrologie und glaziologie-) in experimental sites (which can also correspond to hazardous areas threatening human stakes).

These punctual observations enable scientists to develop models (especially a serac falls prevision model with a precision of 1-2 weeks range) and trends for some specific sites but general trends cannot really be proposed.

5.2 Glacial hazards / Glacial Lake Outburst Flooding – historical processes regarding climatic issues

5.2.1 "Glacial Lake Outburst Flooding" sensitivity and links with the climate

There are different types of glacial lakes, notably supra-glacial lakes, located on the glacier surface and pro-glacial lakes, located at the glacier front. The climatic conditions and glacier dynamics (indirectly and not exclusively influenced by climatic conditions and a potential temperature increase) explain these lake formations.

Pro-glacial lake occurrence is closely linked to glacier retreat. When the glacier retreats, moraines can become dams, thus creating pro-glacial lakes. These dams are often constituted with unstable materials and very low cohesion (some of these moraines can also be partially frozen). The over-digging ice free basin following the glacier retreat can be filled with liquid precipitation and the water released during the glacier and snow cover melting, eventually becoming a pro-glacial lake.

Pro-glacial lakes can also appear behind glacial rock bolts, *e.g.* at the Rhône glacier (Swiss Wallis). If the dikes bursting leading to floods are a threat, this is far less plausible for the lakes behind a rock bolt.

Supra-glacial lakes can also be the consequence of the glacier dynamic, as supposed at the Belvedere glacier in 2002. This lake is thought to be the consequence of the strong advance of this glacier since 2000[2]. The climatic conditions can also lead to the formation and extension of the supra-glacial lakes. This kind of lake needs further study to better understand the conditions that led to their creation as well as the method of safely draining the lake (uncertainties during the Rochemelon Lake draining concerning the ice channel behaviour during the operation).

Séracs falls in glacial lakes can also create waves (as the 50 cm wave observed at the Arsine pro-glacial lakes, 14th of September, 1996). These waves can potentially cause a dike to burst.

5.2.2 Observed impacts of climate change on "Glacial Lake Outburst Flooding"

No observed impacts of climate change on Glacial Lakes Outburst Flooding are currently available in the referenced literature.

5.3 Glacial hazards / Glacial water pocket – historical processes regarding climatic issues

5.3.1 Glacial water pocket sensitivity and links with the climate

The formation and the bursting of glacial water pockets (both intra-glacial and sub-glacial pockets) remain unknown processes. Liquid water flows inside glaciers are also quite unknown today. In the Mont Blanc massif, some water release and their consequences have been observed at the Trient glacier, at the Mer de Glace and at the Tête Rousse glacier (1995).

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[2] Even if glacier retreat is general, some particular glaciers can be advancing.

All these observations of liquid water release cannot yet be linked with clearly identified causes : they could be the consequence of accelerated melting of some part of the glacier, of the bursting of small glacial water pockets, of the flow of precipitation falling on the glacier or also of unknown intra-glacial liquid water flows.

5.3.2 Observed impacts of climate change on glacial water pocket

Considering the lack of knowledge mentioned above, the observation of glacial water pockets evolution is impossible to assess.

5.4 Glacial hazards / Sérac falls – historical processes regarding climatic issues

5.4.1 Sérac fall sensitivity and links with the climate

Sérac falls are quite a frequent phenomenon for glaciers and constitute a part of their natural ablation process. The link with climatic conditions is mainly indirect because the sérac falls are influenced by the glacier movements and dynamic, themselves influenced by climatic parameters. A glacier with a strong dynamic experiences frequent sérac falls.

A mean temperature increase would lead to an ablation increase and an accumulation decrease (unless the precipitation increase hypothesis for high altitude is confirmed and strong enough to counterbalance the effect of temperature). This would result in a negative mass balance and the glacier flow should decrease, as well as the sérac flows. This evolution should be experienced in the long term and the evolution of sérac falls for the next 20-30 is quite uncertain.

In some extreme cases, it is the whole terminal part of the glacier tongue that can break off from the glacier and fall downstream. This kind of phenomenon occurred, for example in 1949 at the Tour glacier (Haute-Savoie France) and in 1965 at the Allalin glacier. Hanging glaciers can effectively break off from their anchorage site if the “freezing conditions” at their base is no more garantied. The switch from a “cold” glacier thermal mode (the glacier sticks to the bed rock because of the low ice temperature) to a “temperate” glacier thermal mode (many liquid flows can lubricate the glacier at its interface with the bed rock) would thus be the main consequence of climate change affecting hanging glaciers and their stability. This is even more worrying because a warming of the cold glacier located at high altitude has been highlighted in the Alps. Some “hazardous” sites have been identified; Dôme du Goûter et Taconnaz (Haute Savoie, France where sérac falls on a voluminous snow cover lead to avalanches), Grandes Jorasses (Aoste, Italy) or Randa/Weisshorn (Swiss Wallis).

5.4.2 Observed impacts of climate change on sérac falls

Sérac fall localisation: A study done at the Monte Rosa (Swiss Wallis) has shown that more new sérac fall triggering zones have developed at higher altitude than were present before. This report is the only source mentioning a spatial shift of the sérac fall triggering zones and it is premature to draw general conclusions.

6. STORMS – HISTORICAL PROCESSES REGARDING CLIMATIC ISSUES

6.1 Data concering the storms

In France, there is no exhaustive inventory for the storms for the last centuries, the wind measures networks have been implemented only in the beginning of the 20th century. It is possible to use air pressure data, available since the end of the 18th century for thirty stations, to extrapolate the storm activity (this method seems to be very efficient). The exceptional events leading to important damages (and also kept in mind by the populations) are generally well documented. But these extreme and punctual events alone are not sufficient for a storm evolution assessment.

6.2 Storm sensitivity and links with climate

When the winds are stronger than 89km/h (corresponding to the 10 degree on the Beaufort scale), they are considered as "storm". Most of the storm hitting Europe form over Atlantic, between 35 and 70° latitude. These storms occur mainly during winter and autumn in Europe (especially between November and February). The winds are the direct consequences of pressure differences. The climate and global warming influence on storm activity remains unknown. The storm creation is closely linked to the barocline instability (which is preponderant in the depression formation). But the link between the North Atlantic Oscillation and the storm is blurred.

It is quite premature to propose a storm evolution assessment regarding the available knowledge and modelling.

6.3 Observed impacts of climate change on tempests

Tempest intensity (France): There is no significant trend for the intensity tempest evolution in France between 1950 and 2000.

Tempest frequency: There has been a slight tempest frequency increase over the North Atlantic during the 20th century, but the intensities events remained unchanged. In France, around 15 tempests are recorded in France each year. The interannual variability of the tempests is very important, for example, 25 events in 1962 against 7 in 1968. One on ten is usually considered as "strong" (*i.e.* at least 20% of the departmental stations record an instantaneous maximum wind above 100km/h), the frequency of such events is around 1.4 event/year over the last 50 years. There has been a slight decrease of the tempest number over the last 50 years in France, but this trend between 1950 and 2000 is not significant.

List of Acronyms

- **BRGM:** Bureau des Risques Géologiques et Miniers (Office for geologic and mining risks, France)
- **EPA:** Enquête Permanente sur les Avalanches (Permanent avalanche monitoring, France)
- **GLACIORISK:** Survey of extreme glaciological hazards in European mountainous regions
- **KLIWA:** Klimaveränderung und Konsequenzen für die Wasserwirtschaft (Climate change and consequences for water management, Germany)
- **LGGE:** Laboratoire de Glaciologie et de Géophysique de l'Environnement (Laboratory of glaciology and environmental geophysics, France)
- **MEDAD:** Ministère de l'Écologie, du Développement et de l'Aménagement durables (Ministry for ecology, sustainable development and landplaning, France)
- **ONF:** Office National des Forêts (National office for forest, France)
- **RTM:** Restauration des Terrains de Montagne (Mountain soils rehabilitation service, France)
- **VAW:** Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (Research institute for hydrology and glaciology, Switzerland)

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CHAPTER 2

COUPLING CLIMATE CHANGE AND HYDROLOGICAL MODELS TO CALCULATE THE DESIGN OF TORRENT CATCHMENTS

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1. INTRODUCTION AND AIM

Climate Change is expected to strongly influence the hydrological cycle with consequences also for extreme events regarding intensity and frequency. An increase in average daily precipitation sums is expected globally. Should these predictions also be valid for the alpine area, an increased number of floods and disastrous mud avalanches must be expected (e.g. Hohmann, 2003).

Although there are claims that an increase of extreme events already can be observed, it must be pointed out, that it is very difficult to prove such developments, because extreme events are rare and reliable statistics therefore hard to come by. This holds true for extreme precipitation events and even more so, because of the increasing complexity of influencing factors, for their impacts.

Assessment of future developments in consequence of climate change must be based on climate models and suitable precipitation-run-off models coupled to these. This means that reliable models are needed, suitable for the conditions of future climate and an adapted natural environment of vegetation and soils.

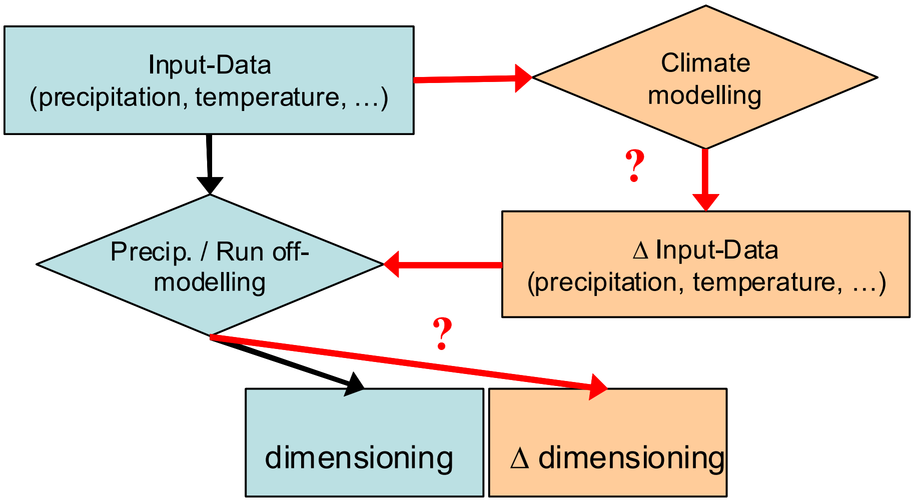
The Interreg III B Project ClimChAlp aims to analyse the possible impacts of climate change on society and natural hazards and to develop adaptation strategies for the Alpine Region.

Workpackage 5 (WP5) focuses on climate change and its consequences for natural hazards. One of the natural hazards considered in detail is run-off in torrent catchments. The present project aims to assess the suitability of hydrological models to calculate design events for torrent catchments under changed climate conditions and thus to answer such questions as:

- What impact does the expected climate change have on design events of torrents?
- What changes in input data for precipitation-run-off models are necessary when coupling them to climate models?
- Can climate models supply input data for precipitation-run-off models comparable to presently used data sets regarding temporal and spatial resolution?

It is expected that the quality of the results obtained by hydrological and run-off models strongly depends on the type of the model and on type and quality of input variables. An assessment of the sensitivity of hydrological models on the catchment and slope segment scale to different input parameters (precipitation, site factors, etc.) by varying the input parameters (climate parameters) needs to be made. Based on the results of such a sensitivity analysis it will be possible to find the model approaches best suited for the calculation of the hydrological impacts of climate change on alpine torrent catchments. In addition the analyses should indicate necessities for higher precision in hydrological models.

Figure 1: Impacts of climate change on design of torrents



The assessment of suitability of frequently used hydrological precipitation/run-off models for the calculation of the hydrological impacts of climate change on alpine torrent catchments is based on climate scenarios calculated by the Institute of Meteorology of the BOKU University of Natural Resources and Applied Life Sciences in the framework of the ClimChAlp Project.

2. METHODOLOGY

2.1 Torrents and Catchments

The digital register of torrents and avalanches in Austria encompasses 12.171 torrents. The largest (233 km²) and the smallest (0,4 hectar) catchment are found in the Tyrol. The average catchment size is around 4,7 km². Only 4 % exceed an area of 25 km². According to the scaling of catchments proposed by KLEEBERG et al. 1999 (Tab.1) the majority of Austrian torrent catchments are found in the meso scale.

Table 1: Scaling of torrent catchments

Micro scale	Meso scale	Macro scale
<0,01 km²	0,01 - 100 km²	> 100 km²

Source: KLEEBERG et al. (1999)

One of the first questions that need to be addressed in assessing the impacts of climate change on design discharge of torrent catchment areas is the definition of the design event. According to ETAlp (ETAlp, 2003) the design event is calculated based on a design storm and parameters characterizing the influence of the catchment. Boundary conditions relevant for the formation of run-off must be defined and a run-off formation model must be developed. The following table (Tab.2) lists relevant boundary conditions according to ETAlp.

Table 2: Relevant Boundary Conditions for the run-off formation to assess design discharges in torrent catchments (ETAlp 2003)

Boundary Condition	Sub-condition	Characterization
Precipitation	Intensity and Duration (and annuality)	convective heavy precipitation of short duration
		strong upslide precipitation of longer duration
		Transition Scenarios
	Development	block shaped
		increasing intensity towards the end
		DVWK-distributed
	Type	liquid (Rain)
		solid (Hail)
		solid (Snow)
System	Pre-event moisture	hydrophob (dry)
		sealed (frozen)
		unsaturated (moist)
		saturated (rained on, snow melt)
	(seasonal) management cycle	spring
		autumn
	Vegetation cover	current vegetation
		potential vegetation
		Human interventions (leveling,…)
Time of concentration	Influences	Not influenced by human action (channel)
		accelerated (artificial channel)
		delayed (Retention)
	Snow cover	Sponge buffer effect of the snow cover
Area	Spatial Extent of precipitation	Over the whole area
		Over parts of the area
	Intensity distribution over the area	undiminished (less than 10 km²)
		diminished (more than 10 km²)
	Direction of motion of precipitation field	With the direction of flow
		Against the direction of flow
		Across the direction of flow

Source:ETAlp, 2003

Climate change affects both, the design event and some of the boundary conditions. Within the framework of ClimChAlp these boundary conditions were analysed regarding

(1) the possible impact of climate change and

(2) the availability of qualitative and quantitative data on this influence from climate models.

The analysis was made for the macro- as well as the meso-scale of individual catchment areas.

2.2 Climate Change and Climate Change Models

Climate Change was anticipated by scientists long before it manifested itself with sufficient clarity in the meteorological data. Since the late 1960ies scientists have developed global climate models with increasing sophistication to provide plausible support for their warnings about climate change and its consequences. Since the late 1990ies meteorological data provided new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities (IPCC 2001), and interest in possible impacts of climate change increased. This created rising demand for data other than temperature, as a large part of possible impacts is influenced by precipitation, by radiation or e.g. by wind. And although these parameters are contained in every global climate model, the results in general are less reliable than those for temperature. It also helped to initiate and then speed up the development of methods to downscale global results to the regional and local level, as it had been shown that regional and local changes could differ significantly from global changes – in fact even the sign of change could, in some cases, be reversed.

Over the last decade, both, global climate model reliability and downscaling models have significantly improved. Yet, there are still a large number of uncertainties and possibly unknowns, as e.g. the unexpectedly rapid melting of polar ice recently demonstrated. Downscaling has become a powerful tool, but reliability in the case of small scale processes, especially if connected to precipitation events, is still low. Model results require very careful interpretation, taking understanding of the models applied and of meteorological processes into account.

The type of quantitative input needed for hydrological models is not supplied by global climate models – the intermediate step of downscaling to the regional and local scale is generally necessary, using either dynamical or statistical downscaling methods. Dynamical downscaling nests dynamical climate models of increasingly fine spatial resolution, using models with coarser grids to supply initial and boundary conditions. Statistical downscaling makes use of transfer functions, frequently altitude dependant, derived from climate observations of the past and grid point values of global scale climate models to enhance spatial resolution, simultaneously taking account of local influences not included in global climate models.

The methodologies of downscaling, their strengths and weaknesses are discussed extensively in Chapter 2 of the ClimChAlp Climate Change report and will not be repeated here.

Topography provides an additional challenge to climate modelling. Topography is generally smoothed in models, the degree of smoothing depending on the spatial resolution of the model. The higher the resolution, the steeper the slopes can become, and this can present an additional problem in modelling the dynamics. In general models are expected to produce more reliable results in flat terrain than in mountainous regions, but it must not be overlooked, that topography also influences many meteorological fields, and these fingerprints can be used to improve model performance. Environmental conditions such as e.g. frozen ground, snow cover or snow melt are strongly dependent on the topography, and should be reproduced in climate models or input in some other manner to be taken into account in hydrological models.

Downscaled climate models can be coupled to vegetation models to derive quantitative information on expected changes in the vegetation canopy (forest development, timberline, management changes, …). However, here too, reliability is still a problem and is expected to increase with growing experience.

3. CLIMATE FACTORS INFLUENCING RUNOFF

3.1 Precipitation

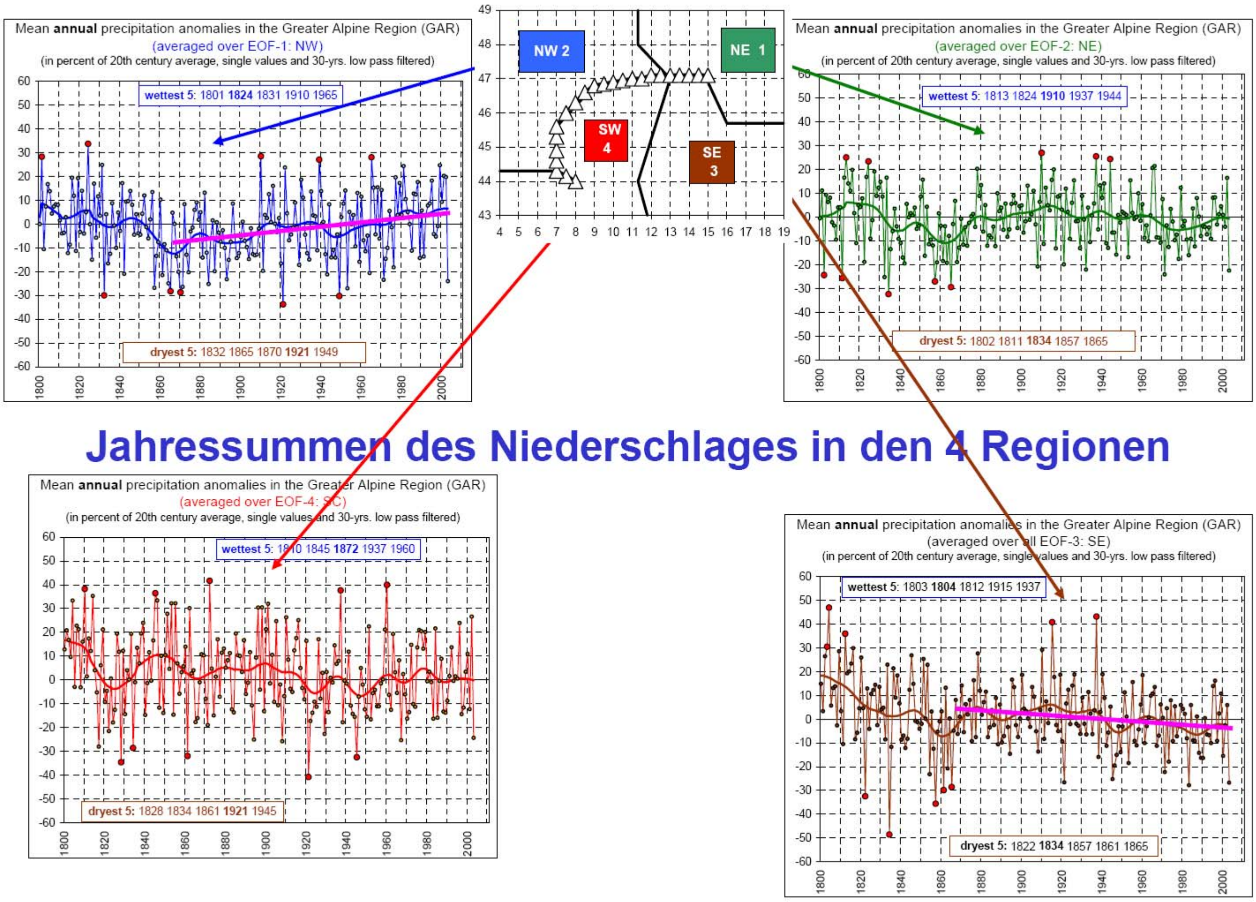
3.1.1 Changes in Precipitation: Intensity, Duration and Annuality

Temperature changes induce changes in the water cycle of the atmosphere. Saturation water pressure in the air increases with temperature (Clausius-Clapeyron´s Law) - the maximum water vapour contained in a volume of air increases by 8% for every degree Celsius of warming (Graßl, 2005). On the global scale, water vapour content in the atmosphere over oceans increased by 1,2% per decade over the last 15 years (IPCC 2007). In the past, the average life time of water in the atmosphere was 9 days, with about 40 days turn about time. With climate change and increasing temperature the water cycle is expected to intensify in spite of more or less constant evaporation potential of the land surface (Rahmstorf, 2006). This can imply changes in type, amount, intensity and duration of precipitation as well as frequency of extreme events.

3.1.1.1 Changes in average precipitation: precipitation sums and seasonality

The change signal in precipitation sums in the alpine region is much less pronounced than the temperature signal. Homogenized time series over the last 250 years of instrumental precipitation data for the Greater Alpine Area show diverging trends in four alpine regions (Brunetti et al. 2005; see Fig. 2). In the last century precipitation sums have decreased in the southern and eastern part of Austria, while they have remained constant or increased in the western and northern parts.

Figure 2: Changes in annual precipitation sums in four sub-regions of the Greater Alpine Region



Source: Brunetti et al. 2005

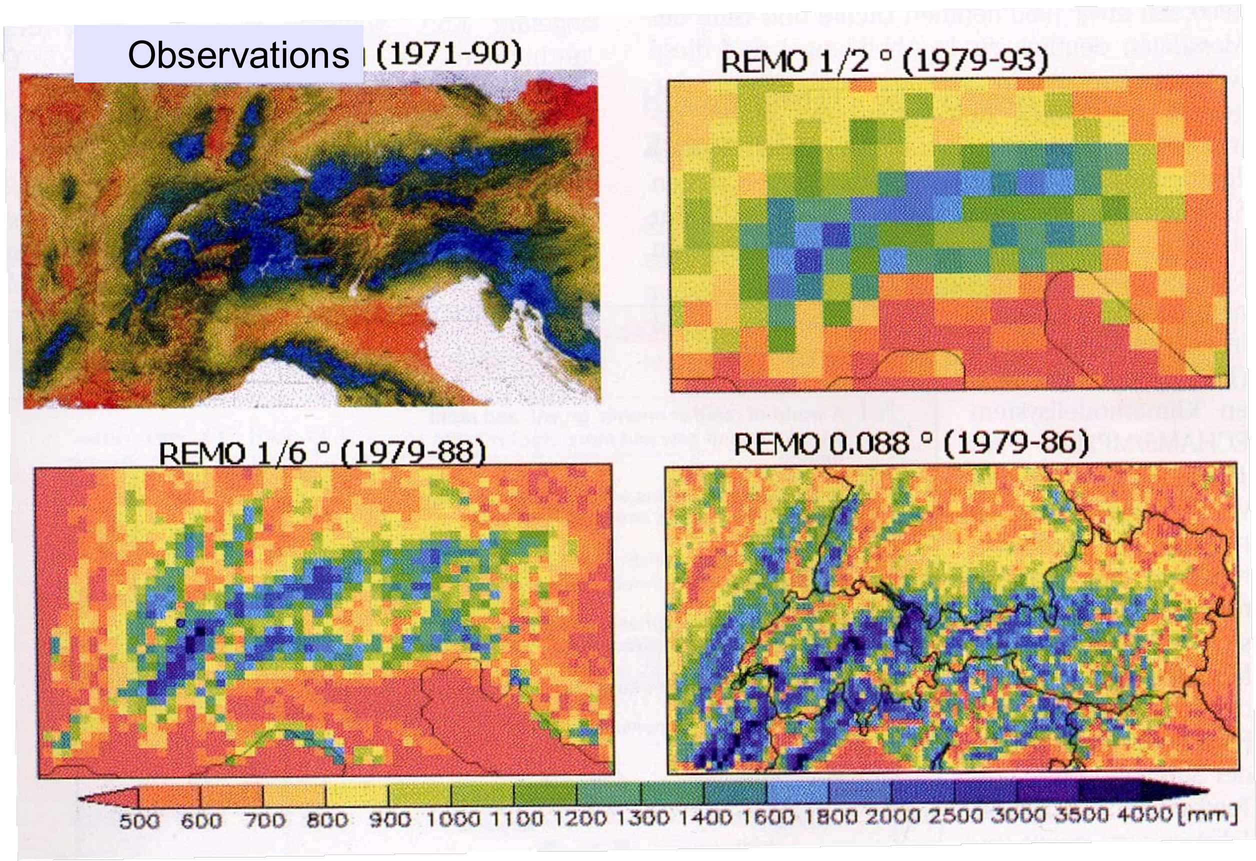
Statistically significant seasonal changes have been observed in parts of Europe. Graßl (2005) e.g. finds a decrease in precipitation during summer in southern Germany and southern France and accordingly expects an increase in the frequency of drought conditions. However, seasonal precipitation sums vary strongly, and significant long term trends are hard to find in past precipitation data.

Future climate change scenarios on the global and regional scale indicate significant precipitation increases in northern Europe (Scandinavia) and decreases in southern Europe (Mediterranean region). The Alpine Area is located in an area of transition, with overall decreases more likely than increases.

The spatial pattern of precipitation in the Alpine area depends to a certain degree on the spatial resolution of the downscaling model, as can be seen from the REMO results (Jacob 2007; fig. 3). Yet, on the whole, downscaled models in general indicate a decrease of precipitation in summer and an increase in winter. The REMO model runs based on the global climate scenario A1B e.g. show a decrease of 30-50 % in summer for the period 2071 to 2100 compared to the period 1961 to 1990. In winter precipitation remains unchanged or increases slightly (fig. 4).

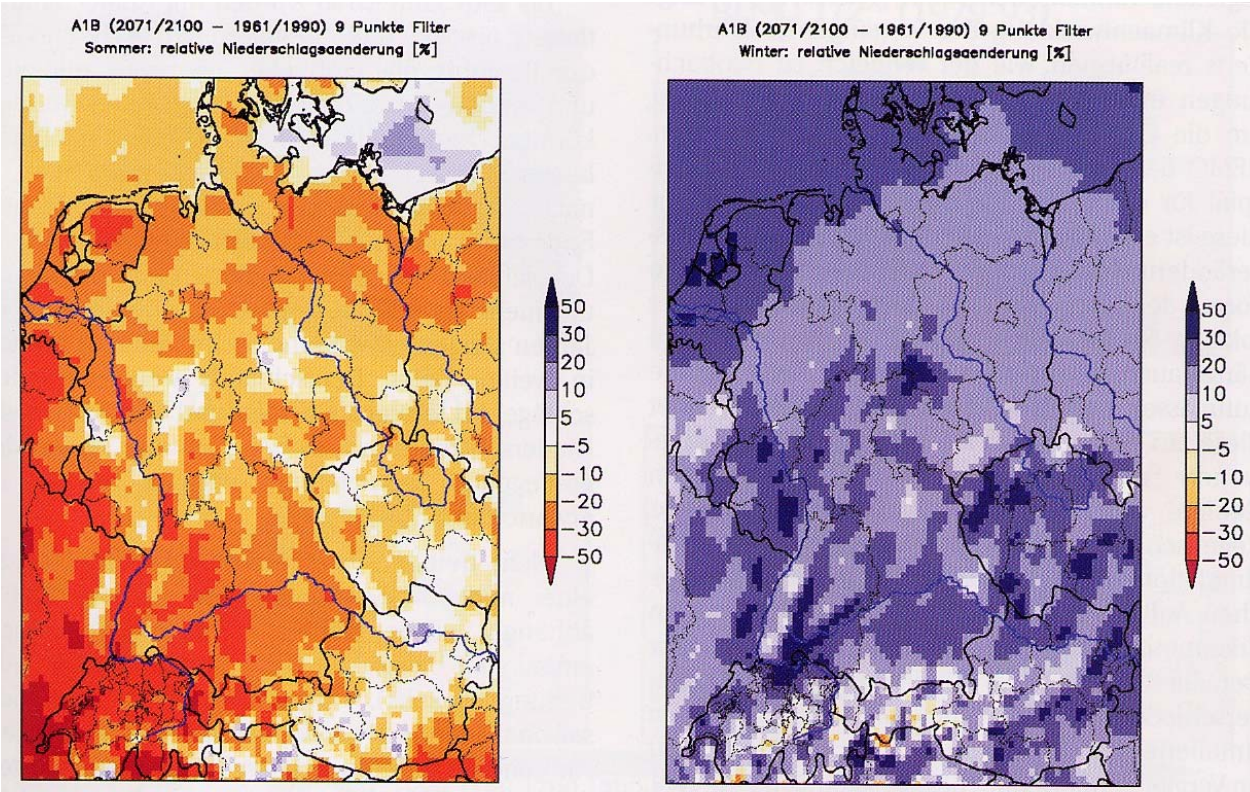
Model runs made in the framework of Reclip:more (reclip:more 2007, Beck et al. 2007), based on the global emission scenario IS92aon the other hand shows a significant increase of precipitation in winter in Austria and slight (spring and summer) to significant (autumn) decreases for the rest of the year (reclip:more 2007, Beck et al. 2007; see fig. 5).

Figure 3: Annual precipitation analysed by Frei et al. 2003 (left top) and calculated by the REMO model for 3 different spatial resolutions (50 km, 20 km and 10 km).



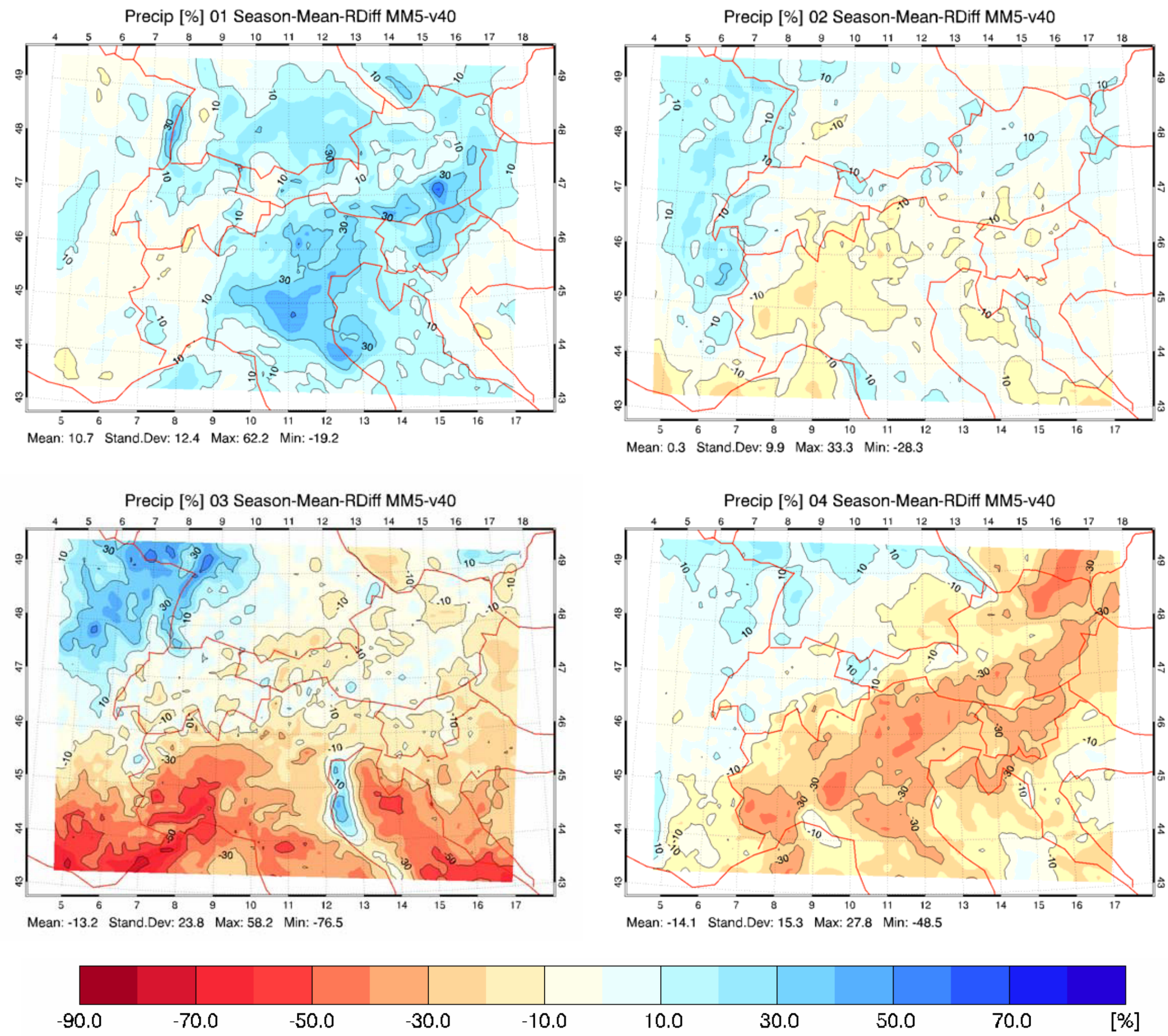
Source: Frei et al. 2003 and Jacob 2007

Figure 4: Seasonal precipitations changes as calculated by the REMO model for the scenario A1B for the period 2071 –2100 as compared to 1961-1990 (summer left, winter right)



Source: Jacob 2007

Figure 5: Changes in seasonal precipitation sums as calculated by Reclip:more for the scenario IS92a for the period 2040 –2050 as compared to 1961-1990 (top: winter left, spring right, bottom: summer left, fall right)

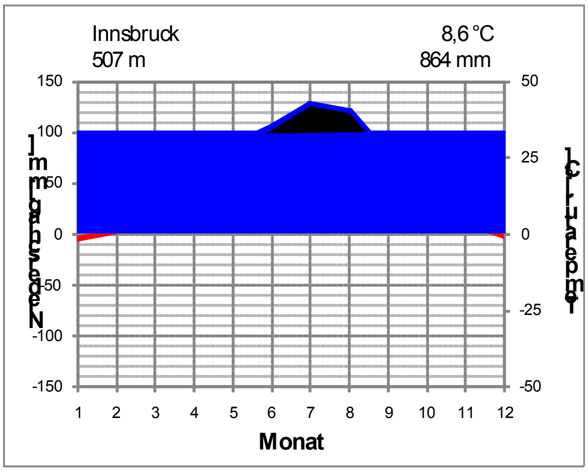


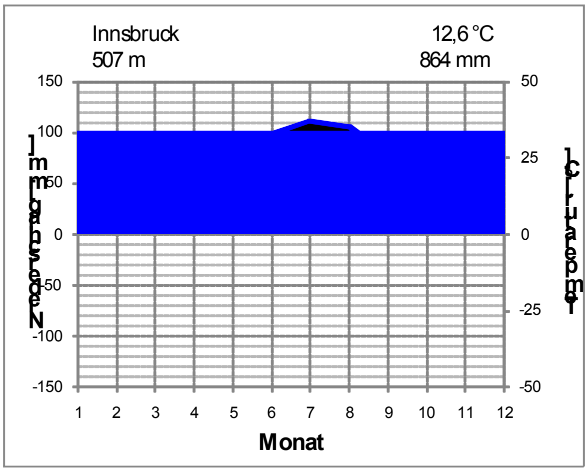
Source: Reclip:more 2007

What impacts on the torrent catchments and on their design can be expected from these changes in the average precipitation conditions?

Figure 6 shows the comparison of a climate diagram for Innsbruck for the present situation (Mühr 2002) and a scenario resembling the REMO scenario with an increase of 4°C in 100 years with the same annual precipitation sum, but dryer summer months and wetter winter months (Kohl hoc loco). The resulting, more homogeneous precipitation distribution would indicate a decrease in frequency of mood slides and floods.

Figure 6: Climate diagram for Innsbruck – present (Mühr 2002) and for a temperature increase of 4°C, precipitations decrease in summer and increase in winter (Kohl hoc loco).





Source: Mühr 2002 and Kohl (hoc loco)

However, a direct influence of changes in the average precipitation on the design event in torrent catchments in the Alpine area can not be deduced from these scenarios.

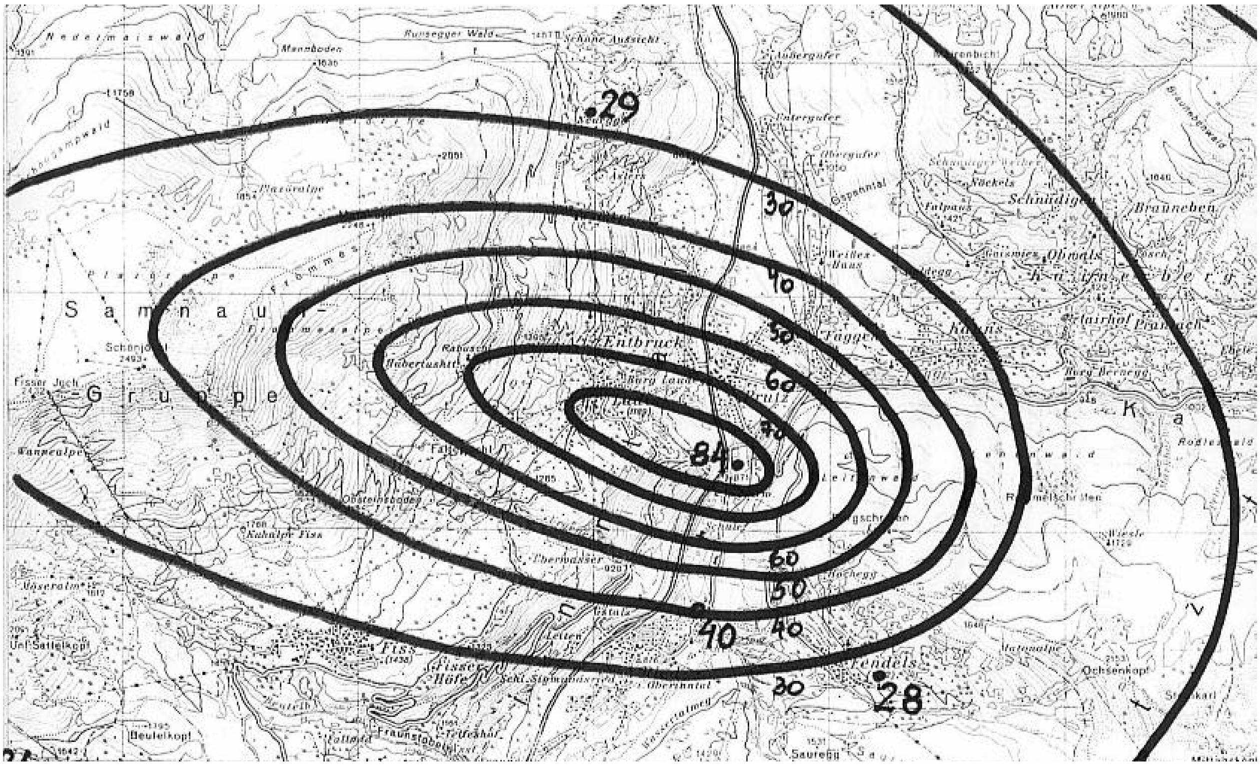
There might be indirect negative effects on torrent and flood events through changes in average precipitation amounts, temporal and spatial patterns, precipitation types and impacts on environmental conditions (moisture, etc.). These will be addressed in later chapters.

3.1.1.2 Changes in Extreme Precipitation Events – design storms

Essentially two different types of extreme events must be considered: short term intensive precipitation events and heavy precipitation events of longer duration.

The thunderstorm near Prutz in the Tyrol of the 12.08.2000 (see Fig.7) influencing the Urgenebnerbach can serve as an example of a short term extremely intensive precipitation event. The thunderstorm was a typical, thermally induced, isolated event. These events generally last about one hour and have a diameter of only about 10 km (Ingo, 2000). The reconstruction of the Isohyets of the 12.08.2000 indicate a core region of about 3 km² and a decrease in precipitation by 50 % within an area of about 45 km².

Figure 7: Isohyets, Urgenebnerbach / Oberes Gericht / Tyrol, 12. August 2000



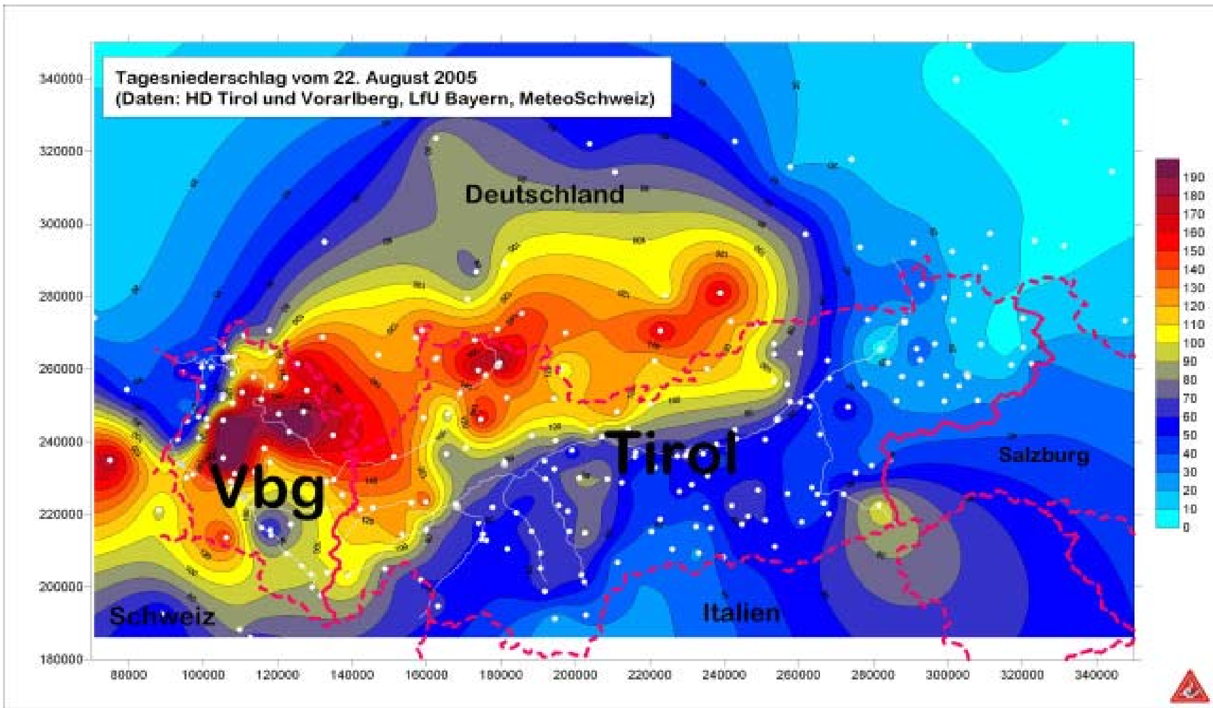
Source: GATTERMAYR 2003

Frontal thunderstorms have a much larger spatial dimension than these thermal thunderstorms. They extent some 20 km across the front and along the front lengths of several 100 km are frequently found.

Weather situations with strong upslide precipitation of longer duration are not unusual in Austria and have repeatedly led to floods in Austria in the past.

The severe floods in August 2005 in Austria were caused by cyclones that developed over the Golf of Genova under the influence of an upper level cut-off low. From August 20th this cyclone intensified, causing heavy precipitation in the southeren and southeastern parts of Austria. Following the Vb-trajectory, the cyclone moved slowly from northern Italy over eastern Austria to the Czech Republic and then on to Poland. This caused the areas of precipitation to move from the south to the north of the main alpine ridge on the 21. and 22. August. There it was intensified by strong northerly flow and the Stau effect along the Alps (BMLFUW 2006). Figure 8 shows a reconstruction of the daily precipitation sums of August 22nd 2005 for the Tyrol and Vorarlberg

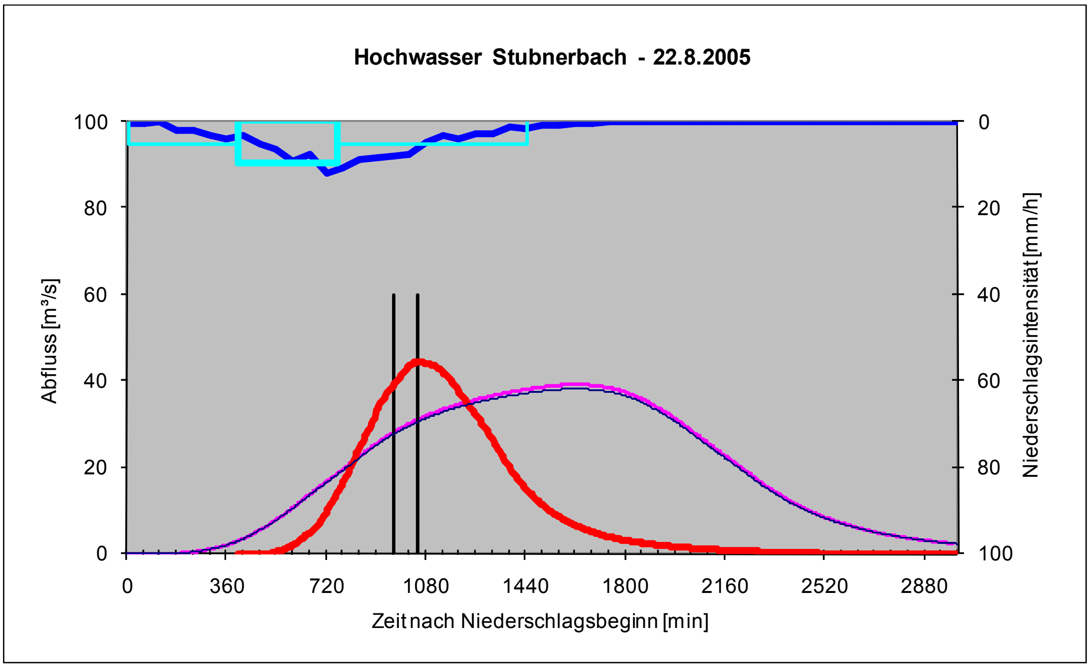
Figure 8: Precipitation sum [mm] for 22nd August 2005 in Tyrol and Vorarlberg



Source: IAN-BOKU; in BMLFUW 2006.

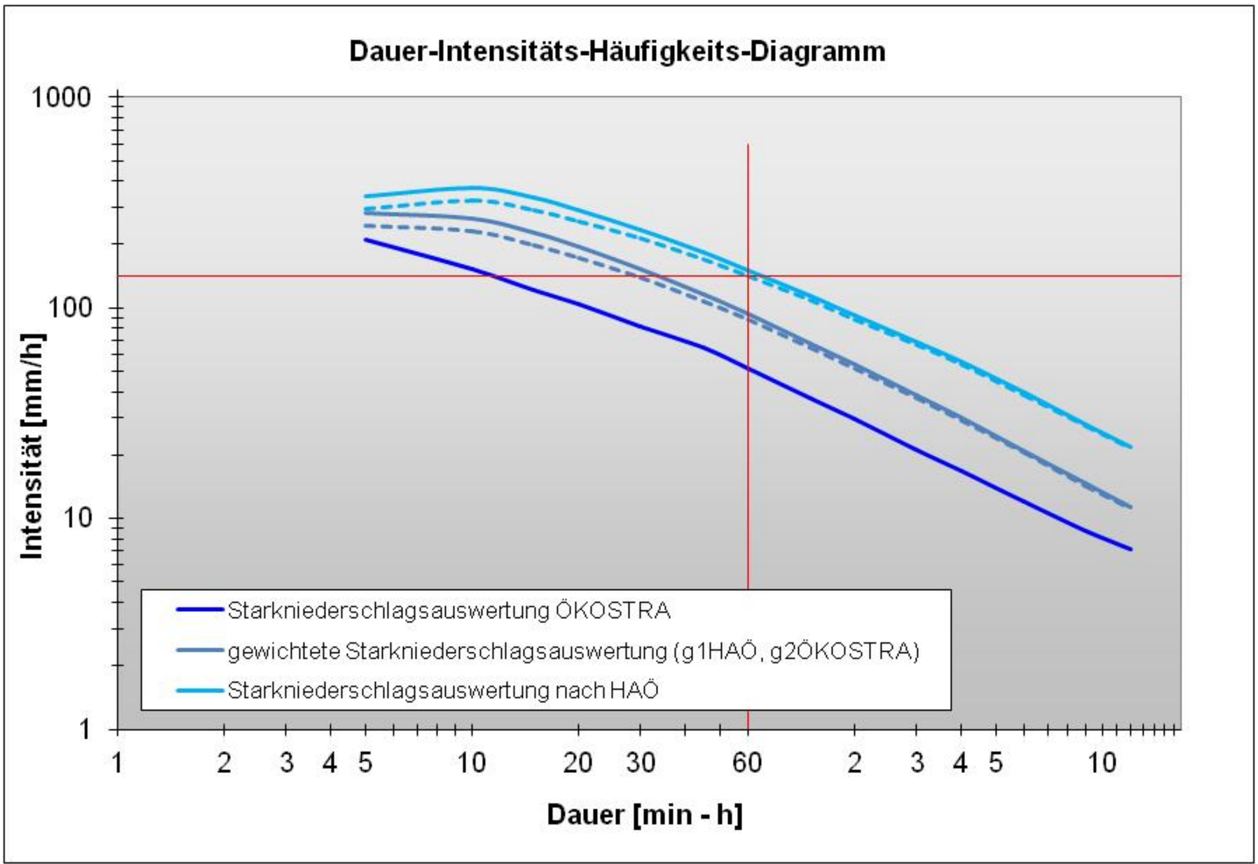
Precipitation intensities in none of these areas were exceptional, but the high intensities combined with the long duration of about 30 hrs caused the problems. Figure 9 shows a reconstruction of the hydrograph of the Stubenbach near Pfunds in the Tiroler Oberland, a community that suffered severe damage, based on a precipitation/runoff model (ZEMOKOST) and the assumption of two different block precipitation events. The simulation with the time-adjusted 6-hr block event causing 56 mm of precipitation, as registered during the event, reproduces the period of maximum damage very well.

Figure 9: Simulation of the hydrograph with the model ZEMOKOST: magenta: block precipitation event of 24 hrs, intensity 5,0 mm*h^{-1}; red: time adjusted block precipitation event of 6 hrs, intensity 9,6 mm*h^{-1}; period of the largest damages (vertical black lines) 23.8.05 between 00:30 and 02:00; dark blue: precipitation graph at the station Kappl.



The design of torrent catchment areas is more dependent on such extreme events than on average precipitation. In assessing the impact of climate change it is therefore the change in extreme events that is of primary relevance. In general, the design flood of torrent catchment areas is based on a design storm and catchment characteristics that determine the clear water flows. The design storm itself, however, can vary strongly with the methods chosen to determine it. Gattermayr (2003) suggested in the framework of the project ETAlp to combine observations and model calculations to determine the design storm. Figure 10 demonstrates the high uncertainties involved in these analyses by comparing the results of three approaches, based on either measurement data or model results alone and combinations of these for the catchment Stampfangerbach/Söll/Tirol.

Figure 10: Comparison of precipitation intensity diagrams using three different methods to analyse heavy precipitation events in the Stampfangerbach/Söll/Tirol catchment (annuality 150 years). Explanation in the text.



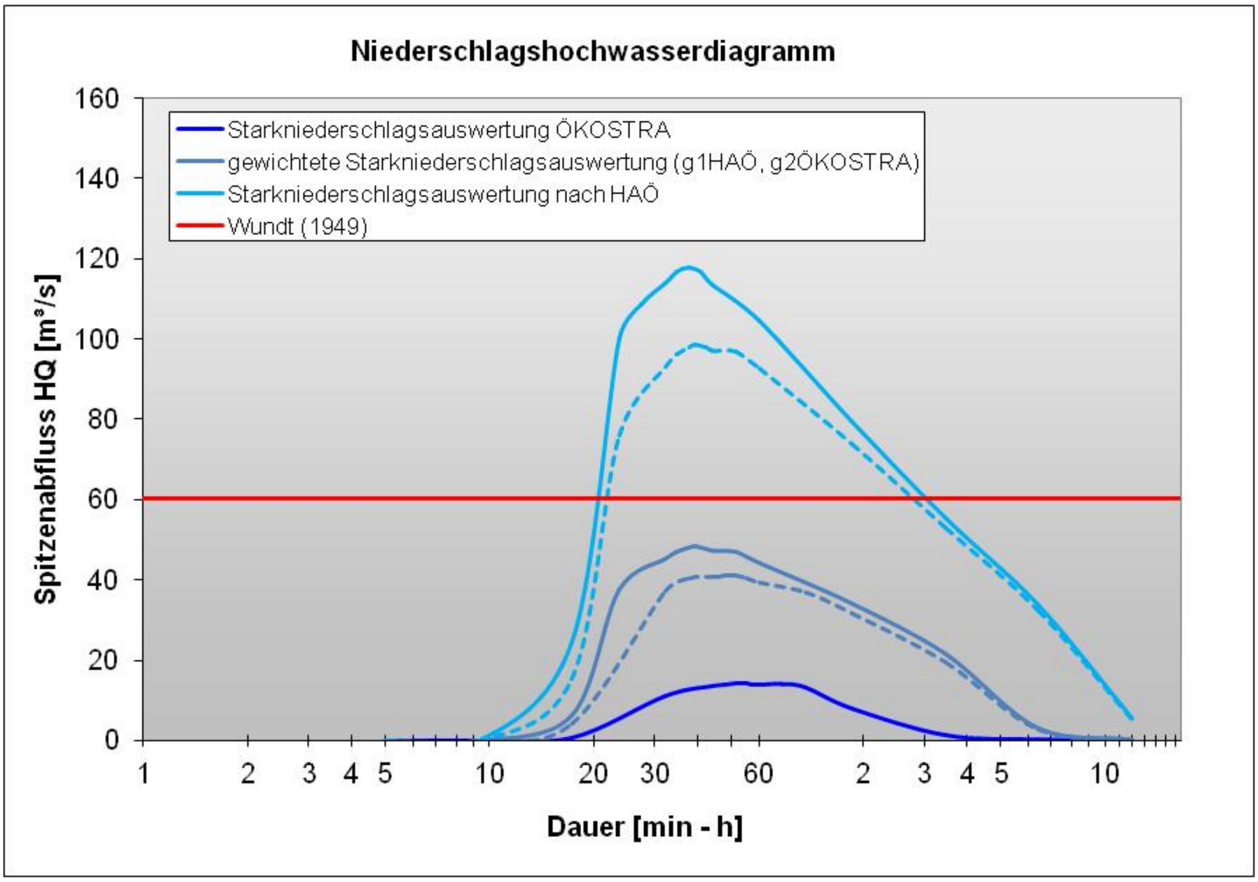
Source: Data from the HYDROGRAPHISCHER DIENST in Österreich.

ÖKOSTRA is an interpolated statistical extreme event analysis of measured precipitation data. However, the quality of such regionalized precipitation data strongly depends on the availability of data. In flat terrain with a higher density of precipitation stations results are of better quality than in alpine areas with few rain gauges (Merz 2006).

In order to compensate for the lack of data, the statistical analysis of measured data was coupled with the orographic-convective model (OKM) of the Hydrological Service (Lorenz und Skoda 2000) to derive the method used in the Austrian Hydrological Atlas HAÖ for heavy precipitation events. Essentially the Lorenz-Skoda model calculates the precipitation sum occurring in the center of a convective cell, irrespective of its movement. Due to the small scale nature of these cells and the comparatively sparse measurement stations, rain gauges as a rule register smaller values than analysed by this model. This is why analyses based solely on rain gauge data generally underestimate total precipitation. An empirical reduction is applied (dashed lines in Figure 10) to reduce this discrepancy, but a very significant difference remains – in the example presented a factor of 1:2,7 for a precipitation event of 1 hour. The distance between the 4 measuring stations used is on the order of 15 km each. However the difference is mainly due to the orography: the stations are situated in valleys (about 400 to 1000 m a.s.l), while the terrain within the catchment area rises up to 1828 m (Hohe Salve), with an average height of 1025 m. Recently attempts have been made (Vicuinik 2006) to modify the analyses of measurements by weighted values of the HAÖ data, to gain "presumably real rated values" (hN optimised – middle lines in Figure 10). Even if it is not possible to define "true" rated values, this procedure represents a certain compromise between the two extremes, ÖKOSTRA and HAÖ.

In Figure 11 the effect of the design storm on the clear water flows is demonstrated, comparing the five models of Figure 10. As can be seen, differences are very large.

Figure 11: Precipitation-flooding-diagram: comparison of maximum runoff as a function of duration using different design storms for the catchment area Stampfangerbach/Söll/Tyrol (annuality 150 years), N/A-model ZEMOKOST



Compared to these uncertainties, the impact of climate change is expected to be small. However, expected changes in intensities and amounts of precipitation on the local scale can not yet be reliably quantified (Petraschek in OcCC 2003). Dynamical downscaling is being used for daily precipitation values at the larger scale (100 km^2), statistical methods to about a 1-km grid, but even finer resolution would be needed for precipitation modelling at the torrent catchment area scale. This is beyond the scope of present models (see chapter 2 for more details). Design storms in principle could be downscaled where ever precipitations data are available in high resolution: 1,3 and 6 hour precipitation data from ERA data or control runs could be downscaled and the percentiles (annualities) could be compared with observations. The transfer function could then be applied to future climate scenarios. However, climate models with insufficient resolutions are unlikely to contain the signal of small scale extreme events, and thus tend to underestimate these. This increases the problem of the uncertainties. An increase of the design storm as calculated by ÖKOSTRA of 10% due to climate change would not raise the precipitation any where near the calculations based on HAÖ.

The effect of precipitation intensity on surface runoff can be studied by artificial watering. The Department of Natural Hazards and Alpine Timberline of the Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW) has made rain simulations at different sites since the 1980ies. For different initial conditions and rain intensities the relationship with saturated surface runoff has been derived (Kohl 2006).

If the runoff formation does not itself cause a change in the process due to increasing water level on the slope, an effect that occurred only in about 5% of the case studies, the runoff coefficient shows a small, linear increase with rising rainfall intensity (Markart et al. 2004). An additional 10% in the intensity increase the peak runoff by 10 to 15%, depending on the runoff coefficient. The lower the runoff coefficient, the higher the increase. At the catchment scale the characteristics of terrain and vegetation are essential. For the Stampfangerbach catchment, an increase of the design storm by 10% would cause raise the calculated design event by about 25%.

Thus, if the design storm could be defined unambiguously and if climate change were to cause an increase in precipitation intensity, significantly higher design discharge would have to be expected. However, a quantification is currently not possible.

3.2 Changes in the temporal development of precipitation events

When assessing design discharge precipitation events are generally assumed to be of block shape, but when individual events are analysed, the intensity distribution during the event is important. According to ETAlp especially precipitation events with increasing intensity towards the end can lead to catastrophic events, while those with maximum precipitation in the beginning or the middle of the event are less likely to cause such events.

Changes in these precipitation types cannot be described by climate models of any scale at present. In view of the many other uncertainties, entering into modelling of this aspect does not seem useful at this time.

3.3 Changes in precipitation form

According to EtAlp combinations of rain and hail, rain with variable altitudinal limits of snow fall, rain on snow and snowmelt are the influencing factors for the runoff formation relevant to the assessment of design discharge in torrent catchment areas.

3.3.1 Hail

According to OcCC (2003) the frequency of occurrence of the four synoptic situations leading to extreme hail events in Switzerland have increased since 1940. This could indicate that a further increase can be expected with climate change. However, hail events frequently occur on an extremely local scale, that cannot yet be handled by climate models with any confidence, and certainly no indications on size distributions of hail particles can be expected at this time.

The influence of hail on surface runoff is not quantifiable at present. The runoff coefficient (C, ψ) of bare soil have to be defined accordingly for the calculation of design discharge in case of potential for hail events. Hail must also be taken account of in case of assessment of the disposition of erodible debris sources. However, hail is mainly important as a “silent witness” for high precipitation intensities (ETAlp 2003).

3.3.2 Snow

In reality temporal and spatial changes in the altitude of the snow line and the existence of snow cover have direct influence on runoff. In some cases the rising of the snow line can be decisive for the exceedance of damaging flood levels. Rise of the snow line combined with increased precipitation in winter could significantly increase the flood risk in winter in the alpine lowlands and the Alpenvorland in this season. In catchments in higher elevations the rise of the snowline could even affect flood risks in summer (WWF 2006).

However, for the calculations of the design event in torrent catchment areas realistic worse case scenarios are calculated, and therefore it is always assumed that all precipitation falls as rain. Thus the transition rain-snow is not of relevance for these calculations. The role of snow cover for the whole system and the time of concentration will be discussed in later chapters.

3.4 System

Climate change directly or indirectly influences all soil-vegetation systems: the systems themselves and their hydrological characteristics (e.g. type of vegetation) or their hydrological conditions (e.g. moisture or saturation of the system) can be changed.

3.4.1 Changed Conditions (antecedent moisture)

As shown in Table 2 the following conditions can be distinguished (ETAlp 2003):

- hydrophobic (dry)
- sealed (frozen)
- unsaturated (moist)

- saturated (rain fed, snow melt)

Hydrophobic (dry)

As dryer summers with more frequent heavy precipitation events are expected hydrophobic effects that at first increase surface runoff in case of heavy precipitation can gain importance. Dried out humus layer under a dense spruce canopy or accumulation of necromass at mat grass stands can lead to significant surface runoff. The occurrence of such effects depends on the distribution of hydrophobic hydrological response units in the catchment area. The fact that in the majority of cases such areas are secondary anthropogenic units (Piceetum nudum, Nardetum) emphasises the need for a well adapted vegetation cover.

Sealed (frozen)

On one hand the increase of precipitation in the form of rain during winter could indicate that frozen ground will occur less frequently as climate changes. On the other hand, cold spells with temperatures below freezing could increase the occurrence due to lack of snow cover. Together this might indicate that fluctuations could increase (Schär 2004).

Unsaturated (moist)

In middle latitudes a significant part of the radiative energy in summer is used for evaporation. Dryer soil thus leads to increased temperatures (one important reason for the significant increase expected in summer temperatures), and at the same time to a larger water up take capacity of the soil during precipitation events. Studies in Switzerland have shown that even with an increase of 20% of precipitation sums or intensities pore volumes are not filled to maximum capacity. Thus surface runoff and the risk of floods will not increase more than proportionally Naef et al. (1998). To a certain extent these findings are in contradictions to those of the BFW as discussed in chapter 3.1.1.2 : Rising rainfall intensities are related with higher surface runoff coefficients. The average exhaustion of the retention volumes of the soils will change according to the present scenarios: less likelihood of moist soils in summer, more frequent and longer pre-filling in winter. As convective storms, generally occurring in summer, are most important for the design discharge no over proportional increase in flood risk is to be expected due to these changes.

Saturated (rain fed, snow melt)

The frequency of the condition „saturated due to rain“ follows from the above – increasingly frequent in winter, increasingly rare in summer. Saturation due to snow melt must be addressed separately, however.

In macro-scale catchments the increase of precipitation in winter and the simultaneous rise of the snow line will increase winter runoff. Especially in catchments with glaciers temperatures above freezing up to high elevations, heavy precipitation to high altitudes, significant production of melt water from snow and reduced storage capacity on the glacier surface due to snow melt can lead to flooding events. Since all of these factors become more likely with climate change, large catchments in the alpine area could experience increased risk of flooding due to snow melt.

The effect of snow melt on small alpine catchments were shown by Braun und Weber (2006) for the Vernagt glacier. Also in the meso-scale the coincidence of several factors is needed to produce extreme floods:

- thin or water saturated snow cover
- high rates of ice melting and strongly reduced storage capacity of glaciers
- temperatures above freezing all the way to the level of the ridges
- intensive precipitation in the whole catchment area.

As described above, for the design of torrent catchments realistic worst case scenarios are to be assumed according to ETAlp. The combination of the above factors would be such a worst case scenario. Therefore, as long as the design storm remains unchanged, changes in snow melt will not influence the results.

To which extent a more frequent occurrence of this combination of factors influences the design storm through the annuality and therefore increases the design discharge, cannot be answered due to lack of a suitable data base.

3.4.2 Changes in Vegetation and Soil

Climate change has a number of direct and indirect consequences on vegetation and soil that in turn can influence local climate conditions leading to further impacts on the biosphere. In the long run, global changes such as climate change, UV-radiation increase or increasing deposition of airborne pollutants can also impact socio-economic developments in the alpine region. It must however be kept in mind that on the short term direct human actions, such as development of infrastructure or forest management, generally have much greater impact on alpine vegetation and soil systems than climate change.

Changes in the seasonal precipitation pattern, as e.g. the expected increased dryness throughout summer and fall, affect trees to different extents, thus leading to a change in composition of forests. This is to a certain extent counteracted by the increasing CO2-concentration, that reduces the opening of stomata and therefore water loss.

Past climate change events have led to loss of species, especially in the highly specialised alpine ecosystems (Wieser 2007). Due to their high sensitivity alpine ecosystems can serve as early indicators of change. It is often claimed that mountain vegetation cannot adapt at the rate required by present day climate change. However, this is true either for maladjusted ecosystems, or for specialists in extreme locations. The systematic upward movement of stone-pine in the Inneralpine Tyrolian regions to altitudes above 2500 m in the last decades is proof of the enormous speed with which vegetation adapted to the site can react to change.

Temperature increase over the past decades has led to an increase in the length of the vegetation period. This leads, according to model results, to increased carbon sequestration in subalpine forest ecosystems. This also gives evergreen Climax-tree types (e.g. the stone pine) an advantage over pioneer-types that lose their foliage (e.g. the larch). Experiments show that some plants cannot profit from the earlier onset of spring and the longer summer, probably due to increased occurrence of frosts (Wipf 2006). A climate with warmer winters could remedy this and thus lead to enhanced plant growth and more rapid decomposition of litter on the ground. Climate change thus favours succession in higher altitudes and can therefore contribute to the upward spreading of the subalpine dwarf shrub belt. Studies have proven alpine dwarf shrubs to have a positive hydrological effect. Therefore a systematic increase of dwarf shrubs in the catchments of torrents by way of management measure is being considered.

In the majority of cases the current timberline in the Austrian Alps is an expression of the forest management of centuries. Overall, however, the upward trend in the timberline is at least in part the result of increasing temperatures. This also holds true for accelerated formation of soil and more frequent disengagement of rapidly draining pores that increases the capacity of forest soils to take up water in case of extreme precipitation events. Such events - convective rains of high intensity - are expected to become more frequent. As has been shown in chapter 3.1.1.2 in case of increased precipitation intensities, areas with reduced runoff disposition react with a more pronounced increase in runoff than areas with a high runoff disposition.

Extreme events, such as e.g. extreme heat as in the years 1976 and 2003, can cause damage to vegetation (e.g. in the scots pine stands in the area of Brixen, southern Tyrol) that is not immediately visible but diminishes plant resistance (Minerbi et al. 2006). The extent of the damage only becomes clear in later dry years, when trees are either seriously damaged or die. This effect will be of special importance at dry sites and sites with periodic water stress – composition of tree species can significantly change here.

All of this shows that in afforestations for the selection of tree species climate change and its possible impacts must be taken into account.

3.5 Time of Concentration

The time of concentration is mainly determined by topography and roughness, but there is also a direct dependence on precipitation and system scenarios. Among the systems scenarios anthropogenic reduction of channel travel time is of most interest. However, the impact of climate change here is only regarded concerning the particular case of the sponge buffer effect of the snow cover up to the complete permeation.

Every 10 cm of snow cover delay the onset of runoff by about 3,6 minutes (Kohl et al., 2001). In Fuchs et al. (2000) this topic is treated in detail. Understanding these processes is especially helpful for the analysis of individual events. For the design case however, a realistic worst case scenario regarding the environmental conditions as described in chapter 3.4.1 must be assumed. Thus a sponge buffer effect of the snow cover needs not be considered, independent of the possible impacts of climate change.

3.6 Area

Apart from the precipitation amount in the design storm the temporal and spatial extent of the design storm is essential for precipitation-runoff modelling. The assumption of a temporal and spatial variability of precipitation (extent of the precipitation area and direction of motion) is – according to ETAlp – only useful for larger catchment areas. Analysis of past events (chronicles) can help to evaluate the importance of these factors for each individual torrent.

3.7 Conclusions on the impact of climate change and the availability of relevant data from climate models

The above considerations are summarized in the table below (Table 3) – an extension of Table 2 to include for each boundary condition the possible impact of climate change and the availability of qualitative or quantitative information from climate models.

As can be seen, most boundary conditions are impacted by climate change, either directly or indirectly. Essentially only factors influenced by man, especially regarding time of concentration are not impacted by climate change. As was to be expected, on the whole information on the macroscale is more readily derived than on the mesoscale, and qualitative information can be derived for more situations than quantitative information. Practically no information is available or can be derived from climate models on the development of the precipitation events and on the area parameters. Filling this last gap appears to be more important than supplying information on precipitation development. Models are not very helpful regarding hail either, but as the importance of hail for torrents and mudslides is not very clear so far, this does seem to be an essential caveat in this respect. This might be different when addressing damage to agricultural crops.

On the other hand information essential for torrent catchments can be derived from climate change models. However, it must be cautioned that this implies suitable downscaling and informed interpretation of the individual models, as described in Chapter 2.

Table 3: Relevant Boundary Conditions for the run-off formation for the assessment of design discharge in torrent catchments (according to ETAlp 2003), climate change impacts and availability of relevant qualitative and quantitative data from climate models for different spatial scales.

Legend: Data can be derived from models: Data can be derived from models with reservations : Data cannot be derived from models: xxxxxxxxx

Relevant Boundary Conditions for the run-off formation for the assessment of design discharge in torrent catchments (according to ETAlp 2003)			Impact of climate change	Information that can be derived from models			
				Macroscale		Mesoscale	
				qualitative	quantitative	qualitative	quantitative
Precipitation	Intensity and Duration (and annuality)	convective heavy precipitation of short duration	direct				
		strong upslide precipitation of longer duration					
		Transition Scenarios					
	Development	block shaped	direct				
		increasing intensity towards the end					
		DVWK-distributed	none				
	Type	liquid (Rain)	direct				
		solid (Hail)					
		solid (Snow)					
System	Antecedent moisture	hydrophobic (dry)	direct				
		sealed (frozen)					
		unsaturated (moist)					
		saturated (rain fed, snow melt)					

	(seasonal) management cycle	spring	indirect	through external models to a limited extent			
		autumn					
	Vegetation cover	current vegetation	indirect				
		potential vegetation					
		Human interventions (leveling,…)	none				
Time of concentration	Influences	Not influenced by human action (channel)	none				
		accelerated (artificial channel)	none				
		delayed (Retention)	none				
	Snow cover	Sponge buffer effect of the snow cover	direct				
Area	Spatial Extent of precipitation	Over the whole area	direct				
		Over parts of the area					
	Intensity distribution over the area	undiminished (less than 10 km²)	direct				
		diminished (more than 10 km²)					
	Direction of motion of precipitation field	With the direction of flow	direct				
		Against the direction of flow					
		Across the direction of flow					

Source: ETAlp., 2003, modified

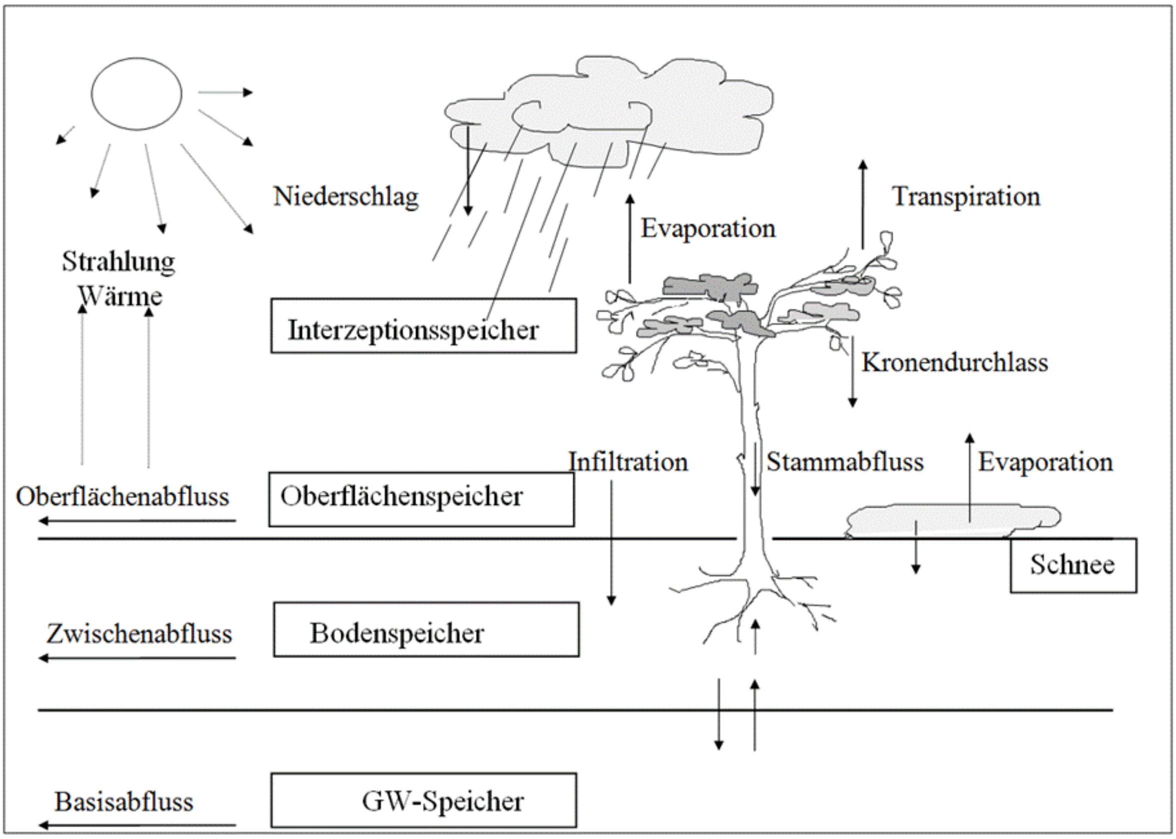
4. PRECIPITATION-RUN-OFF-PROCESS MODELLS (NA-MODELLS)

4.1 Description of phenomena

Run-off and erosion in alpine catchments are controlled by complex interactions in the atmosphere-vegetation-soil-subsoil system. The mathematical description of these processes therefore remains an approximation based on conceptual models of the processes and algorithms for the calculations. Input is needed regarding the characteristics of the catchment (topography, land use, soils), initial conditions and (generally) also model parameters that serve to calibrate the model.

A simplified picture of the processes taking place during a precipitation event is given in Fig. 1.

Figure 12: Simplified, schematic view of energy and moisture flows



Source: DYCK/PESCHKE (1995) in HEINECKE (1999)),slightly changed

Precipitation falls on a catchment area

- one part is retained by vegetation: interception,
- one part falls or is drained onto the soil: precipitation through the canopy,
- melt water from snow permeates the snow cover and reaches the soil (from this moment melt water and rain water are subjected to practically the same processes!).
- one part of the water is retained in depressions on the surface: depression storage.
- Another part of the water infiltrates the soil: infiltration.

- One part of the water flows on the surface and reaches a water body: surface runoff.

Infiltrated water or water retained in depressions is subjected to the following processes:

- One part never is fed into the run-off but is stored in vegetation of soil and evapoates: run-off losses due to evaporation and transpiration.
- One part moves rather rapidly, underground but near the surface towards a water body: Interflow, hypodermic run-off.
- One part penetrates deeper into the soil, but moves comparatively rapidly through rough pores and tubes towards a water body: preferential flow.
- One part penetrates slowly into the pores of the soil matrix and also permeates slowly out of the soil: Matrix flow.
- Water that permeates the surface layer of soil can penetrate into the cavities and clefts of the sublayer and can move more or less rapidly through these towards a water body: Karst water, cleft water, groundwater of pores.

4.2 Hydrological Run-off Models

4.2.1 Basic Approaches

Hydrological models to calculate run-off simplify the natural processes in varying degrees. Therefore mathematical models describe processes that do no exist in reality. This makes it impossible to gain reliable information on nature from models. Simulations with models can only be relied upon when they are validated with adequate measurements in nature. In this case, certain extrapolations beyond the observations are permissible. The more complex a model is, the more difficult it is to gain the data necessary for calibration and subsequent validation on independent data sets (Anderson and Bates, 2001). The reliability of simulation results for events not included in past observations, e.g. design or extreme events or events under changed environmental conditions (changes in land use, climate change) tends to increase, the better the model describes the processes and the more information on the catchment area the model can handle. "The model gives the right answers for the right reasons." In the following this will be called the "prognostic power" of the model.

In the course of the decades since Sherman (1932) published his work on the Unit Hydrograph a vast number of precipitation-run-off models has appeared in the literature - and disappeared again for the largest part (for a compilation of model types see Singh, 1995; for application oriented model descriptions see Merz und Blöschl, 2002, and Barben et al., 2001). This makes it useful to classify models according to certain criteria. Such criteria could for instance be a) the degree of detail in the subdivision of the catchment area and b) the degree of detail with which processes are described. Todini (1988) classified the hydrological models according to the following criteria α) purely stochstic models, β) lumped integral models (integral blockmodels, black-box models), γ) distributed integral models (conceptual models), δ) distributed differential models (process models). In the following criteria a) and b) will be used for classification.

4.2.2 Categorization according to the degree of detail in the subdivision of the catchment area

Lumped models: The catchment area is considered as one unit, no subdivision is made

Typical representatives: Unit Hydrograph-Modell; Models in the IHW- and HEC-Model pool (see e.g. Dooge, 1959; Nash, 1957).

Characteristics: manual calibration required based on data (precipitation and hydrographs) measured in the catchment; not transferable to other catchments. Model quality depends on quality and length of data series for the calibration process and the quality of the model for the formation of runoff.

Knowledge of the terrain: hardly usable.

Detailed knowledge of precipitation patterns (convective cells, cell trajectories, …): not usable

Advantages: robust, transparent, negligible calculation times

Draw backs: the intrinsic assumptions of linearity and stationarity are only first order approximations to nature, but the are basic to the validity of the superposition principle that is at the heart of the models. The runoff formation model is essential for the quality of the lump model.

Prognostic power: very questionable

Isochron models: The catchment area is subdivided into strips of equal flow times to the catchment exit (Isochron strips). For each of these separate models of runoff formation can be assumed.

Typical representatives: Rational Method Time-Area-Diagram (ZFD, Gutknecht, 1972); some subroutines of NASIM (Hydrotec 2007; http://www2.hydrotec.de/vertrieb/nasim/).

Characteristics: certain calibrations or at least detailed spatial information on runoff formation are necessary (e.g. maps of runoff coefficients). Determining the flow times can be difficult, as these are event dependent. The number of parameters needed is limited, but understanding and some knowledge of the area is required for the selection of adequate flow time calculations and the estimation of buffer characteristics of the area.

Knowledge of the terrain is helpful.

Detailed knowledge of precipitation patterns (convective cells, cell trajectories, …) can be made use of.

Advantages: negligible calculation times, transparent

Draw backs: The runoff formation model is essential for the quality of the model.

Prognostic power: quite good, if the runoff formation model is good.

Hydrotope models (semidistributed models): The catchment area is subdivided according to hydrotopes (areas with similar hydrological reaction) or in altitudinal zones. Different model types or parameter sets are used for every subunit. The runoff from the individual hydrotopes must be transferred to the catchment exit (flood routing), if the calculation time step is smaller than the flow time from the most distant point to the exit.

Typical representatives: BROOK (Federer and Lash, 1978; Forster, 1992); BROOK 90; HQsim (Kleindienst, 1996); some subroutines of NASIM.

Characteristics: require considerable number of data to describe the area (soil and vegetation types, geological and elevation data, …); certain understanding of the models is required, especially if no digital maps are available for some of the required parameters. Routines for quasi-automatic determination of parameters are being developed (Peschke et al. 1999).

Knowledge of the terrain is helpful.

Detailed knowledge of precipitation patterns (convective cells, cell trajectories, …) can be made use of.

Advantages: generally short calculation times (can be high in GIS applications!), still transparent

Draw backs: The preprocessing to identify the subunits can be time consuming. GIS support useful.

Prognostic power: quite good.

Spatially detailed models: The catchment area is subdivided according to different criteria (e.g. rectangular or triangular grid, contour- and streamlines). Automatic calculation of runoff formation and concentration, generally based on simplified physical laws (see also below: physical models). Soil water content is balanced regarding area and depth and controls runoff formation.

Typical representatives: SHE (Abbot et al., 1986); SWMM; NWSRFS; THALES (Moore & Grayson, 1991); .....

Characterics: theoretically no calibration necessary and universally applicable.

Knowledge of the terrain is helpful, even very helpful.

Detailed knowledge of precipitation patterns (convective cells, cell trajectories, …) can be made use of.

Advantages: very detailed analysis of the catchment is possible

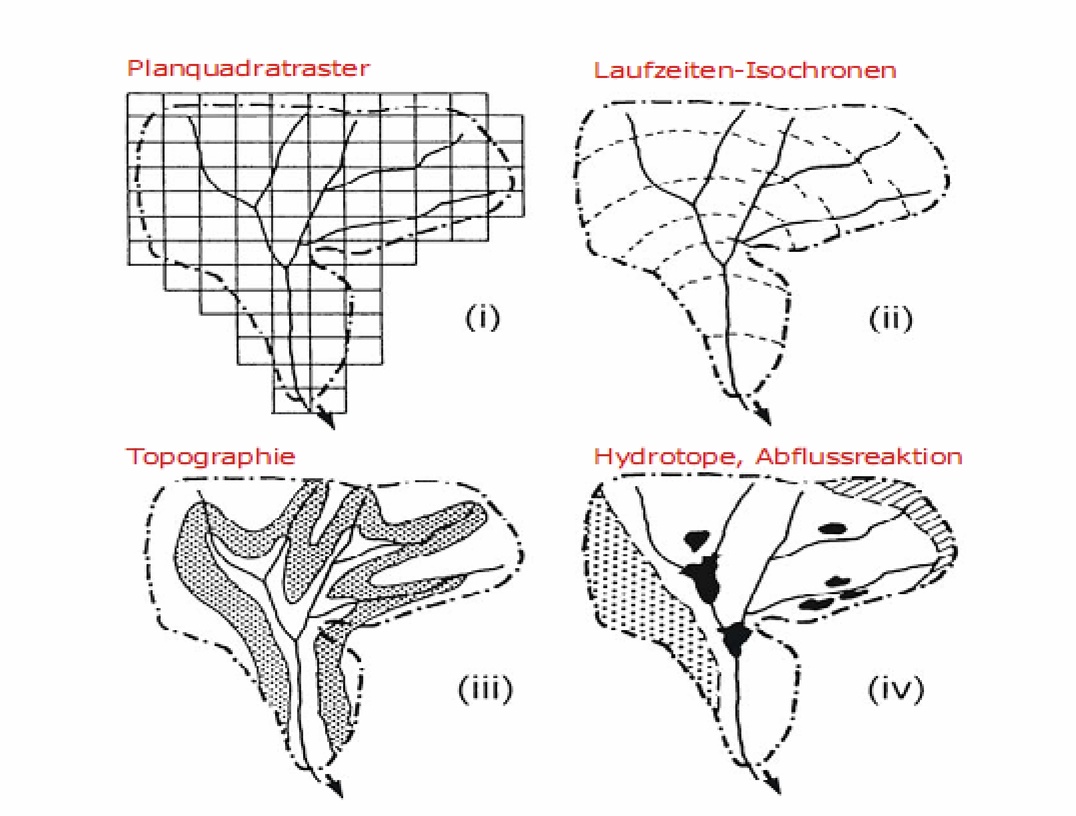
Draw backs:

1) Very high qualitative and quantitative requirements regarding parameters to describe the area (GIS-support necessary), the events (precipitation, temperature, moisture, windspeed, global radiation, long wave radiation, all with a good time resolution). If these are not available, application of spatially detailed models is questionable.

2) Validation of model results requires considerable effort and data. The hydrograph at one single point is inadequate. Spatially detailed data are necessary (e.g. soil moisture distribution in space and depth, runoff for different parts of the catchment)
3) The models are not very transparent and should therefore need schooling to handle.
4) Calculation times can be very long, numerical instabilities can occur and might remain undetected, leading to erroneous results. Calculations within a GIS system can take very long.

Prognostic power: theoretically excellent, but strongly dependent on available information and input data.

Figure 13: Schematic examples of subdivisions in hydrological NA models: (i) spatially detailed model, (ii) Isochron model, (iii) altitudinal model, (iv) Hydrotope model



Source: GUTKNECHT AND BLÖSCHL 2006

4.2.3 Categorization according to the degree of detail with which processes are described

Stochastic Models: based on the statistical description of observed time series, without explanatory value regarding physical processes.

Typical representatives: Time series models; Models based on neuronal networks.

Characteristics: generally require long time series of observations; of limited value for predictions

Knowledge of the terrain can not be put to use.

Parameter: Generally no sophisticated requirements, caveats compensated by calibration.

Prognostic power: very questionable.

System models: empirical models without physical background.

Typical representatives: Unit Hydrograph; in some respects also ZFD; Models that predefine hydrographs; Regression models.

Characteristics: calibration based on observations needed; generally not transferable, but regionalisation approaches attempt to make this possible. Generally used in combination with block models (see above).

Knowledge of the terrain helps little or not at all.

Parameter: Generally no sophisticated requirements.

Prognostic power: questionable.

Conceptual models: Mathematical formulas describe the process that is postulated for the precipitation-runnoff process, e.g. linear storage, cascade of linare storages, parallel circuit of storages or storage cascades, non linear storage.

Typical representative: linear storage in the ZFD, linear storage cascade (Nash), transport of surface and soil water in NASIM or HBV.

Characteristics: Some calibration based on observations needed; transferable with some effort. regionalisation approaches attempt to make them transferable. Generally balancing, not event models, therefore they need a sufficiently long spin-up time. This implies that in practice they need to be run continuously, if they are to be used for runoff predictions. For design events initial conditions must be defined (e.g. dry, moist or wet pre-conditions). Frequently applied in combination with Hydrotope models (see above).

Knowledge of the terrain helps.

Parameter: generally physically meaningfull; low requirements that can be fulfilled. Minimum: storage constant of linear storage; Maximum: Estimate for the water content permeability curve. Runoff formation frequently results from soil water balance. However, parameter for losses (interception, evaporation) and additional input data (air temperature, air moisture, wind speed, radiation and long wave radiation) are needed.

Prognostic power: quite good

Physical Models: Mathematical formulas describe the process that is postulated for the precipitation-runnoff process, e.g. Green Ampt for Infiltration, Richards equation for water movement in the unsaturated soil zone, Darcy's Law on the movement of groundwater, St. Venant-Equations and their simplifications (kinematic Wave, Diffusion analogy, ...) for surface runoff.

Characteristics: they claim not to require calibration and to be universally applicable. These models generally are based on balances, not events, therefore they need a sufficiently long spin-up time. This implies that in practice they need to be run continuously, if they are to be used for runoff predictions. For design events initial conditions must be defined (e.g. dry, moist or wet pre-conditions). This is best done by running the model for several years. Generally used in combination with spatially detailed models (see above).

Knowledge of the terrain is very useful.

Parameter: high requirements of physically meaningful data, involving considerable effort (established pre-processing-algorithms required for larger areas with detailed process descriptions); in general the decisive parameters (e.g. vegetation and soil) not available in the small scale suited to the model concept.

Prognostic power: theoretically excellent.

5. SUMMARY AND CONCLUSIONS

A wide variety of models at the catchment level is used to describe and design torrents. They differ in detail regarding spatial subdivisions and regarding the physical processes resolved. The least sophisticated models are based on simple empirical approaches using basic statistics, the most complex models are based on mathematical descriptions of those physical processes that are sufficiently understood to frame them in equations. Models at the lower end of the sophistication scale make do with little and basic input, those at the upper end need considerable input that generally requires very much effort to generate and in many cases is not available due to lack of field data.

By choosing the most sophisticated model regarding processes and spatial subdivisions for that matching high quality input data are available the best quality of results can be achieved for a specific catchment in general. However, a „physical“ model that describes surface runoff and water flow in the soil matrix, but not along preferential flow paths will produce worse results in a catchment area in which these flows are relevant, than a conceptual model that explicitly takes account of the preferential flow paths, even if using a simple approach. Thus the selection of the appropriate model is essential to achieve good results.

Independent of the sophistication of a model and the quality of the data, every model needs validation, before results can be assigned any reliability. Transfer of validated models to different catchments is theoretically easy for the most sophisticated models, however it necessitates the same large effort in acquiring input data. Simple models need to be newly calibrated when transferred to a new site. In both cases, they need new validation.

Applying models to conditions of future changed climate requires a) knowledge of the new climate in the detail required of meteorological input, b) knowledge of the impact of changed climate on all other input variables of the model and c) knowledge of possible changes in basic processes that would require changes in the physics of the model. This last type of changes is not expected to occur within the range of climate scenarios presently considered, thus can be neglected at present. The impact of climate change on the environment in any catchment area can encompass as divers aspects as changes in spatial and temporal snow cover patterns, glaciated area and vegetation cover, changes in frequency distributions and seasonality of soil moisture or enhancement of erodible debris potentials. In order to describe and quantify these impacts, details of the expected meteorological changes are also needed.

However, as stated in Chapter 2: "For applications in small catchments even the RCMs (regional climate models) with the highest spatial resolution (10 km) are far too coarse to resolve all relevant processes for extreme precipitation events in this scale. To resolve the small catchment scale a different type of RCMs is needed, that directly resolve convective cloud systems. This is not only a question of computer resources, but also of how the processes are represented within the models." These models are not yet available. Thus, the meteorological input necessary for to run hydrological and runoff models under climate change conditions is not available in many cases. On the whole meteorological information on the macroscale is more readily derived from Global Climate Models (GCM) than for the mesoscale, and qualitative information can be derived for more situations than quantitative information. There are considerable gaps, as e.g. regarding area parameters of precipitation. Nevertheless, as major changes in precipitation extremes have occurred and had an impact over the last 40 years, and as further major changes are projected for the coming decades, these changes need to be taken account of in hydrological precipitation/runoff models, as well as in designing torrents. Efforts must therefore be continued to significantly improve the modelling of precipitation in GCMs, in RCMs and in subsequent statistical treatments (see Chapter 2). A further development of some aspects of hydrological precipitation/runoff models and methodologies of torrent designe would be helpful, as uncertainties play a significant role here as well.

The lack of meteorological input to determine the climate change induced impacts on the environment and thus on other input parameters for the designing of torrents is partially of less consequence, as realistic worst conditions are assumed with no reference to frequency of occurrence. In many cases these input data will therefore not change with climate change.

6. RESEARCH REQUIREMENTS

6.1 Hydrology

Hydrological modelling for design purposes in small Alpine catchments is hampered by some deficiencies in data resources (and, to some extent, lack of process understanding as a consequence of that). A short summary which makes no claim to be complete shall be given here and research needs suggested.

6.2 Soil information

Distributed rainfall runoff models suffer from a lack of soil information, especially in forested areas, on a small scale. Flood runoff is formed on small partitions of Alpine catchments, saturated areas and bare soils etc. In general, digital information on the soil-vegetation complex in forested areas does not exist on the adequate scale. Soil depth, field capacity, saturated and unsaturated conductivity, pore space and pore size distribution should be investigated in forested Alpine areas, combined with the plant communities and the geology of the subsurface. This would form a better basis for assessing catchment behaviour.

6.3 Precipitation data

Convective storms causing the greatest floods in torrents are only accidentally observed in rain gauges. Thus, rain gauge data usually do not give the correct information on the precipitation in the torrent catchment. Radar data would be in principle appropriate to supply this information. However, the form of the Z – R relation, where the estimated rain intensity is a function of the sixth power of the drop diameter, causes great uncertainty. For routinely analysing rain by radar measurements an automated procedure for choosing the adequate drop spectra for the different types of precipitation should be developed. Analyses of long term radar data are needed. This would give the adequate data base for design storms for torrent catchments. A similar problem arises if hail is part of the storm precipitation. (In this case not even the discharge reaction of the catchment is thoroughly understood.)

6.4 Design philosophy

In general, for small Alpine catchments there are great discrepancies between design floods estimated on the basis of statistical analyses of discharge data derived from stage data at gauging stations on the one side and on the basis of rainfall runoff calculations with hydrological models on the other side. Usually design floods from gauge data are smaller. The reasons for these discrepancies can be: a) Discharge samples for small Alpine catchments are usually significantly smaller than for precipitation data statistically analysed for design purposes. And, to some extent, a small torrent catchment is something like a big rain gauge which is only accidentally hit by a great convective storm (see the above paragraph). Thus, the usual short discharge data record does not contain a really big flood, whereas design storm data are condensed from more than one rain gauge in a region. b) Design floods for small catchments derived by downscaling from significantly greater catchments are in general too small because the meteorological event type causing the design flood in the great catchment (usually an advective storm with relatively small rain intensities) is different from that causing the design flood in the torrent (usually a convective storm with extremely great rain intensities). Investigations are necessary to bridge this gap between statistically derived and hydrologically calculated design floods.

6.5 Regional climate change szenarios

A comprehensive overview of the skills of state of the art regional climate models within the Alpine area is given in Chapter 2 of the ClimChAlp Climate Change Report. Concerning applications in small catchments even the RCMs (regional climate models) with the highest spatial resolution (10 km) are far too coarse to resolve all relevant processes for extreme precipitation events in this scale. To resolve the small catchment scale a different type of RCMs is needed, that directly resolve convective cloud systems. This is not only a question of computer resources, but also of how the processes are represented within the models." These models are not yet available.

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CHAPTER 3

CASE STUDIES

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List of Acronyms

Abbreviations or Acronyms	Significance
AMC	Antecedent Moisture Condition conform SCS CN (1, 2 or 3)
AVHRR	Advanced Very High Resolution Radiometer
BOKU	University of Natural Resources and Applied Life Sciences, Vienna
CLC	Corine Land Cover
DAD	Depth-Area-Duration
DEM	Digital Elevation Model
DSM	Digital Surface Model
DSS	Decision Support System
DTM	Digital Terrain Model
ED50	European Datum 1950
GCP	Cround Control Point
GIS	Geographic Information System
GPS	Global Positioning System
HD-Carinthia	Regional Hydrographical Service
HEC	Hydrologic Engineering Centre
HEC-HMS	Hydrologic Modeling System
HQ_n	Peak runoff for the reciprocal of the exceedance probability (n) in years
HSG	Hydrological Soil Group
HWE	High Water Event
HZB	Hydrographical Central Office
ICTP	International Centre for Theoretical Physics
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
MRU	Model Response Unit
NDVI	Normalised Difference Vegetation Index
REGCM	Regional Climate Model
RUSLE	Revised Universal Soil Loss Equation

S	Soil Storage Capacity [mm]
SCS CN	Soil Conservation Service Curve Number
SMU	Soil Mapping Unit
STU	Soil Typological Unit
SWE	Snow water equivalent [mm]
UCA	Upslope Contributing Area
USDA	United States Department of Agriculture
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
UTM	Universal Transverse Mercator
VN*n*	Rainfall for the *n* days before
WGS84	World Geodetic System 84
WLV	Torrent and Avalanche Protection Agency
Wundt-Value	Regression relationship for determining the runoff (Wundt, W. 1949)
ZAMG	Central Institute for Meteorology and Geodynamics, Austria

1. SOIL EROSION IN THE ALPINE SPACE

1.1 Abstract

The general aim of our study was an estimation of actual erosion over the whole alpine space and a spatial analysis of soil erosion trends in different IPCC (Intergovernmental Panel on Climate Change) scenarios. A preliminary review of scientific literature regarding soil erosion studies in the Alps was carried out. From this analysis it came out that research experiences studying, by means of models specifically set for mountain areas, soil erosion on the alpine territory as a whole do not exist. Moreover, we found out that few study experiences have been carried out with the aim of deepening the matter of the climate change impact on erosion processes in the Alps with the use of modelling techniques.

This study tries to fill these gaps. The Revised Universal Soil Loss Equation (RUSLE) was applied to the whole alpine space, with a specific setting on mountain areas for slope and rain erosivity parameters. It allowed to produce, with a spatial resolution of 100 m, the map of actual soil erosion and two further maps defining soil erosion rates in IPCC A2 and B2 scenarios. This analysis was carried out by means of the dataset the International Centre for Theoretical Physics (ICTP) of Trieste made us available. It provides daily rainfall values for the years 1960 – 1990 and for the IPCC A2 and B2 scenario 2070 – 2100.

From an integrated analysis of potential and actual soil erosion it comes out the strategic role of cover vegetation in keeping soil losses under control. By analyzing erosion values obtained with RUSLE application, it is evident that almost the whole alpine territory is subject to erosion phenomena. About 32% of the alpine space shows a rather high risk of erosion (> 20 t ha^{-1} yr^{-1}); nearly 50% shows a middle risk (2 – 20 t ha^{-1} yr^{-1}) and the remaining 18% a low risk (< 2 t ha^{-1} yr^{-1}). In the high mountain zone, in particular, more than 25% of the territory is interested by very high erosion rates (> 50 t ha^{-1} yr^{-1}).

From a comparison between actual erosion and soil losses in A2 and B2 scenarios it comes out that our model does not show relevant raises in erosion rates. However, low variations in soil losses rates are observable. In particular, B2 scenario shows a growth of low entity of soil losses over a significant part of the alpine space. In A2 scenario a clear distinction between northern and southern Alps comes out. Northern part should experience a low reduction of soil erosion, whilst in southern areas a rise of soil losses could take place.

On the Italian side of the alpine area, future trends of soil erosion have been investigated taking into account, besides climate data, land use and land cover scenarios. The analysis showed, over the Italian alpine territory, a geographical distribution of soil loss levels similar to the previous assessments. A general very low raise in erosion rates is expected, with an exception for the areas where, according to CLUE-s model simulations, an increase in urban conglomerations and in the extension of forests and permanent crops will occur, to the detriment of arable lands.

1.2 Introduction to Soil Erosion

Soil erosion is becoming one of the questions that most deserve the attention of the entire world community.

The European Union in the Sixth Environment Action Programme (Environment 2000-2010: our future, our choice. Decision of the European Council and Parliament 1600/2002/CE) ratifies that it is necessary to protect soil against the degradation it is subject to, due to the influence of human actions. Moreover, the same Programme ratified the necessity of a thematic strategy for soil protection to be fixed by the services of the European Commission. This document was written by the DG-Environment of the European Commission with the title: "Towards a protection strategy of soil in Europe" (COM (2002) 179). The document takes into consideration eight main threats of soil degradation, three of which are a priority, including the risk of soil erosion.

In September 2006 the thematic strategy was revised (COM (2006) 231 final) and was named as "Thematic strategy for soil protection". Meanwhile the framework directive for soil protection was proposed to the European Council and Parliament (COM (2006) 232 final). The thematic strategy estimates that almost the 12% of the European territory, consisting of 115 million hectares, is subject to water erosion.

Erosion is a complex phenomenon which is affected by many factors such as: climate, soil, morphology, soil cover and, last but not least, the excessive human action on the territory.

At present it is estimated that in the Mediterranean region water erosion could affect the loss of 20/40 t ha^{-1} of soil after a single cloudburst, and in extreme cases the erosion could be of even more than 100 t ha^{-1} (Morgan, 1992).

1.3 Driving forces and processes

Superficial erosion is defined as the particles detachment and entrainment from a loose sediment, identified as soil from an engineering point of view. The phenomenon is also known as soil erosion. Erosion regards, in fact, superficial incoherent sediments including detrital ones, soils as indicated by soil or agricultural science and clayey or incoherent sediments of any origin and age (Casati, 1996).

The most important detachment agent is rain, but the complex phenomenon of erosion is influenced also by other important factors. Erosion is basically caused by three kinds of reasons:

- Geological factors (including rocks tectonics or lithology).
- Modelling agents (water, wind, human action).
- Climate conditions (sun radiation, air humidity, atmospheric pressure, temperature, rain type and distribution) (APAT, 2003).

The forces causing erosion are of two types: endogenous (seismic and tectonic phenomena, etc.) and exogenous (phenomenon related to atmosphere, biosphere and hydrosphere); the latter are the first cause of modelling of dry land. Many different factors affect the erosion processes:

climate, soil, morphology, vegetation, agronomic activity, intervention on and settlement of slopes. All these factors are defined as “elementary factors” of the erosion process.

A further distinction can be made between “energetic factors” (precipitation, runoff, slope and slope length, responsible for the entrainment of soil particles), “resistance factors” depending on the soil characteristics (texture, structure, organic substance, permeability, salinity, etc.) and “anthropic factors” (use of soil, agricultural activity, anticorrosive action).

The erosion phenomenon basically takes place when the energetic factors affect the soil that sets against erosion through its resistance factors. Anthropic factors can determine reductions as well as increases of soil loss (APAT, 2003). As a consequence, an estimation of erosion risks is needed as a support to all decisions, in order to put in practice all the necessary interventions aimed at limiting soil loss.

Erosion is a natural process. The anthropication of the territory caused it to be embittered, generating detriments for human and injuries to the environment.

A clear distinction has to be done between damages caused by soil erosion processes at local level (on-site effect) or in places far from the sites where the loss of soil occurs (off-site effect). The following table (Table 1) lists different kind of on-site and off-site erosion damages.

Kind of erosion	On-site damages	Off-site damages
Water	• Loss of organic matter. • Soil structure degradation. • Soil surface compaction. • Reduction of water penetration. • Supply reduction at water table. • Surface erosion. • Nutrient removal. • Increase of coarse elements. • Rill and gully generation. • Plant uprooting. • Reduction of soil productivity.	• Floods. • Water pollution. • Infrastructures burial. • Obstruction of drainage networks. • Changes in watercourses shape. • Water eutrofication.

Table 1: on-site and off-site effects of erosion (Giordano, 2003)

Erosion is a natural process which usually does not cause any major problem. It becomes a problem when human activity causes it to occur much faster than under normal conditions.

1.4 The study of soil erosion over the Alpine Space

A great number of studies have been carried out aiming at an evaluation of water erosion in the alpine territory. In some areas, in fact, the phenomenon is particularly intense and the erosion rates are high. A literature review on the topic has been carried out and it showed that:

- a lot of research has been done to investigate the physical phenomena on which basis the erosion processes take place, in alpine territory as well as in areas with a complex morphology. These studies show how complex the erosion phenomenon is and how it is influenced by environmental factors. Some of these factors are particularly critical in the alpine areas, such as: the reduction in the cohesion due to ice melting (in permafrost soils), particularly intense rainfall and presence of microclimate areas characterised by specific local conditions. All these factors, together with data often lacking, make modelling soil erosion in alpine areas a challenging item. Moreover, it must be pointed out that most of the models usable to estimate erosion over large areas do not take into consideration causes of the process particularly relevant in mountain territories. Even if the most effective cause of erosion is rain it is obvious that, as human can not manage environmental conditions, the erosion process can be limited or increased by means of agricultural and forest actions. As far as soil is ultimately a finite natural resource, its defence is a priority in the view of maintaining satisfactory levels of its functions.
- Do not exist research experiences studying, by means of models specifically set for morphologically complex areas, soil erosion on the alpine territory as a whole. The only existing data are to be found in studies at continental scale as, for example, “Soil Erosion Risk Assessment in Europe – 2000”, (Van der Knijff et al., 2000) or in local studies which are not significant in view of an analysis of soil erosion in the whole alpine space.
- Few study experiences have been carried out with aim of deepening the matter of the climate change impact on soil erosion processes in the Alps with the use of modelling techniques.

Besides the literature review, a census of research institutes and projects related to erosion in the alpine space has been carried out, through focused research and web search. Table 2 and Table 3 list the main bodies, research institutes and projects whose activities and results have been used to build a picture of soil erosion processes in mountain areas.

Acronym	Subject	Focus on Alpine Space	Country
LNSA	Laboratorio Neve e Suoli Alpini	X	Italy
ISSDS	Istituto Sperimentale per lo Studio e la Difesa del Suolo	X	Italy
LaMMA CRES	Centro Ricerche Erosione Suolo		Italy
SISS	Società Italiana della Scienza del Suolo		Italy
ERSAF Lombardia	Ente Regionale per i Servizi all'Agricoltura e alle Foreste		Italy
ERSA Friuli Venezia Giulia	Agenzia Regionale per lo Sviluppo Rurale	X	Italy
UNI BASEL	University of Basel	X	Switzerland
Cemagref	Institut de recherche pour l'ingénierie de l'agriculture et de l'environnement	X	France
UZH	University of Zurich	X	Switzerland
BMLFUW	Federal Agency for Water Management	X	Austria
LTHE	Laboratoire d'étude des transferts en hydrologie et environnement	X	France
JRC	Joint Research Centre – Land management & Natural Hazard Unit	X	Europe
UIBK	University of Innsbruck		Austria
BOKU	University of Natural Resources and Applied Life Sciences		Austria
UNIBE	University of Bern	X	Switzerland
ARPAV	Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto	X	Italy
INRA	Institut national de la recherche agronomique		France
UNI-LJ	University of Ljubljana		Slovenia
APAT	Agenzia per la Protezione dell'Ambiente e per i Servizi		Italy

	Tecnici		
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research	X	Switzerland

Table 2: main bodies and research institutes whose publications have been consulted

Acronym	Project	Website
	Soil Erosion in the Alps	http://pages.unibas.ch/environment/Forschung/Current_projects/Soil_degr_AlpsCA_e_01.htm
	Quantification of Soil Erosion in an Alpine Watershed of Switzerland	
ECALP	ECological soil map of ALPs	http://eusoils.jrc.it/projects/alpsis/MainAlpine.html
PESERA	Pan-European Soil Erosion Risk Assessment	http://eusoils.jrc.ec.europa.eu/Esdb_Archive/pesera/pesera_cd/sect_h4.htm
CORINE	Coordination of information on the environment	http://dib.joanneum.ac.at/alpmon/home.html
ALPMON	Inventory of alpine-relevant parameters for an alpine monitoring system using remote sensing data	http://dib.joanneum.ac.at/alpmon/home.html

Table 3: main projects whose results have been used within the study

The whole set of information collected has been entered in a purposely created database containing scientific abstracts, research projects and institutes related to erosion in the alpine space. The database has been developed using Microsoft Access and has been structured in order to obtain the needed information easily and promptly (Figure 1).

Figure 1: a database page with information about scientific articles

A file of each article included in the database is available with the complete bibliographical information as well as an abstract. For each institute we made a summary of its main activities. Finally, for each research project general information main objectives and expected or obtained results were entered.

1.5 Modelling soil erosion

1.5.1 Review of soil erosion models

Many methods and models are available to evaluate soil erosion. The models, even if based on some fundamental factors of the erosion process, are different especially in terms of data processing and accuracy of results. As for the latter, models can be classified as follows:

- Qualitative models.
- Semi-quantitative models.
- Quantitative models.

Qualitative methodologies are based on the direct observation of the erosion processes, on air photo interpretation of erosion forms and on the study of the geomorphologic cartography. The soil erosion prediction, in this case, is interpreted as the estimation of its extension in adjacent areas which are similar in terms of pedoclimatic, geomorphologic and land use features. This approach permits to define the different types of risk, but does not provide any data about the quantity (ha yr^{-1}) of removed soil.

The semi-quantitative approach consists of a score-based procedure. On the basis of the best professional judgment, it assigns weights to the determinants of soil erosion proportionally to their relative importance in the erosion process. The main examples of models using a semi-quantitative approach are: the Graviloc Model (1959) and, above all, the P.S.I.A.C. (1968) model. The P.S.I.A.C. model provides a very easy way of use as well as the possibility of identifying rough estimation errors. Its use offers a value of soil erosion in five different intervals. The use of the P.S.I.A.C. model implies the relation between each of the nine parameters (geology, soil, climate, runoff, topography, land use, vegetation, areal erosion, lack of sediment at river mouth) and the corresponding value on the basis of a qualitative evaluation of the physiographic characteristics of the basin (APAT, 2003; ARSSA, 2005).

The more and more complex knowledge of the mechanisms that rule the soil erosion processes permitted to create more and more advanced and reliable models. The quantitative approach is based on the parameterization of the different factors determining erosion. Four different categories of quantitative models exist:

- Empirical.
- Conceptual.
- Physically based.
- Stochastic.

The empirical models are based on observations and on mutual relations, statistically obtained, arising from the analysis of experimental data. They are subject to an inductive logic and can be applied by model calibration. The most important empirical models are: the USLE (Universal Soil Loss Equation) of Wischmeier and Smith (1978) and the RUSLE, derived from USLE.

In 1985, during a meeting, the United States Department of Agriculture (USDA) and other experts in the field of erosion decided to revise the USLE model. They introduced further scientific and technological improvements developed after the release of the USLE manual in 1978. The revision of USLE started just two years later, in 1987, and led to the creation of a new model: the RUSLE. The RUSLE model maintains the base structure of USLE.

Both models consist of a set of equations estimating the soil loss deriving from rill erosion processes (rill – inter rill erosion). The models started from the study of erosion processes concerning a high number of years of parcel observations. The equations they are based on are validated and supported by many scholars (Soil and Water Conservation Society, 1993).

These two models use values referring to the four main erosion factors, such as: climate erosivity (represented by R), soil erodibility (K), topography (LS) and land use and management (CP):

$$\mathrm{A} = R * K * L * S * C * P$$

Even though the structure of USLE has not been changed, the algorithms used to calculate the single factors have been significantly modified in RUSLE. The most relevant improvement introduced by RUSLE consists, perhaps, in the introduction of GIS (Geographic Information System) techniques to determine the erosion factors. Although their limitations (explained in the next paragraphs), they have been largely used, probably because of their simplicity and strength (Desmet & Govers, 1996).

Conceptual models lie somewhere between physically based and empirical models. They are based on:

- physical laws and mathematical equations such as, for example, the continuity equation for water and sediments.
- Empirical relations.

Conceptual models have been focused on predicting sediment yields, primarily using the unit hydrograph concept. Meyer and Wischmeier's (1969) model (Figure 2) is one of the most important models of this category. It considers rainfall and superficial runoff as erosion agents.

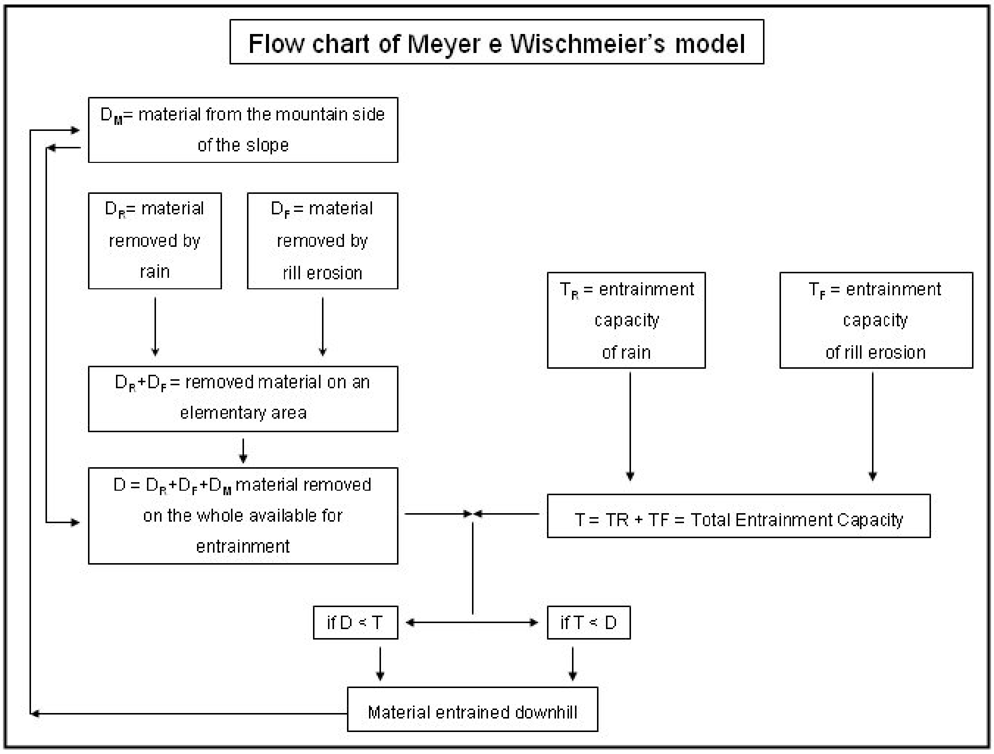

Figure 2: Meyer and Wischmeier's model flow chart

Physically based models try to describe, on the basis of suitable mathematical equations, the essential mechanisms controlling the erosion processes. This kind of models represents a synthesis of the single components causing erosion, including the complex interactions among various factors and their variability in space and time. The result is synergistic, the model as a whole represents more than the sum of the individual pieces. An advantage of physically based models is that they can be improved while deepening the knowledge of natural processes. Among these models, the one with the highest number of studies is WEPP (Flanagan e Nearing, 1995). Developed by the USDA, WEPP is widely used as the USLE successor. WEPP analyses the different processes, both hydrologic and erosive, simulates different elements (climate, wind, etc) and assesses their effects on erosion, using a variable time scale. One of the main limits of this model is that it works on a large scale just on areas having a maximum extension of a few hundreds hectares. Another widespread model is SWATT (EPA, 2002). It differs from WEPP because it works on smaller geographic scales and on annual time scale only. In Europe a physically based model has been recently implemented, EUROSEM. It has been developed on the basis of WEPP but trying to adapt it to the European continent situation.

Even though there is plenty of studies, most of which are still in progress, it is not clear yet whether it is possible to model all the factors affecting soil erosion processes. The complexity of some factors (microbiological, chemical, micro climatic), in fact, could be possibly better analysed through stochastic models. They are used to create random data sequences given in relation to the statistic characteristics of the available data (APAT, 2003).

Models results, compared with values obtained through direct measurements, often provide an unsatisfactory feedback. This is because all models generally need to be set on the specific conditions of study areas. As a matter of fact, soil erosion models basically overestimate the erosion caused by not very erosive rainfalls and, on the contrary, underestimate it in case of extreme events (Nearing et al., 1999). In spite of their limits, the erosion models (a list of the main model is in Table 4) are fundamental to evaluate which factors can be modified by human action and in which way, in order to reduce the phenomenon within sensible tolerability limits.

Soil Erosion Models	Empiric/Physically based /Parametric	Single events/Continuous	Field scale/Basin/ Region	Data request Low/Medium/High	Complexity Low/Medium/High	GIS Integration Low/Medium/High	Difficulty of use Low/Medium/High
USLE (Wischmeier & Smith 1978)	E	S/C	F/B	M	M/H	H	M
EPIC/apex/almanac (Sharpley & Williams 1990)	E	C	F	M	M	L	M
RUSLE (Renard et al. 1991)	E	C	F/B	M	L	M	L
AGNPS (Young, R.A. et al. 1989).	E	S/C	F/B	M	L	H	L
MUSLE (Williams, 1975)	E	S	F/B	M	L	L	M
USPED (Mitasova et al. 1996),	E	C	F/B	M	M	M	L
CREAMS (Knisel, 1980)	Ph	S/C	F	H	M	L	H
SWRRB (Arnold et al.1990)	Ph	C	W	M	M	L	L
PSIAC (1968)	Ph	C	L	L	L	M	H
SPUR (Hanson et al. 1992)	Ph	C	F/B	M	H	L	H
SWAT/HUMUS (Arnold et al. 1995)	Ph	C	B/L	M	M/ H	H	M
GLEAMS 2.1 (Knisel, 1993)	Ph	C	F	H	M	M	H
CASC2D (Julien & Saghafian 1991).	Ph	S/C	B	M	M	H	L
MULTSED (Simons et al. 1980)	Ph	S	B	H	H	L	H
ARMSED (Riggins et al 1989)	Ph	S	B	H	H	L	H
WEPP prof/basin (Flanagan & Nearing 1995)	Ph	C	F/B	M	M	L	M

SIMWE (Mitas & Mitasova, 1998)	Ph	S	F/B	M	M	H	M
ANSWERS (Beasley et al., 1980)	Ph	S	F/B	M	M	H	M
KINEROS (Woolhiser et al., 1990)	Ph	S	F/B	H	M	L	M
EUROSEM (Morgan et al.1993)	Ph	S	F/B	H	H	L	M
SHE (Abbott et al.1986a,b)	Ph	S/C	F/B	H	H	M	M
SEMMED (De Jong & Riezebos 1997).	Ph	S	B/L	H	M	M	H
CSEP (Kirkby and Cox, 1995)	Ph	C	B/R	L	M	M	M
MEDRUSH (Kirkby, 1998)	Ph	C	B	H	H	H	M
EROSION3D (Werner et al., 1997)	Ph	S	F/B	H	H	H	M
ACRU (New & Schulze 1996)	E	C	F/B	H	H	L	H
PISA (Bazzoffi,1993; Bazzoffi et al. 1998)	E	C	B	L	L	H	L
AGQA (Ciccacci et al. 1987)	E	C	B	L	L	H	L
CORINE erosion (EEA, 1995)	P	C	R	L	L	H	L
PESERA (Kirby et al., 2004)	E	C	R	H	H	H	H

Table 4: summary of the main soil erosion models features (Bazzoffi, 2002)

1.5.2 A focus on mountain regions

Soil erosion is a matter of primary importance in mountain areas. The analysis of the existing studies on the topic highlights that the main research methodologies have been developed to study erosion in agricultural contexts or hill areas with a mild climate. Therefore, it is difficult to apply these methods in mountain areas, also because of the extremely complexity of the alpine system.

For this reason, some researchers assert that the most common soil erosion models, as USLE/RUSLE or CORINE EROSION, can not be efficiently applied in an alpine environment because they were designed to be used on hilly terrains for agricultural purposes where sheet and rill erosion processes are prevailing. Furthermore, the above mentioned models are not designed to consider some typical erosion processes of alpine areas, as for example the debris flows.

An efficient model to analyse the real morpho-sedimental processes, should in theory be able to:

- minimize empirical factors and be based mainly on physically based factors.
- Use strong calculation methods.
- Combine all factors involved in the process.

A step forward has been made in this direction with the introduction of new-generation models, as i.e. WEPP (de Rosa, 2004). However, as regards the research related to erosion and, in this case, alpine areas erosion, the more used model is USLE (in one of its different versions: i.e. USLE, RUSLE). As a matter of fact, it is the only model in which input data can be obtained in different ways (measurement, estimation, interpolation).

Advanced models, as WEPP, have been and still are less used because they are often less flexible to be adapted to situations that have not already been parameterized before. Furthermore, USLE is a model used on differentiated spatial scales.

Thanks to its undoubted points of strength, some parts of this erosion estimation model have been incorporated in other models, as for instance: CREAMS, AGNPS, SWAT or ANSWER.

Another advantage in the use of USLE is related to its flexibility, it is always possible to set this equation to adapt it to the environment to be analysed.

As for the alpine and, in general, high mountain areas, a new equation for the calculation of the S factor has been proposed. In other words, the equation is used for the calculation of the influence that slope may have on the estimation of soil erosion. That permitted to overcome the difficulties due to its use in complex areas from the topographic point of view, being the equation suitable to analyse slight slope areas.

USLE is, as a matter of fact, a valuable means that has been and still is largely used, nevertheless, a complete development level of the models WEPP or EUROSEM will probably cause its decline. On a large scale the data input accuracy rapidly decreases and, in addition, erosion processes change with scale and models such as the USLE are not able to cope with this.

Due to these difficulties the soil loss absolute values can not be obtained on a large scale with a reasonable level of confidence. Nevertheless, on the basis of a common data set, models such as USLE may be used conceptually to obtain a relative ranking of soil loss risk.

In the last years a series of research have been carried out to compare erosion model predictions of soil loss with measured data. As for USLE, RUSLE and WEPP, results indicate that the three models are operating at the same accuracy level in the analysis of the soil loss processes; anyway, there is a substantial difference in relation to which many researchers indicate WEPP as USLE successor. WEPP is, in fact, the only among the three models to be specifically designed to predict sediment yield.

On the basis of the above mentioned considerations, we decided to use the RUSLE model. The main reason of this choice is that RUSLE has a more flexible data processing system. A further reason is the acquired experience in the application of RUSLE both on local and continental scale. On the contrary, it is useful to highlight the fact that, as already mentioned, the RUSLE model has been designed mainly for agricultural terrains. Its application in alpine areas could hence lead to a overestimated result of the process of water erosion, above all in relation to geomorphologic factors. However, it is necessary to take into account that the main objective of this research is the assessment of the soil erosion in relation to climate change. From this point of view, the analysis of the cartographic printouts should be considered comparative and not absolute.

1.6 Quantitative analysis of actual erosion on the Alpine Space using RUSLE model

1.6.1 Input data and factors

RUSLE estimates erosion by means of an empirical equation:

$$A = R * K * L * S * C * P$$

Where:

A = (annual) soil loss ($t\ ha^{-1}\ yr^{-1}$).

R = rainfall erosivity factor ($MJ\ mm\ ha^{-1}\ h^{-1}\ yr^{-1}$).

K = soil erodibility factor ($t\ ha\ h\ ha^{-1}\ MJ^{-1}\ mm^{-1}$).

L = slope length factor (dimensionless).

S = slope factor (dimensionless).

C = cover management factor (dimensionless).

P = human practices aimed at erosion control (dimensionless).

As spatial information regarding human practices aimed at protecting soil from erosion were not available, to the P factor was set value 1 and, actually, it has not considered.

The procedures used to estimate the different factors are explained in detail in the following paragraphs.

1.6.2 Rainfall-runoff

The erosion factor R, also known as rain aggressiveness factor, indicates the climatic influence on the erosion phenomenon through the mixed effect of rainfall action and superficial runoff, both laminar and rill. For the assessment of the R factor it is possible to use different procedures.

Wischmeier (1959) identified as the best indicator of rain erosivity a composite parameter, EI_{30}. It is determined, for every rain event, by multiplying kinetic energy of rain by the maximum rain intensity occurred in a time interval of 30 minutes.

Wischmeier's procedure consists in computing R factor as the average, on a consistent set of data, of the sum of EI_{30} values for the whole set of rainfall events in a year.

$$R = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m_n}(E)_k(I_{30})_k\right]$$

Where:

n = number of years.

mn = number of rainfall events occurring in the nth year.

EI_{30} = product of storm kinetic energy (E) and the maximum 30 min intensity (I_{30}).

For a strict computation of R factor, a huge number of pluviometric data with high temporal resolution (30 min) is necessary. Rain aggressiveness factor probably is, among the different components of the soil loss equation, one of the most difficult to derive, above all because rainfall data with adequate temporal resolution are very difficult to obtain over large areas. Rainfall data we could collect during ClimChAlp project are not enough detailed to apply Wischmeier and Smith's procedure to compute R factor over the whole alpine space.

This is the reason because simplified formulas, with lower temporal resolution, were applied. Many of these formulas use the Fournier's index (F) modified by Arnoldus (1980).

$$F = \frac{\sum_{i=1}^{12} p_i^{\,2}}{P}$$

Where:

p = average month rainfalls.

P = average annual rainfalls.

Other equations, instead, are exclusively based on the average annual rainfalls (P).

$$P = \frac{\sum_{i=1}^{n} p_i}{n}$$

Where:

p_i = i^{th} year precipitations.

n = number of years.

Existing literature is not exhaustive with regard to the algorithms to be applied, with the aim of determining R factor, instead of the Wischmeier and Smith's EI_{30} in the alpine zone. We have hence carried out a deep analysis of some of the mostly used formulas (Arnoldus linear (1977), Arnoldus exponential (1980), Renard and Freimund (1994) - F, Renard and Freimund (1994) – P, Lo et al. (1985), Yu and Rosewelt (1996), Ferrari et al. linear (2005), Ferrari et al. exponential (2005), based on mean annual precipitation or on modified Fournier's Index (Table 5).

Author	Equation
Arnoldus (1980)	$R = [(4.17 * F) - 152]$
Arnoldus (1977)	$R = [0.302 * (F^{1.93})]$
Renard & Freimund (1994) - F	$R = [0.739 * (F^{.1.847})]$
Renard & Freimund (1994) - P	$R = [0.0483 * (P^{1.61})]$
Lo et al.	$R = [38.46 + (3.48 * P)]$
Yu & Rosewelt (1996)	$R = [3.82 * (F^{1.41})]$
Ferrari et al. (2005) – linear	$R = [(4.0412 * P) - 965.53]$
Ferrari et al. (2005) - exponential	$R = [0.092 * (P^{1.4969})]$

Table 5: commonly applied equations to estimate erosivity

With this analysis we intended to evaluate the applicability of these methods, developed in different climatic zones, on the alpine region.

A statistical analysis was hence carried out to estimate the degree of correlation (Correlation Coefficient [R^2] and Root Mean Square Error [RMSE]) between R factor values computed by means of EI30 or using the simplified formulas. The analysis was carried out on rain data with high temporal resolution available for 42 meteorological stations in Veneto region, inside the alpine territory. Data were supplied by ARPAV (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto).

With the aim of computing the correlation between the simplified formulas and Wischmeier's R factor, Pearson (r) correlation coefficient was used.

$$r = \frac{\sum\left(x - \overline{x}\right) * (y - \overline{y})}{\sqrt{\sum\left(x - \overline{x}\right)^2 * \sum\left(y - \overline{y}\right)^2}}$$

Where:

x and y = original data and modelled values, respectively.

$\overline{x}$ = mean original data.

$\overline{y}$ = mean modelled data.

R^2 is the square of the r correlation coefficient. It can be interpreted as the ratio between y variance imputable to x variance.

RMSE can be computed by mean of the following formula:

$$RMSE = \sqrt{\frac{1}{n} * \sum_{i=1}^{n} k_i^{\,2}}$$

Where:

n = the number of location subjected to validation.

k_i = the difference between R estimated and R (EI_{30}).

It soon came out a clear difference between formulas based on modified Fournier's Index and the ones using mean annual precipitations. The latter show higher values of R^2.

A first analysis compared EI_{30} erosivity index with R factor values estimated by means of the simplified formulas. Looking at data distribution (Figure 3), it comes out that all simplified formulas over or under-estimate R factor. Among all the other, with growing over or under-estimations at higher R values, Lo et al. (1985) and Ferrari et al. linear (2005) equations show a systematic over-estimation. Lo et al. and Ferrari et al. linear equations show the highest R^2 and among the lowest RMSE values (Table 6). Compared to Lo's equation, Arnoldus (1980) formula shows a lower RMSE value but its R^2 is inferior and its trend inconstant: the higher are R (EI_{30}) values, the higher are the errors. The maximum error caused by Arnoldus is higher than the Lo's one. All these reasons make the equations proposed by Ferrari et al. linear and Lo preferable in comparison with Arnoldus's formula.

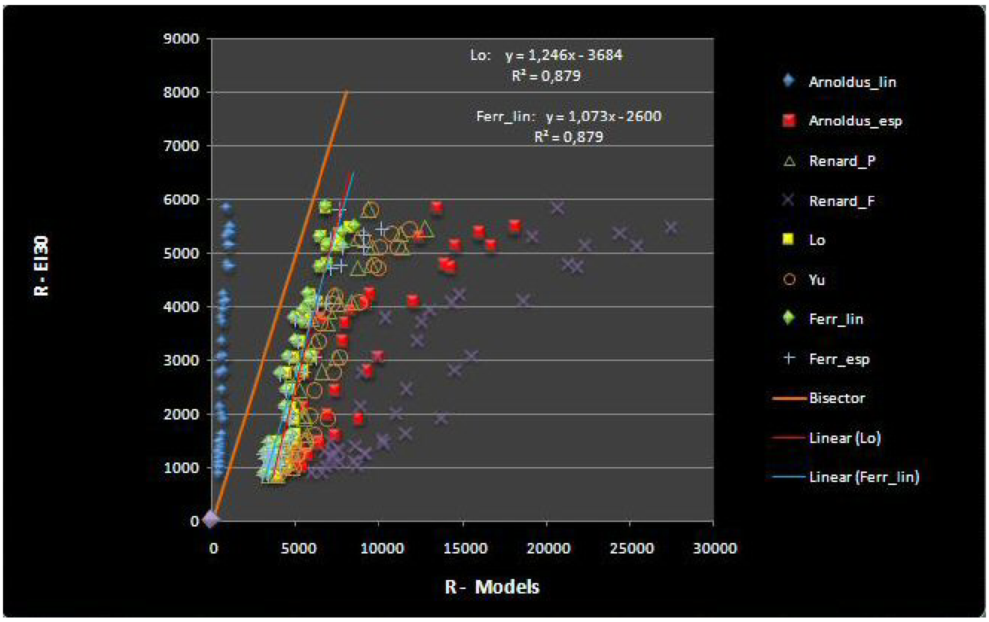

Figure 3: comparison between R factor values obtained with EI_{30} method and simplified formulas

	Arnoldus linear	Arnoldus exponential	Renard P	Renard F	Lo	Yu	Ferrari linear	Ferrari exponential
r Pearson	0.9182	0.9075	0.9292	0.9088	0.9378	0.9146	0.9378	0.9312
R^2	0.8431	0.8236	0.8635	0.8259	0.8795	0.8365	0.8795	0.8672
RMSE	2460	5907	3617	10860	2509	3844	2310	2510

Table 6: r Pearson, R^2 and RMSE values arising from the statistical analysis between R (EI_{30}) and simplified formulas

Ideally, none of the formulas we tested can be considered suitable for a quantitative estimation of erosion on the alpine territory. Unfortunately, the lack of data with adequate resolution got us to apply the best one among them.

Ferrari et al. linear equation shows, with the same R^2, lower RMSE values compared with Lo's formula. In spite of it, we decided to use the latter because pluviometric available data were acquired in Veneto region and we could not determine if they were representative of the whole alpine space. We preferred, hence, to apply Lo's equation which has firm international literature, whereas Ferrari's formula is rather recent.

From simple linear transformations of the adopted formulas it came out the possibility to improve their performances (by linear transformations we mean transformations whose parameters can be obtained by means of the mean square method: that is linear, logarithmic, power, or exponential transformations). By adopting linear transformations, equations showed nearly unvaried R2 values, whereas RMSE values basically improved. As an example, Lo's formula RMSE value 2500 becomes 549.

Due to the limited area the pluviometric data covered and as they were not representative of the whole alpine space, it was not possible to develop a new equation for R estimation.

The rainfall measurement data we used to determine rainfall erosivity factor on the whole alpine space have been provided by the International Centre for Theoretical Physics (ICTP) of Trieste. These data are the output of a prevision model of the climatic change (RegCM, Regional Climate Model), that provides the daily rainfall values for the years 1960 – 1990 and for the IPCC A2 e B2 (2070 – 2100) scenarios. RegCM is a 3-dimensional, sigma-coordinate, primitive equation regional climate model. Version 3 is the latest release. Different reasons explain the choice to use modelled instead of measured data:

- we decided to use dataset sharing the same origin to make more significant comparisons between actual and future rate of erosion.
- Modelled data have homogeneous spatial distribution and accuracy over the alpine space. It warranties to make analysis with the same level of accuracy over the whole study area.

- Last but not least, ICPT data were promptly available at the beginning of the project.

With the use of GIS interpolation techniques and the application of Lo's formula we obtained the current spatial distribution of the erosivity factor R in the Alps (1960-1990) (Figure 4).

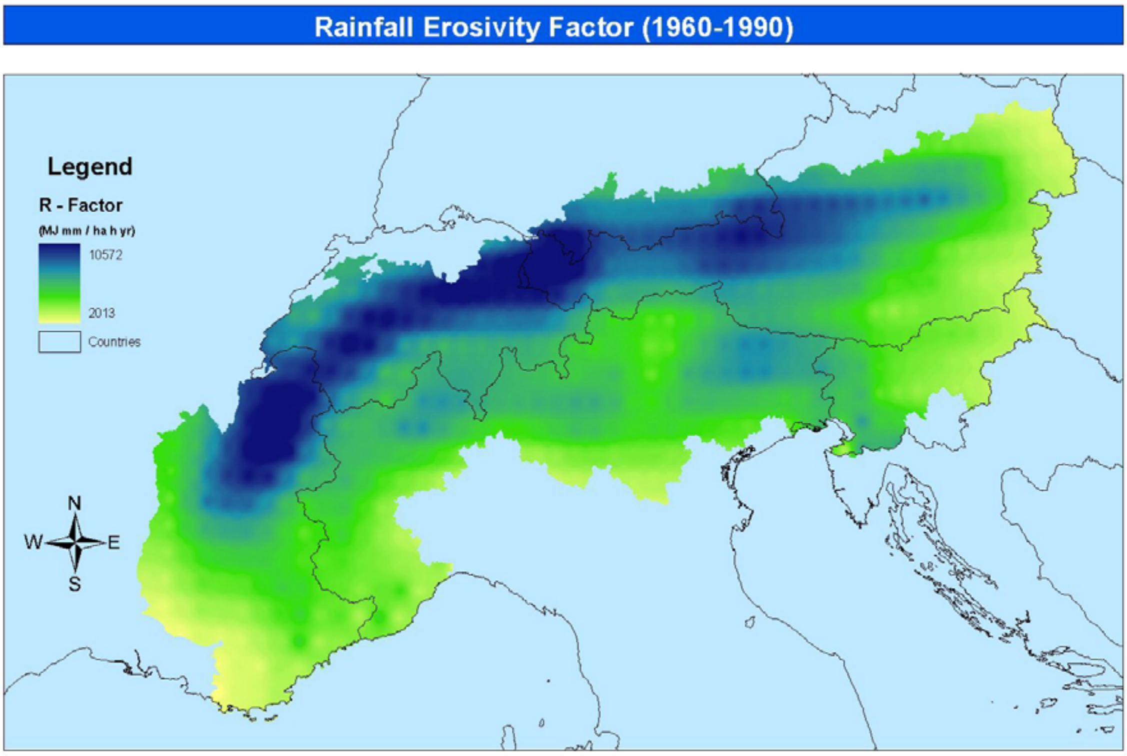

Figure 4: Rainfall Erosivity Factor map (Lo, 1985) based on historic series 1960 – 1990 (MJ mm ha^{-1} h^{-1} yr^{-1})

1.6.3 Soil erodibility

The soil erodibility factor K indicates the erosion tendency of soils. It is defined as the unit erosion index for the R factor in relation to a standard fallow parcel (22.13 m length; 9% slope). On this basis, the value of factors such as length, slope, cultivation and anti-erosion actions becomes unitary. K is usually estimated using the normograph and formulae that are published in Wischmeier e Smith (1978). While these equations are suitable for large parts of USA, they are not ideally suited for European conditions. Romkens et al. (1986) performed a regression analysis on a world-wide dataset of all measured K-values, which yielded the following equation (revised in Renard et al.. 1997):

$$K = 0.0034 + 0.0405 * \exp\left[-0.5\left(\frac{\log D_g + 1.659}{0.7101}\right)^2\right]$$

Where D_g is:

$$D_g = \exp\left(\sum f_i * \ln\left(\frac{d_i + d_{i-1}}{2}\right)\right)$$

D_g is the geometric mean weight diameter of the primary soil particles (mm) and, for each particle size class (clay, silt and sand), d_i is the maximum diameter (mm), d_{i-1} is the minimum diameter and f_i is the corresponding mass fraction.

The database of European soils (SGDBE), in scale 1:1.000.000, has been used to define the soil erodibility factor (Heineke et al., 1998). Texture information in the database is stored at the soil typological unit (STU) level. Each soil mapping unit (SMU) is made up of one or more STU. Due to the type of data concerning the soil texture in the database, some further data processing has been necessary. The processing led to the creation of a soil erodibility value (Table 7) in relation to the texture class (Van der Knijff et al., 2002). For each SMU, a K-value was estimated for all its underlying STU. Then a weighted average was computed, where the weights are proportional to the area of each STU within a SMU. The resulting erodibility map is shown in the following map (Figure 5).

TEXT	**Dominant surface textural class**				
	(Present in: STU)	% clay	% silt	% sand	K
0	No information	-	-	-	
9	No texture (histosols,...)	-	-	-	
1	Coarse (clay <18% and sand > 65%)	9	8	83	0.0115
2	Medium (18% < clay <35% and sand > 15% or clay <18% and 15% < sand < 65%	27	15	58	0.0311
3	Medium fine (clay < 35% and sand < 15%)	18	74	8	0.0438
4	Fine (35% < clay < 60%)	48	48	4	0.0339
5	Very fine (clay > 60%)	80	20	0	0.0170

Table 7: representative texture parameters for each texture class

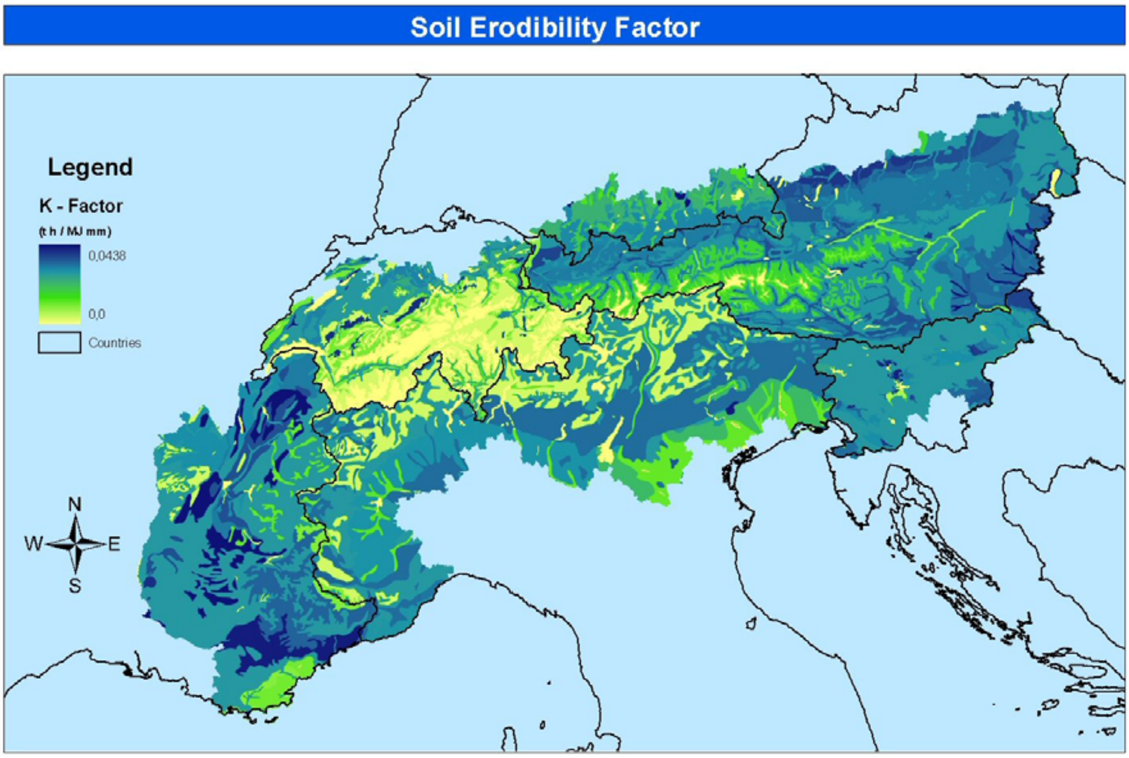

Figure 5: Soil Erodibility Factor map (t ha h ha^{-1} MJ^{-1} mm^{-1})

1.6.4 Slope and Length

The main innovation of the RUSLE model, in comparison with the original model (USLE), is the LS factor. The factor considers the flows convergence and is the result of the combination of the slope (S) and length (L) factors. Many methods have been proposed to improve the calculation of the topographic factor LS, but just in the last ten years a certain accuracy has been reached thanks to the implementation of GIS systems and of digital elevation model (DEM). The L Factor has been substituted by the Upslope Contributing Area (UCA) (Moore and Burch, 1986; Desmet and Govers, 1996), in order to consider the convergence and divergence of the superficial runoff. The UCA area is where water flows in a given cell of the grid. L and S factors have been determined through GIS procedures carried out using the following relation of Moore and Burch (1986):

$$LS = \left(\frac{A}{22.13}\right)^m * \left(\frac{sen\alpha}{0.0896}\right)^n$$

Where:

A = drainage area of a point belonging to a certain cell of the grid.

α = slope.

As suggested by many researchers, the values m and n are considered respectively as 0.4 and 1.3. For the calculation of the LS factor the DEM SRTM (Shuttle Radar Topography Mission) has been used. The accuracy of the DEM is of 90 m.

LS calculation in complex hillslopes is generally problematic for traditional USLE applications, particularly when slope morphology shows great spatial variability (Moore and Burch, 1986; Engel, 1999; Mitasova, 2002). The topographic complexity of the alpine territory, consisting in steep slopes and complex ravine networks, presents significant challenges in estimating the S factor. Therefore, we preferred to modify Moore and Burch's equation. The S factor has been evaluated using Nearing's (1997) formula, that provides more reliable results at high slopes (more than 50%) than those provided by RUSLE, which is used in case of lower slopes.

$$LS = \left(\frac{A}{22.13} \right)^{0.4} * S$$

Where:

$$S = -1.5 + \frac{17}{\left(1 + e^{(2.3 - 6.1 sen\alpha)}\right)}$$

The formula was applied in a GIS environment. A factor has been substituted with the result of the flow accumulation (Flowacc) multiplied by the pixel dimension (cell size). Flowacc consists of the number of cells bringing runoff water to each pixel in the grid.

$$LS = \left(\frac{Flowacc * cell\_size}{22.13} \right)^{0.4} * \left(-1.5 + \frac{17}{\left(1 + e^{2.3 - 6.1 sen\alpha}\right)} \right)$$

The application, in GIS environment, of the above formula brought to the generation of the LS factor map for the alpine space (Figure 6).

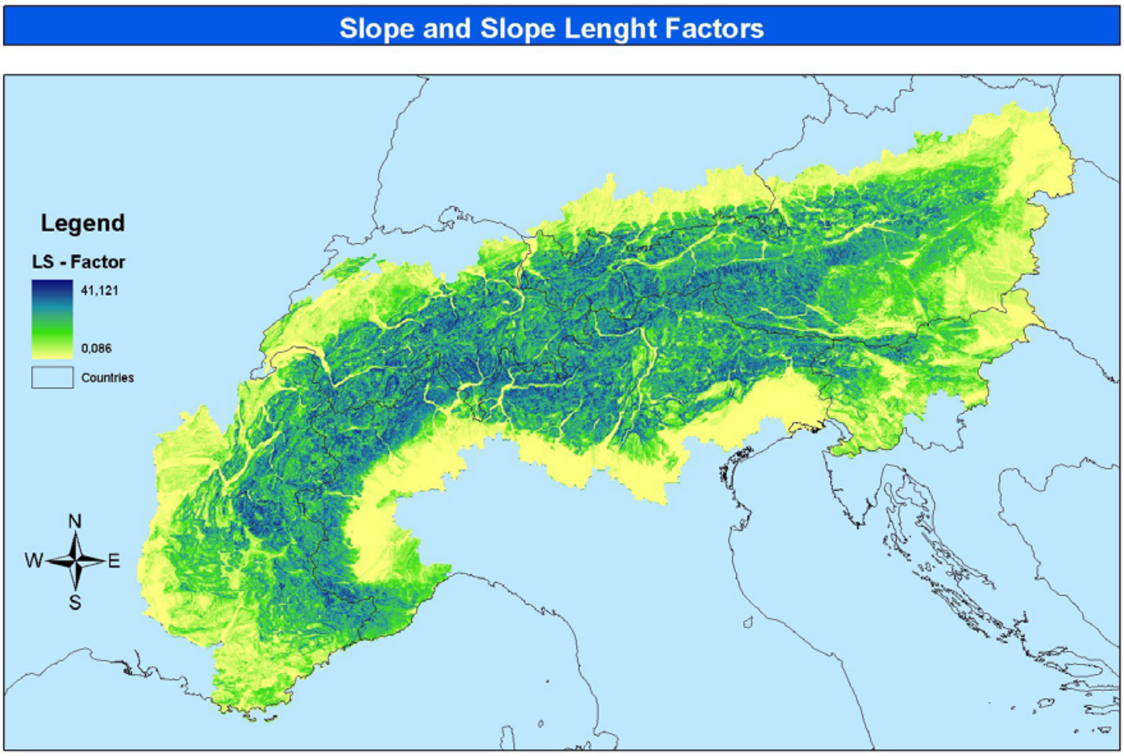

Figure 6: Slope and Slope Length factor map (dimensionless)

1.6.5 Soil cover management

The soil cover factor represents the influence on soil loss of vegetation, terrain cover, agricultural activity, management of agricultural residuals and of soils. The C factor represents the relation between the soil loss in certain agricultural or cover conditions and the erosion that would be obtained from a standard fallow parcel (bare soil). The evaluation of this factor is difficult, because it always depends on changes in terms of environment, cultivations, agricultural activities, residuals management and on the morphology of the plant in the year. The C factor for a certain soil cover typology may have different values. Due to the lack of detailed information and to the difficulties in processing all factors on a large scale, it is difficult to use RUSLE guidelines to estimate the soil cover parameter. Therefore, the average values of literature have been used for this aim (Suri, 2002; Wischmeier and Smith, 1978). The necessary data to establish the C parameter have been provided thanks to the Corine project, a European programme aimed at reproducing maps about soil use, analysing the image of the whole Europe provided by satellite. The calculation of the soil cover factor has been processed using the information layer Corine Land Cover 2000 (CLC 2000) third level. The information layer CLC 2000 is not available for the Switzerland territory. For this area, we decided to use the CLC 1990, in which the Helvetian region is covered. The legends of the Swiss and of the rest of the alpine territory information layers were different. Hence, an intervention aimed at uniforming the data was necessary. To this aim, everything has been traced to the 44 classes of soil use/cover established in the CLC 2000. A C factor value has been assigned to every class, based on literature data (Table 8).

Class ID	Classes	C factor
111	Continuous urban fabric	0.000
112	Discontinuous urban fabric	0.000
121	Industrial or commercial units	0.000
122	Road and rail networks and associated land	0.000
123	Port areas	0.000
124	Airports	0.000
131	Mineral extraction sites	0.000
132	Dump sites	0.000
133	Construction sites	0.000
141	Green urban areas	0.001
142	Sport and leisure facilities	0.001
211	Non-irrigated arable land	0.335
212	Permanently irrigated land	0.335
213	Rice fields	0.335
221	Vineyards	0.550
222	Fruit trees and berry plantations	0.550
223	Olive groves	0.550
231	Pastures	0.010
241	Annual crops associated with permanent crops	0.400
242	Complex cultivation patterns	0.335
243	Land principally occupied by agriculture. with significant areas of natural vegetation	0.100
244	Agro-forestry areas	0.400
311	Broad-leaved forest	0.005
312	Coniferous forest	0.005
313	Mixed forest	0.005
321	Natural grasslands	0.010
322	Moors and heathland	0.010
323	Sclerophyllous vegetation	0.100
324	Transitional woodland-shrub	0.01

331	Beaches. dunes. sands	0.000
332	Bare rocks	0.000
333	Sparsely vegetated areas	0.550
334	Burnt areas	0.550
335	Glaciers and perpetual snow	0.000
411	Inland marshes	0.001
412	Peat bogs	0.001
421	Salt marshes	0.001
422	Salines	0.001
423	Intertidal flats	0.001
511	Water courses	0.000
512	Water bodies	0.000
521	Coastal lagoons	0.000
522	Estuaries	0.000
523	Sea and ocean	0.000

Table 8: soil cover values

The cartographic result is reported in the following map (Figure 7).

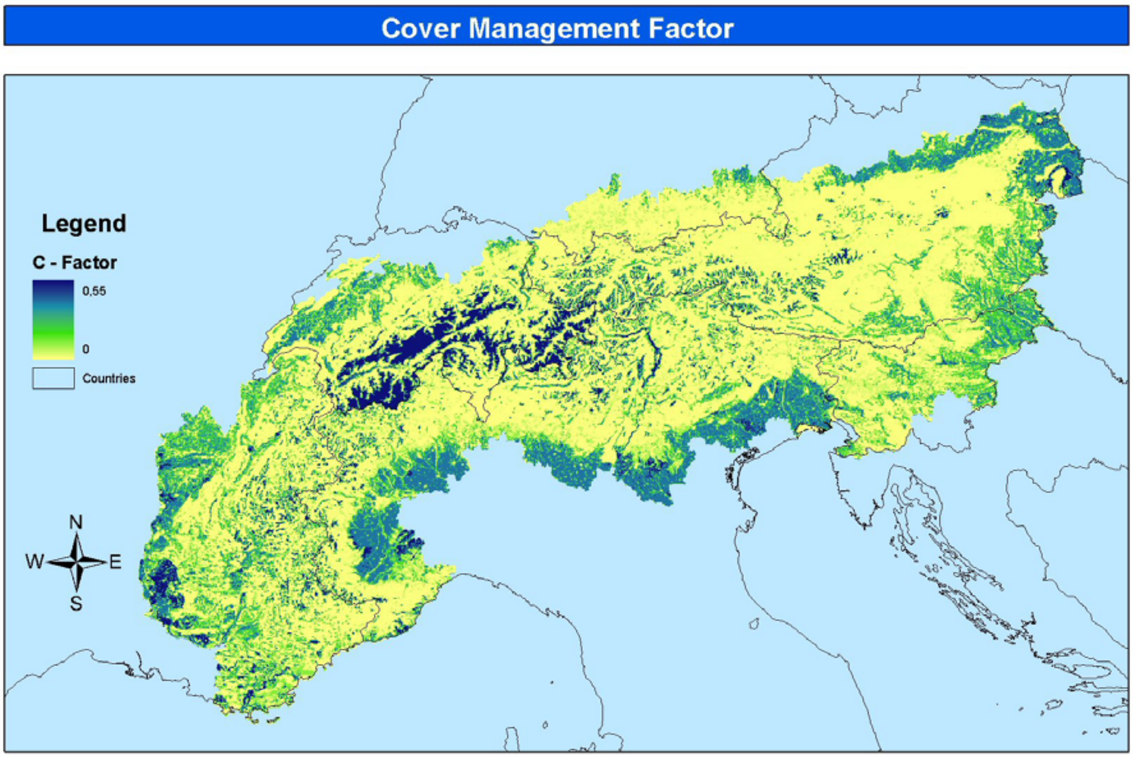

Figure 7: Cover Management Factor map (dimensionless)

Due to the complexity of the territory examined in this work, the approach we used presented some problems. The vast variety of climatic conditions in the alpine areas can cause a large variation both of space and of time in the growing season and in the strength of cultivations. Using a table-based approach, all these factors are not always easy to control. For this reason we made an attempt to use NOAA (National Oceanic and Atmospheric Administration) AVHRR (Advanced Very High Resolution Radiometer) imagery in order to obtain approximate C-factor values. It is a four (AVHRR/1) or five (AVHRR/2) channel radiometer with channels in the visible, near infrared, middle infrared and far infrared parts of the electromagnetic spectrum. The most widely used remote-sensing derived indicator of vegetation growth is the Normalised Difference Vegetation Index (NDVI). We used the Van der Knijff et al. (1999) equation to estimate the C factor starting from the NDVI values.

$$C = \exp\left(-\alpha * \frac{NDVI}{(\beta - NDVI)}\right)$$

Where:

α and β = parameters determining the shape of the NDVI-C curve

The first results we obtained applying this method highlighted the inconsistency of some of the values of the C factor. Van der Knijff (1999) points out that the evaluation of the C factor from NDVI values can be unrealistic, particularly for specific categories such as: grassland and woodland.

Therefore, we decided not to use this method in order to be able to evaluate soil erosion using NDVI values in the future. It will be useful to review the equations available to adjust them correcting possible non realistic values.

1.7 Results and discussion

By integrating the different factors of the RUSLE equation, it was possible to generate, on a GIS platform, the Potential Soil Erosion and Actual Soil Erosion maps (Figure 8 - Figure 9) for the whole alpine space. They define, for each cell of analysis, the quantity of soil (t ha^{-1}) annually lost due to erosion processes.

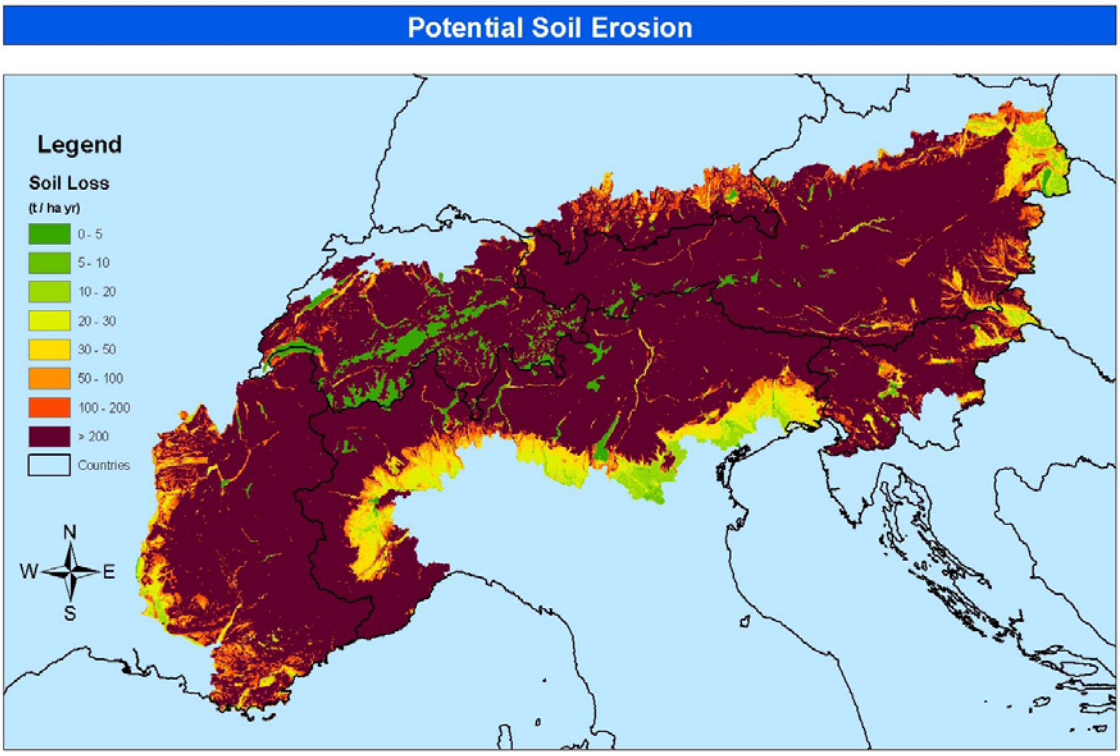

Figure 8: Potential Soil Erosion (t ha^{-1} yr^{-1})

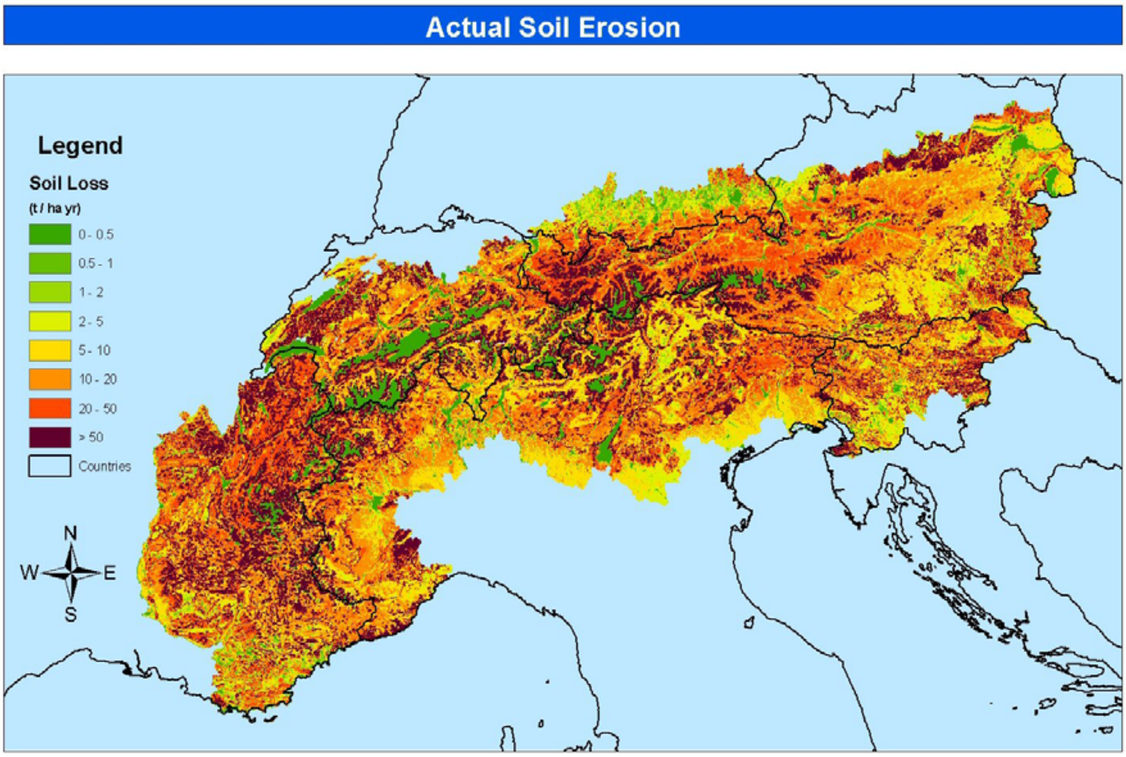

Figure 9: Actual Soil Erosion (t ha^{-1} yr^{-1})

The potential soil erosion map points out the soil loss due to the action of physical factors involved in erosion processes. Hence, it does not consider the action of soil cover. The integrated reading of the two maps show the fundamental role carried out by vegetation in areas potentially exposed to high erosion rates. The mitigating action of soil cover acts reducing kinetic energy drops of water reach the land surface with. It acts on their breaking action and, as a consequence, on translocation of soil particles (splash erosion). Besides, soil cover is a barrier against surface water flowing. This produces a further mitigation of erosive effect (sheet erosion).

By analyzing erosion values obtained with RUSLE application, it is evident that almost the whole alpine territory is subject to erosion phenomena. About 32% of the alpine space shows a rather high erosion (> 20 t ha^{-1} yr^{-1}); nearly 50% shows a middle risk (2 – 20 t ha^{-1} yr^{-1}) and the remaining 18% a low risk (< 2 t ha^{-1} yr^{-1}). Nevertheless, due to the extension of the Alpine Space (the way it has been defined by the Convention of the Alps), it is necessary to carry out a more detailed analysis, linked with geo-litho-morphologic and land use/cover parameters. As it has been previously pointed out slopes, slope length, pluviometric regime and soil cover play a crucial role in the erosive process. The study area was hence subdivided in some classes of landscapes, with the altitude acting as discriminating agent. Elevation shows, at least in the Alps, strong correlations with the other factors previously mentioned. The alpine space was therefore subdivided into four altimetrical zones:

- flat areas (< 300 m above sea level).
- Hill areas (300 – 600 m above sea level).
- Mountain areas (600 – 2000 m above sea level).
- High mountain areas (> 2000 m above sea level).

By analyzing the data relative to the altimetrical zones (Figure 10 and Figure 11), it is possible to notice the relative significance of the different factors of the model:

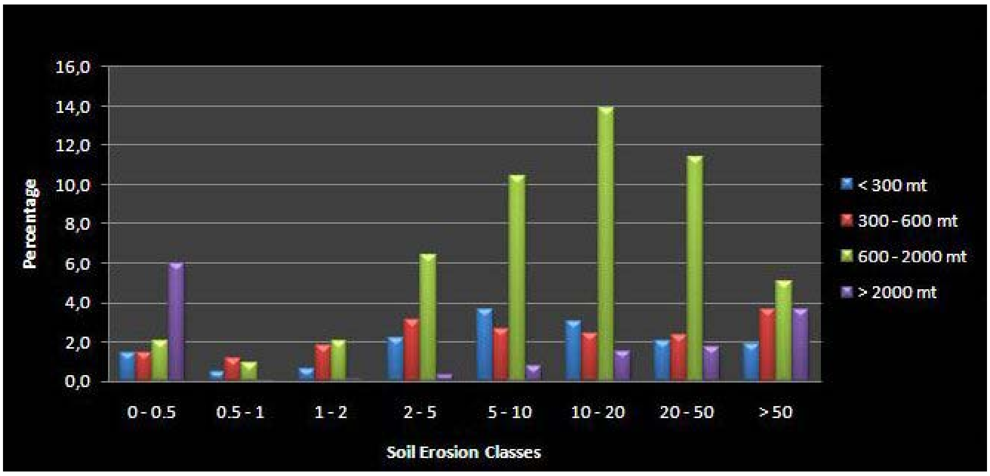

Figure 10: percentage of Actual Soil Erosion in different altimetrical zones

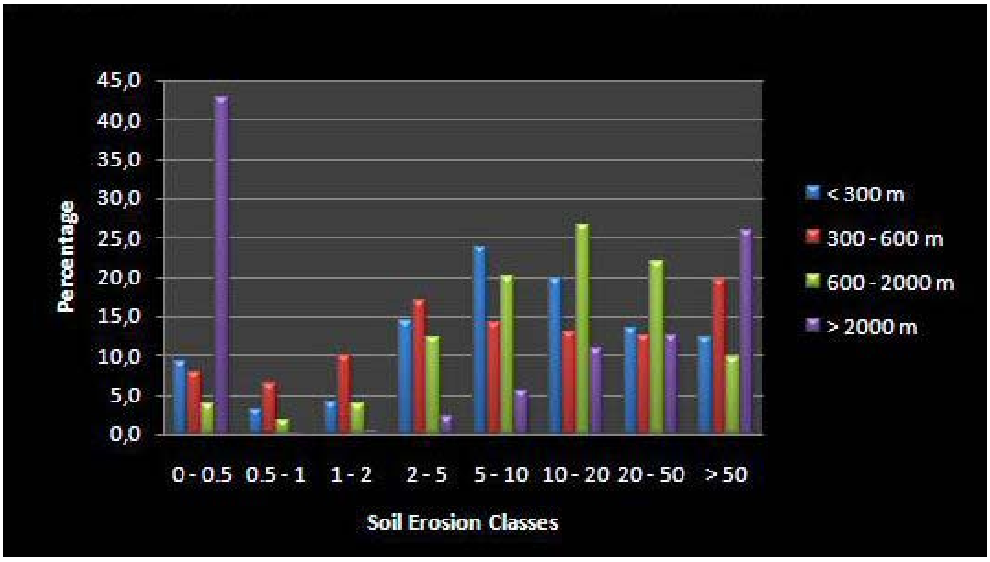

Figure 11: percentage of Actual Soil Erosion within every altimetrical zone

- in the areas below 300 m, nearly the 75% of the territory shows erosion rates lower than 20 t ha^{-1} yr^{-1}. But the remaining 25% is characterized by very high erosion rates. The observation of the C factor map allows to understand that in these areas the role of cover vegetation is low, because the most of these areas are cultivates.
- At higher altitudes (300 – 600 m), the proportion of territory with an erosion rate below 20 t ha^{-1} yr^{-1} diminishes, whilst 20% of the zone shows an erosion rate > 50 t ha^{-1} yr^{-1}. This trend is caused by an increase in slopes which produces very high risk levels in areas with poor cover. On the other hand, the presence of wooded areas contributes in keeping high the percentage of territory with risk level < 20 t ha^{-1} yr^{-1}.
- In the mountain zone (600 – 2000 m) the high presence of forests leaves nearly unchanged, as regards to the lower zones, the percentage of territory with an erosion rate < 20 t ha^{-1} yr^{-1} and allows a reduction of the areas with soil losses > 50 t ha^{-1} yr^{-1}.
- In the high mountain zone, erosion presents a very particular trend. More than 42% of these areas are not subject to soil losses. Moreover, nearly 40% of the remaining territory are interested by very high erosion rates. This is easy to explain with lithologic considerations: at these altitudes, soil is often very thin and bare rocks crops out; but in the areas where soils exist, geo-morphologic characteristics, severe rainfalls and often lacking vegetation cover make them very vulnerable.

After all, without further deepening the item, it is possible to assert that alpine space is, due to its peculiarities, highly vulnerable to erosion risk. But the widespread presence of vegetation cover allows, in a significant part of the territory, to keep it under control and this is the reason because a right management of mountainous region cannot be disregarded.

1.8 Main limits

Erosion assessment in the alpine region, obtained by applying the universal soil loss equation, specifies the quantity of soil yearly moved from a catchment. Every soil particle can undergo different removal and sedimentation cycles. In its way downstream, a huge part of the removed material can sediment due to variations of slope, superficial roughness or land use/cover. RUSLE, which does not consider the sedimentation processes, tends to over-estimate soil loss. Besides, the model is not able to simulate gully erosion, mass movements and riverbed erosion.

The application of RUSLE over the alpine territory, moreover, presented huge difficulties mainly due to problems in finding data. Unfortunately, we were not able to collect the whole set of data necessary for a strict application of the model. We have been often forced to make use of simplified equations, as for R and K factors, or use data with sub-optimal geographic scale, like for C, L and S factors. The simplified equation we used for R factor computation, in particular, though preferable to the other available, tends to over-estimate the measured rates of erosivity and makes scarcely meaningful a validation based on measured data.

These and many other uncertainties propagate throughout the model, resulting in an uncertainty in the estimated erosion rate. Despite these deficiencies and shortcomings, the methodology applied has produced valuable information on alpine soil erosion processes and on their distribution. The spatial analysis, in fact, has allowed the identification of areas which are likely to experience significant erosion rates. More detailed input data and more sophisticated erosion models might warrant a better quantitative estimation of soil losses due to water erosion.

It is however worth noticing that, despite the over-estimation problems, the geographical distribution of soil erosion rates is congruent with the expected results.

1.9 Quantitative analysis of erosion trends on the Alpine Space using RUSLE model, in different climate scenarios

1.9.1 Scenarios data

IPCC identified a set of scenarios (Figure 12) based on socio-economic esteems. They will produce an increase in greenhouse gases concentration and, as a consequence, temperatures could raise from 1.4 to 5.8 °C and rainfall regimes change. Every IPCC scenario comes out from different storylines. Each of them assumes a specific course of future development with diverging final conditions. They cover a while range of key future characteristics such as demographic change, technological and economic development.

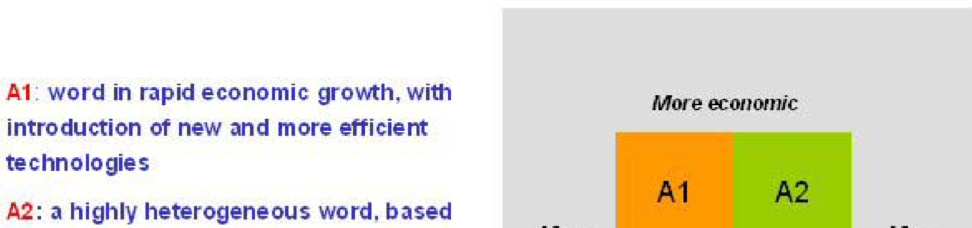

Figure 12: the different IPCC scenarios features

In A1 scenario the world is characterized by a strong economic growth, a decrease, after it has peaked at the middle of the century, in global population and new and more efficient technologies. But this scenario does not warranty on the way the world will develop. The growth, in fact, could be based on the exploitation of different kinds of resources (A1F – fossil fuels, A1T – renewable energies – A1B – both kinds of energies).

A2 scenario is referred to a very heterogeneous world, whose basic feature is the conservation of local identities. Technologic change is slower and fragmented than in other scenarios and economic growth is not very homogeneous. Climatic changes stronger than in other scenarios are foreseen.

B1 scenario shows a demographic trend similar to A1 scenario, but stronger emphasis is given to global solutions for economic, social and environmental sustainability. Raw materials exploitation and energy consumptions are reduced. Specific action aimed at climate protection are not planned.

B2 scenario is based on local solutions for economic, social and sustainability problems. Population is under non-stop growing but with rates lower than in A2 scenario. Economic growth is intermediate and technologic development is slower with respect to A1 and B1 scenarios. This scenario is hence oriented to environment protection and social equity but it focuses on local and regional levels.

1.9.2 Input data and factors

Climate change potential in raising soil erosion is evident, but it is difficult to estimate. The aim of our study, in the framework of ClimChAlp project, was giving an estimation of the potential impact of changing climate on soil erosion processes inside the alpine region.

The quantitative estimation of soil erosion trends resulting from ongoing climate change was carried out, like for the actual erosion definition, by means of the universal soil loss equation (RUSLE). The factor K, L, S and C layer coincided with the ones used for actual erosion estimation. Lo (1985) formula was instead used to generate new maps of erosivity factor R. To this aim ICTP RegCM A2 and B2 scenarios data were used (Figure 13 and Figure 14).

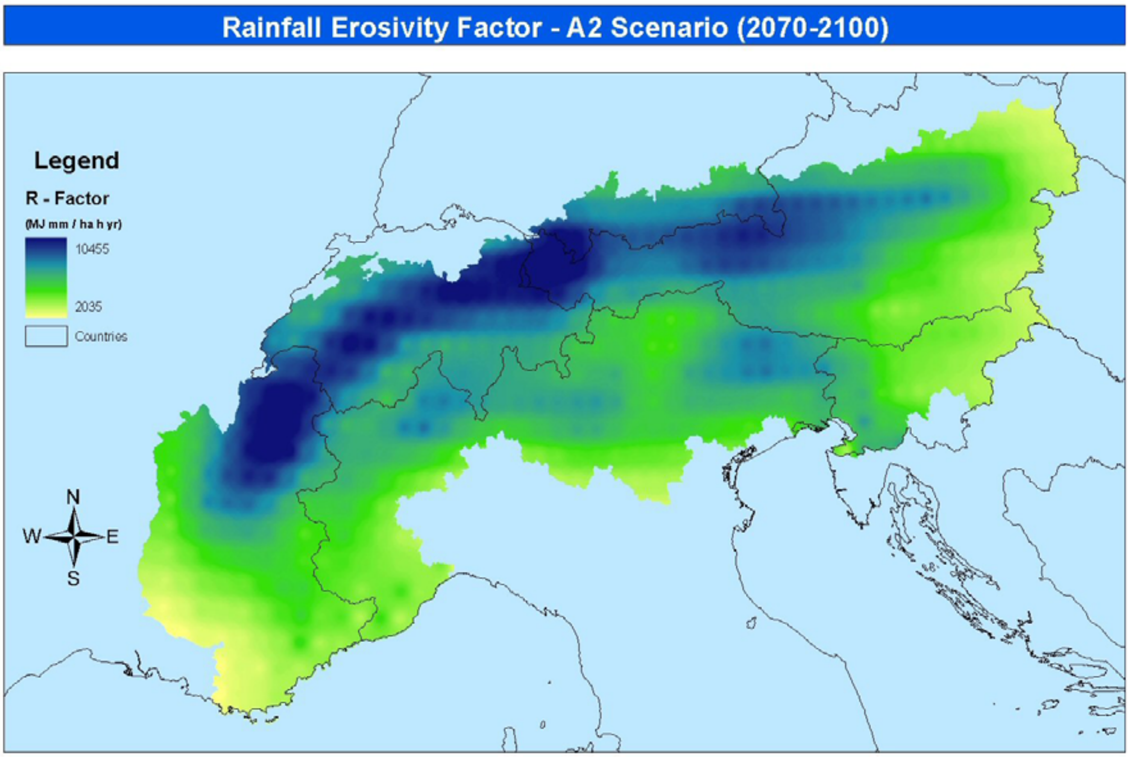

Figure 13: Rainfall Erosivity Factor map (Lo, 1985) based on A2 scenario data (2070 – 2100) (MJ mm ha^{-1} h^{-1} yr^{-1})

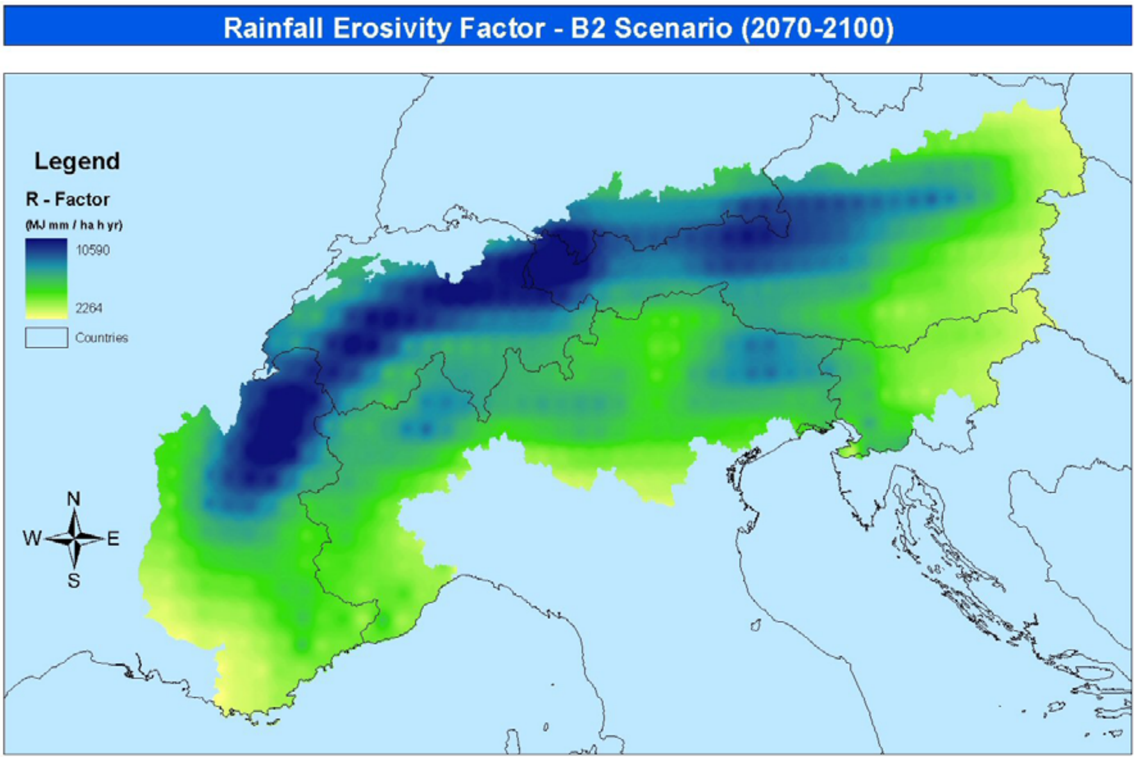

Figure 14: Rainfall Erosivity Factor map (Lo, 1985) based on B2 scenario data (2070 – 2100) (MJ mm ha^{-1} h^{-1} yr^{-1})

1.9.3 Results and discussion

The integration of the different factors of universal soil loss equation allowed to achieve two erosion maps based on climatic data referred to A2 and B2 (2070 – 2100) climatic data (Figure 15 and Figure 16). These maps have been compared with the map of actual erosion. The analysis allowed the definition of soil erosion trends in relation to different scenarios of climate change (Figure 17 and Figure 18).

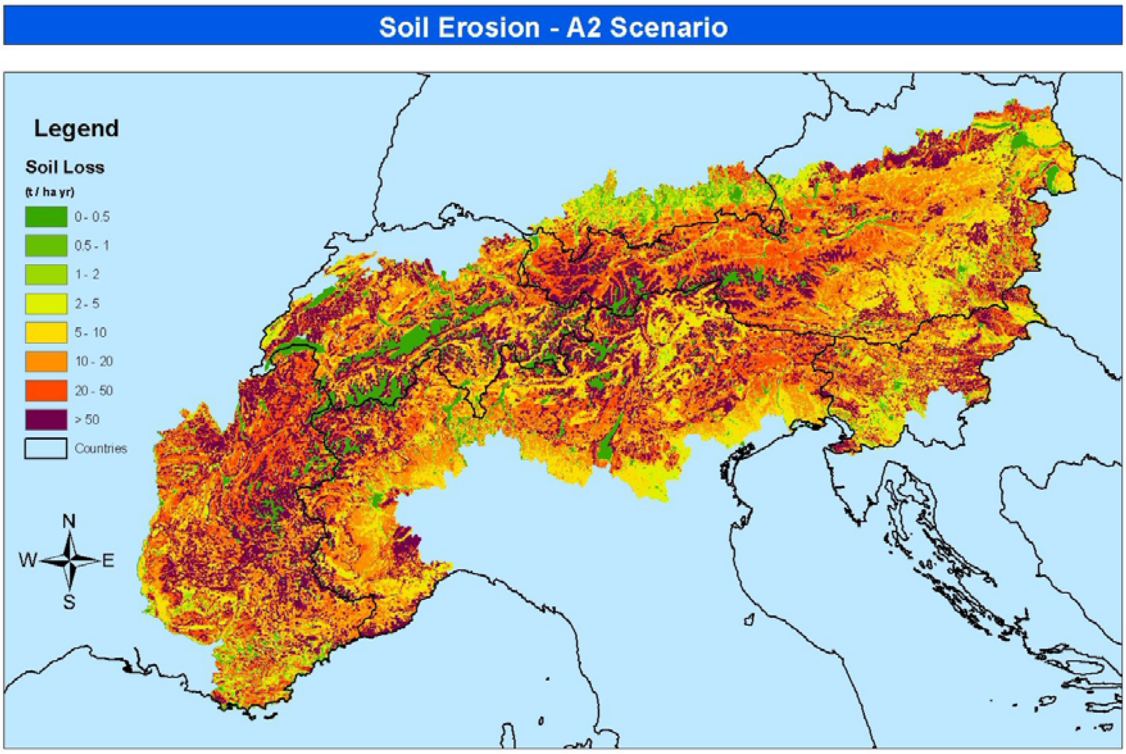

Figure 15: A2 scenario Soil Erosion (t ha^{-1} yr^{-1})

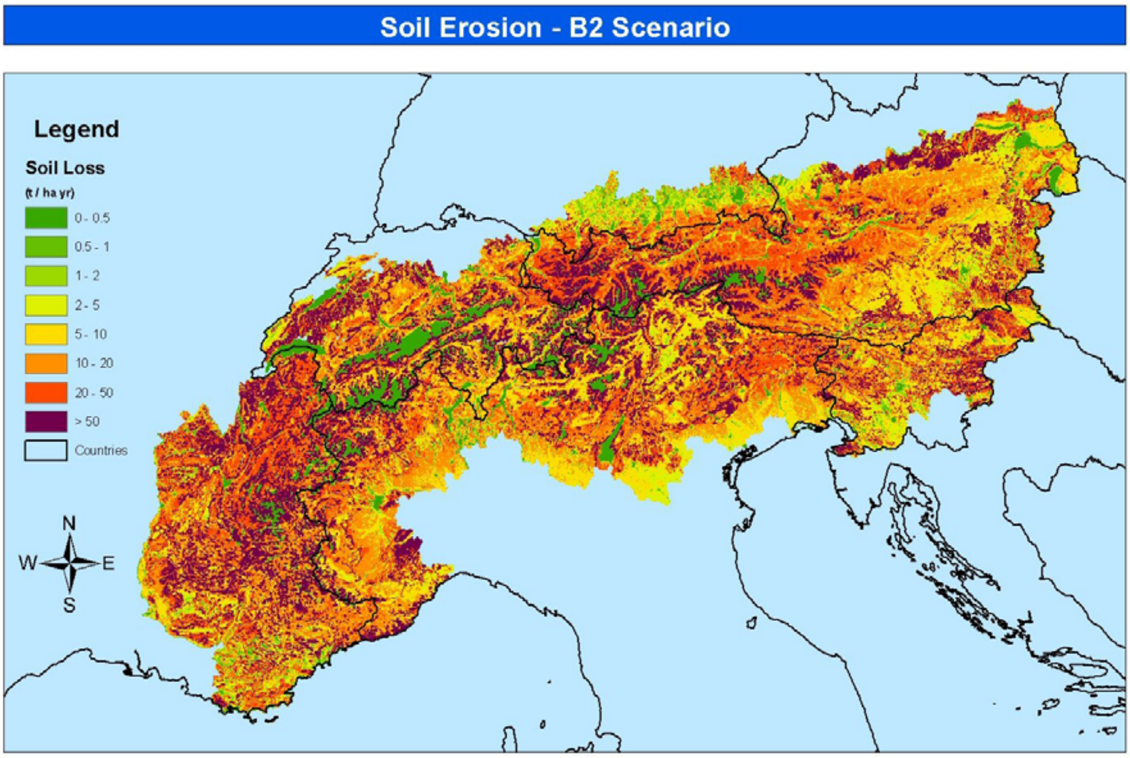

Figure 16: B2 scenario Soil Erosion (t ha^{-1} yr^{-1})

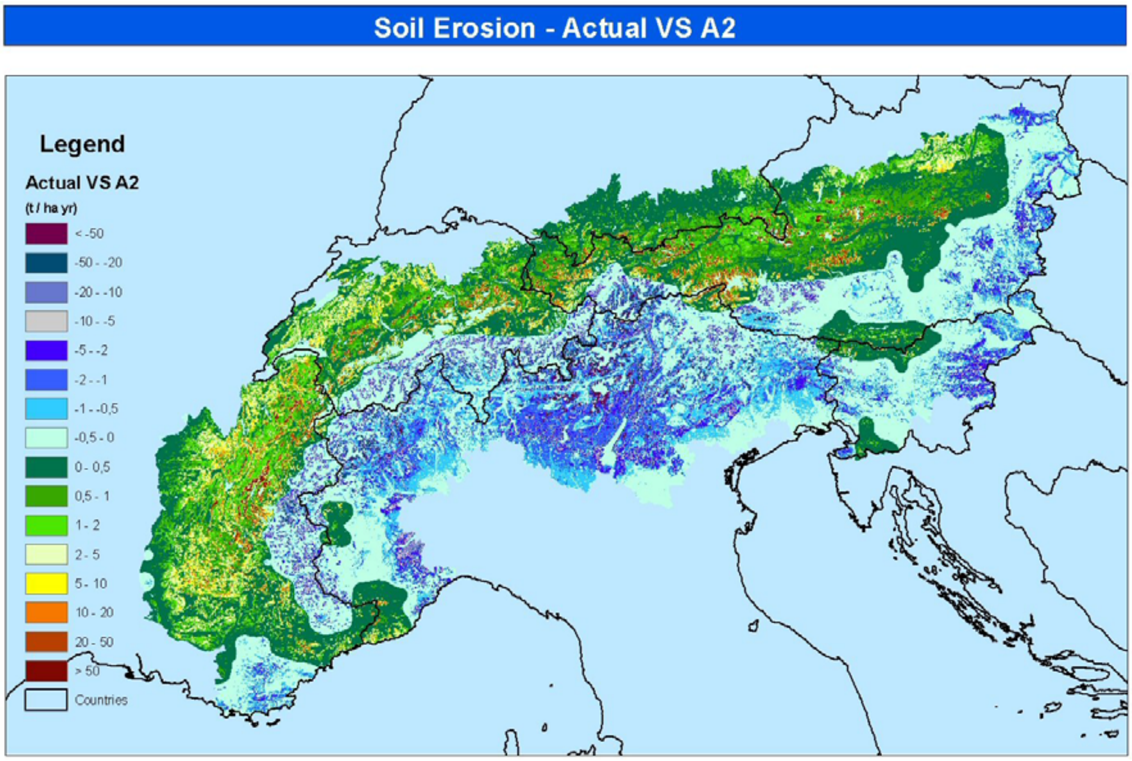

Figure 17: Soil Erosion trend. Actual vs. A2 scenario (t ha^{-1} yr^{-1})

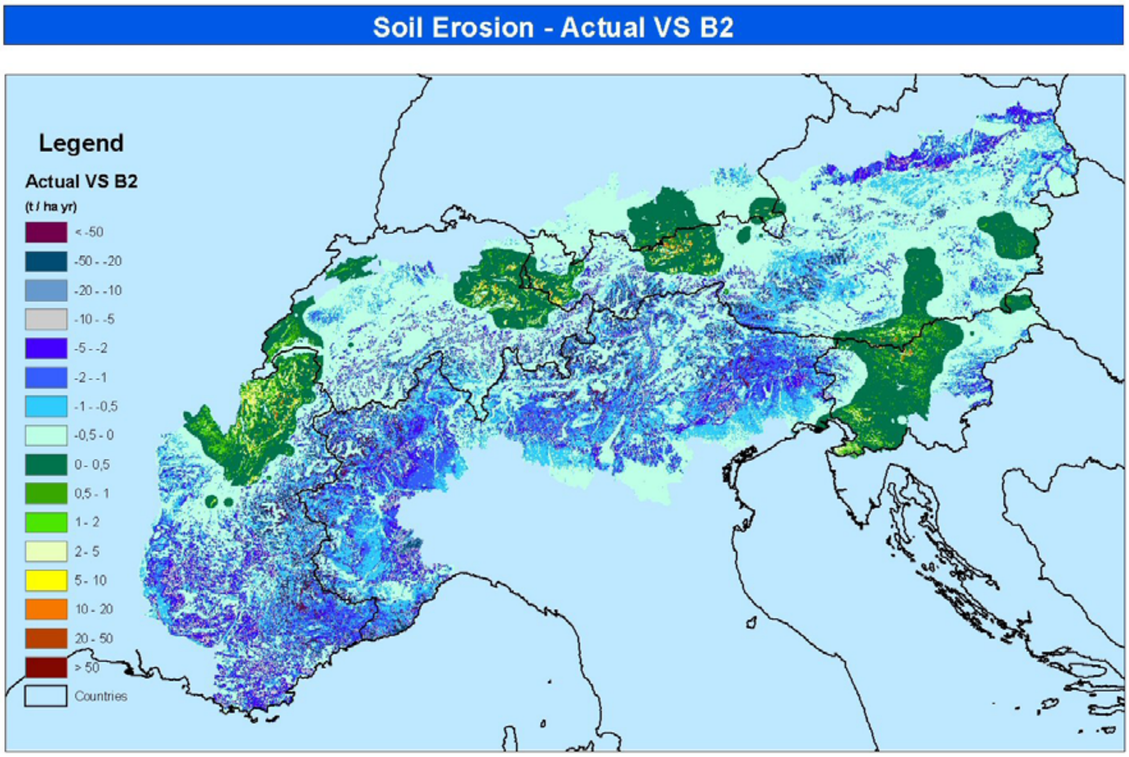

Figure 18: Soil Erosion trend. Actual vs. B2 scenario (t ha^{-1} yr^{-1})

From the analysis some evaluations come out:

- from a general comparison between actual soil erosion (1960 – 1990) and future soil losses (A2 and B2 scenarios. 2070 – 2100), it is evident that erosion rates remain nearly constant (Figure 19). The spatial extension of each class, in fact, is almost unvaried.

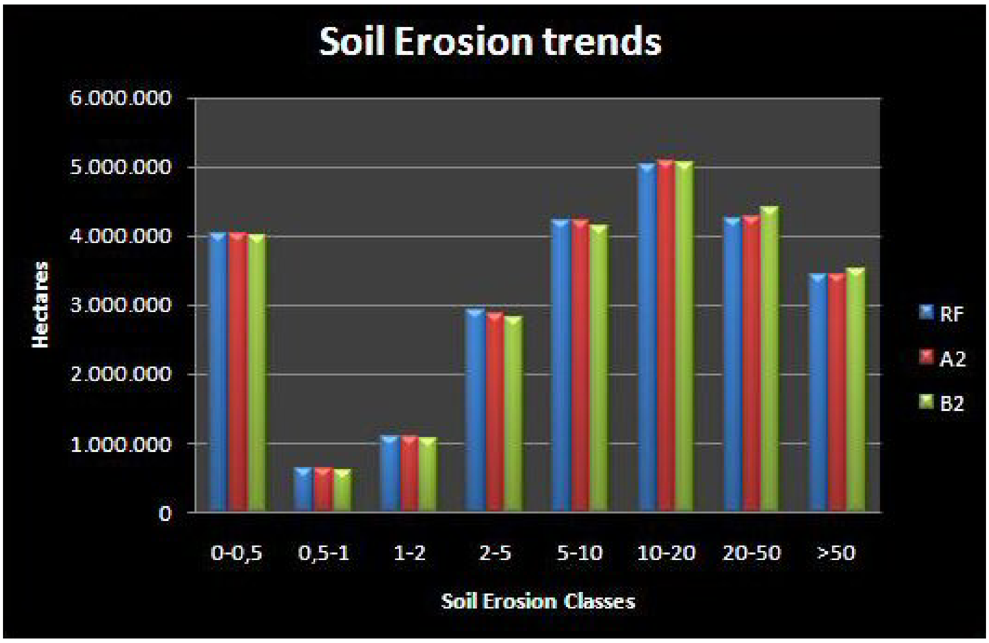

Figure 19: spatial extension of soil erosion classes in the analysed scenarios.

- By comparing the relative variations of soil losses in future scenarios with the actual situation, a low increase in areas with rate of erosion > 10 t ha^{-1} yr^{-1} comes out. As a consequence, areas with an erosion rate lower than that decrease (Figure 20). This phenomenon is more pronounced in B2 scenario. This scenario shows, in particular, a low increase in the extension of areas with an erosion rate higher than 20 t ha^{-1} yr^{-1} rising from 31.7 % to 32.7 %. Also the analysis on altimetrical zone gives, compared to the actual situation, a similar distribution of soil erosion rates.

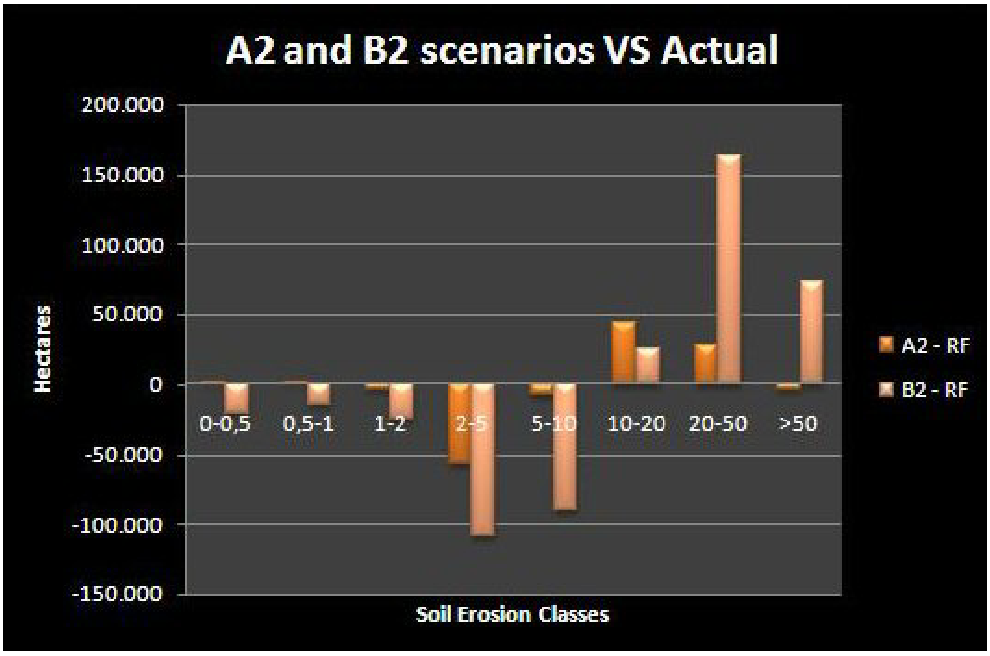

Figure 20: relative variation of soil erosion in A2 and B2 scenarios compared with actual erosion

- Some evidences arise from a spatial analysis of maps defining, for each grid cell, differences between actual erosion data and A2 - B2 scenarios (Figure 17 and Figure 18). B2 scenario shows a general growth of soil losses over a significant part of the alpine space. The increase is, however, of low entity. From A2 scenario comes out, instead, a strong distinction between northern and southern Alps. Northern part should experience a low reduction of soil erosion, whilst in southern areas a rise of soil losses should take place.

Ongoing climate change contributes to arise the spatial variability of rainfalls. They should decrease in subtropical areas and increase at high latitudes and in part of the tropical zones. The precise location of boundaries between regions of robust increase and decrease remains uncertain and this is commonly where atmosphere-ocean general circulation model (AOGCM) projections disagree. The Alps are just located in this transition zone. This is the reason because, as a consequence of the expected climate change, a very little variation in soil erosion rates over the alpine space was predictable. RegCM model, which produced rainfall data used in this study, places the transition zone more southward in B2 than in A2 scenario. Due to this difference in the placement of the transition zone, even though A2 scenario foresees heavier climate change than other scenarios, the B2 scenario shows, over the Alps, higher rainfall rates. This is the reason because in B2 scenario a higher number of areas with erosion rates > 10 t ha-1 yr-1 are present. In A2 scenario, moreover, prevailing winds come from the south. This explains the sharp demarcation line between northern and southern Alps and the increase of rainfalls on the southern side. B2 scenario is characterized by a low increment in soil erosion rates, even if some isolated areas present an opposite trend, which is difficult to explain. The investigation of these phenomena requires further analysis, going beyond the aims of this study. They are possibly explainable from a modelling point of view and could be due to non linearity problems, easily coming out at these scales. To justify their origin different models should be used, with the aim of a deeper calibration of results. This is the reason because IPCC derived results of its four report on climate change making use of 20 climate models.

As mentioned before, soil erosion trends in the alpine region are mainly attributable to changes in rainfall regimes. A better estimation of soil losses in climate change scenarios could be assured by evaluating future variations of cover management factor.

1.10 A Focus on the italian alpine territory: soil erosion trends in climate and land use changes scenarios

As outlined in a previous paragraph (par. 1.6), soil cover is one of the factors that mostly influence soil erosion processes. With the aim of determining the spatial distribution of erosion rates in future scenarios, on the Italian side of the alpine territory it has been analysed, beside the climatic component, the evolution of land use and land cover. To this aim, the CLUE-s (the Conversion of Land Use and its Effects at Small regional extent) model (Verburg et al., 2002) was applied. It is a land use change model able to simulate a reliable future distribution of land use/land cover.

1.10.1 The CLUE-s model

The CLUE-s model uses two modules, a module of non-spatial demand and a module of allocation spatially explicit. In the non-spatial demand module the changes in land use are estimated for a series of years at the aggregate level. Then, the spatial module has to translate the changes in demand into changes in land use pattern within the study region using a raster-based system.

The model, its theoretical bases, the type of parameterization and the input data derivation are deeply described in the Chapter 3 (“Climate impact scenarios on forest biodiversity and land use changes in Alpine zone”) of the ClimChAlp Climate Change Report.

1.10.2 The application of the CLUE-s model

Here, we briefly want to focus on:

- the land use classes considered in the simulation.
- The driving factors used to explain the land use preference.
- The types of simulations made.

Regarding the land use classes, we used the following re-classification (Table 9) of the CORINE LAND COVER legend at the third level for the year 2000, according to the parameterization of C-factor.

The aggregation of classes into macro-classes was made both taking into account codification of the C-factor reported in literature and the similarity among land uses in order to reasonably associate them in the land use change dynamics.

As regards the driving factors, after several attempts aimed at an adequate run of the model, and after studying previous works about land use change modelling with CLUE-s, the most adequate predictors were selected, derivable from datasets already existing. All data were thoroughly checked and updated. In particular, it was decided to work with 12 driving factors falling into different categories: socio-economic, accessibility, geography, biophysics, climate etc. (Table 10).

CORINE LAND COVER classes	CLUE-s classes	C-factor value
111	0	0
112		
121		
122		
123		
124		
131		
132		
133		
141	1	0.001
142		
211	2	0.335
212		
213		
242		
221	3	0.55
222		
223		
231	4	0.01
241	5	0.4
243	6	0.1
244	7	0.4
311	8	0.05
312		
313		
321	9	0.01
322		
324		
323	10	0.1
331	11	0
332		

333	12	0.55
334		
335	13	0
411	14	0.001
412		
421		
422		
423		

Table 9: reclassification of the CORINE Land Cover classes (first column) at an aggregate level (second column) according to the parameterization of C factor (third column)

DRIVING FACTORS OF LAND USE CHANGES
1. density of workers in industry and other services (employed per sq. Km)
2. density of enterprises in industry and other services (enterprises per sq. Km)
3. population density (inhabitants per sq. km)
4. distance from channel network (m)
5. distance from transport network (m)
6. distance from urban centre (m)
7. elevation (m a.s.l.)
8. aspect (clockwise from north)
9. slope (% rise)
10. depth to rock (categorical variable)
11. organic carbon in the topsoil (categorical variable)
12. soil erodibility (categorical variable)
13. mean annual precipitation (mm)
14. mean annual temperature (°K)

Table 10: list of the driving factors considered for the application of CLUE-s

All the input data, spatialized or not, had to be imported into GIS format (GRID structure) and homogenized (the Projected Reference System was WGS84 UTM zone 32 N, their final resolution was 250 meters), in order to allow an easy implementation of the procedure, to make all the necessary analyses and overlays among different layers and to supply the results with the same structure.

Among the input parameters, we have to specify the possibility or not, for each land use class, to be converted into another land use class. This was made by means of a conversion matrix class by class, reporting 1 if the conversion is allowed and 0 if it is not allowed. In this case, only the conversion of urban land uses toward other classes was not allowed.

Then it was necessary to evaluate the stability of different land uses, that is their capability to resist to some stresses. This stability was indicated with an index varying from 0 (dynamic land use) to 1 (stable land use) (Table 11).

CLASSES	Elasticity
0	0.41
1	0.28
2	0.37
3	0.56
4	0.25
5	0.55
6	0.54
7	0.49
8	0.47
9	0.56
10	0.56
11	0.56
12	0.56

Table 11: list of the elasticity values given to each land use class

A further basilar input datum for the application was the map of “restricted” areas representing those areas protected or managed in a manner that does not permit existing land use to change. It was decided to consider, as a region of un-permitted changes, the one consisting in lakes (class 511 of the CORINE LAND COVER legend) and in Special Protection Zones (ZPS) according to Italian regulations.

Finally, we made two types of simulations: the former considering as climatic input (precipitation and temperature) the ones predicted by IPCC scenario A2 and the latter considering the IPCC scenario B2. The A2 and B2 scenarios are both relative to 2070 - 2100 period.

1.10.3 Soil erosion trends in future climate and land cover scenarios

The maps of land use classes resulting from the previous simulations were used as input layers (after their re-sampling to 100 m of resolution) of land use for the RUSLE model. In particular, they were used to associate to each pixel of the study area a value of C factor according to Table 9.

Land cover maps in A2 and B2 scenarios show very little differences. By comparing these maps with actual land use data some trends, relative to specific classes, come out:

- the “artificial surfaces” class raises from 6.5 % to 8 %.
- Permanent crops raise from 2.4 to 4.7 %.
- Further rises, although of lower importance, concern the classes “forests” (from 30 to 30.8 %) and “scrubs and/or herbaceous vegetation associations” (from 10.5 to 11.2 %).
- Arable land, on the contrary, strongly decrease and lower from 32 to 28.5 %.
- The other classes are nearly unvaried.

The application of RUSLE model with CLUE-s A2 and B2 scenarios as input for C factor computation showed, over the alpine space, a geographical distribution of soil loss levels similar to the previous assessments. By comparing actual vs. A2 and B2 erosion maps (Figure 21: Soil Erosion trend in the Italian alpine territory. Actual vs. A2 (climate and land cover) scenario

and **Error! Reference source not found.**), it comes out a general low raise in erosion rates both in A2 and in B2 scenarios. However, in A2 scenario, at specific areas where a low reduction of rainfalls is expected, an attenuation of soil loss rates could take place (Figure 22).

Locally, both in A2 and B2 scenarios, erosion maps show a large number or areas, often small, which are expected to experience a reduction in soil erosion rates. They are prevalently located at areas where, according to CLUE-s model simulations, an increase in urban conglomerations and in the extension of forests and permanent crops is expected, to the detriment of arable lands.

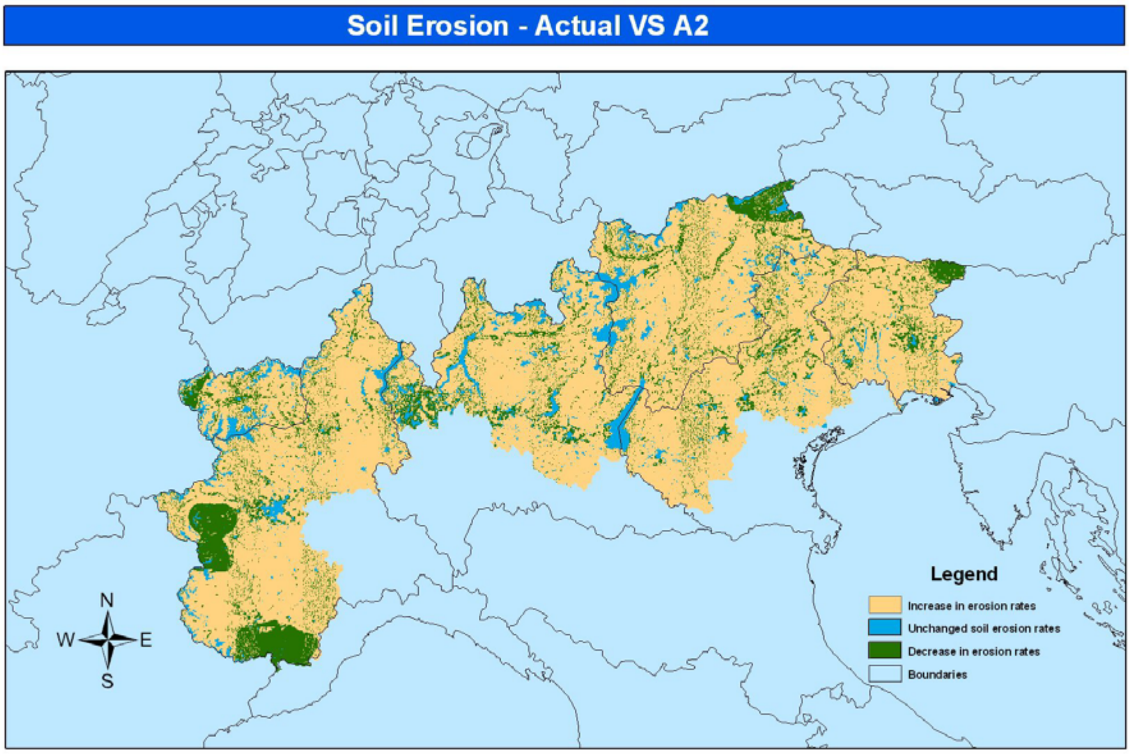

Figure 21: Soil Erosion trend in the Italian alpine territory. Actual vs. A2 (climate and land cover) scenario

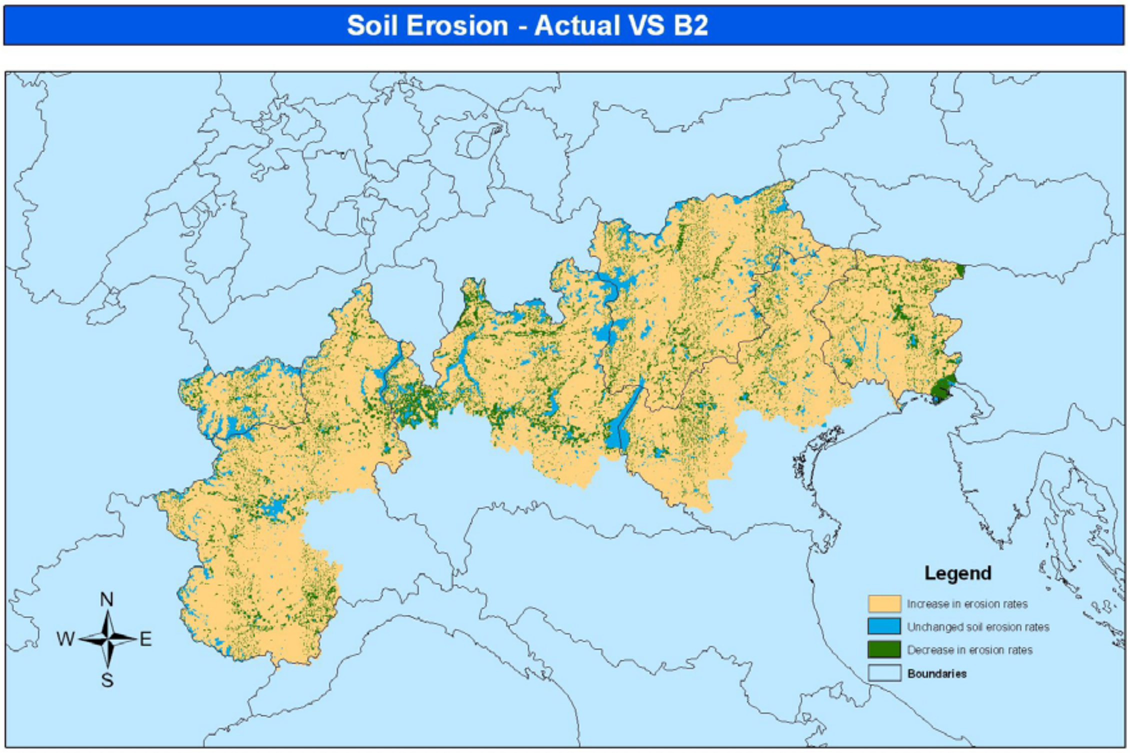

Figure 22: Soil Erosion trend in the Italian alpine territory. Actual vs. B2 (climate and land cover) scenario

1.11 Conclusions

With this study, soil erosion processes over the whole alpine space were estimated, with the specific aim of comparing actual erosion rates (1960 – 1990) with the A2 and B2 (2070 – 2100) IPCC scenarios data.

The alpine region is a highly complex area. The study shows that the territory of the Alps is subject to a high vulnerability with regard to soil erosion. About 32% of the alpine space, in fact, shows a rather high risk of erosion (> 20 t ha^{-1} yr^{-1}). In the high mountain zones, in particular, more than 25% of the territory is interested by very high erosion rates (> 50 t ha^{-1} yr^{-1}). Vegetation cover plays a key role in mitigating the soil loss processes. The vulnerability of the Alps is mainly imputable to the geomorphologic complexity of their territory and to the type of rainfall they are subject to. As regards erosion trends in future climate scenarios (IPCC A2 and B2 data), our methodology points out that over the alpine space raises in soil losses are not expected to be significant. In spite of that, some evidences come out: B2 scenario shows a growth of low entity of soil losses over a significant part of the alpine space. In A2 scenario a clear distinction between northern and southern Alps comes out. Northern part should experience a low reduction of soil erosion, whilst in southern areas a rise of soil losses should take place.

The analysis performed on the Italian side of the alpine region, taking into account, besides climatic data, land use and land cover scenarios, showed a geographical distribution of soil loss levels similar to the previous assessments. A general low raise in erosion rates, both in A2 and in B2 scenarios, is expected. Some areas could, on the contrary, experience a reduction of soil losses as a consequence of local reduction of rainfall rates and of an increase in urban conglomerations and in the extension of forests and permanent crops, to the detriment of arable lands.

Erosion processes are extremely complex and a huge number of factors influence them. Different datasets are hence necessary with the aim of modelling soil losses. Suitable spatial and thematic resolution are often difficult to obtain over large areas. Our results could be improved making use of a digital elevation model with better spatial resolution, of more accurate information relative to soil structure and of a larger number of rainfall data with adequate temporal resolution. As regard to the latter data, during ClimChAlp project the lack of time made not possible the collection of a significant set of adequate rainfall information. With the aim of complying with the time scheduling of the project, we preferred to use a dataset of modelled data. They were promptly available and assured a better comparison of actual and future soil losses in different climate scenarios.

One of the most critical points in soil erosion studies is the estimation of rainfall erosivity. The climate model we used makes available rainfall data with daily resolution. It is not adequate for the strict computation of R factor in the universal soil loss equation, which requires a temporal resolution of 30 minutes.

To get round this problem, simplified algorithms can be applied. By the use of monthly or yearly average rainfall data they allow the computation of R but they do not take into consideration the specific intensity of single rainfall events. As climate change could produce a tendency to tropicalization, with highly intense rainfall events, a complete understanding of climate change impact on erosion trends is difficult to obtain.

As regards future investigations, a downscaling approach will be useful for a better comprehension of water erosion processes in the Alps. It would allow to carry out more and more accurate predictions and estimations at regional or local scales. To this aim, evaluations on possible future variations of timberline, pastures or woods distribution and vegetation cover are critical. It is moreover crucial to take into better consideration the erosivity power of snow melting processes, which can strongly influence soil erosion phenomena, both sheet and rill. Above all, further researches should be carried out with the aim of a better determination of rainfall erosivity factor. It still persists, moreover, the need for a deep calibration and validation of models, by means of field measures and with monitoring activity on soil and their degradation.

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1.13 Aknowledgments

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2. POTENTIAL IMPACTS OF CLIMATE CHANGES TO THE DELIMITATION OF FLOOD AND DEBRIS FLOW HAZARD ZONES

2.1 Introduction

The assessment of the 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 by means of the reconstruction of historical processes (backward directed indication) or by means of simulation models (forward directed indication, Kienholz et al. 2004). In practice, both approaches mostly are combined. Normally, the hazard assessment is made for the actual state of the studied system (e.g. torrent catchment, landslide area, etc.). Assumed that future system changes due to the impacts of climate changes will occur, the hazard assessment made for the present system status will be only partially valid for the future system status. Once changes in the environmental system occurred, the future geomorphologic processes will not occur exactly in the same way as in the past. Thus, backward directed indication of natural hazards and the interpretation of the past geomorphologic processes also named as "silent witnesses" for assessing actual processes will increasingly be subjected to uncertainties. In a narrower sense, past observation data (e.g. precipitation series) could probably not represent the future system status.

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.

The institutions responsible for the planning of risk reduction measures need a trend or some idea about the dimensions of the future requirements to the protection measures regarding potential impacts of climate changes. These two case studies were made to assess possible changes in the natural hazards situation on two specific sites. The aim was to contribute to the actual discussion for the adaptation of risk management practices to the consequences of climate changes.

2.2 Method

In this study, the sensitivity of the common methods and procedures for the delimitation of flood and debris flow hazard zone maps against climate changes was analysed. The focus of this 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 against changes of the needed input parameters. Because of these requirements, no RCM or weather generator models were used for the generation of potential data series for extreme precipitation events representing the future climate conditions (2050-2100).

Based on the analyses of relevant literature regarding the impacts of climate changes to the intensity and frequency of flood and debris flow hazards made within this project (www.risknat.org, Eschgfäller 2007), the consequences of the expected changes of environmental parameters that are considered in the hazard assessment were analysed. 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 sensitive against 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 snowfall altitude during extreme rainfall events is higher than the mountain crests and all precipitation contributes to runoff. Thus, only the impacts of a potential increase of the intensities of extreme precipitation events to the delimitation of hazard zones was analyzed. On the basis of the literature review, a possible increase of at maximum 20 % of the precipitation intensity is assumed for this sensitivity analysis (Eschgfäller 2007).

The sensitivity analysis was made on two case studies:

- the Mareiter Bach river, representing alpine torrents with a catchment area of about 400 sqkm
- the Tschenglser Bach torrent, representing small and steep alpine torrents with a catchment area of smaller than 20 sqkm

The results of these analyses were two hazard maps for each study area, one representing the hazard situation under present climate conditions, one representing the hazard situation under future conditions. The hazards 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 case studies have been selected because there had been existed preliminary studies representing the actual hazard situation under present climate conditions. This fact leads to an assessment of the potential future hazard conditions within the short period of the ClimChAlp project.

2.2.1 Case study “Mareiter Bach”, Vipiteno/Sterzing, Autonomous Province of Bolzano South Tyrol

The Mareiter Bach basin lies in the north of the Autonomous Province of Bolzano South Tyrol. The river endangers parts of the Vipiteno Basin and the city of Vipiteno/Sterzing and confluences with the Eisack River. The catchment area is 210 sqkm. This study area is a representative example for alpine torrential rivers with a relatively high hazard potential for settlements.

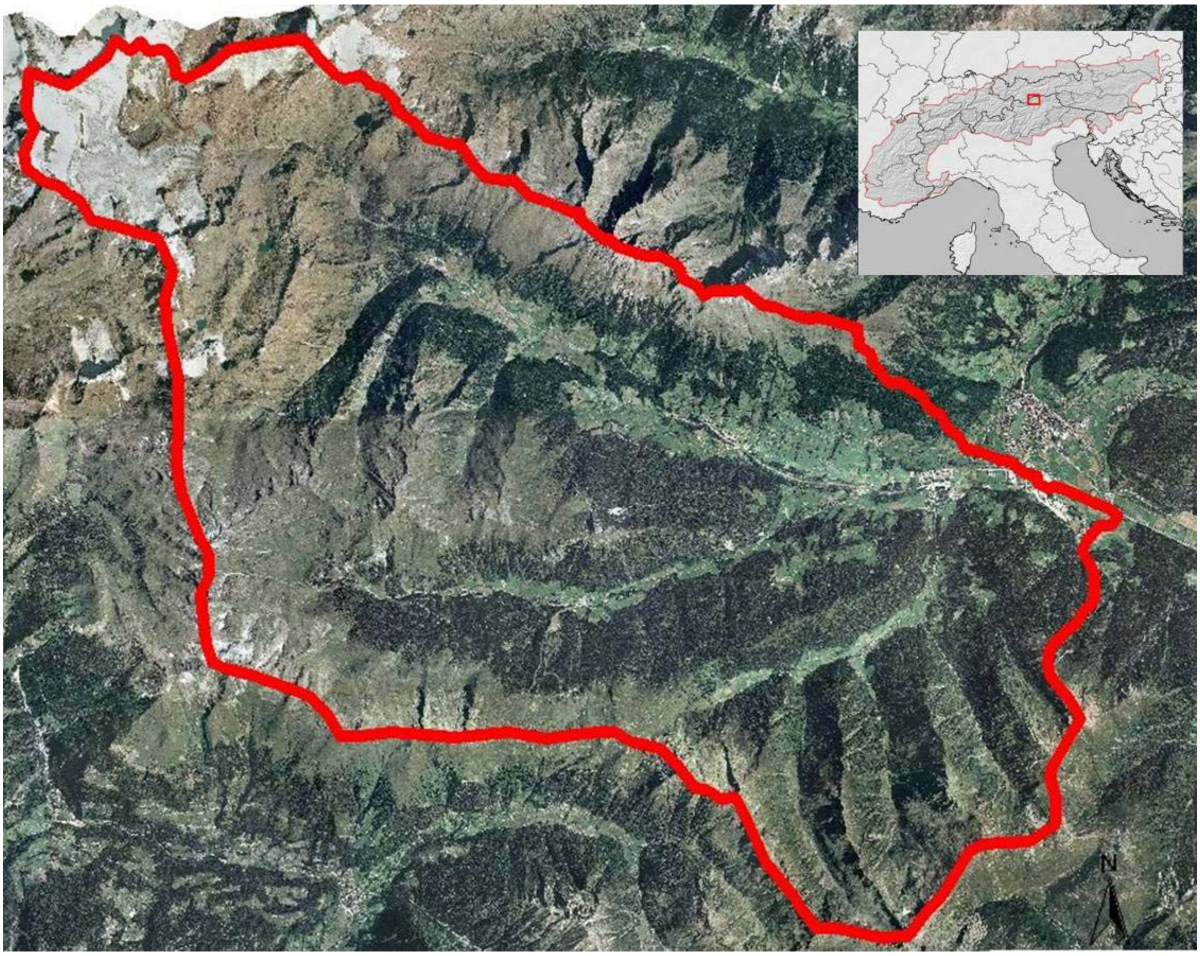


Figure 23: Localisation and delimitation of the Mareiter Bach catchment

For the assessment of the present flood hazard situation of the Mareiter Bach for the Vipiteno basin, we followed this procedure (Scherer 2007):

- 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 verification of the rainfall-runoff model,
- simulation of the inundation processes for each return period,
- delimitation of the hazard zone map,
- analysis of the exposed buildings.

The statistical analysis of the precipitation time series was based on the measurement stations of Ridnaun (31 measurement years). In the analysis, precipitation events with duration of 1, 3, 6, 12 hours were considered.

The statistical analysis was repeated, adding 10 % resp. 20 % to the maximum of the recorded events of each year. The result of the procedure was a fictive time series under assumption that the recorded rainfall events will occur in the future with the same sequence but with increased intensities (Scherer 2007). For the discharge prediction, the rainfall-runoff model Hec-HMS and the SCS-approach was used and adapted to the catchment characteristics of the Mareiter Bach. The calibration of the model was made within the Interreg IIIB project "River Basin Agenda" (Scherer 2005). For the simulation of the indundation processes, 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 2005) and Heinimann et al (1998).

2.2.2 Case study "Tschenglser Bach", Tschengls/Cengles, Comunity of Laas/Lasa, Autonomous Province of Bolzano South Tyrol

The Tschenglser Bach torrent lies in the western part of the Autonomous Province of Bolzano South Tyrol. The torrent endangers parts of the community of Tschengls and confluences with the Etsch River. The catchment area is 11 sqkm. This study area is a representative example for systematized alpine torrents eroding older deposits in permafrost degradation areas. 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 bed load 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 (Zischg 2007). The Tschenglser Bach is systematised by sediment retention basins and check dams.

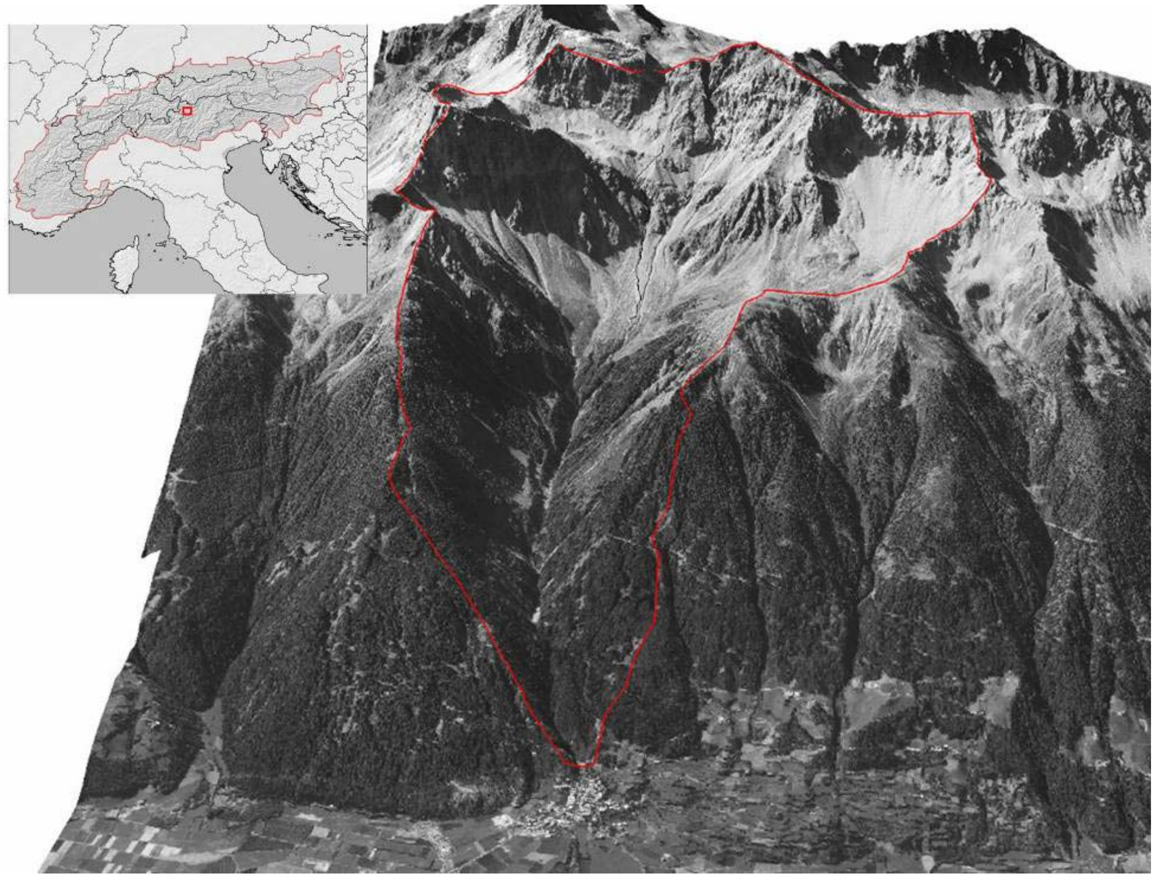


Figure 24: Localisation and delimitation of the Mareiter Bach catchment

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

- 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 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.

The calculation of the rainfall characteristics representing the present climate was made following the procedures of VAPI (Valutazione delle portate in Italia). The analysis was repeated, adding 20 % to precipitation characteristics for the relevant return periods (IPP 2007). The results of the procedure are modified input parameters for the hydrologic and hydraulic simulations representing the future climate conditions with assumed increases in rainfall intensities for precipitation events with duration of 1 and 2 hours. For the discharge prediction, the rainfall-runoff model Hec-HMS and the SCS-approach was used and adapted to the catchment characteristics of the 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 U.S. 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 2005) and Heinimann et al (1998).

Figure 25: Debris flow channel in the Upper Tschenglser Bach catchment

Figure 26: Recently deglaciated areas and debris flow starting zones in the Upper Tschenglser Bach catchment

2.3 Results

The results of the procedures described above were the hazard maps describing the hazard situation on the basis of simplified assumptions representing present and future climate conditions. The main focus laid more on the comparison of the two hazard situations rather than on the single hazard assessment itself.

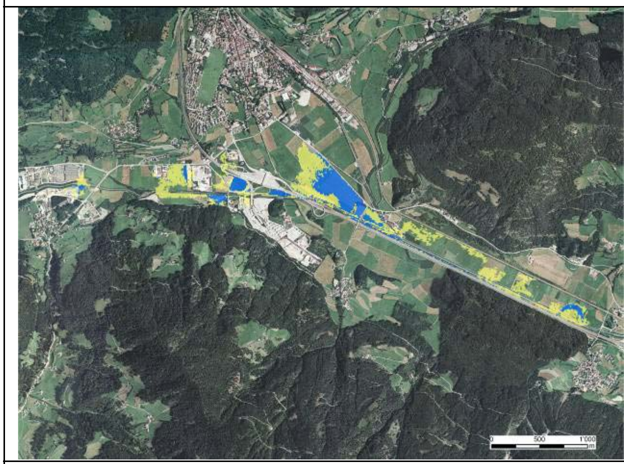
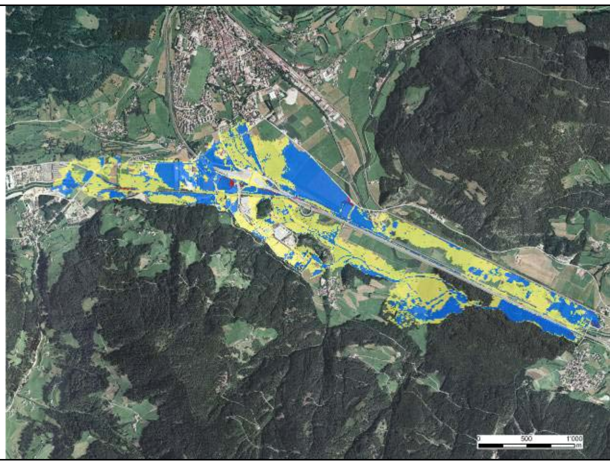
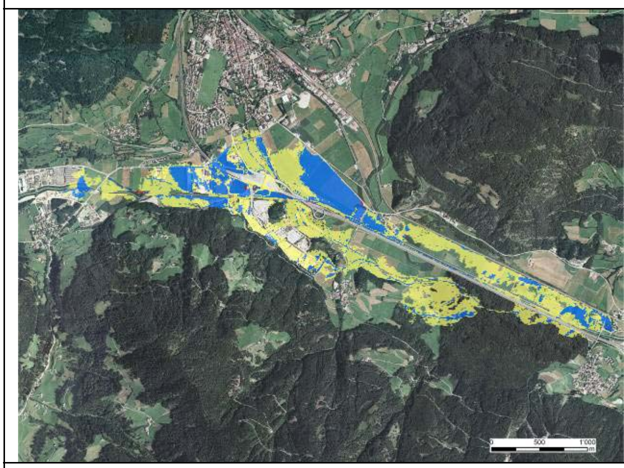
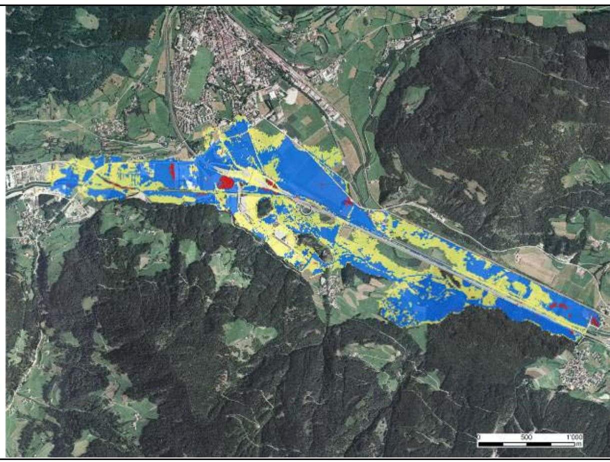
2.3.1 Case study "Mareiter Bach"

By increasing the rainfall intensities for the design events describing the basic assumptions for the delimitation of the hazard zone maps by 10 % resp. 20 %, the parameters needed for hazard evaluation changed as follows:

return period of a rainfall event, duration 24 h	N_{tot} (precipitation) [mm]			Q_{max} (discharge) at confluence [m^3/s]		
	scenario 2000	**scenario + 10 %**	**scenario + 20 %**	**scenario 2000**	**scenario + 10 %**	**scenario + 20 %**
30 years	106.6	117.23	127.9	212.5	263.8	299.6
100 years	125.7	138.26	150.8	272.6	337.8	383.9
200 years	136.6	150.3	164.0	333.3	381.9	431.8

Table 12: Calculated rainfall and runoff values for relevant return periods and different climate conditions (Scherer 2007)

The following illustrations show the spatial changes of the inundation processes.

<table>
<tr><td>scenario 2000</td><td>scenario + 20 %</td></tr>
<tr><td></td><td></td></tr>
<tr><td>flooded area of a discharge with a return period of 30 years (HQ30) representing the actual climate conditions</td><td>flooded area of a discharge with a return period of 30 years (HQ30) representing potential future climate conditions</td></tr>
<tr><td></td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td>flooded area of a discharge with a return period of</td><td>flooded area of a discharge with a return period of</td></tr>
</table>

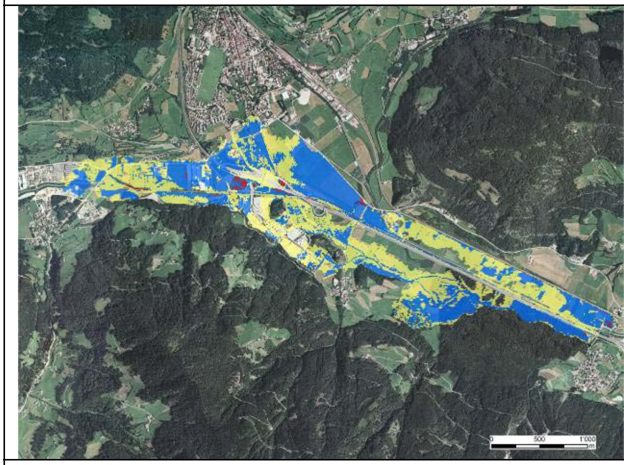
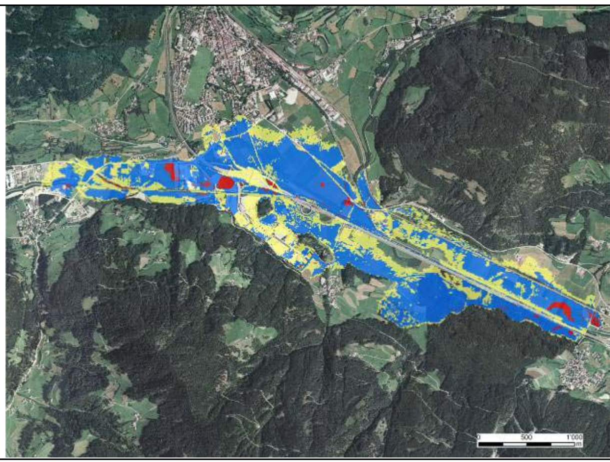
100 years (HQ100) representing the actual climate conditions	100 years (HQ100) representing potential future climate conditions
	
flooded area of a discharge with a return period of 300 years (HQ200) representing the actual climate conditions	flooded area of a discharge with a return period of 300 years (HQ200) representing potential future climate conditions

Figure 27: Changes in flow depths and affected area of the inundation process in the Vipiteno 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

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). The delimitation of the hazard zone maps by considering flow depth and flow velocity without further on-site investigations show the following changes due to impact of climate changes:

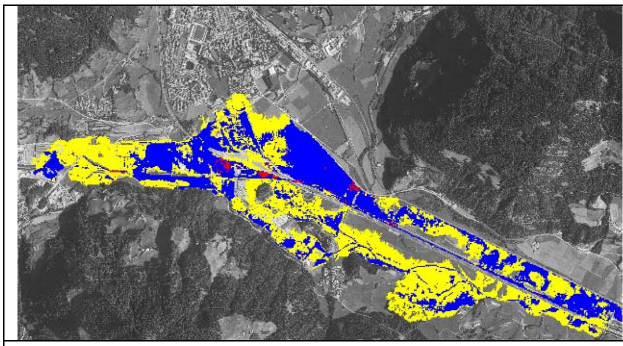
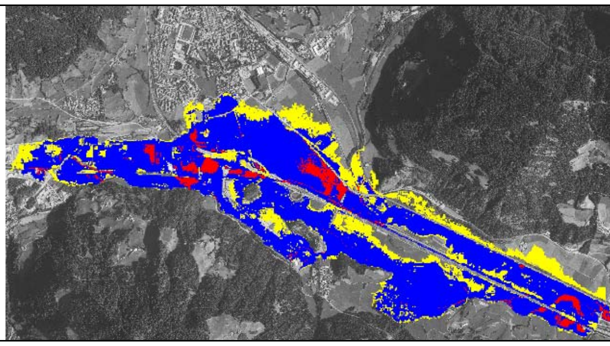
	
results of inundation modelling representing the present climate conditions	results of inundation modelling representing the assumed future climate conditions

Figure 28: 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)

The number of endangered buildings increased as following:

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

Table 13: Calculated rainfall and runoff values for relevant return periods and different climate conditions (Scherer 2007)

The study confirmed the results of prior analyses that the discharge capacity of the Mareiter Bach in the Vipiteno basin is lower than the discharge of a design event with a return period of 30 year. Either considering the effects of climate changes to the hazard situation or not, this fact leads to the endangerment of parts of the Vipiteno basin also during relatively frequent events. The historical analyses of flooding events in the Vipiteno 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 have a larger extent than the flooded areas of a design event with a return period of 100 years representing the actual climate conditions. 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 red zones increased significantly. The changes in the extent of the hazard zones implicate changes in the number of exposed buildings. Under the assumptions made in this study, the buildings exposed to 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 in 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.

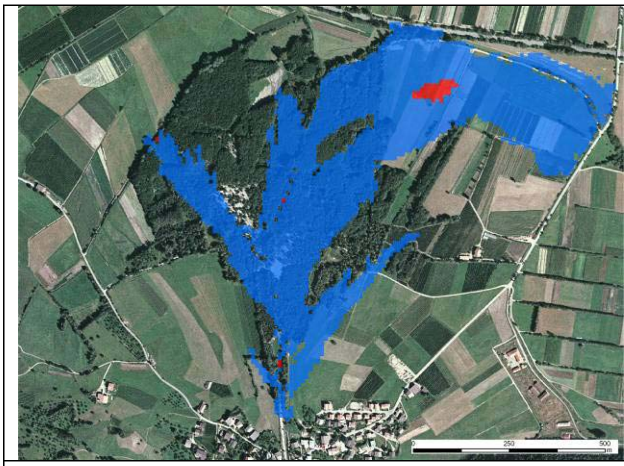
The potential effects of changed input parameters as the precipitation intensity to the extent of the hazard zones are not negligible for land use planning purposes. Usually, the hazard assessment of floods bases on the statistical analysis of relatively short data series for precipitation and discharge 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 short data series, the calculated values for the design event representing the future climate conditions are laying within the 95% confidence intervals 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.

2.3.2 Case study "Tschenglser Bach"

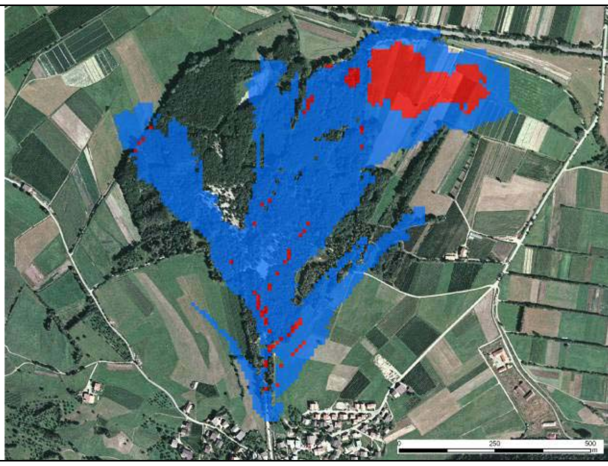
By increasing the rainfall intensities for the design events for the delimitation of the hazard zone maps of 20 %, the parameters needed for hazard evaluation changed as follows:

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	59000	80000
100 years	74.2	89.0	47.3	70.4	73000	110000
300 years	81.2	97.5	63.5	86.5	83000	119000

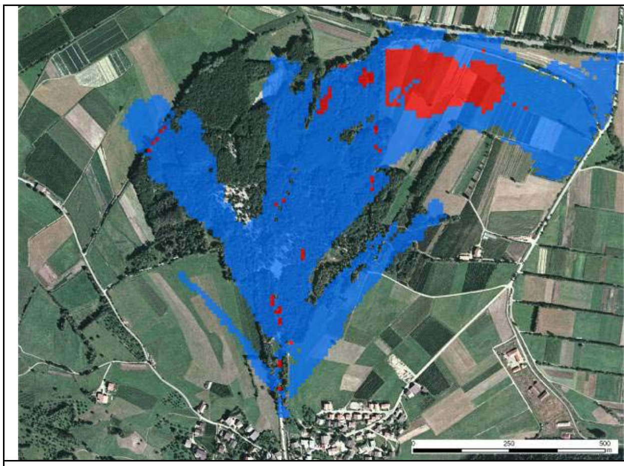
Table 14: Calculated rainfall and runoff values and bed load transport for relevant return periods and different climate conditions (IPP 2007)



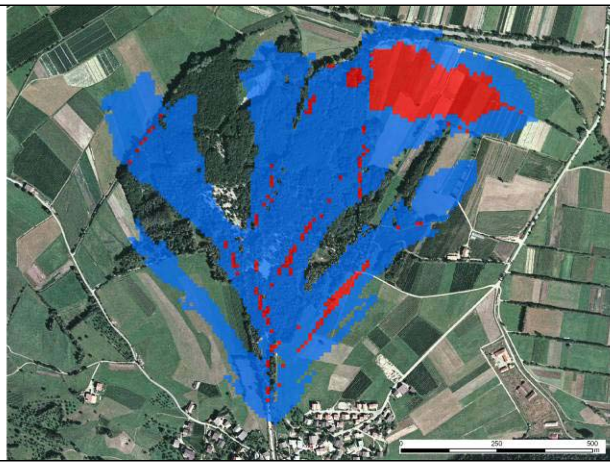
Flow depths for a design event with a return period of 30 years. Critical shear stress parameter of 400 Pa. Present climate conditions.



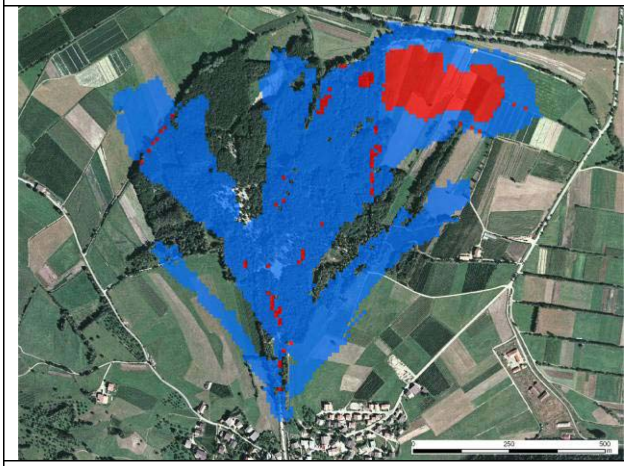
Flow depths for a design event with a return period of 30 years. Critical shear stress parameter of 400 Pa. Future climate conditions.



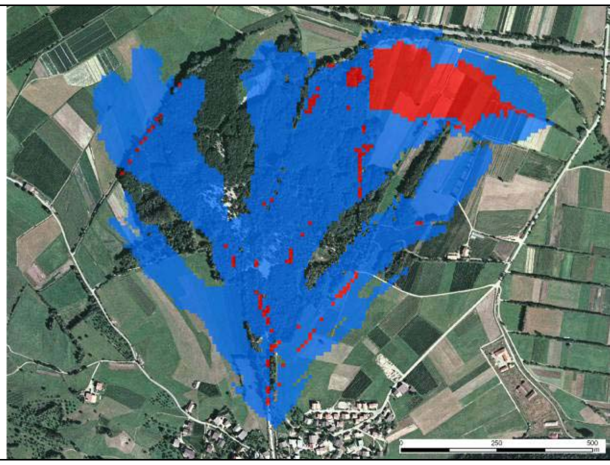
Flow depths for a design event with a return period of 100 years. Critical shear stress parameter of 400 Pa. Present climate conditions.



Flow depths for a design event with a return period of 100 years. Critical shear stress parameter of 400 Pa. Future climate conditions.



Flow depths for a design event with a return period of 300 years. Critical shear stress parameter of 400 Pa. Present climate conditions.



Flow depths for a design event with a return period of 300 years. Critical shear stress parameter of 400 Pa. Future climate conditions.

Figure 29: Changes in flow depths and affected area of the debris flow processes of the 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

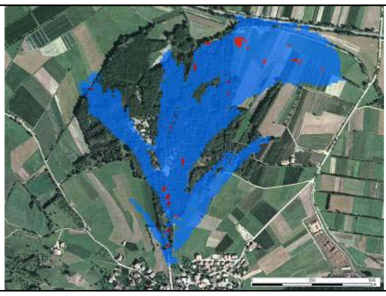
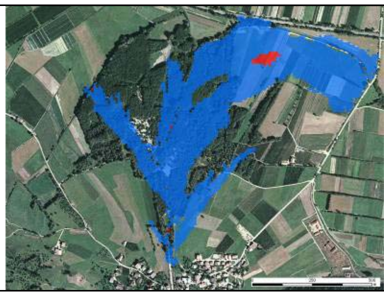
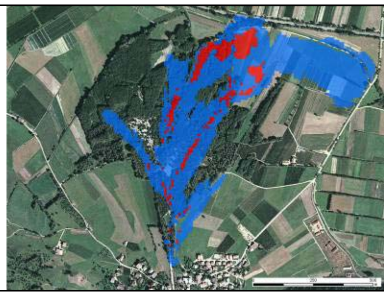
		
Flow depths for a design event with a return period of 30 years. Critical shear stress parameter of 200 Pa. Present climate conditions.	Flow depths for a design event with a return period of 30 years. Critical shear stress parameter of 400 Pa. Present climate conditions.	Flow depths for a design event with a return period of 30 years. Critical shear stress parameter of 800 Pa. Present climate conditions.

Figure 30: 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

The assumed increase of 20 % of the input parameter rainfall intensity for the design events 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. The areas affected by debris flows increases of about 4 – 30 % if the assumed future climate conditions are considered in the simulation model. The changes in the extent of the hazard zones do not have consequences for the settlements und do not influence the risk situation.

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.

2.4 Conclusions

The case study of the Mareiter Bach river showed possible consequences of climate changes to the hazard situation of an alpine river. The calculated increase of discharge due to the assumed increase of 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 of 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.

The case study of the 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 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 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 higher operating expenses.

Nevertheless, the assumed future changes in the input parameter “precipitation intensity” lay within the uncertainty of the modelling approaches used today for the delimitation of the hazard zones.

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3. WATER BALANCE AND SCENARIO SIMULATION USING THE MODEL LARSIM

3.1 Abstract

Within the Interreg IIIB Project ClimChAlp, two project partners, the Office of Government Tyrol, Austria and the Bavarian Environment Agency, Germany, commissioned a study on the application of the water balance model LARSIM to the catchment of the alpine river known as “Großache” or “Alz”, in order to investigate possible climate change impacts on the water balance with a special focus on flood events. The river has its source near Kitzbühel in Austria, where it is known first as the Kitzbüheler Ache and then later as the Großache. From the point where it crosses the Austrian-German boarder until the Chiemsee it is known as the Tiroler Achen and from the Chiemsee till it flows into the river Inn it is called the river Alz.

The study was designed as a pilot project. The catchment of the Großache/ Alz was chosen as the case study area because part of it has typically alpine characteristics and part of it lies in the northern foothills of the Alps, making it an interesting and challenging test area. It has an area of approx. 2200 km², of which approx. 1400 km² constitute the catchment of the lake Chiemsee. In the south of the catchment the altitudes of individual peaks reach 2300 m, the catchment outlet lies in the lowlands at about 350m above sea level. The steep gradients mean that flash floods are a natural hazard typical for the case study area. The Großache/ Alz regularly experiences flooding. The flood discharge observed at the catchment outlet Burgkirchen in August 2002 was 481 m³/s, compared with an average discharge of about 69³/s.

First, the water balance model LARSIM (Large Area Runoff Simulation Model) was applied to the Großache/ Alz catchment. The model was set up with a raster-based discretisation of 0.5 x 0.5 km. Due to the focus on flood events the model was calibrated using hydrometeorological input data and measured discharges in hourly time steps. From the results of the statistical performance criteria it can be concluded that the calibrated model performs well, and is therefore suited for the purpose of water balance simulations for future climate scenarios.

In a second step of the case study, a methodology to analyse and quantify the impacts of climate change on floods with a hydrological model was tested. Based on the findings of the IMK/IFU (Kunstmann et al. 2007) the results of the regional climate model REMO (Jacob et al. 2001) were used for scenario simulations with the water balance model LARSIM for the alpine catchment of the Großache/ Alz. The RCM REMO covers Germany and parts of the northern Alps at a spatial resolution of typically 10 x 10 km in a transient simulation from 1960 to 2100 assuming the so-called SRES A1B greenhouse gas emissions scenario. For the water balance simulation for the future scenario in this study, the assumption was made that land use remains constant.

In the course of the study, the regional verification of the so-called control run of the RCM (1971-2000) in comparison to “measured data” revealed some shortcomings and limitations of current RCM for complex mesoscale catchments, like the systematic errors contained in any available regional climate model data. For example, one problem encountered was the overestimation of mean precipitation for present conditions in large parts of the catchment Alz and differences in the mean spatial precipitation pattern. Similar deviations can be found when

analysing the calculated runoff from the water balance model. Despite all uncertainty resulting from the model chain and the small size of the investigation area, the results for the future show a slight increase in mean precipitation and discharge and to a lesser extent in evapotranspiration in the course of the century. In the context of natural hazards, an increase in discharge was found, which does not, however, constitute a statistically significant increase in flooding for the case study area. For the Period 2070-2099 regional climate models are in agreement that a significant increase in precipitation can be expected in winter and spring (Kunstmann et al. 2007) so an increase in flooding for this period appears likely.

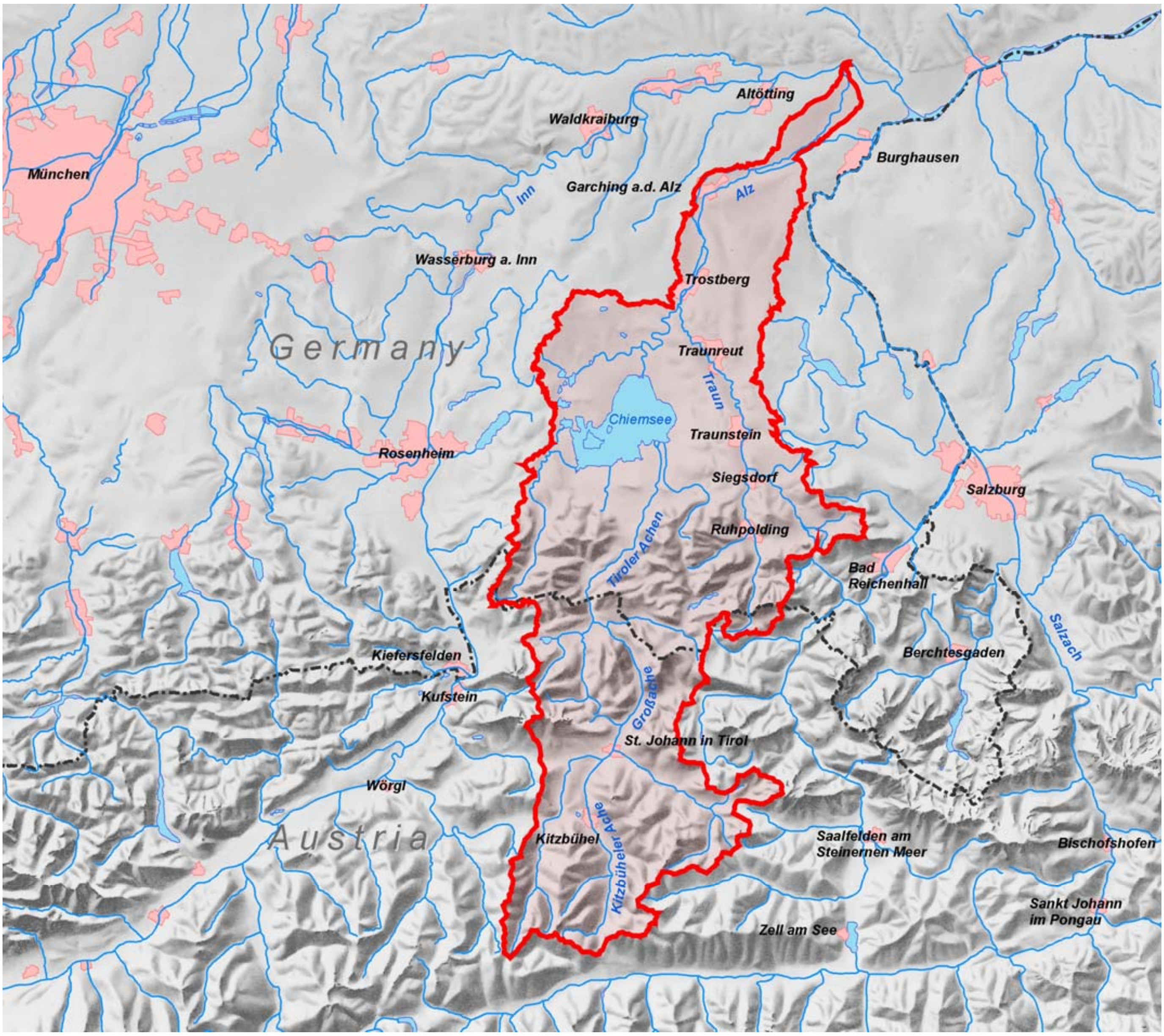
The study is primarily considered to be a first contribution for regional impact studies on future climate change impacts on runoff in a complex terrain like the Alps. At the same time, it demonstrates existing shortcomings and limitations of current regional climate models for hydrological research. Clearly, it is necessary that this pilot study is followed up in projects that look closely at methods of dealing with the systematic errors of climate scenario modelling at the river catchment scale, especially for the Alpine Space with its particular characteristics.

3.2 Introduction

The study on the application of the water balance model LARSIM to the catchment of the alpine river known as "Großache" or "Alz" and the investigation of possible climate change impacts on the water balance with a special focus on flood events, was designed as a pilot project. The river in the case study area has its source near Kitzbühel in Austria, where it is known first as the Kitzbüheler Ache and then later as the Großache. From the point where it crosses the Austrian-German boarder until the Chiemsee it is known as the Tiroler Achen and from the Chiemsee till it flows into the river Inn it is called the river Alz. In this report it will be referred to as the Großache/ Alz. The catchment of the Großache/ Alz was chosen as the case study area because it combines typically alpine characteristics in the south with the characteristics of the foothills of the Alps in the north. It lies partly in the German and partly in the Austrian Alps, it has an area of approx. 2200 km², of which approx. 1400 km² constitute the catchment of the lake Chiemsee. The north of the catchment lies in the lower lands at about 350m to 600m above sea level. The south of the catchment is mountainous with steep gradients. Altitudes of individual peaks reach 2300 m. There are comparatively few densely populated areas in the catchment, and large parts are either wooded or have another type of vegetation cover e.g. alpine meadows. The steep gradients mean that flash floods are a natural hazard typical for the case study area. The average annual maximum discharge (MHQ) measured at the catchment outlet Burgkirchen is about 260m³/s, compared with an average discharge of about 69³/s. The flood discharge observed at the same gauge the in August 2002 was 481 m³/s (GKJ 2002).

Within Work Package 5 of the Interreg IIIb Project ClimChAlp, the water balance model LARSIM was applied to the Alz catchment to examine the effects of possible climatic change on the water resources with a special focus on natural hazards, in this case flooding. Nevertheless, the presented model could also be used for other objectives, such as the low flow and mean flow simulation, as the calibration was not focussed solely on flood peaks, but also took the water budget as a whole into account.

This projects has received European Regional Development Funding through the INTERREG III B Community Initiative
Alpine Space
Interreg III B



3.3 The hydrological model LARSIM

The water balance model LARSIM is a mesoscale model to simulate the water balance of large river basins continuously (Bremicker, 2000). LARSIM was developed on the basis of the river basin model FGMOD (Ludwig, 1982), which is used as a reliable tool for flood forecasting in several flood forecast centres in Germany. Not only does it incorporate the generation of runoff in the area and the translation and retention in river channels, but also the processes of interception, evapotranspiration and water storage in soils and aquifers. Snow accumulation and snow melt can be taken into account as well as artificial influences (e.g. storage basins, diversions or water transfer between different basins).

LARSIM combines proven deterministic hydrological model components, which are generally applicable as far as possible and which are based on accessible system data for the land surface.

Emphasis is laid on the reliable determination of evapotranspiration by using the Penman-Monteith equations (DVWK 1996). Evapotranspiration and the soil water budget are calculated separately for the different land uses and the field capacities of the soils.

Figure 32 shows a schematic diagram of the model LARSIM. Runoff calculation is based on a separation of the precipitation into three different runoff components (base flow, interflow, surface runoff).

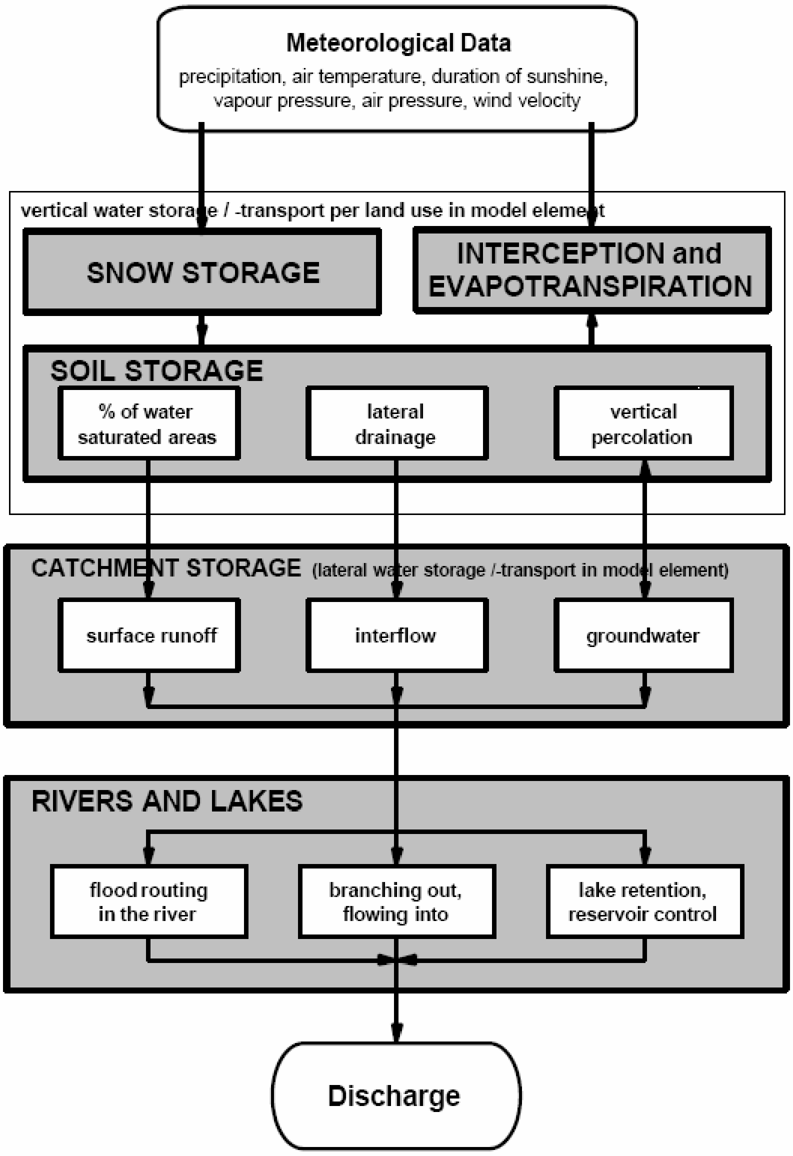


Figure 32: Schematic diagram of the LARSIM model

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

The calculation of the runoff components is based on the Xinanjiang model (Zhao 1977), a soil moisture balance model which was applied in the modified version of (Dümenil & Todini 1992). One of the basic assumptions of the model is that an increase in soil moisture of the model cell correlates with an increase of the water saturated areas of the model cell. Thus, runoff formation depends on repletion of storage, and the percentage of water saturated areas in the model is considered to be variable in time. Precipitation falling on the saturated areas leads to surface runoff. The runoff components of interflow and base flow are also calculated depending of the current soil moisture content of the model element as lateral drainage or vertical percolation.

The flow direction of each grid element is given by one of eight possible flow directions, recognising the slope and the river system. Catchment storage is calculated for direct runoff and base flow runoff within each grid element using parallel linear reservoir approaches.

The calculation of translation and retention in channels implemented in LARSIM is only dependent on the channel geometry and the roughness conditions, thus avoiding the introduction of further calibration parameters in the water balance model. To keep the model complexity manageable, it is assumed that consistent geometrical proportions apply for the viewed channel section, which can be described by a twin-trapezium cross-section. Furthermore, in determining the stage-discharge relationship, the discharge is presumed to be stationary and homogeneous. The implemented channel routing uses a variable storage coefficient method developed by Williams (1969). The channel width and depth were calculated according to the downstream hydraulic geometry theory developed by Leopold and Maddock (1953). This theory describes the interrelationships between dependent variables such as width, depth and area as functions of independent variables such as discharge.

In recent years, LARSIM has been used in several climate change scenario simulations, for example within the first phase of the project BALTEX (BALTic Sea EXperiment) , where LARSIM was developed to make it compatible with the climatic model REMO (Bremicker et al. 2000). REMO is a regional hydrostatic climate model which was developed by the Max Planck Institute for Meteorology in Germany in co-operation with the DKRZ (Deutsches Klimarechenzentrum GmbH), the DWD (German Weather Service) and GKSS (research centre belonging to the Helmholtz Gemeinschaft in Germany) on the basis of the former numerical weather prediction model of the German Weather Service (EUROPA-MODELL, EM, Majewski 1991). LARSIM was implemented as a grid-based hydrological model, describing the interaction of the whole water cycle between atmosphere, biosphere and land phase. It has been verified on various scales for different river basins, for example in the study carried out by (Gerlinger, 2004) within the project "KLIWA" ("Climate Change and Consequences for Water Management"). Here LARSIM was used in combination with different methods for downscaling data from global circulation models, including REMO/ECHAM4, for the Neckar river basin.

3.4 Application of LARSIM in the Großache/ Alz Catchment

Input Data:

For the catchment of the Großache/ Alz, a model was set up based on raster cells (square grid 0,5 X 0,5 km). The model structure was based on digital system data using a geographical information system. The system data necessary for the model is: the elevation model, schematic reproduction of the river network, land use and the field capacities of the soils. The elevation model is shown in Figure 33. For land use in the Großache/ Alz catchment, the CORINE classification was used (CORINE, 1999) for both the Austrian and Bavarian side of the catchment (Figure 34). For the available water capacity of the soils, various data sources were used for the Bavairian and the Austrian side. For the Bavarian part of the catchment the available water capacities were taken from (BÜK1000) and for the Austrian part the values were derived from land use maps and localised measurements. For each raster cell up to 16 land use classes were considered separately. The data of water transfer systems (canals) and the model of the lake "Chiemsee" which is an important factor in the Großache/ Alz Catchment are also included. The meteorological input data necessary for the calibration of the model are time series for precipitation, air temperature, vapour pressure, hours of sunshine or global radiation, wind velocity and air pressure. Time series of discharge measurements complete the list of necessary input data.

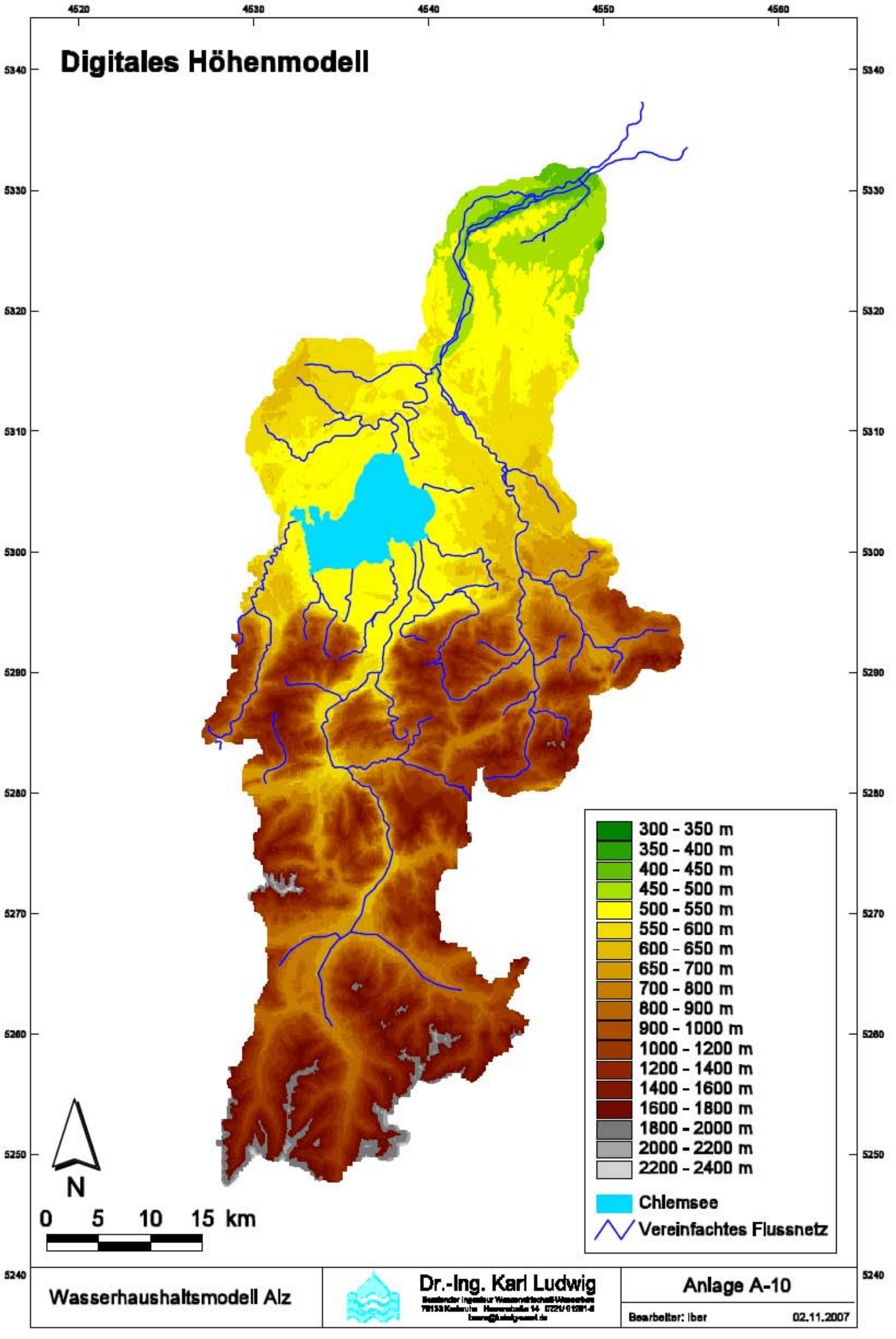


Figure 33: Digital elevation model of the catchment of the Großache/ Alz

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

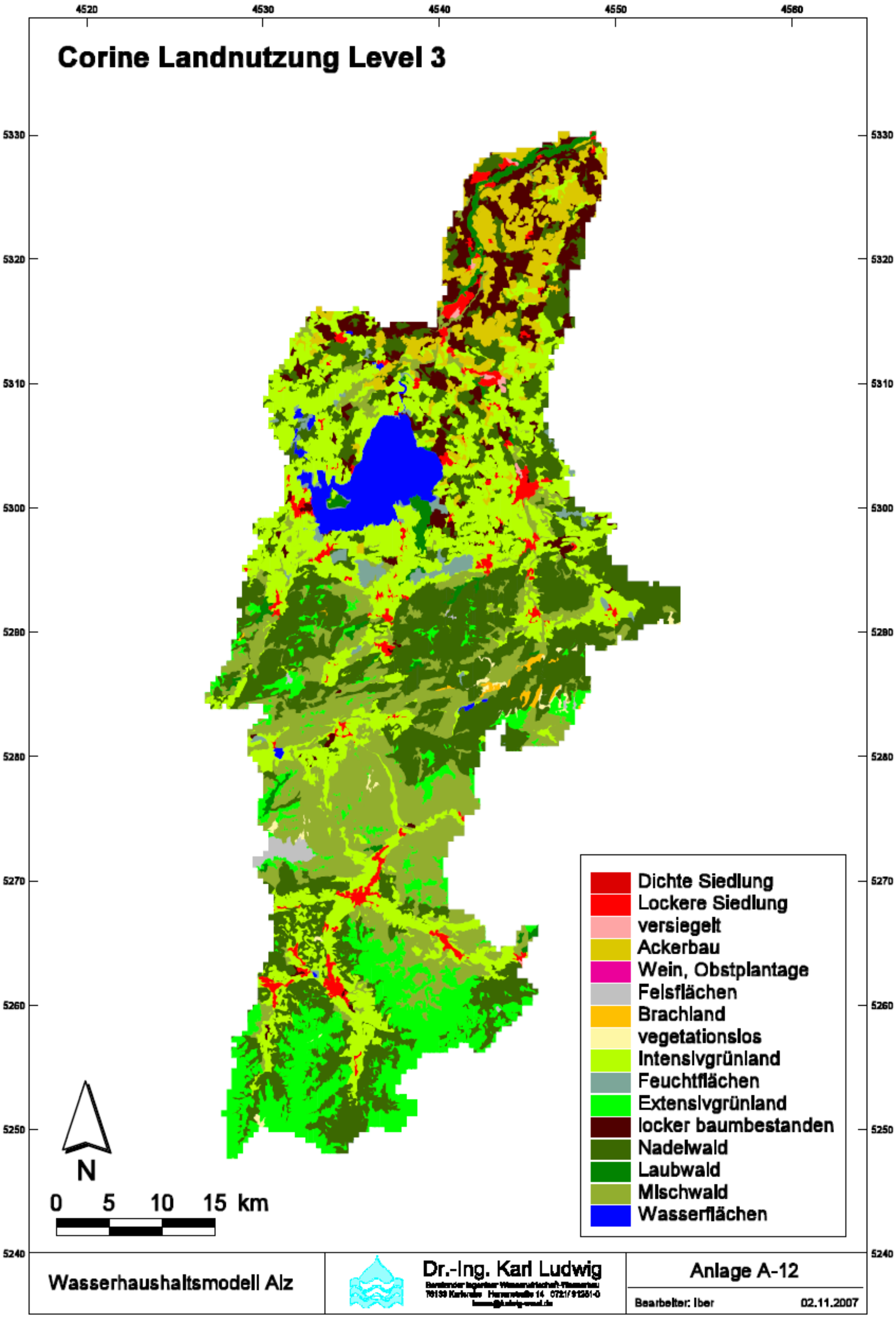


Figure 34: Land use in the catchment of the Großache/ Alz according to CORINE

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

Calibration:

The calibration of the LARSIM model was difficult, due to a shortage of long time series in hourly time steps of most of the important hydrometeorological parameters. This shortage of input data was especially problematic for the part of the catchment with alpine characteristics and also affected the parameterisation of the snow melt model.

The calibration was performed for the 15 gauges listed in Table 15. Also listed in Table 1 is the size of the corresponding subcatchments (AEo) in km². The location of the gauges within the catchment is shown in Figure 35. The available time series of hourly measurements for discharge began in 1990 for most of the 15 gauges. In large parts of the catchment and the surrounding area, hourly measurements of the hydrometeorological data necessary for the calibration and validation of a water balance model with time steps of one hour, only began in the year 2000. Consequently, only the period from 2000 to 2005 was available for the calibration and validation of the seven model parameters. As a five year time series is already very short for the calibration of a model of this kind, especially bearing in mind the complex characteristics of this partially alpine catchment, the whole of the available time series was used for the calibration, which meant that a validation of the calibrated model for a different time period was not possible.

Sation code.	Gauge Name	Tributary	AEokm²	State
201913	Kitzbühel (Bahnhofsbrücke)	Kitzbüheler Ache	153	Tirol (A)
201921	Sperten	Aschauer Ache	147,4	Tirol (A)
201939	St.Johann in Tirol	Kitzbüheler Ache	332,4	Tirol (A)
201947	Almdorf	Fieberbrunner Ache	165,3	Tirol (A)
202283	Kössen - Hütte	Großache	701,4	Tirol (A)
18454003	Staudach	Tiroler Achen	951,9	Bavaria (D)
18463004	Prien	Prien	92,7	Bavaria (D)
18403002	Seebruck	Alz	1399,3	Bavaria (D)
18487501	Wernleiten	Rote Traun	91,2	Bavaria (D)
18484503	Fritz am Sand	Weiße Traun	86,4	Bavaria (D)
18484000	Siegesdorf	Weiße Traun	182,0	Bavaria (D)
18481006	Hochberg	Traun	182,4	Bavaria (D)
18483500	Stein	Traun	367,4	Bavaria (D)
18407003	Trostberg	Alz	1962,3	Bavaria (D)
18408200	Burgkirchen	Alz, catchment outlet	2222,0	Bavaria (D)

Table 15: Overview of gauges with data available for calibration and catchment Area per gauge

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

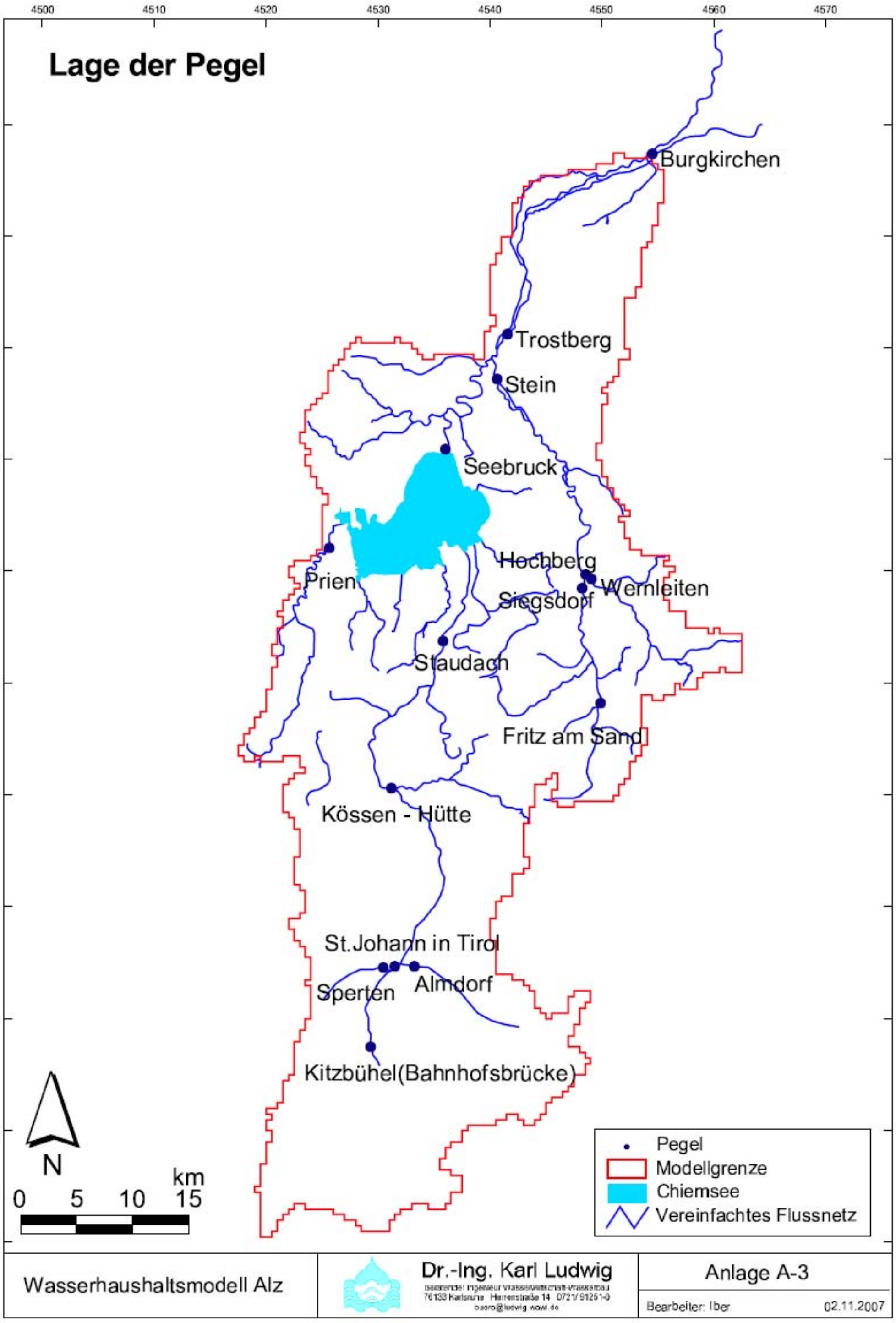


Figure 35: Overview of the gauges in the catchment of the Großache/ Alz

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

To judge model performance, the discharges measured and calculated for the calibration period were compared by different means of statistical criteria (see Table 16).

Gauge	River	coefficient of determination r^2	Model efficiency	lnNS Model efficiency	Ratio Qcalc/Qobs
Kitzbühel	Kitzbüheler Ache	0,77	0,68	0,79	1,05
Sperten	Aschauer Ache	0,74	0,71	0,79	1,07
St. Johann	Kitzbüheler Ache	0,80	0,77	0,81	1,05
Almdorf	Fieberbrunner Ache	0,82	0,79	0,77	0,98
Kössen	Großache	0,83	0,77	0,80	1,10
Staudach	Tiroler Achen	0,86	0,85	0,85	1,02
Prien	Prien	0,63	0,39 b	0,37a,b	1,02
Seebruck	Alz	0,88	0,87	0,88	1,02
Wernleiten	Rote Traun	0,70	0,64	0,55	0,98
Fritz am Sand	Weiße Traun	0,74	0,60	0,49	0,96
Siegsdorf	Weiße Traun	0,81	0,73	0,67	0,96
Hochberg	Traun	0,81	0,75	0,63	0,94
Stein	Traun	0,78	0,74	0,64	0,94
Trostberg	Alz	0,80	0,57	0,48b	1,05
Burgkirchen	Alz	0,80	0,26 b	0,32 b	1,20

Table 16: Overview of the statistical values which are the criteria for the assessment of the calibration

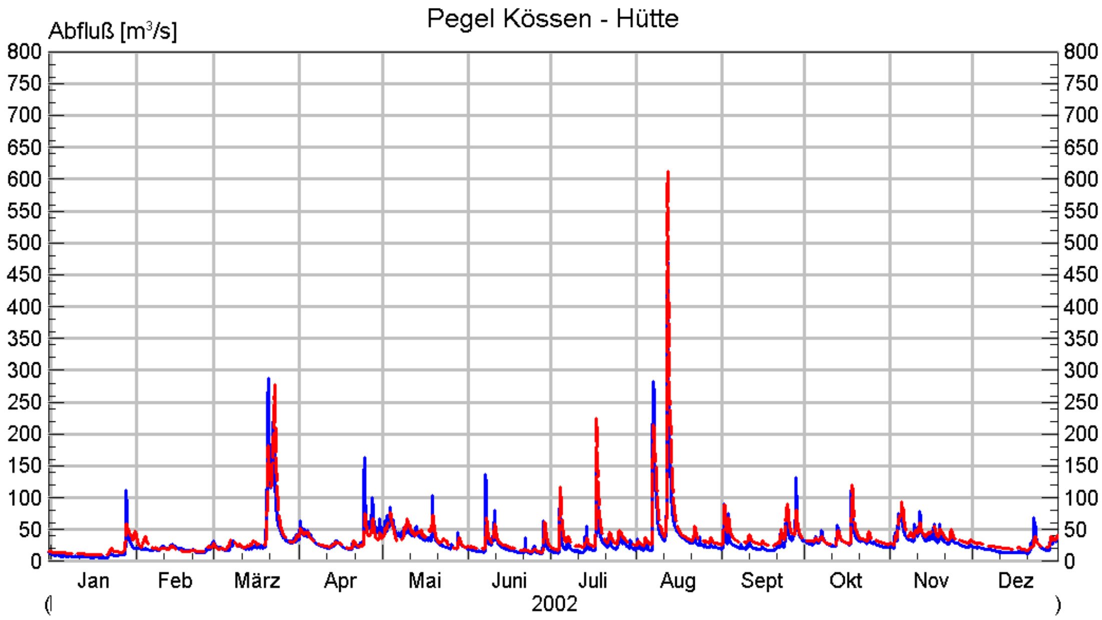
a = the year 2005 was excluded from the evaluation due to a number of implausible measured values
b = in low water periods there is significant interference with the discharge regime, as water is diverted into neighbouring canals (Prien canal and Alz canal)

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

The coefficient of determination r^2 is a measure of the model performance for reproducing the characteristics of flood events. With the exception of the problematic gauge Prien (see footnote in Table 16), this value is 0,7 or above, which can be interpreted as adequate, good or in some cases even very good model performance for flood events.

The model efficiency is a measure of the average discrepancy between measured and observed discharge for the whole discharge regime. Again a value of 0.7 or more can be interpreted as good performance, with 0,5 to 0,69 still counting as adequate. It is for this parameter that considerable problems are most apparent for the gauges Prien and Burgkirchen. This is due to the fact that in low water periods there is significant interference with the discharge regime around these gauges, as water is diverted into neighbouring canals (Prien canal and Alz canal). The diversion of water into the canals can only be modelled to a certain degree, as it is a manually regulated, and therefore partially arbitrary, process. Without the gauges influenced by the canals, the average value for the logarithmic Nash-Sutcliffe model efficiency coefficient for the water balance model of the Großache/ Alz is 0,72, which means the model is also able to model the discharge dynamics with special emphasis on low water well. The ratio of observed to calculated discharge Ratio Qcalc/Qobs (last column Table 16), is a measure of how well the model is able to reproduce the overall water balance. The fact that for the calibration presented here the value does not differ too greatly from 1, despite the problem of the diversion of water into the canals, shows that the calibrated water balance model presented performs well for the water budget too. Additionally, the visual comparison of measured and simulated discharge graphs (see Figure 36 below for an example) was used to optimise the quality of the model calibration. The degree of agreement between measured and calculated discharges in the calibration period is higher for gauges with catchment areas of several hundred km² and for flood events (measured by the coefficient of determination r^2). Larger catchments are more precisely simulated because the heterogeneities in the catchment due to specific natural characteristics and the influence of single hydrometeorological stations are averaged out.

Overall it can be concluded that the calibrated model performs well, and is therefore suited for the purpose water balance simulations for future climate scenarios. The results of the water balance model for the Alz catchment provide a variety of detailed areal and time dependent information of individual components of the water cycle. The simulated distribution of the water balance components in the catchment is plausible. As an example for model results, the calculated mean yearly evapotranspiration for the calibration period 2001-2005 is shown in Figure 37.



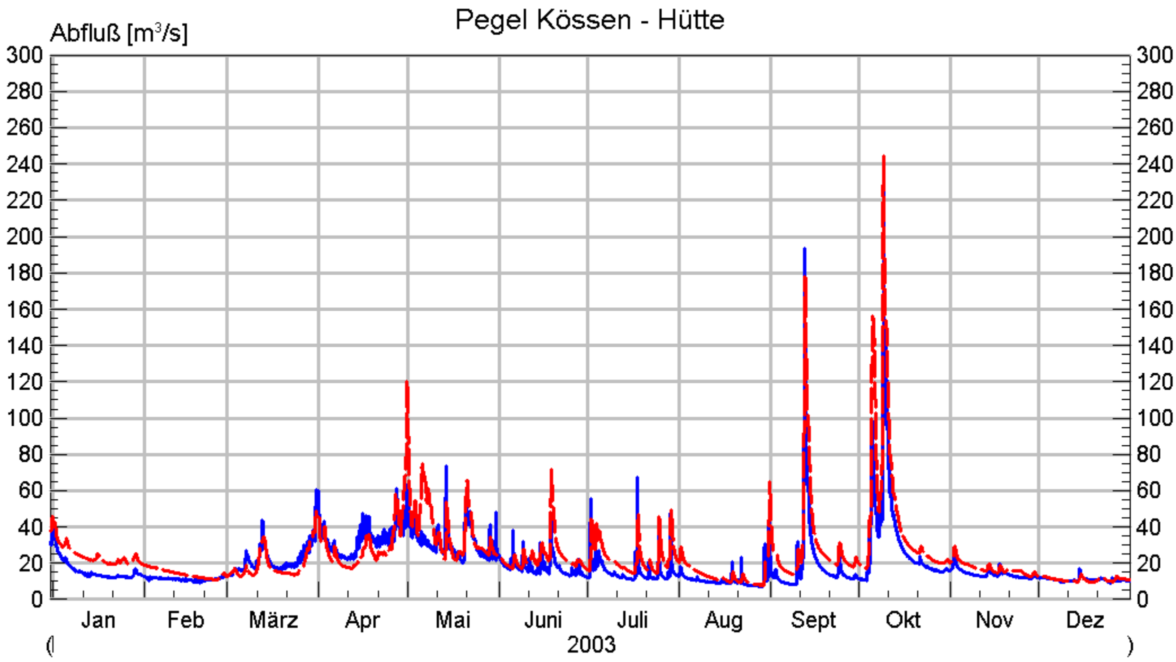


Figure 36: Measured and simulated discharge graphs for the gauge Kössen-Hütte for 2002 (top) and for 2003 (bottom)

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

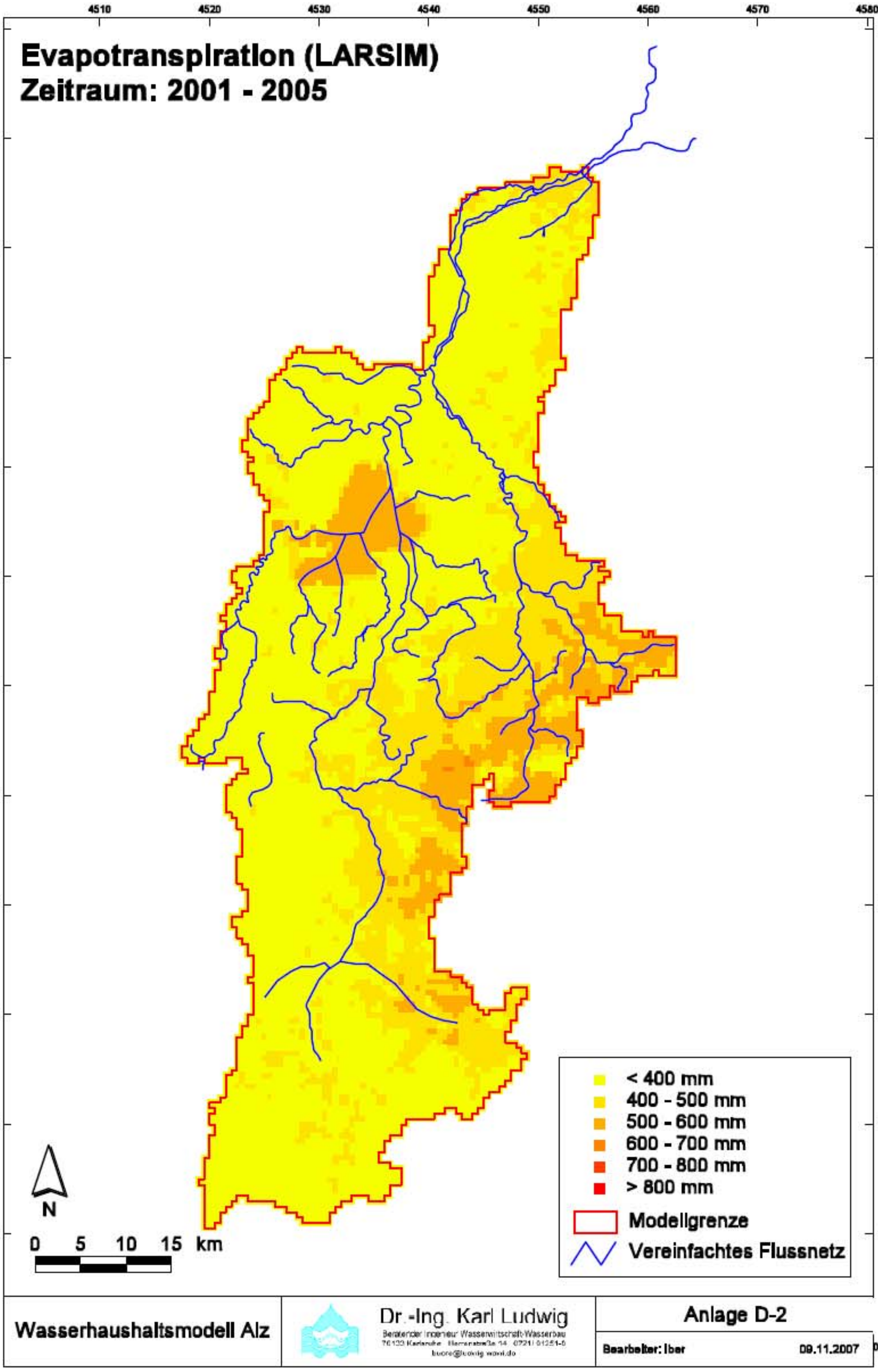


Figure 37: Mean yearly evapotranspiration used for the calibration

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

3.5 Effects of Possible Climate Change on the Water Balance

This study was carried out under the header "Climate Change and Resulting Natural Hazards" (Work Package 5 of ClimChAlp). Consequently, one of its central aims was the analysis of how possible climate change could affect the water balance in the catchment of the Großache/ Alz, and thereby affect the likelihood of destructive flood events. Figure 38 shows the general methodological approach to the application of climate change modelling to questions relevant to water management at the river basin scale.

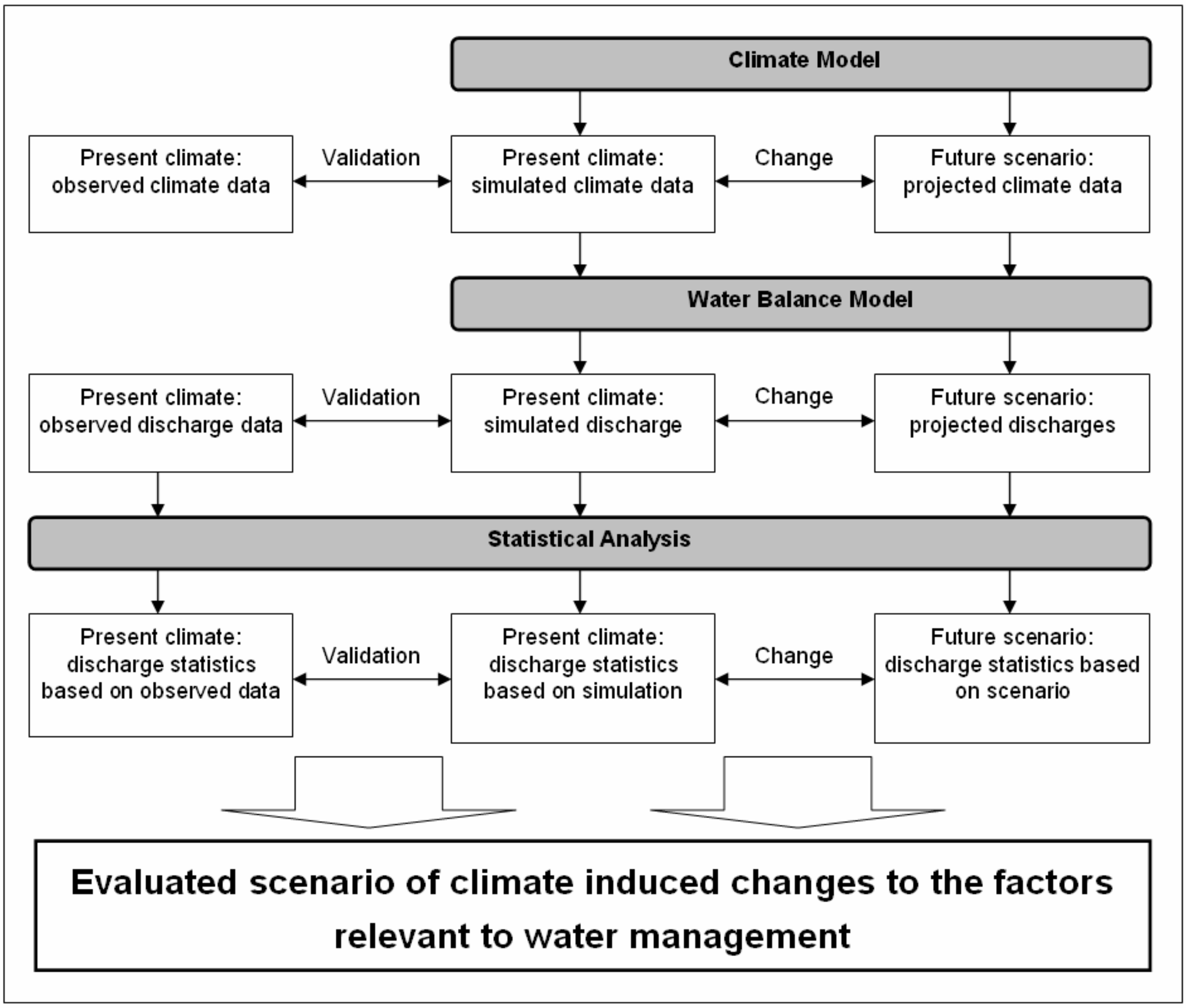


Figure 38: General approach to the application of climate models to water budget simulations with a view to water management and discharge regime

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

A prerequisite for the quantification of a possible climate change induced shift in the water balance is hydrometeorological data for a future scenario. Because of the focus on extreme events, in this case flooding, and because of the comparatively small size of the catchment and its complex orography, with alpine characteristics in the south and lower land in the northern foothills, the data used had to have high temporal resolution with at least hourly values. Used as input for the water balance model, such data can be the basis for the simulation of future scenarios for extreme events at the river catchment scale. For the water balance simulation for the future scenario in this study, the assumption was made that land use remains constant.

At the outset of this study, it was assumed that it would be possible to identify one or several regional climate models (RCMs) that perform comparatively well in the Alpine Space, and that these would be able to provide the type of high resolution data necessary for the simulation of the water balance and extreme events in the case study area. An investigation was carried out within ClimChAlp Work Package 5, to establish which of the available RCMs were best suited for this purpose (Kunstmann et al. 2007). The study confirmed the assumption that only models that are available at a high resolution (both spatial and temporal) should be used for this purpose. The report recommended that only regional climate models that have a cell size of no more than 20 km x 20km should be used. This restriction reduced the list of available RCMs down to a four model "short-list": HIRHAM (Christensen et al.1996, Christensen et al. 2007) CLM (Böhm et al. 2006), RegCM (Giorgi et al.1993) and REMO, whereby REMO only covers the German and north Austrian part of the Alps. The systematic errors (biases) of these models were assessed by means of a direct comparison of seasonal mean values of precipitation and temperature for the RCM simulations for the past (1961-1990) with observed values for the same period. The report concluded that the Alpine Space is a very difficult area for small scale regional climate modelling. All four of the short-listed RCMs showed varying, and sometimes quite significant, biases depending on the season or on the investigation area within the Alpine Space. This meant that, at the scale in question and especially for an area like the Großache/ Alz catchment with its partially alpine characteristics, all four of the short-listed RCMs could be expected to have shortcomings simulating present conditions, and consequently also future scenarios.

In the course of the study it transpired that though the short-listed RCMs existed in comparatively high temporal resolutions for parts or all of the Alpine Space, at the time of the study (December 2006-October 2007), access to a lot of this data was restricted. At this time, the only RCM for which hourly input data was available and accessible was the RCM REMO (Jacob et al. 2007), with a comparatively high spatial resolution of approx 10km (10 arc minutes, see Figure 39). Therefore, the next step of this study, the simulation of the water balance using input data from regional climate model data, is based solely on data form the RCM REMO. The IPCC scenario used was A1B (IPCC 2007), the boundary forcings are provided by ECHAM5. The developers of REMO advise that at REMO precipitation data as input for water balance modelling should be averaged over at least 9 cells, to compensate for the fact that REMO, like other RCMs, has a certain level of uncertainty in the location and distribution patterns for hydrometeorological parameters. Figure 9 shows that an average of 9

REMO cells over the catchment of the Großache/ Alz would be more or less equivalent to using one average value for the whole catchment. As stated earlier in this report, and as shown in the digital elevation model in Figure 3, the catchment of the Großache/ Alz does not have uniform characteristics that would warrant the use of average values for the whole catchment for parameters such as temperature or precipitation. As this project is a pilot study that also aims to demonstrate how the methodology described above could be applied in practice, a decision was made at this point to use the unchanged REMO data with the discretisation of the REMO grid as input data for the water balance model. This factor should be kept in mind when evaluating the simulation results, especially for subcatchments of the Großache/ Alz which are often only covered by one or two REMO cells.

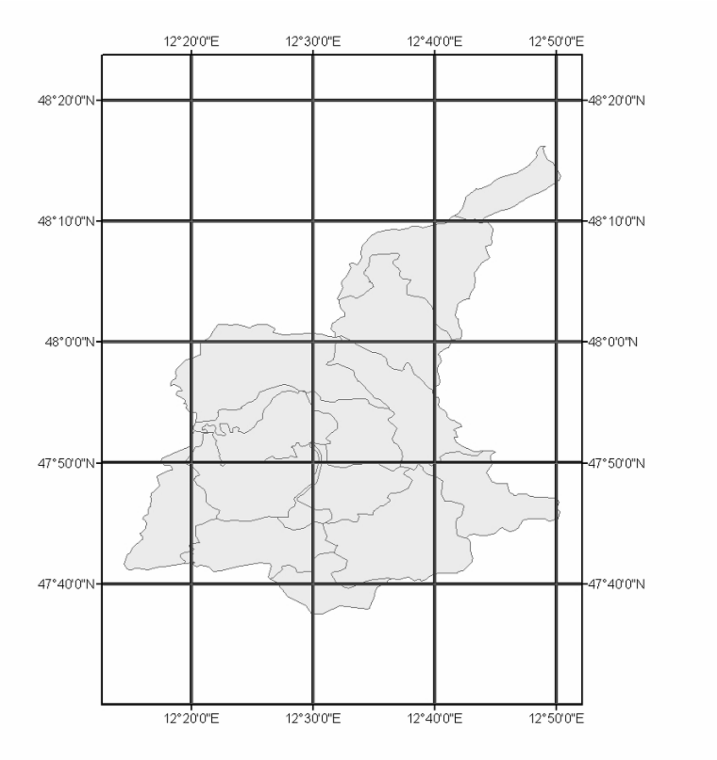


Figure 39: The Großache/ Alz catchment overlaid with the 10 arc minutes resolution grid of the REMO model

Source: (Kunstmann et al. 2007)

It also has to be stated clearly that climate models, whether global or regional, only allow conclusions to be drawn about possible developments in climatic periods of approximately 30 years. The periods chosen for the analysis of the simulation results were: The recent past (1971-2000), the near future (2021-2050) and the distant future (2071-2100). The model data for the period in the past is frequently referred to as the "control run". In order to assess the performance of the model, the results of the control run can be compared with measured values. To establish which "climate change signals" are contained in the model results, the projections for the near or distant future must be compared with the control run rather than with observational data. This is because modelled data and (gridded) observational data have different biases that would otherwise have to be taken into account.

Control run:

A comparison of the simulated water balance components for the whole catchment for the period 1961-1990 with observed values (Figure 40) shows that precipitation and discharge are overestimated. The observed values were taken from the Hydrological Atlas for Germany (HAD, 2003) and the Hydrological Atlas for Austria (HAÖ, 2007). The mean total annual precipitation calculated in the control run for the Großache/ Alz catchment is approximately 2000 mm per year. This is at least 300 mm per year greater than the average yearly value actually observed in the same period in this area. This constitutes an overestimation of average total annual precipitation of about 19%. The overestimation of evapotranspiration in the control run is relatively small with a value that is about 5% higher than the observed amount for the whole of the catchment. This leads to an overestimation of discharge for the whole catchment in the order of 26%.

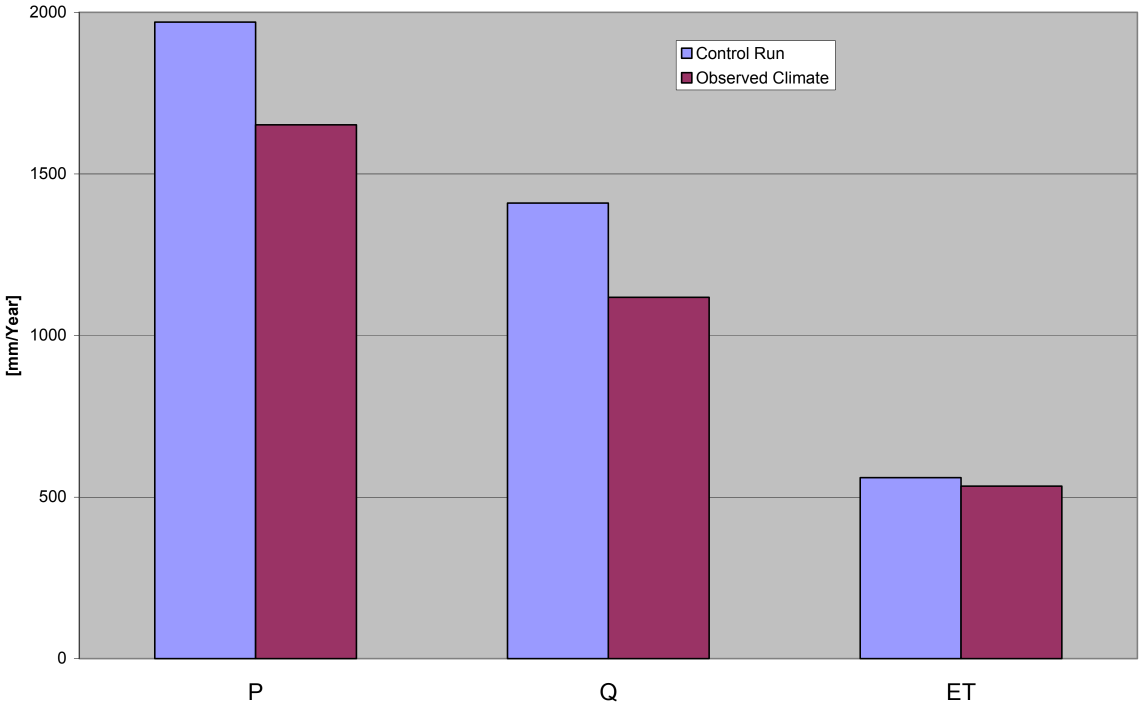


Figure 40: Simulated and observed average annual water balance components for 1961-1990 for the whole Großache/ Alz catchment (Area 2222km² - approx 9 REMO cells). Simulated values from control run REMO-LARSIM. Observed values from Hydrological Atlas of Germany (HAD) and Hydrological Atlas of Austria (HAÖ).

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

A comparison of the distribution of the water balance components in the catchment for the control run and observed values show that the control run overestimates precipitation in the western part of the catchment, whilst underestimating it in the eastern part of the catchment.

This tendency is the same for discharge. The comparison of average discharge values (for 1971-2000 where measured data was available, otherwise for 1978-2000) shows that the model chain REMO-LARSIM has problems simulating present conditions in some subcatchments of the river Großache/ Alz.

This can be seen clearly at the gauge St. Johann in Austria, where the average yearly discharge for the period 1978-2000 is overestimated about 30% (not shown), in some summer months the average monthly value is even overestimated by over 100% (

Figure 41). However, this is not the case for all subcatchments. At the gauge Stein for example, the average monthly discharges for the period 1971-2000 is simulated comparatively well (Figure 42).

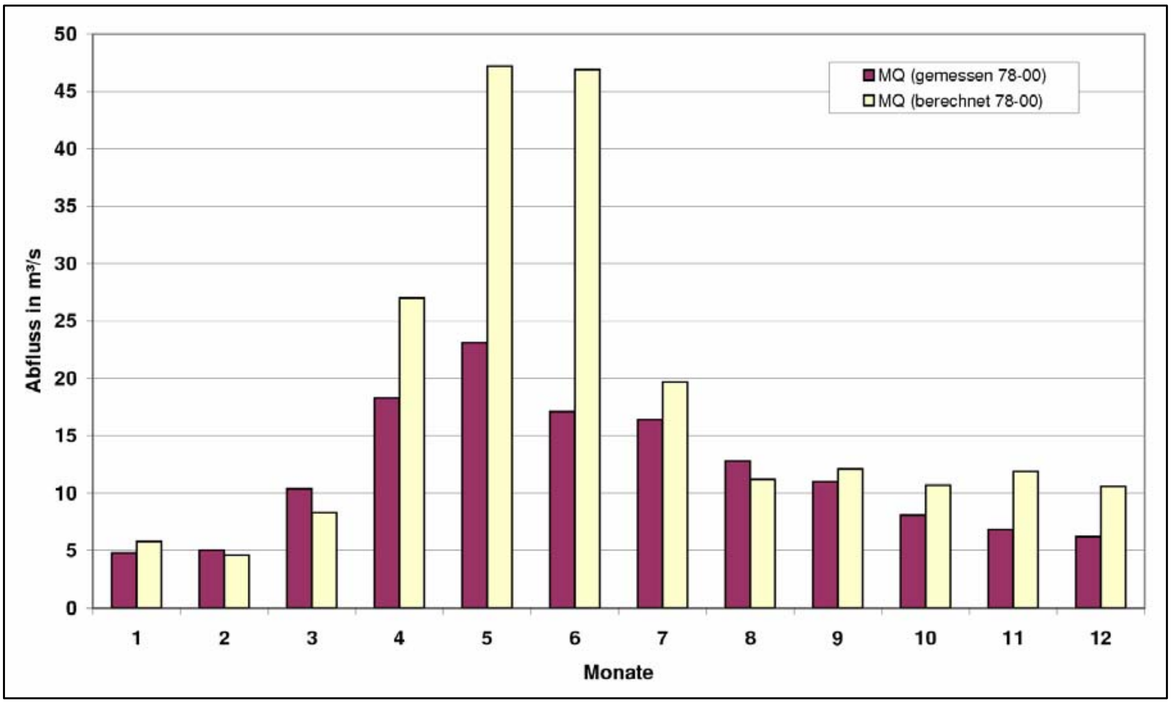


Figure 41: Average monthly discharge for the gauge St. Johann in Tirol, Austria. Observed (bordeaux) vs. control run (cream).

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Envrinment Agency, Germany and the Office of Government Tyrol, Austria.

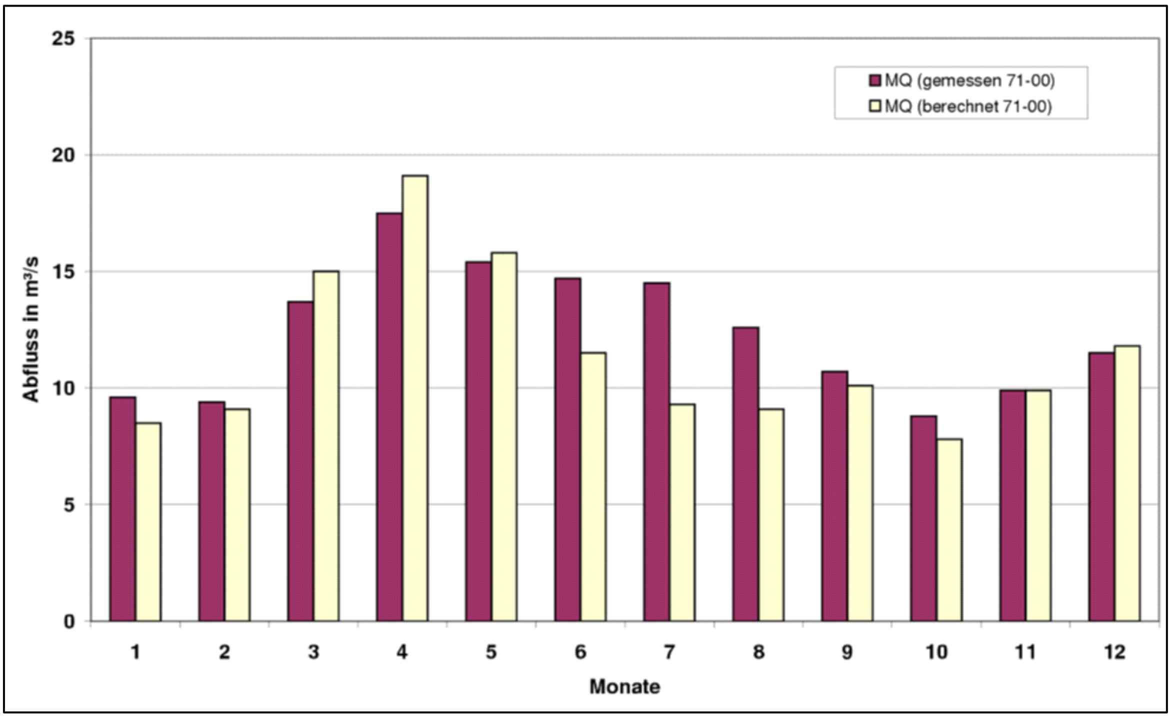


Figure 42: Average monthly discharge for the gauge Stein (Bavaria). Observed (bordeaux) vs. control run (cream)

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

Natural hazards:

With a view to the subject of natural hazards, in this case flooding, the performance of the model chain in reproducing extremes is of interest. Again, this can be assessed by means of a comparison of measured values and control run results, for example for average monthly flood discharge values. For the gauge St. Johann (Figure 43) in the upper part of the catchment, the average monthly flood discharges are greatly overestimated by the control run in some months, whereas in other months control run and measured values are similar. This is not the case for the gauge Stein (Figure 44) which lies in the lower part of the catchment. Here the control run underestimates the measured values in some months, whilst reproducing the pattern quite successfully for other months.

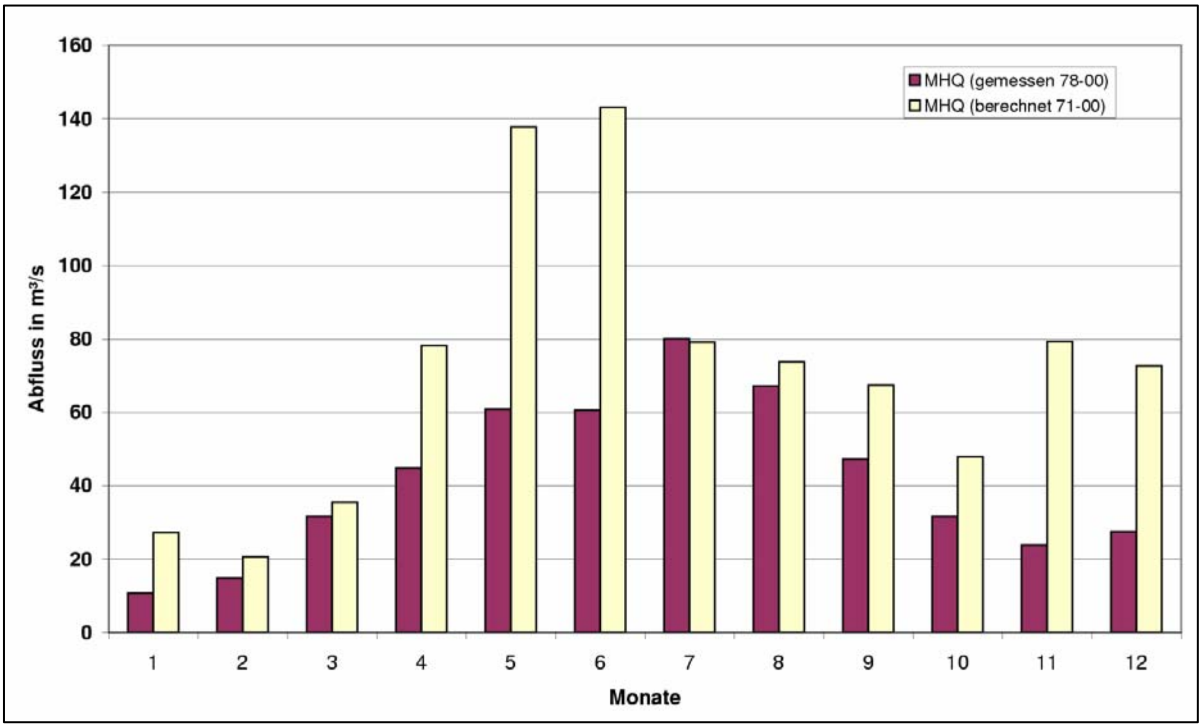


Figure 43: Average monthly flood discharge for the gauge St. Johann (Tirol, Austria). Observed (bordeaux) vs. control run (cream)

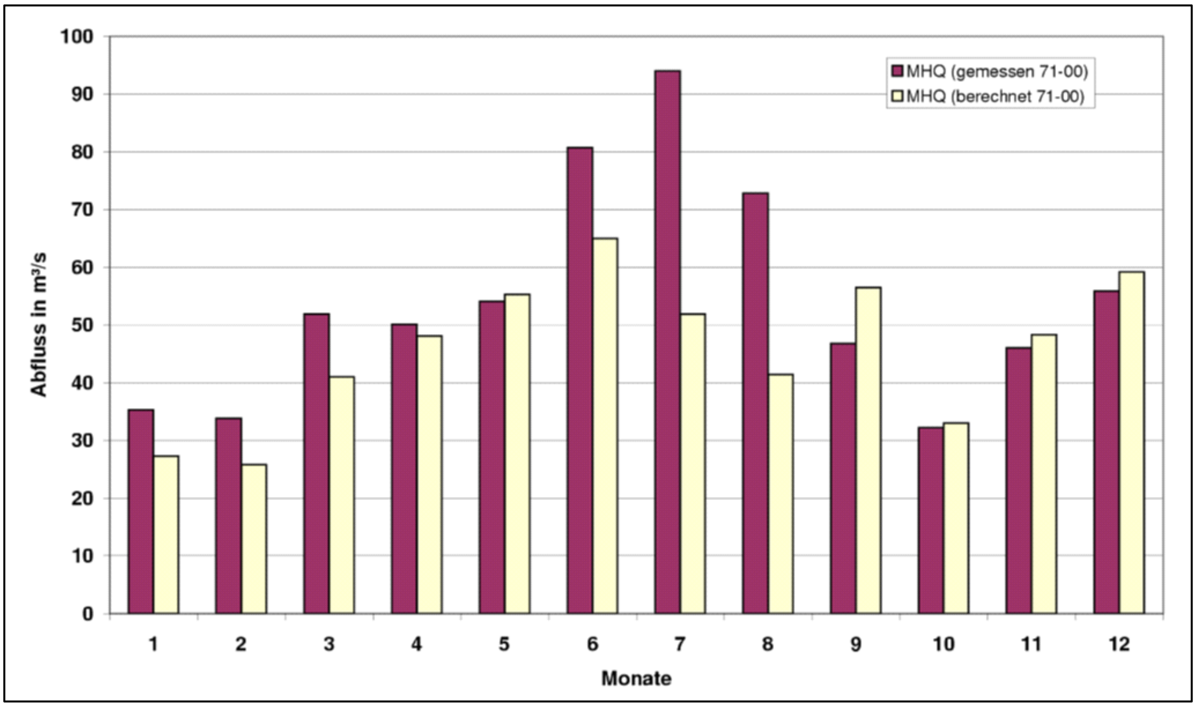


Figure 44: Average monthly flood discharge for the gauge Stein (Bavaria). Observed (bordeaux) vs. control run (cream)

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

A small part of the discrepancy between control run discharges and measured values can be attributed to difficulties with the calibration of the LARSIM model. The influence of the regional climate model on the final result is far greater. The overestimation of precipitation in western parts of the catchment led to an overestimation of discharge in the western subcatchments, and consequently at the gauge St. Johann. For the eastern part of the catchment (gauge Stein) the reverse was the case. The over- or underestimation of the discharge at these gauges, both for monthly average discharge and monthly average flood discharge, was much greater for some months than for others. The summer months seem to be particularly problematic. Naturally, the simulation of extremes is more difficult than the simulation of average values, as there are much greater uncertainties connected with extreme events. This investigation is a first pilot study for the complex task of using regional climate data for regional and local impact studies in the Alpine Space. More detailed evaluations are clearly necessary and should be carried out in studies similar to this one.

Near and distant future:

When trying to identify possible future water balance trends in the case study area for the period between 2001 and 2100, it appears that the simulated precipitation distribution only varies slightly and shows only a slight overall increase. The same can be said for evapotranspiration and discharge in this period. This is in line with the general trends identified for the Alpine Space.

The next step planned for this investigation was to establish whether the water balance simulation for the catchment of the river Großache/ Alz for a future scenario based on the RCM-data shows any tendencies towards a change in flood event patterns. One way of visualising such trends is to compare the sequence of largest floods per year in each decade. The following graph (Figure 45) shows that for the gauge Stein, for which the model chain REMO-LARSIM appears to have delivered comparatively good results in the control run, there is no significant difference between the range covered in the control run and the range in the REMO based projections.

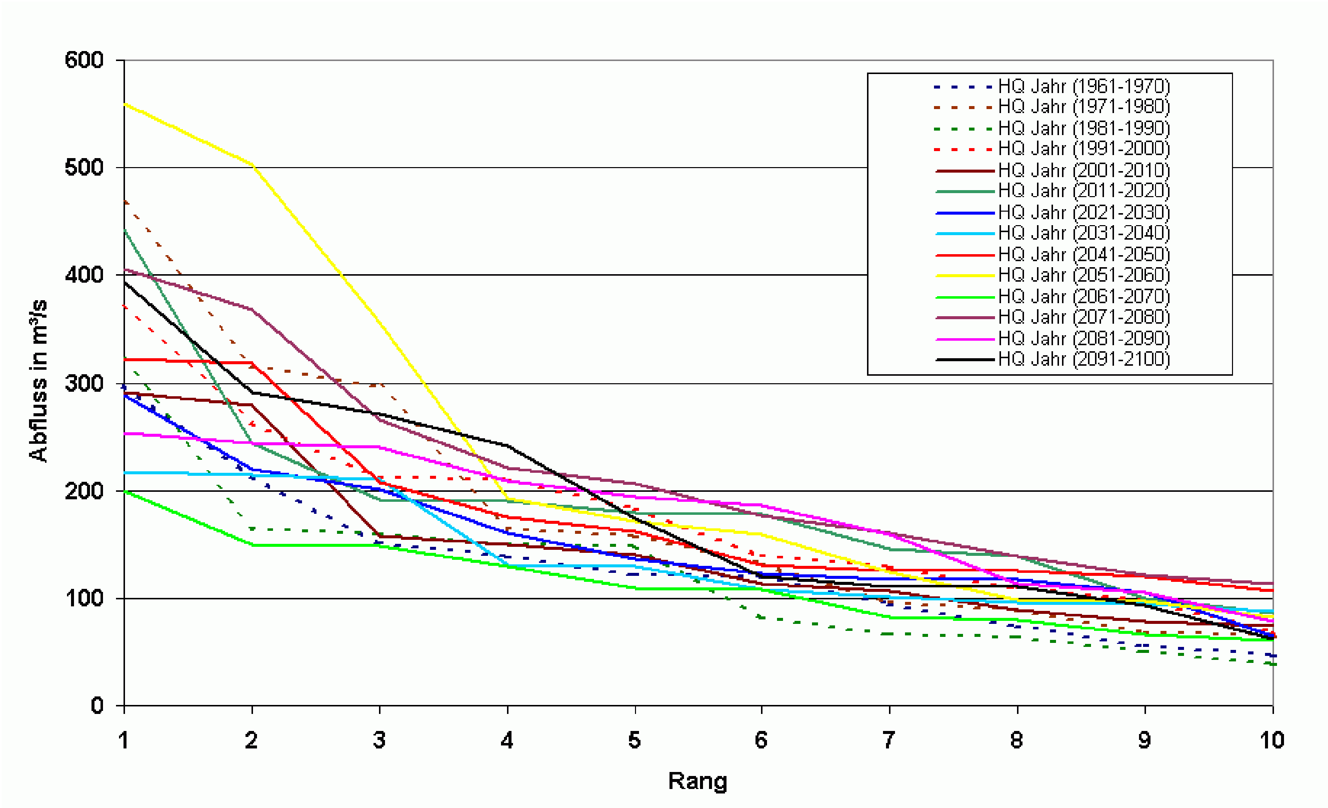


Figure 45: Water balance model simulation results based on data form the regional climate model REMO: Simulated 10 largest yearly flood discharges per decade for the gauge Stein for the past (control run 1961-2000) a future scenario (2001 -2100)

Source: ClimChAlp: Water Balance and Climate Scenario Simulation for the Großache/Alz Catchment - Final Report (2007) Ingenieurbüro Dr. Ludwig Karlsruhe, commissioned by the Bavarian Environment Agency, Germany and the Office of Government Tyrol, Austria.

3.6 Conclusions

The objective of this pilot study for the Großache/ Alz catchment was to analyse and quantify the impacts of climate change on floods with a hydrological model. The methodology applied was based on the use of regional climate model data as input for a water balance model. For the water balance simulation for the future scenario in this study, the assumption was made that land use remains constant. The choice of regional climate model was based on the results of an investigation that was carried out within ClimChAlp Work Package 5, to establish which of the available RCMs was best suited for the analysis of how possible climate change could affect the water balance of the catchment of an alpine river such as the Großache/ Alz (Kunstmann et al. 2007). In the course of the study it transpired that all of the "short-listed" RCMs available and accessible at the time of the study (December 2006-October 2007) have shortcomings and limitations when the focus is placed on reproducing the present climate at the scale of the river catchment of the Großache/ Alz. Firstly, there is the bias in precipitation and temperature values produced by the climate models. The RCM REMO also had difficulties reproducing the spatial distribution of precipitation in the catchment, a problem that is at least partly due to the alpine characteristics, especially the orography, of the case study area. It can be concluded that the discrepancies between the simulated values and the observed values for the control run period result, in part, from the fact that REMO, like other RCMs, has a certain level of uncertainty in the location and distribution patterns for hydrometeorological parameters which becomes relevant at the scale at which this case study was carried out.

The results of a water balance simulation for the period 1961-1990 using climate data from the model REMO for the whole catchment (area 2222 km² - approx 9 REMO cells) were compared with observed values. The comparison showed that not only precipitation but also discharge and evapotranspiration are overestimated. A comparison at the subcatchment scale showed that the model chain REMO-LARSIM had some problems simulating average monthly discharges and average monthly flood discharge for different gauges in the catchment. The calculated deviations between modelled and measured runoff-parameters result predominantly from the deviations in the RCM precipitation and their spatial distribution. Whilst in some months calculated and observed average discharge values were quite similar, in other months there was a tendency to over- or underestimate the average monthly flood discharges, depending on the location of the subcatchment of the respective gauge.

This investigation is a first pilot study for the complex task of using regional climate data for regional and local impact studies in the Alpine Space. More detailed evaluations are necessary and should be carried out in studies similar to this one. The results described endorse the findings of the study by (Kunstmann et al. 2007). This leads on to the question of whether, at this moment in time, simulations using RCM-data as input for water budget models should only be carried out at the scale of large river basins, using input data averaged over a larger number of climate model cells.

As there is an undeniable need for information at the scale of smaller river catchments, especially in the sensitive and complex Alpine Space, there is a further alternative: the regional climate model data could be "corrected" based on observational information before it is used at the kind of scale presented in this study. The question of bias and distribution correction for data from climate models is currently the subject of international scientific debate. For practitioners wishing to use regional climate model data, for example at the scale relevant for water management, this subject is becoming highly relevant.

This study is considered to be a first contribution for regional impact studies on future climate change impacts on runoff in a complex terrain like the Alps. At the same time, it demonstrates existing shortcomings and limitations of current regional climate models for hydrological research, thus endorsing the conclusions in (Fowler et al. 2007) that up till now insufficient consideration has been given to applied research on enabling stakeholders and managers to make informed and robust decisions when considering hydrological impacts of climate change. Therefore it is necessary that this pilot study is followed up in projects that look closely at methods of dealing with the systematic errors of climate scenario modelling at the river catchment scale, especially for the Alpine Space with its particular characteristics. Further studies at different spatial and temporal scales will have to be carried out, in order to assess which type of correction procedure is best suited to deliver useful and reliable results for which type of problem. In view of the difficulties described above, the results presented in this report can only be seen as a first estimation for the quantification of the degree to which the parameters relevant for natural hazards in the Alpine Space may change at the scale of an alpine river catchment such as the Großache/ Alz as a result of global warming. Despite all uncertainty resulting from the model chain and the small size of the investigation area, the results for the future show a slight increase in precipitation and discharge and to a lesser extent in evapotranspiration in the course of the century. In the context of natural hazards, an increase in discharge was found, which does not, however, constitute a statistically significant increase in flooding for the case study area. For the Period 2070-2099 regional climate models are in agreement that a significant increase in precipitation can be expected in winter and spring (Kunstmann et al. 2007) so an increase in flooding for this period appears likely.

3.7 Literature

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4. RAINFALL/RUNOFF MODEL FOR SMALL CATCHMENT AREAS IN THE LAVANT VALLEY FOR DETERMINATION OF POTENTIAL FUTURE EFFECTS THROUGH ASSESSMENT OF REGIONAL CLIMATE CHANGE SCENARIO

4.1 Abstract

Extreme events such as floods and mudflows have occurred more frequently in the last period at the Lavanttal catchment area (Carinthia / Austria). Therefore it seemed to be necessary to reconsider the existing knowledge base. Main threats resulted from sediment deposits in torrential catchment areas. Heavy bed load and suspended load transport can occur especially at the rivers Fraßgrabenbach, Pressingbach, Reisbergerbach, Arlingbach, and Weißenbach after intensive rainfall. At smaller and steeper catchment areas, summer thunderstorm rainfalls can also trigger debris flows, which could reach the valley plain. Several scenarios concerning climate change impact on future potential risk of natural hazards were investigated for 12 small catchment areas between 8 and 108km² in the Lavanttal region. The extended model area (including river Waldensteinerbach) is approximately 484 km² in area and covers the entire intermediate catchment area of the river Lavant between the gauging station St. Gertraud and the left tributary of river Lavant, the river Jaklingbach. The gauged catchment area (108.8km²) on the northern side of the gauging station St. Gertraud – river Waldensteinerbach - was also included in the model calibration and in the scenario simulations.

For this purpose, a detailed runoff model was set up. The model was calibrated on ten well-documented flood events out of several flood events observed during the last 2 decades. Recorded time series of precipitation from 13 stations, discharge observed at four gauging stations, as well as snow depth, and air temperature data were used.

The investigated case studies were classified as scenarios for the current state and scenarios for future conditions. For the current state precipitation distributions and runoff hydrographs were used, which were coordinated with the Hydrographical Service of the Carinthia Regional Office. The future condition scenarios resulted from discussions during the compilation of historical flood events, considerations of climatologists and results from the climate change module. Afterwards, it was investigated which appropriate counter measures, in terms of changes in land use, could induce adequate mitigation effects on the flood hazard.

The first event, out of several case studies, which were investigated, was the intense rainfall event of 8 October 1980 (Scenario A) with rain heights between 90 to 110mm per day. The main fraction of precipitation was superposed by snowfalls because of a temperature descent. Using the runoff model, extended by a snow melt module, the event has been reconstructed. As a climate change scenario, a 4°C increase of the air temperature has been induced with the effect that the entire precipitation in the catchment area had fallen as liquid rain. Compared to the current conditions, the simulation shows an increase in the peak runoff of up to 48% for AMC2 (soil moisture condition). The future condition scenario (temperature increase) has shown higher flows for the worst case precipitation distribution compared to the uniform distribution of precipitation. River flow would increase by 60% for the largest catchment areas and increase by 250% for the smaller basins, e.g. river Kleiner Weissenbach (7.9km²).

The investigation of the impact of the extreme observed rain fall (daily total of 268 mm) under modified soil moisture conditions and increasing intensity using the worst case precipitation distribution (redistributed on 3 hours = Scenario B1) brought the recognition that already under dry soil moisture conditions an estimated peak flow event of 5000 year return period would be reached. The estimated peak runoff under the soil moisture condition "normal" amounts for a 100 year return period event (= HQ100-value).

The impact of the variation of the soil moisture condition for the event in August 2005 at the gauging station St. Jakob (river Weissenbach), which was observed as a HQ10 event at the station Fischering, was quantified in the Scenario B2. The simulation for "wet" soil moisture conditions brought an increase of the peak flow, compared to the “dry” soil condition from $12m^3/s$ to $32m^3/s$. This corresponds to a discharge increase from a HQ5 to a HQ10 event.

The Scenario C identifies the runoff peaks for convective 100 year return period rainfalls taken from extreme rainfall statistics. The base for the estimation of potentially possible convective precipitation was the Hydrological Atlas of Austria - HAÖ (Skoda et al., 2005). The calculated peak runoffs exceed the current highest estimated 100 year return period flood discharges - HHQ100 - by 10% to 65%.

The possible impacts of climate change concerning the convective heavy precipitations by increasing rainfall intensities by 10%, 15% and 20% using the same rainfall distribution and duration, were investigated through the Scenario D. For a 20% increase in rainfall - compared to Scenario C - a mean increase in the peak outflow of approx. 38% was registered.

Flood events often occur in small, delimited areas and pre-warning times are too short. Economic loss is lower in small torrent catchment areas, compared to large river watersheds. Austrian Alpine catchment areas are characteristically mainly forested. The potential successes of land use changes in terms of an extension of forest land and soil melioration for the mitigation of floods was studied in Chapter 4.5.3 - Mitigation of floods by land-use management in forested and agricultural areas. By increasing the forest area by 10%, the impact on the peak flow was not detectable. The study of the consistent soil cultivations of arable land across slopes in the catchment area with significant acreage, led to a mitigation of the runoff peaks, depending on the acreage of the respective catchment area from 1.3% to max. 9.6%.

The precipitation-runoff model could be improved if additional data were collected. Following a description of the study area and its major geomorphologic characteristics, the methodology is outlined together with the adopted hydrological model for the runoff simulation and with the obtained results and comparisons. Finally, the possible impacts were quantified and discussed in the light of mentioned literature, based on the simulation results and assuming changes of the land use and meteorological conditions.

4.2 Introduction

The studied lateral tributaries of the Lavant Valley lead, in recent years, to flood events endangering the settlements. In the light of scientific findings and the media debates on climate change, a review of the existing designing basis for risk assessment over long periods seemed necessary.

The streams that were studied in this work are listed in the (Table 17). For calibration purposes, the original processing area of approx. 260 km² was extended to a total of approx. 484 km². The runoff model includes the whole catchment area between the Lavant River stream flow stations St. Gertraud and Fischering and the northern basin of Waldensteiner River. The watersheds are small catchment between 8 to 108.8km ².

River	Watershed area km²	Tributary
Klein Weissenbach	7.97	left-side
Jaklingbach	16.28	left-side
Pailbach	16.38	left-side
Woisbach	16.56	right-side
Reidebner Bach	17.44	left-side
Auenbach	25.82	right-side
Frassbach	36.38	left-side
Reisberger Bach	47.40	right-side
Prössingbach	48.84	left-side
Arlingbach	54.70	right-side
Weissenbach	58.73	right-side
Waldensteiner Bach	108.80	left-side

Table 17: Studied tributaries (drainage areas based on 10x10m DHM)

4.2.1 Purpose and scope

The project "Climate Changes, Impacts and Adaptation Strategies in the Alpine Space" in the framework of the INTERREG IIIB Alps Program of the EU deals extensively with the issues of climate change and there derived impacts on the prevention of natural hazards. Under the partnership lead by the Bavarian State Ministry for Environment, Health and Consumer Protection (STMUGV) aims of this project are searching answers on the strategic level, dealing with the protection against natural hazards under the consideration of possible climate changes.

Using a rainfall-runoff model for 12 small watersheds areas in a catchment area of 484km² in the Lavant Valley, the outflow behaviors for Current and possible Future Situation have been investigated. The input data consists of:

- terrain data (10x10m Raster) for the physical characteristics
- stream topology (dendritic system)
- soil and land use data
- measured data like rainfall, air temperature, snow cover and stream flow from monitoring gauge stations

For synthetic torrential rainfalls, convective heavy precipitations (Skoda et al., 2005) were used.

4.2.2 Description of study area

The tributaries examined in the study cases are both left and right tributaries of the Lavant River in the area of Wolfsberg district between: 14 ° 38'17 .46"East, 46 ° 45'38 .34"North and 15 ° 01'40 .79"East, 46 ° 57 '37 .64"Nord (WGS84). The Lavant itself is a left tributary of the main river in Carinthia, the Drau. The watersheds are located in the district Wolfsberg. The highest terrain areas in the catchment reach at the western edge 2,140m (Große Speikkogel) and the main outlet at the mouth Jaklingbach is 400m above sea level, the height difference amount 1,740m. The average gradient of the total catchment area is 16% and the maximum slope reaches 69%.

The landscape of the basin varies, near the River Lavant and near e Wolfsberg town area, the agriculture competes with the pressure of the urbanization and industry. In the higher regions the forest is dominating the grass / pasture land.

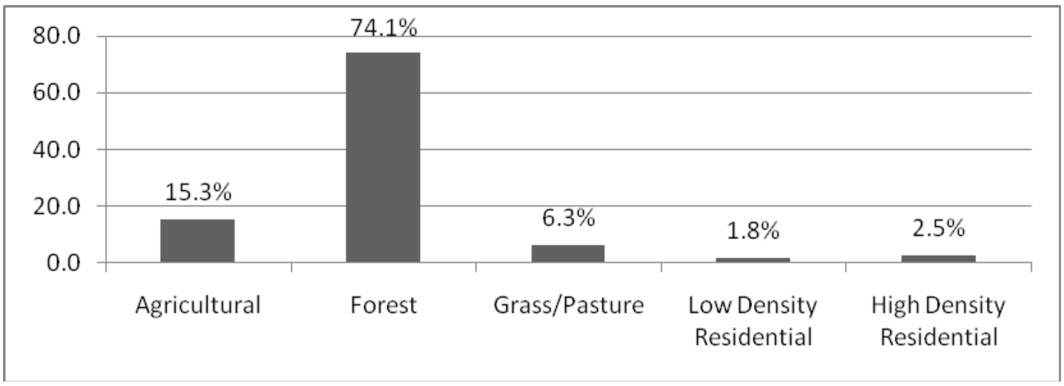


Figure 46: Land use distribution in the Catchment area

Small Weissenbach is a small left tributary of Lavant with a catchment area size of 7.9km². It discharges in the Lavant between the right tributary of the Lavant, Arlingbach and the left tributary of Lavant, Pailbach. Small Weißenbach rises with 2 sources east of the town of Wolfsberg at an altitude of about 1,100m on Zoderkogel and slightly northwest of it and flows about 5.5km in the south-west up to its confluence with the Lavant in Wolfsberg. The catchment area is oriented to south-west and has a length of approximately 5km and a width of about 2.4km. The river is on its entire length in the competence of WLV.

Jaklingbach with a catchment area size of 16.3km² is also a left tributary of Lavant; the stream has a total length of approx. 11.2km, and rises at Siebenbrunn on the west flank of the Steinschneider at an altitude of ca. 1,920m. The river flows to the West-South-West, the confluence with the Lavant happens south of St. Andrä. The catchment area is relatively stretched, and the total length is about 10.5 to a width of about 2.3km. From kilometer 5.1 the Jaklingbach lies in the competence of WLV.

Pailbach in the higher region also called Paulebach discharge as left tributary in the Lavant between the Lavant left tributary Small Weissenbach and the right Lavant tributary Reisberger Bach. With a total area of 16.4 km² is catching the area around Rieding, Michelsdorf, Paildorf and St. Stefan. The total length of the main channel is about 8.4km. The catchment area has a maximum width of 2.4km and a Length of 6.4km. According GZP - WLV 1988 in case of flood, the water ranged up to the Settlement, in 1966 the road was flooded and the river banks have been overflowed. During floods the torrent is arriving high velocities – due a too narrow River regulation – and leads to erosions and endangers roads and the Settlements which are close to river.

Woisbach has an elongated catchment with numerous right side tributary. It has a total area of approximately 16.6km², and a river length of 13.4km. The creek rises at the eastern flank of Speikgogel at approx. 1,850m above sea level. The current limit of forest lies by approx. 1,700m. The competence limit is roughly in river kilometerage 2.9 in Winkling. According to the local sources, repeated floods are endangering the settlements. In the event of a disaster, according WLV a sediment transport of rd. 20,000m³ can be expected.

Reidebner Bach is a left side tributary of the River Lavant and discharge into it between the right side Lavant tributary Woisbach and left side tributary of Lavant Jaklingbach in St. Andrä. It rises at the western flank of the Steinschneider at an altitude of 1,510m above sea level. The main channel has a length of 9.95km and the catchment area is oriented towards the WSW and has a maximum length of about 9km and a broad stretch of about 1.9km. Reidebner Bach upstream of Wutschbach mouth in Schilting and Wutschbach itself lies in the competence area of WLV. The WLV indicates that hardly boulders from the upper reaches are to be expected; river bed erosions in the middle part and erosion in the forest area above the trench head exist. In a disaster event, approx. 2,000m³ of sediment are expected. In the case of flood, according to the statements of the resident, the country road is overflowed and residential houses are endangered.

Auenbach is draining the area around Prebl and discharge into Lavant northern from Wolfsberg between the left-side Lavant tributary Prössingbach and the right-side Lavant tributary Weißenbach. The source of the stream lies on the southern flank of Schulterkogels in the Saualpe at an altitude of about 1,350m. The Auenbach flows approximately 12.5km towards Southeast until its confluence with the Lavant at an elevation of about 460m; the length of the source to the competence border is about 8.8km. The biggest length of the catchment area is approximately 8.4 km and the greatest width expansion amounts rd. 3.1km.

Frassbach is a left-side tributary of Lavant, comes up from many sources on the western flank of the Renneiskogel at an altitude of about 1,500m and flows into the Lavant north of the mouth of the left side Lavant tributary Prössingbach in St. Gertraud area. The catchment area is oriented to the West; the main stream has a length of approx. 10.9 km. At the river kilometre 1.6, Frassbach confluence with the Limbergbach. The catchment area has a length of 10.3km and a broad stretch of 4.7km. The entire catchment area lies in the competence of WLV. The size of the catchment area amounts rd. 36.4km².

Reisberger Bach is a right tributary of Lavant. Shortly before the River mouth, Reisberger Bach confluence with the Frauenbach. Reisberger Bach has a total length of about 16.5km, and the catchment area has a maximum longitudinal length of approx. 15.4 km and the width strain comes at 3.5km². The Frauenbach rises at the eastern flank of the Hofkogels at an altitude of 1,230m, the Reisberger Bach itself has its own sources on the eastern flank of Ladinger Spitz in the Saualpe in an altitude of approx. 205m. The WLV describes Reisberger Bach as a great torrent with a big sediment potential. The competence of WLV lies at Frauenbach at approximately kilometre 5.3 and at Reisberger Bach itself at about kilometerage 3.8. The annual sediment transport is evaluated by approx. 2,000m³ and the max. expected sediment is about 40,000m³. The existing bed load trap in hectometre 64 has a capacity of approx. 30,000 m³. According to statements by local resident on Reisberger Bach sometimes the water ranged up to the settlements. Last flood disasters were registered in 1956 and 1967.

Prössingbach is a left side Lavant tributary discharging in the Lavant approx. 470m south of the mouth of the Fraßbach River. The basin has a total area of 48.8km². In the middle part of Prössingbach confluence with its largest tributary Rassingbach. The Prössingbach rises at the north flank of the Great Speikkogel and flows over a total length of approximately 13.5km towards northwest. The catchment area is Wes-Nord-West oriented and is almost entirely in the competence of WLV.

Arlingbach is a Lavant right tributary. The stream rises with several sources at the eastern flank of the mountain between Speikkogel and Kienberg in 1,900 to 2,000m above sea level. The towards to east stretched catchment area is rd. 54.7km² big, the length strain arrive approximately 16.3km, and the.max. width strain amount rd. 5.45km. From river kilometerage 4.4, Arlingbach lies in the competence of WLV. In documents of WLV Arlingbach is described as a big torrent, with considerable sediment deposits; By flood levels are long stretches of the main channel and some close to river buildings endangered; according to statements made by the resident west of Jöbstlbach the river banks are overflowed .

Weissenbach is joining in his middle part the Klippitzbach and Litzerbach and discharge in the Lavant as right side tributary between the right side Lavant tributary Auenbach and Arlingbach in urban area, in the middle of the city Wolfsberg. The river has a length of about 18.1km, and the catchment area is to Est-South-Est oriented, have a length of approx. 17.8 km and the maximum width expansion amounts about 6.3km. The River rises with numerous sources, the highest source is at the northeast flank of Geierkogels at approx. 1,600m elevation and at the east versant of the Forstalpe (2,020m above sea level). Most of the River is in the competence of WLV. The WLV characterized Weissenbach as a water reach stream. In the past high water events destroyed the main road and individual objects were endangered.

Waldensteiner Bach stream rises on the western flank of Stoffkogels at an altitude of 1,550m; the brook flows first to the north roughly along the mountain chain and then swings to the west, so that, after about 18.3km it discharge in the Lavant northern of Tiwimberg. The captured catchment area covers an area of about 108.8km², the maximum longitudinal strain is approximately 11.6km and the width strain reached 12.8km. The total catchment area is oriented to the west.

4.3 Historical flood events in the project area

4.3.1 Actual events

21. and 22. August 2005:

The event was centered on Carinthia, in the middle and lower Lavant Valley, particularly in the area Wolfsberg. The Lavant tributaries Auenbach and Weißenbach flowed over the banks, their peak outflows matched a 7 to 10-years return period event. Auenbach (approximately 10 - 15 residential and commercial properties flooded) caused most damages. The peak flows at Auenbach reached to 13m³/s ± 2m³/s. The torrential rain fell in two phases on 21 and on 22 August and caused two flood waves of similar magnitude. The Lavant River reached in Fischering the 10-years high water Mark, in the upper reach the peak values were approx. by the 1-yeark Mark (Hydrological Regional Service, 2005).

20 June 2004:

Centre of flood events formed the lower Lavant Valley area, particularly the St. Paul in Lavanttal. The Auenbach (Wolfsberg) and Reisberger Bach (St. Andrä) caused smaller floods. The Lavant reached at the Fischering gauge station approx. 165m³/s, which corresponds approximately to a HQ20. In the whole province of Carinthia, there were recorded rainfalls between 70 and 100mm (Hydrological Regional Service 2004). The Flood report dated August 2005 points out that in June 2004 at the St. Jakob gauge station a peak outflow of 22m³/s ±2m³/s has been observed.

4.3.2 Collection of historical events

4.3.2.1 Goal definition

With the consideration that "what has already happened - can happen again" observations of flood events and landslides were thoroughly investigated. The historical recordings of torrential rain and outflows represented for the study cases the main usable data basis. Traditions and written of extreme heavy rainfall, mudflows, landslides and flood events complete the big picture of rare natural flood disasters. The obtained results represent a benchmark for the consideration of the election and plausibility of scenarios and interaction of various influencing factors. The main assumption was until know that historical records will recur with the same probability as in the past. As part of the investigative series on climate change, such considerations are questioned. The historical records are to be seen as references concerning requirements of natural hazard investigations.

4.3.2.2 Archives and historical sources

The following historical sources of flood disasters have been used:

- Years 792 – 2003: *Hochwasserchronik* 792-2003(Amt der Kärntner Landesregierung, BMLFUW, 2004)
- Year 1660 - *„Eine Abrutschung von der Koralm im Jahre 1660"*, (Fresacher, 1916), (Carinthia I)
- Year 1916 „*Eine Naturkatastrophe im Lavanttal*", (Wittmann, 1916), (Carinthia I)
- Year 2002 - *Ereignisdokumentation - Hochwasser August 2002*, (Zenar, Univ. für Bodenkultur Wien, 2003)
- Year 2004 – "*Hochwasser vom 20.06.2004 – Lavanttal – St. Paul"*, (Amt der Kärntner Landesregierung, Abteilung 18 – Wasserwirtschaft / Hydrographie, 2004)
- Year 2005 - *Hochwasser vom 21-22.08.2005*, (Amt der Kärntner Landesregierung, Abteilung 18 – Wasserwirtschaft / Hydrographie, 2004)
- Year 2005 – "*Das Hochwasser in Österreich vom 21. bis 25. August 2005",* (Abteilung VII/3 – Wasserhaushalt (HZB), 2005)

Others sources:

- Austrian Hydrological Atlas – HAÖ. Institute of Water Management, Hydrology and Hydraulic Engineering – University of Natural Resources and Applied Life Sciences, Vienna (Skoda et al., 2005)
- Rainfall and stream flow records – Central Institute for Meteorology and Geodynamics Austria, Provincial government of Carinthia, Department 18-Water Management / Hydrographical Service
- Hazard zone planning - Torrent and Avalanche Protection Agency Department Carinthia, Section: Middle and Low Carinthia, 1988
- Voluntary Firebrigade Wolfsberg, St. Margarethen, Firefighters Chronicle

4.3.2.3 Classification of documentation and events

The targeted natural disasters were torrential rains followed by floods, landslides and mudflows. The most important basis on past flood events were the rainfall and stream flow records of the gauge stations in the catchment area. Existing records of flood events were thoroughly investigated. The documentations consist of several well documented reports of the official state institutions (Regional Hydrographical Services, WLV, HZB, BOKU Vienna), with detailed information of rainfalls and runoff volumes and of the temporal and spatial variability.

The very accurately described some observations of private individuals (Carinthia I), local resident, however, give little or no evidence concerning the discharge volumes, but very impressive descriptions of the intensity of the runoff events and the extent of the destruction.

4.4 Runoff Model

4.4.1 General items

The model was used to study the local hydrological response of the Lavant tributaries in the middle Lavant Valley area by different rainfall and soil conditions (see Table 17).

The main results of the study are the results of the analysis of runoff events for the Lavant tributaries under different rainfall loads at different states of the soil storage capacity in the catchment area. For the rainfall-runoff model, first were identified the necessary data types and the data availability; the selection of the runoff model was sensible influenced by the data availability. The data records have been collected and verified and finally the input data base with historical records was set up. The model was calibrated on several historical flood events with a return period between 1 and 30 years. Testing and validation runs followed and complete the runoff-model set up phase. With this calibrated model the hydrographs for different study cases were simulated. The studied aspects involve rainfall variability and/or changes of soil moisture content in the targeted watersheds.

4.4.2 Delineation of basin physical characteristics

The hydrological investigated catchment area includes 12 main watersheds (Table 17). The partitioning in 47 smaller sub-basins has been dictated by the existing geographical/topological conditions, such as water courses, settlement areas and competence boundaries between Torrent and Avalanche Protection Agency Administration and Federal Administration.

The drainage delineation of the sub-basin boundaries was performed using the HEC-geoHMS software (US Army Corps of Engineers - Hydrological Engineering Center, 2003). The computations of the fill sinks, flow accumulations and flow directions were the subject of GIS pre-processing. The finally obtained boundaries and streams have been verified and after small changes, especially near Lavant River, validated. Physical characteristics of streams and sub-basins have been extracted from the terrain data and stored as attributes in the watershed table. The extracted parameters were physical characteristics and have been used to estimate the hydrologic parameters. The spatial diversity in the model area is represented by simulating the basin as a set of sub-areas. Characteristics assigned to each sub-area (MRU) include physical parameters as slope, elevation, flow length, soil type and vegetation type.

4.4.3 Development of precipitation-runoff model

The used Hydrologic Modeling System HEC-HMS (HEC-HMS, 2006) software is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff.

The latest developments also offer the possibility of snowmelt and surface detailed (terrain and rainfall) input records. For modelling, several methods are available, the choice of each procedure is highly dependent on the targeted results (parameters), conditions of the area to be examined and database. The computer code has been constantly updated and is based on over 30 years of development time. HEC-HMS belongs to the new generation software, and is recognized as a "state of the art" engineering tool.

The actual version 3.1.0 of the HEC-HMS used in this study simulates hydrologic processes that occur in Lavant Valley (Figure 47) as a single event conceptual model with simulation times over round one week, ignoring the Evapotranspiration part which influences by such short events can be neglected.

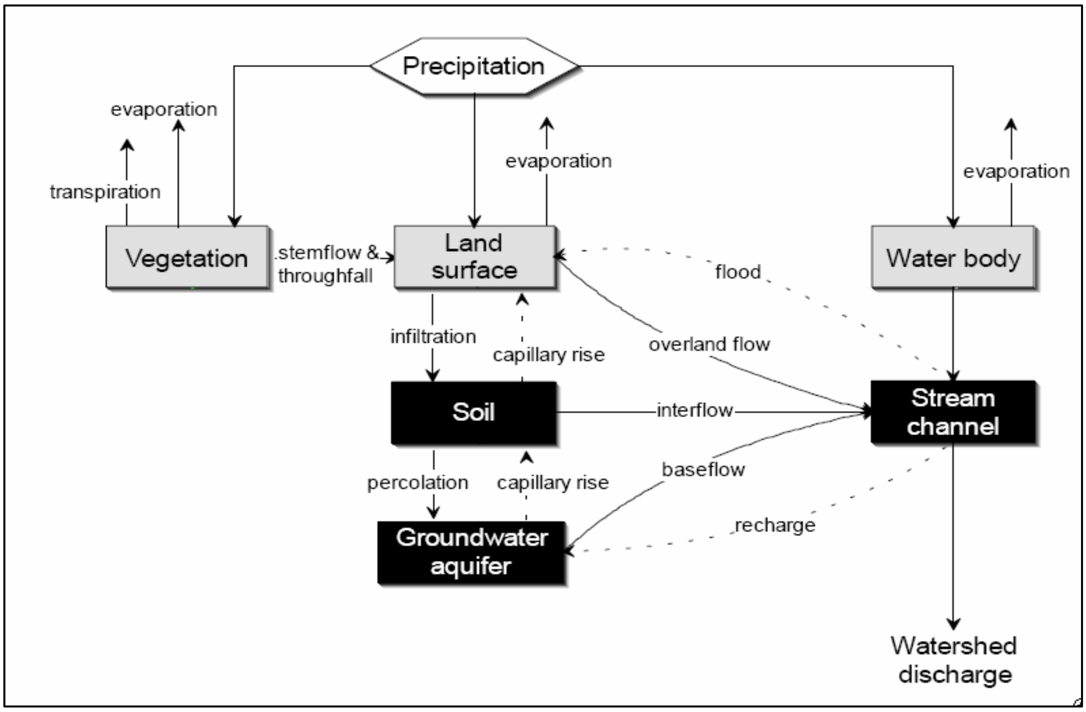


Figure 47: Scheme of the Precipitation Runoff Modeling System HEC-HMS

The runoff model is composed of several modules (Table 18). A detailed description of the combination of modules used in this study is provided in the documentation of the HEC-HMS (HEC-HMS, 2006). The long-time series with the recorded rainfall, drains, air temperatures and snow cover for the calibration and for the testing scenarios are read directly from an external – for this purpose created – DSS database. The calculated results for the target watersheds are also in a DSS database deposited. From the results databank, a hydraulic model (like HEC-RAS) can directly access the computed hydrographs. In Addition to the spatial characteristics, model inputs included time series of measured or estimated precipitations and air temperatures. The model distributes the data from the locations of the rainfall gauge stations in a dynamically way. Missing data are automatically replaced by next near gauge station and diffused over the watershed sub-areas considering for air temperature also differences in elevations and for all type of gauge stations distances between MRU and the stations. At each MRU, the runoff-model simulates a sequence of hydrologic processes in 15 minutes time step. At the end of each time step, several model outputs, including surface runoff as peak discharge and runoff volume, precipitation loss, total excess and total baseflow (for snowmelt also SWE, temperature, liquid water content, etc), are available at each MRU. The computed MRU flows are the input for the stream flow. The contribution from the upstream assigned MRU are accumulated and routed downstream to simulate the computed stream flow at the various stream locations represented by the nodes. Snowmelts were modelled with the temperature index method implemented in the HEC-HMS up to ver. 3.0.1. The temperature index method is an extension of the degree-day approach to model a snowpack. A typical approach to the degree day is to have a fixed amount of snowmelt for each degree above freezing. This method includes a conceptual representation of the cold energy stored in the pack along with a limited memory of past conditions and other factors to compute the amount of melt for each degree above freezing. As the snowpack internal conditions and atmospheric conditions change, the melt coefficient also changes. The Temperature-Index method uses 12 parameters, more of them, like PX (threshold between precipitation falling as rain or snow), base temperature or ATI-Meltrate coefficient are quite well defined and can be relatively easy set up. Sensible parameters like ATI-Meltrate function or water capacity have to be calibrated (HEC-HMS, 2006).

Name of Module	Model	Module function
Runoff-volume module	SCS curve number (CN)	The Soil Conservation Service (SCS) Curve Number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture,
Snowmelt module	Temperature-index	The snowmelt method determines if precipitation is rain or snow, and tracks the accumulation and melt of the snowpack (Temperature-index Method).
Direct runoff module	Clark's UH	Represent the Translation - Attenuation or reduction of the magnitude of the discharge as the excess is stored throughout the watershed.
Baseflow module	Linear reservoir	Linear-reservoir volume accounting model.
Routing module	Muskingum	Storage in the reach is modelled as the sum of prism storage and wedge storage.

Table 18: Modules used in the precipitation-runoff model

4.4.3.1 Basin Monitoring System

For the calibration of the model, the historical records of daily and hourly and even 15 minutes values of the measuring stations were available in digital form by the Hydrographical Service of Carinthia and Styria Provincial Governments available. For the stations Preitenegg and St. Andrä, the stations operated by ZAMG were also available after consultation with ZAMG.

The catchment precipitation measuring stations and stream flow stations (Table 19, Table 20) are delivering consistent and redundant data beginning with 1988. The longer series, from 1976, are available for the station St. Gertraud. The highest observed water level at the lowest stream flow gauge station (Fischering) has a return period of approx. 30 years. Findings like differences between daily values and higher-resolution data series of precipitation monitoring gauges have been corrected; however, potential sources of error in the used stream flow records couldn't be totally excluded.

Station name	HZB-Nr.	Height [m]	Longitude	Latitude
Forst-Saualpe	114801	700	14°47'14"	46°51'36"
Hochfeistritz	114074	965	14°35'46"	46°46'50"
Knappenberg	114603	1050	14°33'54"	46°56'06"
Preblau	114306	790	14°48'07"	46°55'45"
Pustritz	114330	790	14°44'41"	46°44'50"
Wolfsberg	114702	440	14°50'33"	46°49'15"
St.Andrä	114421	402	14°49'46"	46°45'50"
St.Michael Wolfsberg	114793	510	14°47'58"	46°50'00"
Hofkogel-Saualpe	192046	1300	14°43'00"	46°50'00"
Preitenegg	114314	1035	14°55'06"	46°56'19"
Hebalpe	112334	1310	15°00'38"	46°55'44"
Glashütten	112243	1275	15°03'36"	46°49'29"
Kloster-Rettenbach	196050	1150	15°03'17"	46°53'56"

Table 19: Rainfall gauge stations

The most important precipitation gauge stations are (see Figure 48 and Table 19) with rd. 20% percent surface share, Preitenegg and Wolfsberg, followed by Hofkogel-Saualpe with rd. 17% of the whole catchment area (see also Figure 62). The allocation is based on the Thiessen-polygon method but the runoff-model calculations of rainfall into the model have been made using Inverse -Distance method.

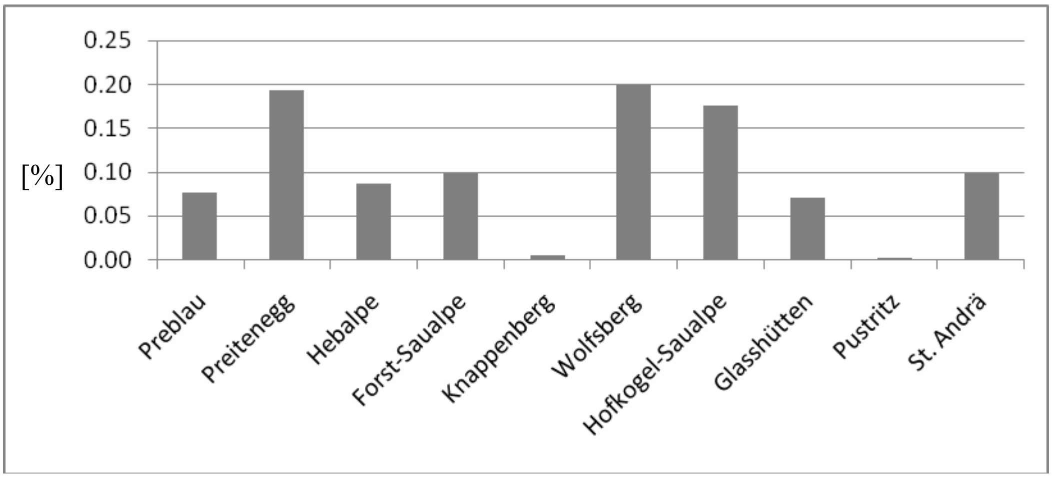


Figure 48: Surface share of the precipitation gauge stations

Station name	Operator	Time Series	Time step
Fischering (715.6km²)	HD Carinthia	01DEC1988 - 01JAN2007	hour
St. Gertraud (380.2km²)	HD Carinthia	01DEC1976 - 01DEC2006	hour
St. Jakob (55.9km²)	HD Carinthia	01JAN1983 - 01JAN2006	hour
Waldenstein (108.8km²)	HD Carinthia	01JAN1997 - 01JAN2006	hour

Table 20: Stream flow gauge stations and Time Series

4.4.3.2 Model parameterization

The data acquisition for land use and permeability was based on the "Land use Map of Carinthia" (2002). The soil component of the hydrological model describes, in a simple mathematical scheme, the complex physical processes as interception of the rainfall by the vegetation, the surface ponds storage and the separation of the precipitation in precipitation loss and excess.

The excess rainfall is largely dependent of the saturated permeability of the soil - a difficult to measure parameter for natural surfaces. The set up of the spatial variability of soil permeability in small catchments areas is a subjective task, (the studies of (Dunne, 1978) show that Hortonian overland flow occurs seldom in humid regions because of the high infiltration rate of that soils).

Models predicting surface runoff as a result of partial saturation of surface storage are nonlinear, for many models which are predicting surface runoff as a result of partial saturation of surface storage, surface runoff occur when cumulated rainfall excess the saturation capacity of surface storages, such as surface ponds and interception. Subsequently, rainfall is separated into surface and subsurface fluxes depending on the degree of saturation of soils. As the degree of saturation of soil layer, or the saturated fraction of the basin surface (Moore, 1983), (Beven, 1979), (Todini, 1996) increase, the runoff tends to depend more linearly on the rainfall, irrespective of the time history of the hyetograph. Accordingly, uncertainties in the assumed parameters affect the runoff volume predicted less violently.

This is the reason why a relatively simple model of saturation excess type was adopted by several authors to simulate floods, many of them in the Alps (Mancini et al., 1998; Brath and Montanai, 2000), (Sackl B, 2006), etc.

In this study the Curve Number Method (United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, 1986) was used. The soil storage capacity (S) is here an important parameter (also in more sophisticated models).

By events with rainfall volumes exceeding the storage capacity, the non-linearity between the cumulative runoff volume and the excess rainfall volume disappear. The dependence of the soil moisture on the storage capacity is adjusted according to the precipitation volume in the five days preceding the event. Infiltration rates of soils vary widely and are affected by subsurface permeability as well as surface intake rates. Soils are classified into four classes (A, B, C, and D) according to their infiltration rate, which is obtained for bare soil after prolonged wetting.

The used soil class map, based on the detailed "Provincial Government of Carinthia Soil Map", has been obtained with the classification from Table 27. Extensive experiments conducted worldwide, facilitated a quite detailed cross reference table (Table 21 and Table 39) between soil permeability, storage conditions and land use classes. These tables are one of the key reasons for the wide diffusion of the SCS method in the hydrological practice. Detailed physically based methods are more difficult to apply over large basins due of lack of information on physical soil parameters in relation to different land-use practices. The concentration times have been estimated with the wide used Kirpich Formula:

$$tc=(0.868 \text{ x } L^3/\Delta H)^{0.385}$$

with L [km] and ΔH in [m]. The routing model uses the Muskingum method; however the parameters were subject of calibrations. The computations were made with a base flow estimated as average for the best fitting of the calibration events. For the study case in this work (Scenario A – Oct1980) which compute snowmelt, the used parameters and the made assumptions are highlighted in the Chapter 4.5.2.1.

The Unit Hydrograph was computed using the Clark Method thus near the time of concentration also the retention coefficient of the watersheds could be used. The analysis of flood event and the estimation of local precipitation is based on point precipitation measurements. Runoff events of a certain recurrence interval period "n" are caused in small catchment areas through n-years precipitation of a higher intensity (short duration) as in relatively larger catchment areas where precipitation intensity of the same return period are lower. While in small catchment areas point rainfalls are significant, in larger catchment areas the flood events follow after longer rainfalls; thereby the intensity of the rain decreases with growing of the storm area; this concerning, a depth-area-duration reduction of the precipitation has to be applied. The average precipitation P [mm] of a heavy rainfall event is represented as a function of the precipitation area A [km²], relative to a maximum precipitation on the grid point Pmax [mm] follows predetermined period for level D [min], and return time Tn [years] in the general form:

$$P = P_{max}(T_n) \exp(-k A^n)$$

where k and n are empirical parameters. It was used a „soft" reduction: $k = 0,19 D^{-0,56}$ and $n = 0,5$. In this study, torrential rainfalls on watersheds under 30km² have been not reduced. The soil moisture condition at the begin of the rainfall was accounted through the (Table 26) Antecedent Soil Moisture Condition (SCS CN Method)

Land use	Hydrological Soil Group				Treatment
	A	B	C	D	
Crop	143	80	48	35	Contoured and terraced row crops, good conditions
Crop (row crop)	171	104	70	55	Contoured and terraced row crops - transversely to slope: good conditions
Forest	452	169	94	68	Wood and forest land: fair conditions
Grass/Pasture	593	184	104	72	Pasture and range land: good conditions
Residential	162	85	52	38	Average lot size < 1000m²
Urban	76	45	28	22	Average lot size < 500m²
Waste land	76	41	25	16	Poor vegetation

Table 21: Maximum storage capacity S [mm] – for AMC2 conditions for the land use and permeability classes adopted in the study

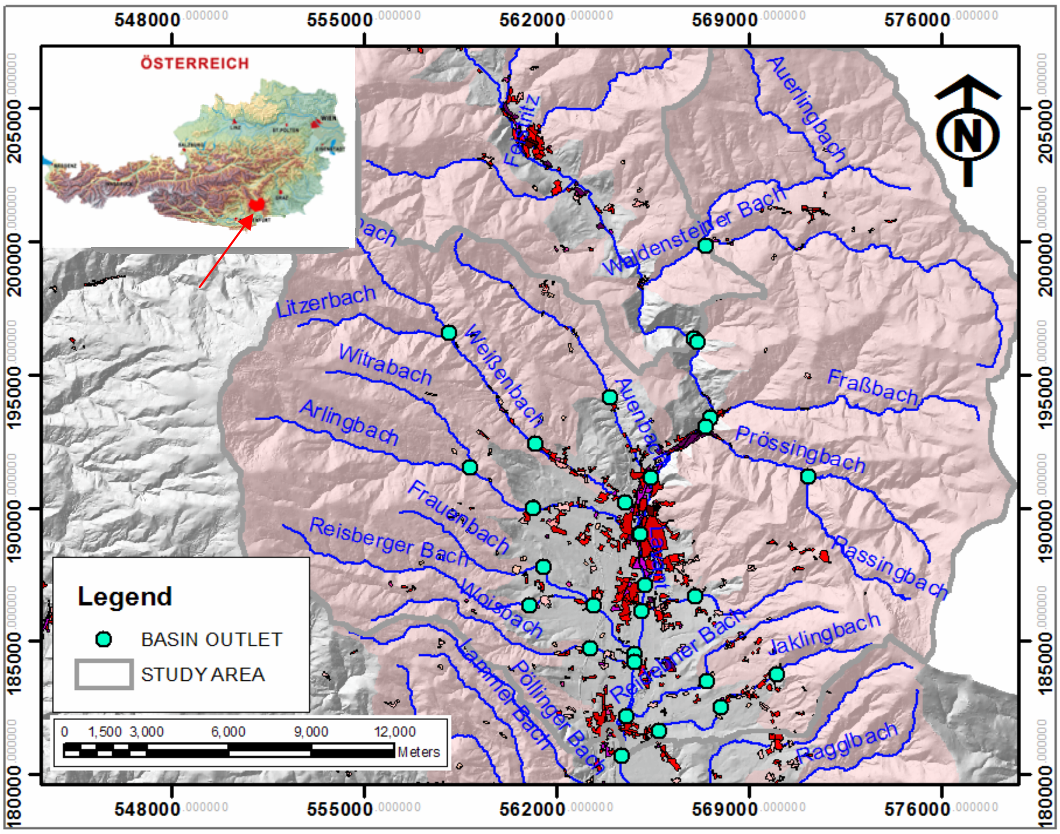


Figure 49: Hydrological basin with administration competence borders, drainage network, populated areas and catchment outlets

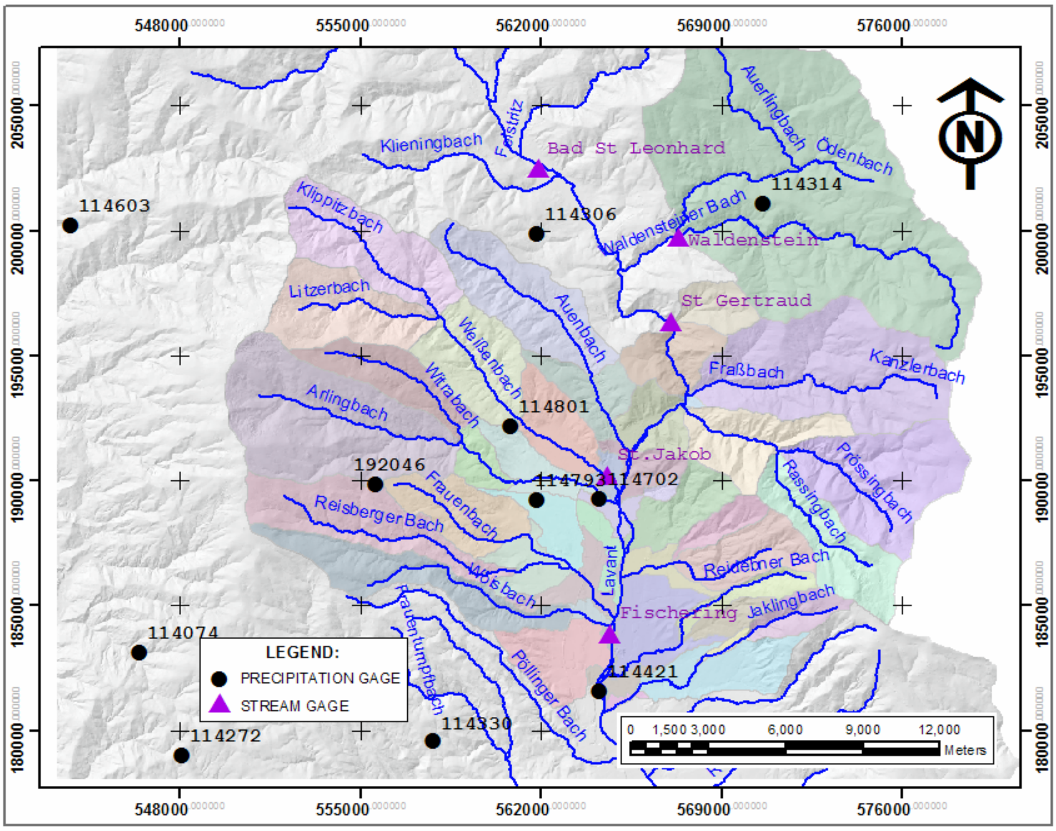
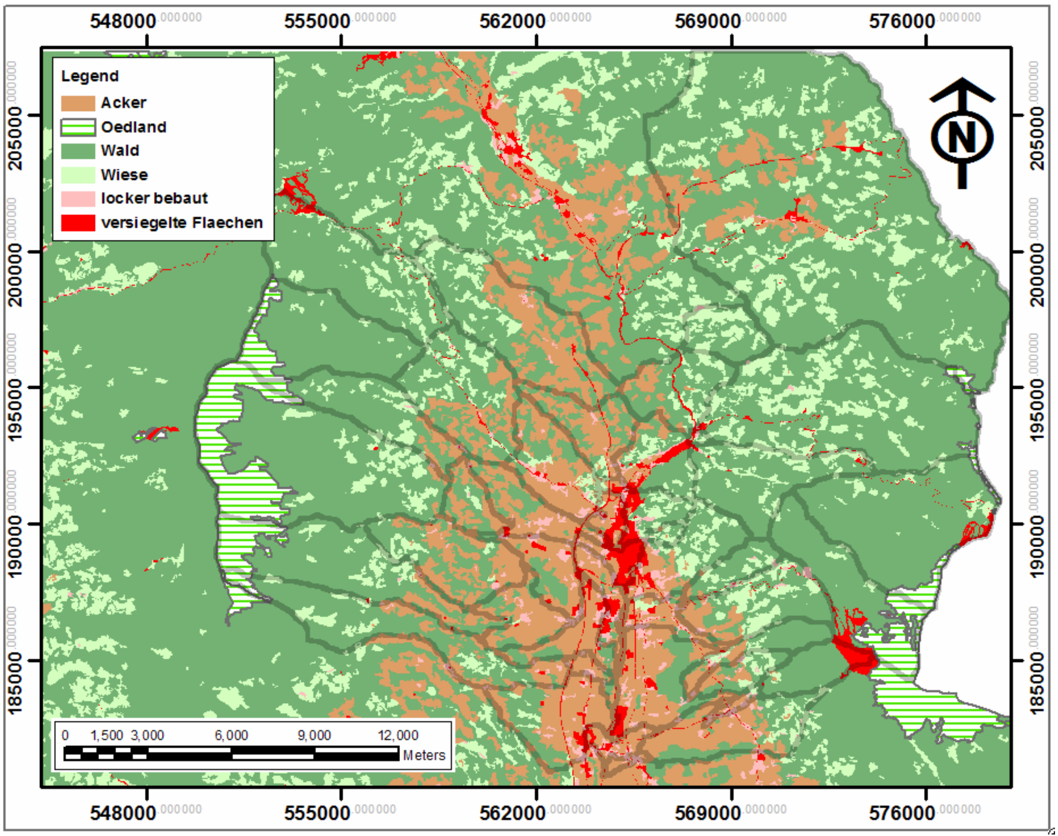


Figure 50: Catchments areas with gauge stations and drainage system



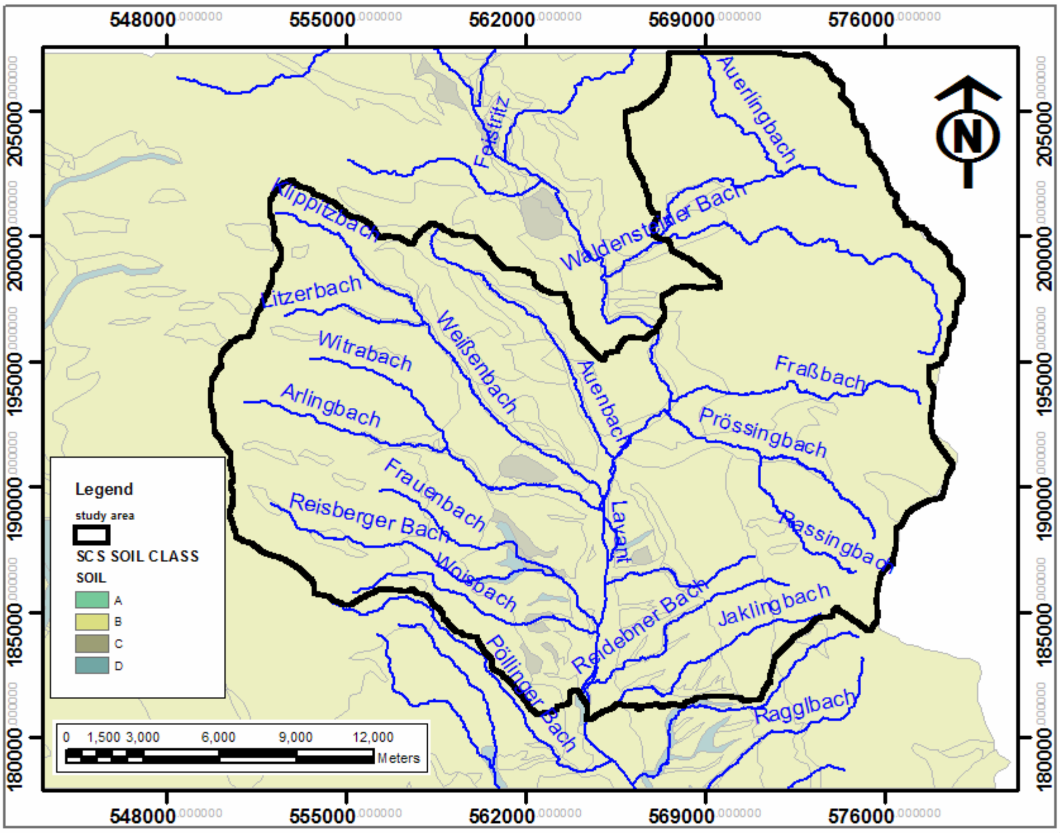


Figure 51: Land use Map (reclassified)

Figure 52: Hydrological Soil Group Map

4.4.3.3 Model calibration and testing

During the calibration, simulated flows were compared to estimated stream flows and the model was calibrated by adjusting the model parameters until the fit between the observed and estimated value was reasonable. The observed precipitation data were available as daily values and for some stations and periods also in hourly and even in 15 minutes time steps.

For the model calibration and validation procedure, out of total 20-years records, 10 flood events were selected; six events were used for calibration, the other 4 were used for testing. There were 4 stream flows (Table 20) and 13 precipitation gauge stations (Table 19) available. To be able to use the high definition rainfall records even if they were not for all the events contiguous, the inverse distance precipitation method was used. Originally designed for application in real-time forecasting systems, have the ability to automatically switch from using close gauges to using more distant gauges when the closer gauges stop reporting data. The latitude and longitude of the gauges is used to determine closeness to one or more nodes specified in each sub-basin.

The selected calibration events took place between 1989 and 2005, which corresponds to the highest level on Fischering stream flow station. With the St. Gertraud stream flow records as source boundary condition, for historical events the runoff-model can simulate the hydrological response of the entire Lavanttal northern from St. Andrä.

Event	Station	Waldenstein		St. Gertraud		St. Jakob		Fischering	
	Period of simulation	Peak time / Peak flow [m³/s]		Peak time / Peak flow [m³/s]		Peak time / Peak flow [m³/s]		Peak time / Peak flow [m³/s]	
1	18.06.04-24.06.04	20.06.04 15:00	17.2	20.06.04 14:00	49.5	20.06.04 14:35	4.8	20.06.04 20:00	189.7
2	19.08.05-26.08.05	21.08.05 12:45	16.5	21.08.05 13:00	40.1	21.08.05 12:37	12.0	21.08.05 12:00	135.1
3	30.06.89-10.07.89	-	-	04.07.89 02:00	53.6	04.07.89 02:15	4.7	04.07.89 01:00	106.8
4	09.07.99-16.07.99	11.07.99 06:30	16.4	11.07.99 08:00	58.4	11.07.99 05:00	3.6	11.07.99 08:00	100.8
5	21.07.99-28.07.99	23.07.99 00:45	15.5	23.07.99 03:15	59.5	23.07.99 23:15	4.7	23.07.99 23:00	97.8
6	02.10.05-09.10.05	05.10.05 02:15	22.3	05.10.05 03:00	45.8	-	-	05.10.05 04:00	92.2
7	10.08.05-17.08.02	12.08.02 09:00	10.9	12.08.02 08:00	34.2	11.08.02 11:34	3.7	12.08.02 09:00	82.8
8	16.08.99-20.08.99	17.08.99 02:15	12.9	17.08.99 01:00	36.7	17.08.99 01:36	3.6	17.08.99 01:00	81.7
9	20.08.99-24.08.99	20.08.99 20:00	11.8	20.08.99 21:00	46.8	20.08.99 19:13	3.5	20.08.99 19:00	75.6
10	13.09.95-18.09.95	-	-	14.09.95 22:00	22.3	14.09.95 20:45	2.8	14.09.95 22:00	41.8

Table 22: High-water events used for model calibration and testing

The higher peak flows at the Fischering station has a return period of rd. 30-years and the stream flow stations St. Jakob and Waldenstein reach to max. 5 years (Table 30, Table 31 and Table 32).

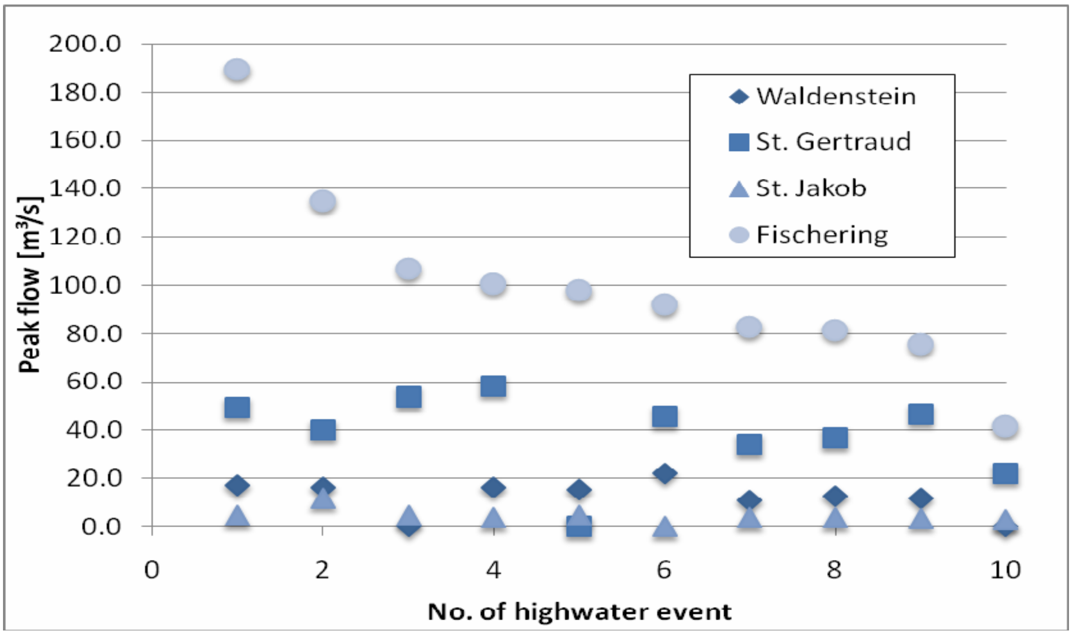


Figure 53: Peak discharges of the calibration/testing events

During calibration, the starting values of the parameters, inside the tolerance bandwidth, were adapted, until the adjustment of the computed outflow hydrographs to the measurements was acceptable. With adjusted base runoff, parameters for hydrograph recession, initial loss, curve numbers and Muskingum parameters for the routing, for further testing and validation calculations the model parameter were frozen. The SCS-CN number and the parameters of the hydrograph (f_p) have been adapted with non-discretionary approach; the SCS CN was calibrated for all sub-catchment areas of a brook with the same ratio.

For all sub-basins similar conditions of the calibrated CN-values to the starting CN-values were obtained. The CN which control the losses and the watershed storage were reduced to 0.8 of the initial start value. Based on the total rainfall of the 5 previous days, CN class changed for two events from AMC1 to AMC2. The global hydrograph coefficient (f_p) factor varies by the first 6 events between 0.8 and 1.15.

The test runs with fixed f_p values (unit hydrograph parameter) between 1 and 1.1. As part of the validation, only the curve number class according to the soil moisture condition were changed.

For all 10 flood events, the measured and simulated runoffs and volumes were compared, the detailed results for the streams gauge stations Waldenstein, St. Jakob and Fischering are listed in the Appendix D – (Table 30, Table 31 and Table 32).

In summary, the largest documented flood event reached at Fischering around HQ_{30}, the next largest was around HQ_{10} and the last amounts to approximately HQ_1. At Waldenstein and St. Jakob the largest outflow peaks reach approximately HQ_5. The test calculations for the flood events No. 7, 8, 9 and 10 has in comparison of the peak outflows at

Fischering a deviation from -1%, -16%, +3.3% and -3.6%. For the runoff volume the deviations amounted -2.3%, +23%, +7.1% and +8.3%.

At gauge Waldenstein the simulation error for peak flow compared with the observed, comes to +16%, -14% and +0.03%. The simulated runoff volume error is +7%, +15% and -6%.

The St. Jakob gauge reach during the calibration and testing roughly match values. The testing runs for runoff peak mostly overestimate the observations by +140% +97% +98% and -15% (higher errors by smaller events and comparable error of rd. 15% by rd. HQ_5 event). The simulated runoff volume error amounts to -32% +48% +28% -8%.

This concerning it is to mention that the hydraulic calculation of the Hazard-Zone Project in Wolfsberg (Terneak, 2005) provides for this cross section a flow channel capacity of approx. 25m³/s. Also, the flood report (Hydrographical Service) estimates for June 2004 also a value of 20 to 24m³/s. Moreover, sensitivity analysis of the model parameters for these records delivered constant significantly higher values than those of the measurements. It was also observed that at higher outflows (such as for ex. from HWE No.2), the differences are much smaller. Thus, the calibration was done with less emphasis on the records of the stations Wolfsberg. Additionally to the CN-class, the influence of the soil moisture condition is modelled through the global hydrograph factor f_p as listed below:

- f_p=1 for AMC1
- f_p=1.1 for AMC2
- f_p=1.2 for AMC3

4.5 Driving forces and processes – link with climate change

4.5.1 General Items

The model area has approx. 484km² and covers the entire intermediate catchment area of Lavant between St. Gertraud gauge station and the mouth of the Lavant left tributary Jaklingbach, including the north watershed of Waldensteiner Creek.

4.5.2 Scenarios

For a series of 12 small watersheds between 8 and 108km ² in the Lavant Valley in the region of Wolfsberg District, several scenarios for the impact of climate change on the future potential risk of natural hazards have been computed:

- Scenario A - Study case of the intense rain- and snowfall event from 8. and 9. October 1980 under possible changed climate conditions.
- Scenario B1 - Torrential heavy rains under changed AMC, investigations of the greatest daily runoff occurred, seasonality of heavy rains.

- Scenario B2 - The impact of the variation of the soil moisture conditions for the August 2005 flood event at the stream flow station St. Jakob
- Scenario C - Runoff peaks for the convective 100-year torrential rainfalls from extreme rainfall statistics.
- Scenario D - Possible impacts of climate change in form of more intense convective rainfalls. Study of the increasing in rainfall intensity by 10%, 15% and 20% by constant rainfall distribution and duration.

4.5.2.1 Scenario A – Increasing of Snowfall limit

In Austria, the snow is a major factor, the storage of the rainfall in the snow cover plays in the water balance a significant role. The estimation of quantities of melt water is a key component in the design of flood defence measures. The case study reconstructs the situations from October 1980 when heavy rains superposed with snowfalls without producing floods events and compare results with those from increasing air temperature as climate change effect by the same and by increased precipitation intensity.

On October 8, 1980, there was a very intense precipitation event in the catchment area of Lavant Valley with daily totals between 90 and 110mm. The expected high outflows did - due to the temperature fall – not happened. The snowfall limit is, conform St. Andrä measuring station, in the night of 8. to 9. October decreased to 0.0°C.

The daily total values for the precipitation gauge stations Preitenegg and St. Andrä were disaggregate. For the other stations, the values have been averaged from the stations Preitenegg, St. Andrä and Reichenfells. The used data series for the case study are ranging from 8. October 1980 00:00 to 13. October 1980 23:45. For the precipitation, distributions 2 different forms were used: a uniform distribution and a right-side skewed distribution. For the skewed distribution, 70% of the rainfall was concentrated in the night of 8. to 9. October between 05:00 and 07:00 pm. The calculations were performed using precipitation and air temperature data of the gauge stations supplied from the climate change model (Formayer, 2007). For the upper model boundary – station St. Gertraud – the available historical stream flow record was used as a source boundary condition. The snow cover data were used singular for calibration and judgments considering the correctness of the simulated snow-water-equivalent. At the beginning of the event, a zero snow cover was measured.

For the snowmelt model following settings were made:

- PX: Discriminate between precipitation falling as rain or snow; set to 0.5°C.
- Base Temperature difference between the base temperature and the air temperature defines the temperature index used in calculating snowmelt; se to 0°C.
- Wet meltrate: the rate at which the snowpack melts when it is raining on the pack; set up to 4mm/°C-day
- Rain rate limit: discriminates between dry melt and wet melt; set up to 1mm/day

- ATI Meltrate: coefficient is used to update the antecedent meltrate index from one time interval to the next; set up to 0.98.
- Cold limit: accounts for the rapid changes in temperature that the snowpack undergoes during high precipitation rates; set up to 200mm/Tag
- ATI coldrate: 0.84.
- Water capacity: amount of melted water that must accumulate in the snowpack before liquid water becomes available at the soil surface for infiltration or runoff ; set up to 4%.

The vertical spatial variability of the watersheds was described by dividing the sub-basin cover in 300m thick height bands. For each layer were defined the temperature gradient of rd. -0.4 °C/100m altitude (lapse rate), elevation and land share of the height band. Other specific factors, due to the lack of snow before the precipitation, were set to zero.

As a climate change effect a steady warming of 4°C on all air temperature dates has been induced. This had the effect that almost the entire precipitation in the catchment area fell as rain.

The status quo was compute for the AMC1soil condition and a uniform distribution of rainfall. The climate change scenario was simulated for AMC1 and also for AMC2, both of them for the uniform distribution (“Cur G”and “Fut G”) of precipitation and also for a right skewed (“Fut R”) rainfall distribution.

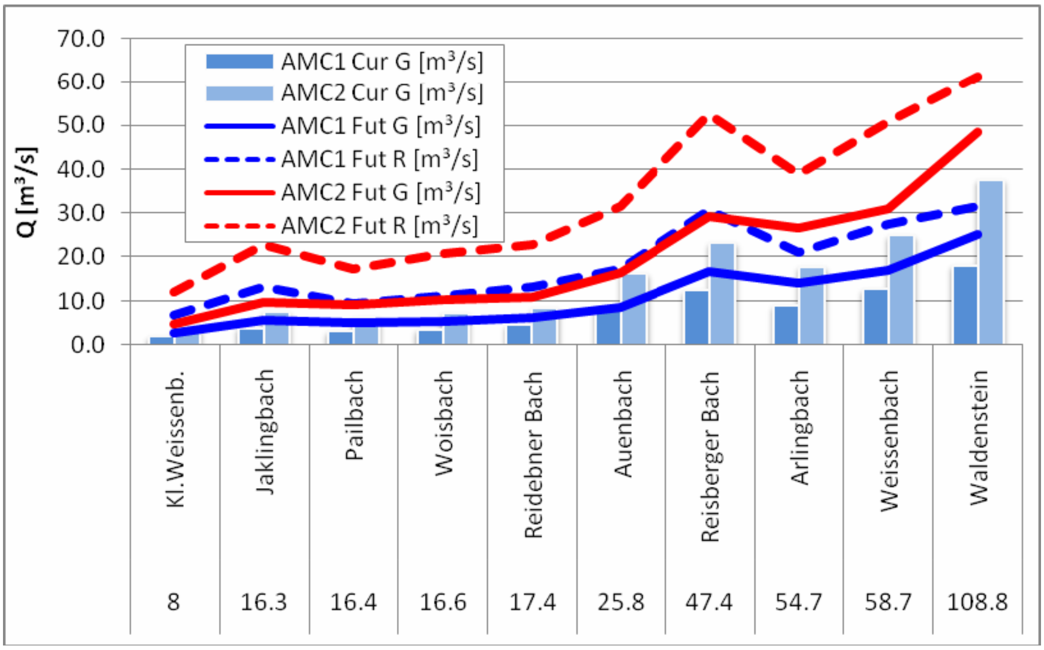


Figure 54: Model results - Scenario A. 8.-9. October 1980

In the status quo, the model calculates for Waldensteiner Bach an average snow-water-equivalent (SWE) of 30mm. The stations Preitenegg give for 9. October rd. 100mm new snow cover, this mean round 10 to 13mm SWE observed versus the 30mm simulated; however, wind influences on the observed data could not be quantified. The dispersion of SWE values in the catchment area and the distribution in the high-altitude areas of the sub-basins is relatively wide. Thus, the higher layers of the right southern tributaries watersheds as Arlingbach compute a snow water equivalent; with peaks up to 102mm. Detailed results of the simulation for Current and Future Conditions by different soil moisture conditions and different rainfall distribution are listed in the Table 33. More details are available under Appendix E – , Figure 68 to Figure 72. For the climate scenario the SWE values reached values over 30mm only for high altitudes and only for very small surfaces. The averaged values and the comparison level for the Fischering show that almost all precipitation falls as rain.

By uniform distribution of rainfall and soil moisture conditions AMC1, the simulated climate scenario flows exceeds the current situation flows by 4% at Auenbach, and by 58% at Pailbach. For AMC2 soil conditions, due to temperature series influences, the differences amount from 1% to 44%.

The discharges of the future conditions in the unfavorable right-skewed distribution rainfall compared with those of the uniform distribution show that this has a major influence. Differences from 60% to 220% of the peak flow are the consequence.

A comparison of the runoff-volumes between actual and climate scenario for the medium soil moisture and a steady rainfall distribution shows an increasing of climate scenario by 40% to 100%.

The in Appendix E – Figure 72 represented computed hydrographs at the Fischering station is by rd.10% overestimated. The reason for this lies in the model set up (DAD-value), however the targeted statements are the Lavant tributaries and not Lavant River itself, thus the simulated hydrographs for this station has to be seen more as qualitative evaluation.

4.5.2.2 Scenario B1 – Maximum observed daily precipitation

Highest daily value for rainfall measurements was registered at station Preitenegg at 24 July 1913 and amounts 268.1mm.

Extreme observed daily precipitation (Source HAÖ):

- 16 Aug 1910 – 127.6mm St. Andrä
- 24 Jul 1913 – 268.1mm Preitenegg
- 06 Sept 1916 – 156.9mm Glashütten
- 18 Aug 1989 – 100.5mm Pustritz
- 07 Jan 2006 -- 141mm Hofkogel-Saualpe

The regional hydrographical Service gives also for the Wolfsberg gauge station a max. value of rd. 250mm (Figure 55:), this is just rd. 7 % under the max. (HAÖ) value from station Preitenegg.

Station name	HZBNR	Lat.	Long.	Height [m]	N15M	N60M	N3H
St Andrä	114421	46°45'50"	14°49'46"	402	99.4	175.6	238.9
Hofkogel-Saualpe	192046	46°45'50'	14°49'46"	1300	117.4	213.7	292.1
Forst-Saualpe	114801	46° 51' 36"	14° 47' 14"	700	107.7	192.9	262.9
Preblau	114306	46° 55' 45"	14° 48' 07"	790	109.1	196.1	267.4
Preitenegg	114314	46°56'19"	14°55'06"	1035	113.6	205.4	280.6
Wolfsberg	114702	46° 49' 15"	14° 50' 33"	440	99.3	175.4	238.7
Glashüten	112243	46° 49' 29"	15° 03' 36"	1275	119.0	217.4	297.3
Knappenberg	144603	46° 56' 06"	14° 33' 54"	1050	114.4	207.4	283.3
Hebalpe	112334	46° 55' 44"	15° 00' 38"	1310	118.0	215.3	294.1
Pustritz	144330	46° 44' 50"	14° 44' 41"	790	99.4	175.6	238.9

Table 23: Convective torrential rains for Sensitivity analysis

Source: (Formayer, 2007)

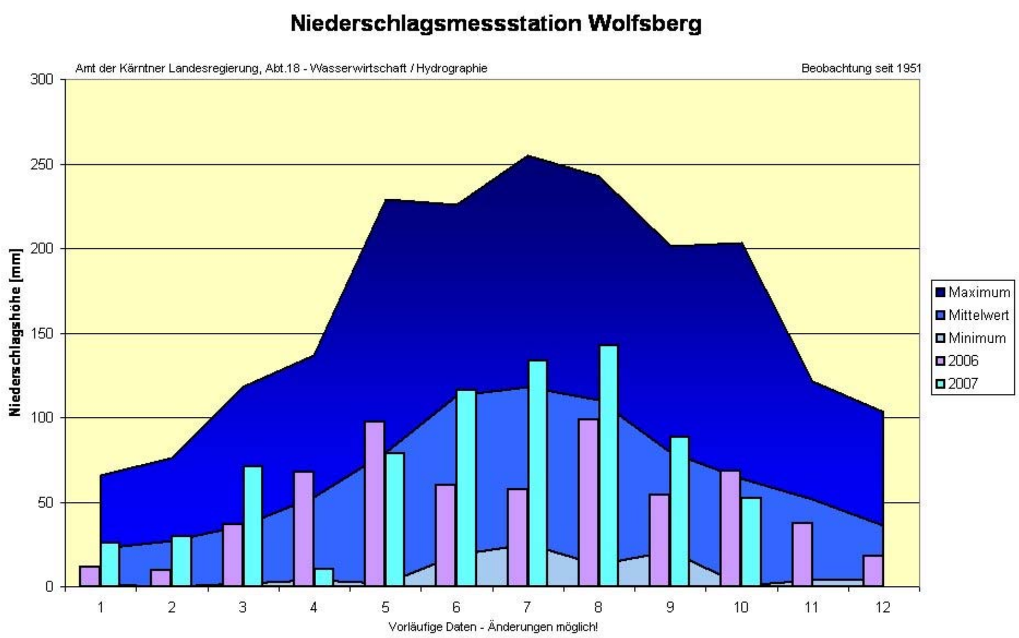


Figure 55: Statistic analysis of precipitations - Wolfsberg

Again, the month with the maximum values is July. The statistical analysis of the Hydrological Atlas - HAÖ is giving for the seasonality of the max. annual daily rainfall, the months of July-August and for the seasonality of the annual floods the month of August. Based on these findings, even if at first glance the totals rainfall look very high, comparison with the August floods in the Dresden area where even 380mm were observed, confirm the assumptions, several rainfall loads have been simulated.

The calculation was done for the durations of 15, 60 and 180 min for the soil moisture conditions AMC1 and AMC2 for uniform and right-side skewed rainfall distributions. For the uniform distribution of precipitation, it is assumed that the total rain is falling in the period, so that the 60 minutes duration stage was divided into 4 equal parts and the 180 min in 12 equal parts. By the right-side skewed distribution, it is also assumed that the whole day precipitation fall within the period, but the rainfall intensity is right side distributed. It was assumed that in the last 15 min of the 60 min duration, the 15 min stage value is reached. By the 180 min dissemination, the assumption that in the last 60 min, the 60 min stage value is reached (Formayer, 2007). The Scenario was computed at a 15 min time step.

The Figure 56: shows the results of the model calculations for the various river basins. The 3 hours torrential rainfalls conduct in all sub-basins to max. discharge peaks. For smaller sub-basins, including Auenbach, the peak flows result from right-side skewed distribution of the rainfall and for the bigger watersheds starting with Reisberger Bach, due influence of the DAD-factor, the peak flows results from the uniform distributed rainfall. However, the differences amount to max. 3%. The computed discharges and runoff-volumes are listed in (Table 34, Table 35) the Appendix E – .

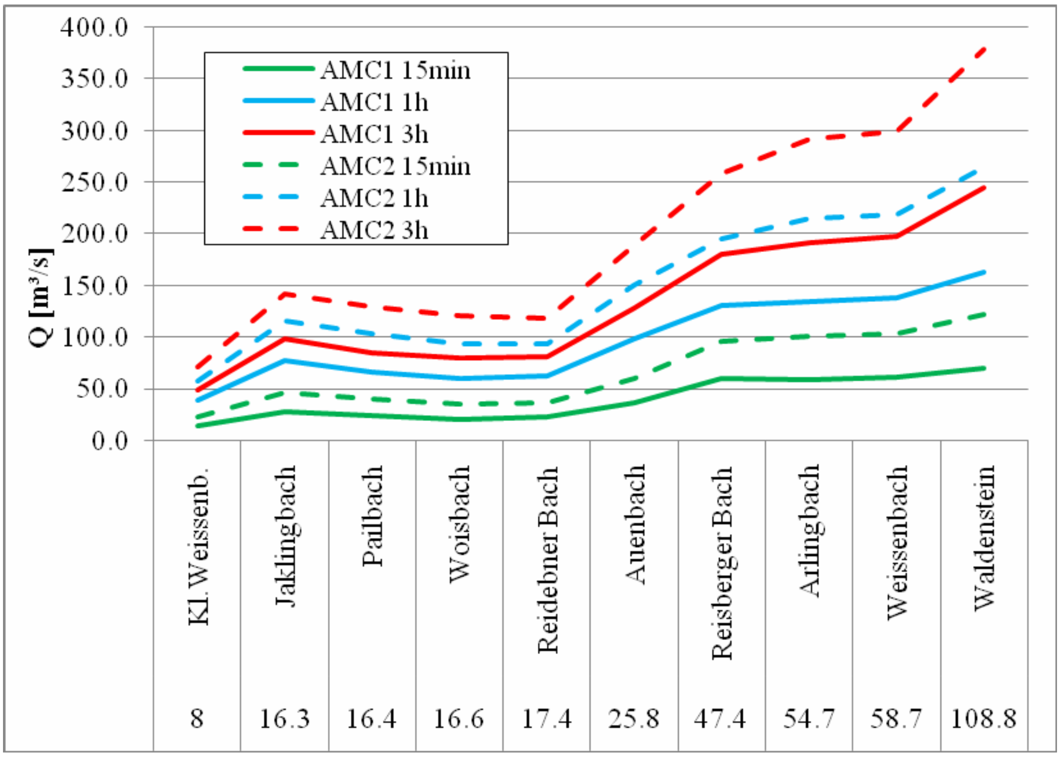


Figure 56: Model results - Scenario B1

By the soil moisture condition AMC2, comparing with AMC1, an increasing of the peak flows between 43% and max 55% has been obtained.

Comparison with actual design flood values shows that already for soil moisture condition of class I (AMC1), an increasing of the discharges by 3-times over the values for a 100 year return period happened. The very intensive heavy rainfalls with daily values of 280mm redistributed in just 180 min and in the unfavourable rainfall distribution, the actually estimated peak flow events of 5,000 years skip.

Differences between the peak flows by soil moisture conditions „dry“ and „normal“ for this extreme hazard scenario amounts approx. the peak flows of the 100-year flood.

4.5.2.3 Scenario B2 – Flood event from Aug. 2005 at Weissenbach

In this study case was investigated the impact of the variation of the soil moisture conditions on the event from August 2005. The recorded stream flow amounts rd. HQ_5 at St. Jakob station and slightly above HQ_{10} at the Fischering station.

The historical stream flow record at St. Jakob shows for 21st August a peak flow of 14.4m³/s. This is the largest up to date recorded outflow at this station. The bandwidth of the discharges was computed (HD-Carinthia) and limited between 12 and 14.4m³/s. It is significant that by another flood event in June 2004 the recorded peak flow of max. 14.3 m³/s is given in the High-water Report of HD-Carinthia with 22 ± 2m³/s. This is around 7m³/s (approx. 70%) higher than the peak flow of the record. In addition, the High-water Report 2005 is approximating for Auenbach and Weissenbach a return period of about 7-to 10 years which pursuant to the HD-Service is approximately 27m³/s.

Simulations for 15, 60 and 180min heavy rain falls, according to information provided by the Hydrological Atlas Austria-HAÖ for all three soil moisture conditions have been performed.

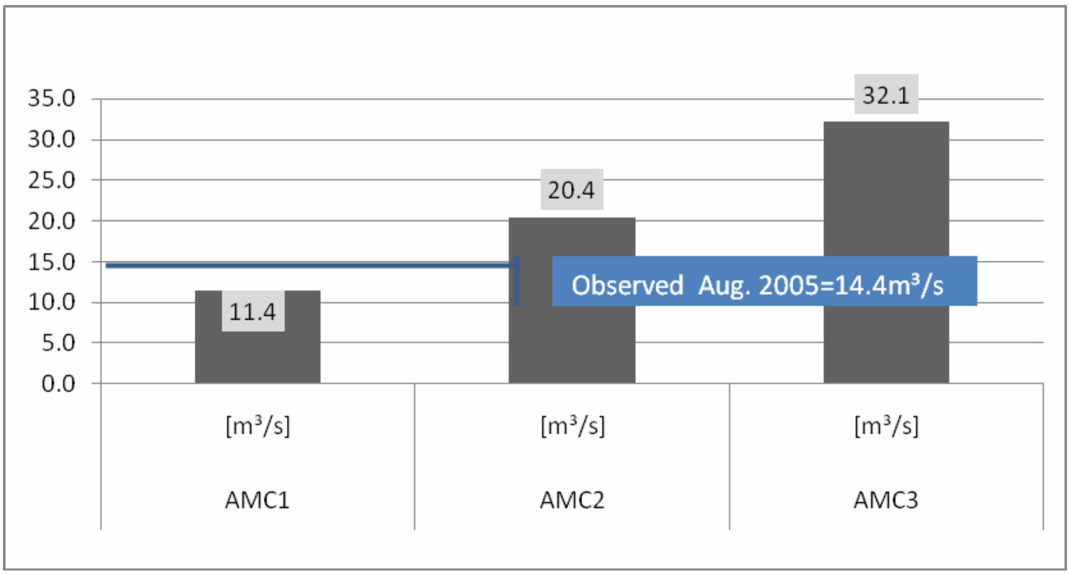


Figure 57: Model results - Scenario B2

Gauge station St. Jakob

It has been made a reduction of the point rainfall (Depth-Area-duration DAD) as in Chapter 4.4.3.2 already specified. The model simulations results in a range of possible peak outflows between 11.4m³/s for AMC1 and max. 32.1 m³/s for AMC3 conditions. The precipitation measuring station Wolfsberg (see Table 28) reports for the previous 5 days (VN5) a 43mm rainfall amount and for VN21 132mm which conduct to the assumption that AMC2 conditions has to be used. For this condition, a peak outflow of 20.4m³/s was calculated. This is much higher as the observed 14.4m³/s, but match quite well the peak in the High-water Report and the calculated channel capacity from the Hazard-Zone-Plan Wolfsberg (Terneak, 2005). The comparison shows that the peak runoff for AMC3 is approx. 3 times higher as the peak flow for AMC1 (see Table 35) and the runoff volume is 2.5-times higher as that one of the AMC1 conditions.

4.5.2.4 Scenario C – Convective heavy precipitations

The runoff computation based on Lorenz-Skoda synthetic rain for different disseminations identifies the runoff peaks for the convective 100-year torrential rain falls from extreme rainfall statistics. The base for the estimation of potentially possible convective precipitation was the Hydrological Atlas Austria-HAÖ (Skoda et al., 2005). For the precipitation gauge stations (Table 24), the heavy precipitation evaluations for a period ranging from 15, 60 and 180 minutes with a return time of 100years were in 15 minutes increments disaggregate (Formayer, 2007).

The calculation was done for the disseminations of 15, 60 and 180min for the soil moisture conditions AMC1 for uniform and right-side skewed rainfall distributions. For the uniform distribution of precipitation is assumed that the total rain is falling in the period, so that the 60min. duration stage was divided into 4 equal parts and the 180 min in 12 equal parts.

By the right-side skewed distribution is also assumed that the whole day precipitation fall within the period, but the rainfall intensity is right side distributed. It was assumed that in the last 15min of the 60min duration the 15min stage value is reached. By the 180min dissemination has been made the assumption that in the last 60min, the 60 min stage value is reached.

Station name	N15M100 [mm]	N60M100 [mm]	N3H100 [mm]
St Andrä	69.6	122.9	167.2
Hofkogel-Saualpe	82.2	149.6	204.5
Forst-Saualpe	75.4	135.0	184.0
Preblau	76.4	137.3	187.2
Preitenegg	79.5	143.8	196.4
Wolfsberg	69.5	122.8	167.1
Glashütten	83.3	152.2	208.1
Knappenberg	80.1	145.2	198.3
Hebalpe	82.6	150.7	205.9
Pustritz	69.6	122.9	167.2

Table 24: Convective heavy precipitations for Tn=100yr.

(Source: HAÖ)

The model accounts for the soil moisture class AMC1 at all streams, a maximum peak flow was obtained for the 3-hours dissemination. For the smaller stream catchment areas including Auenbach, the maximum peak runoff resulted from the right-side skewed rainfall distribution, for the larger streams decisive was the uniform distribution of precipitation.

The reason for this lies in the DAD-factor, by larger catchment areas and the reduction of the point precipitation rises accordingly.

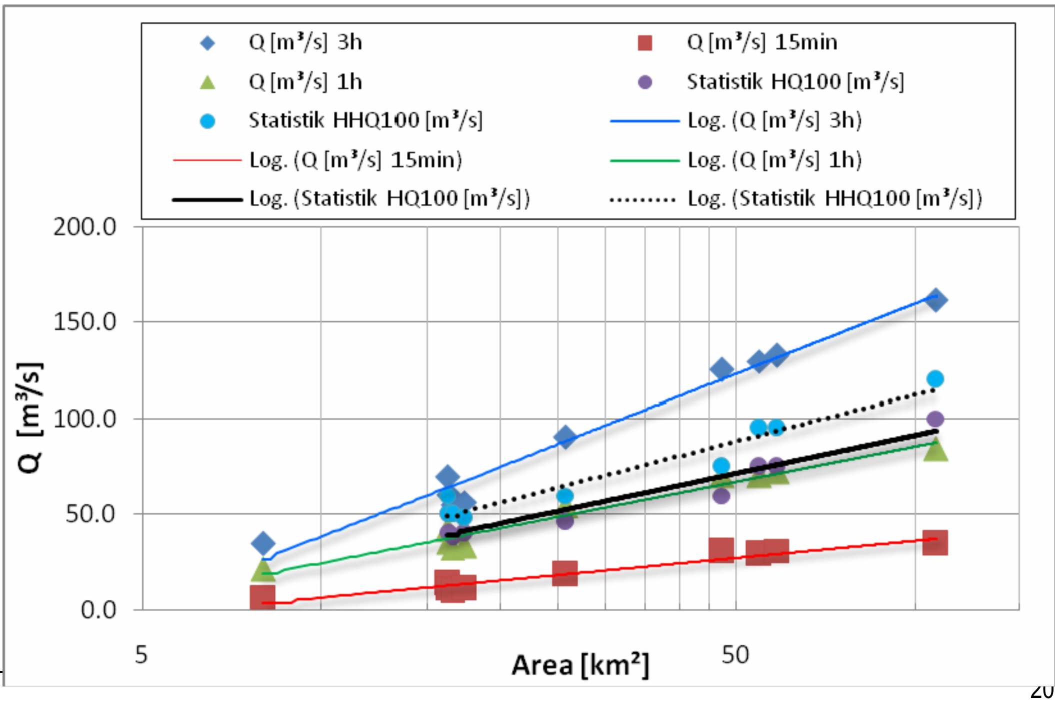


Figure 58: Model results - Scenario C

Soil moisture condition AMC1. Comparison with the design flood values for Tn=100 years

The calculated peak flow for the studied watersheds exceed by 10% to 65% the current estimated highest flood design values.

The detailed (Table 37) with the results of the model calculation, compare them to the "Wundt-Values“. As one of the most popular formulas Wundt (1949) in the form:

$$q = c \cdot A^m$$

whereby q is the runoff value, c is a factor, A is the catchment area and m is the slope of the relationship in the double logarithm representation. This function is still determining runoff in unobserved areas, because the dependence of the runoff from the catchment area size for many Austrian waters sufficiently accurately describes as far the parameters c and m applicable elected.

The simulated flow peaks for the 3 hours duration results in a Wundt-Value (c) between 0.7 and 0.9, for comparison, the HHQ100 (HD-Carinthia) have a Wundt-Value between 0.52 max. 0.81.

4.5.2.5 Scenario D – More intensive heavy precipitations

Possible impacts of climate change in the form of more intense rainfalls by an increase in rainfall intensity by 10%, 15% and 20% by constant rainfall distribution and duration has been investigated. The model calculations carried out based mainly on the assumptions already made in the Scenario C with major changes concerning the precipitation intensity.

The used precipitation for duration of 15, 60 and 180 min with even and right-side skewed distributions (see Chapter 4.4.5.2.5), were increased with 10, 15 and 20% by maintaining the same distribution and duration.

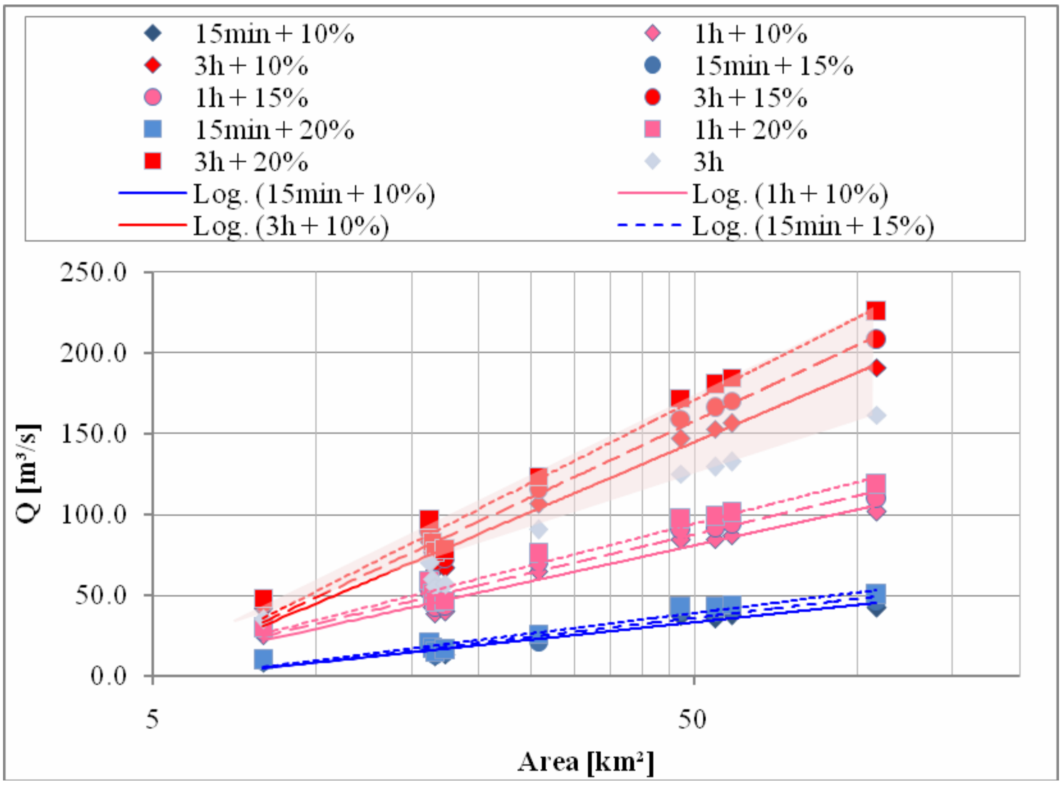


Figure 59: Model results - Scenario D

Flow peaks for increased precipitation intensity with 10, 15 und 20%, Tn=100Years.

15, 60 und 180 min Disseminations for soil moisture conditions AMC1. Comparison with Scenario C (3h)

The model accounts, for the soil moisture class AMC1 at all streams, the highest flow for the 3-hours dissemination. For a 20% increase of the rainfall results compared to the scenario C; an exceed in the peak outflows - hatched area - from 37% to max. 40% have been computed. Model results are listed in the Table 38 (see Appendix E –).

4.5.3 Comparative Study, counter measure

The main target of the study case is to investigate possible mitigation effects of floods by land use management in forested and agricultural areas.

The characteristics of the watersheds influence the runoff concerning the form of hydrograph as well as the peak value or recession constant. There is a complex correlations system of parameters of the rainfall (duration, intensity), of the snowmelt and of the watershed (relief, land use, soil moisture etc.). These correlations are currently only partially known, and still the subject of scientific studies. During the discussion of the influence of land-use management and counter measures, the positive effects of the forest areas on the soil stabilization and balancing effect on the flood events has been underlined.

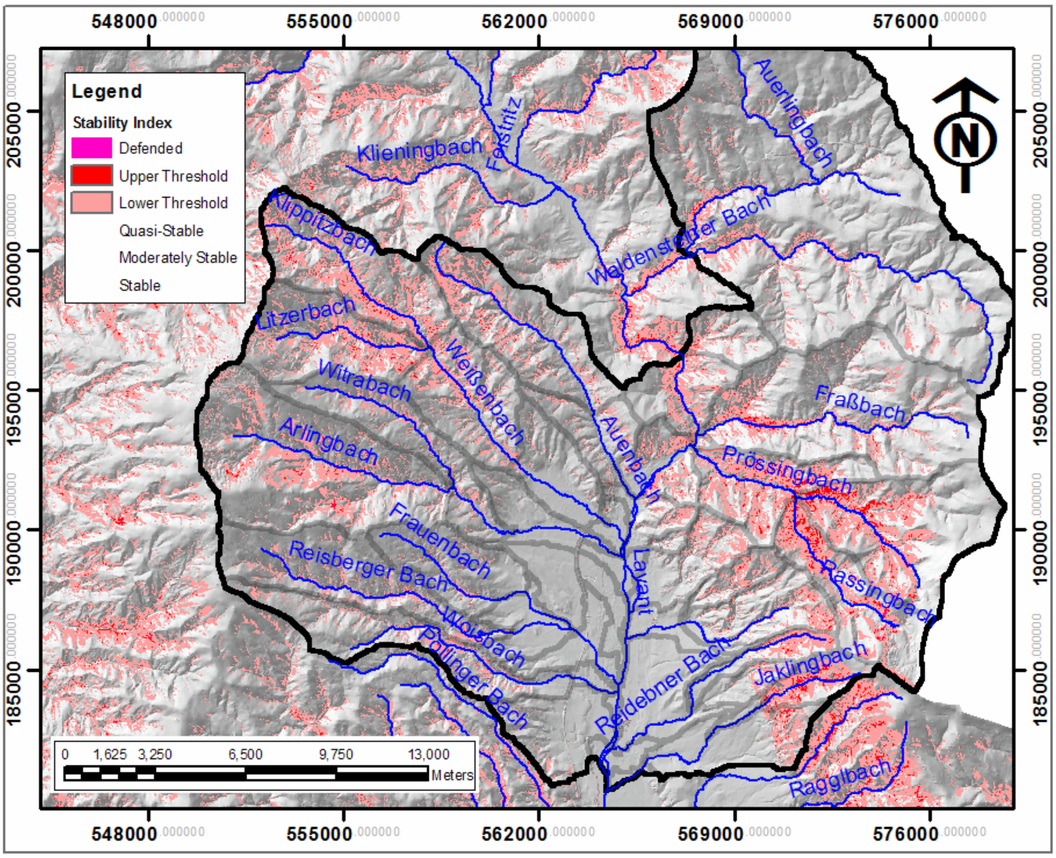


Figure 60: Stability analysis - SINMP2. Potential erodible surfaces

The Forest Inventory from 2000/02 (BFW, 2004) is pointing to a steady increase of the forest area. Compared with the first inventory period 1961/70, the forest area exceeds the old total by about 270,000 ha. This is an increase of 44% to 47.2%, or around. 3.5% in 45 years. In the study area were no detailed information's concerning the regional forest development available. Regarding potential development of the protection forests, the definition of sensitive areas and an evaluation of the possible growing of the areas covered by protection forests was computed based on the SINMAP2 model (Robert T. Pack, 2005). The model is a GIS application for the delineation of unstable/erodible surfaces. It has been used in this study to quantify the areas with unstable slopes. The stability analysis (Figure 60) classified 16% of the surveyed area as unstable. For the purpose of this study a 10% growing of the forest-covered surfaces has been studied. Using GIS procedures, the forest areas were buffered to obtain a 10% increasing with corresponding reduction of pasture and grassy land. The impact of a 10% more forest through changed weightings of storage capacity S[mm] of the watersheds lead to the conclusion that the SCS CN (curve number) are only marginally affected – about 1% changes – and no evident effects on the hydrographs could be computed.

Surface runoff is generated commonly on agricultural land, but then often routed though forest areas to the small streams. The retention capacity of the landscape has to be increased. This is especially possible in agricultural areas, where soil working methods can be modified for increasing water retention capacity and infiltration capacity. The surface runoff of arable land is dependent of the soil working state and method and of the current state of vegetation but also of soil working direction. Significant mitigation effects have small landscape depressions.

The results of the erosions experiments with artificial heavy rainfall at various locations, in different vegetation units for different soil working methods, (Johann K, 1985) shows that the geological situation and the underground play an important role, but the slope and the slope length in their importance compared with the vegetation and its management are strongly in the background. The management of arable land is an important factor in terms of the risk of surface runoff. A dense, vegetation reduces the surface runoff. Through another investigative series, (Konrad M., 1985) studied the influence of soil working on the surface runoff, in particular, the effect of soil working direction across the slope. The results of the field trials (Konrad M., 1985, S. 115, 125) on cornfields and the effects on the max. soil storage (see Table 21) was converted in model parameters and the impact of the induced changes in the soil storage has been quantified for the tributaries of the Lavant River using the runoff-model.

For quantifying the effects, the modified **Scenario D** has been used. For the set up of the runoff model it was used a fairly conservative approach. One side because a part of the arable land is already worked transverse to the slope, on the other side changes of the storage capacities of the soil were measured only on cornfields. Thus, the (S) parameters for arable land were averaged. It is to mention that the positive retention and infiltration effect is available just for a time period; the erosion effects are diminishing the mitigation effect. The model results (

Figure 61) show like expected a dependence of surface share of the arable land and the more or less reductions of the peak outflows. Thus, the effects are between rd. 1.3% by Waldensteiner Bach - a stream with very little agricultural land - and max. 9.6% for the watershed of Reisberger Bach where the arable land is present in a relatively large proportion. As expected a structured landscape with elements across the fall line should be preferably preserved and promoted, the more difficult question that this study case tried to answer is how big the mitigation effects of land use management could be.

River	Reduction of the peak flow in percent
Kl.Weissenb.	5.4%
Jaklingbach	5.1%
Pailbach	2.0%
Woisbach	7.5%
Reidebner Bach	2.4%
Auenbach	6.0%
Reisberger Bach	9.6%
Arlingbach	2.5%
Weissenbach	2.7%
Waldenstein	1.3%

Table 25: Effects of the soil working direction comparative to Scenario D for a 3h heavy rainfall

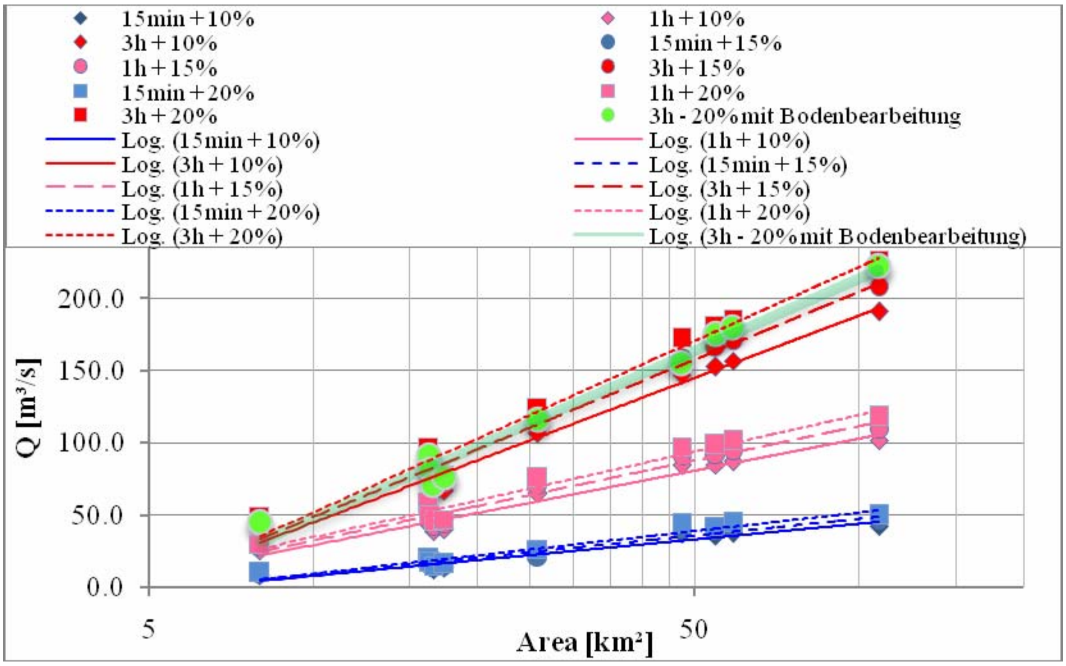


Figure 61: Model results, effects of the soil working direction for soil moisture condition class AMC1. Comparison with

4.5.4 Results and discussions

Current climate studies indicate that by the end of this century in the Alps is expected an increase in precipitation in the winter months from about 15 to 40 percent.

The results of the Climate Change Study (Niedermair M.,BOKU Wien, 2006), the trend analysis of the Hydrological Atlas Austria, and the Climate Change Report (Moser J., 2007) are clearly showing that in the study area climate change effects are evident.

4.5.4.1 Actual situation

According Flood Chronicle and recent flood events, Lavant Valley is a region with intensive flood events. The historical stream flow records of the Lavant gauge stations Fischering registered the highest flow peak with a return period of rd. 30 years; however, the frequency of the last high-water events is increasing.

According to the conclusions of Regional HD-Carinthia, (Moser J., 2007) the annual totals rainfall of the last century shows that in Carinthia a slightly downward trend is happening, especially in the south of Carinthia (Drau-, Gail, Klagenfurt-Basin and Southern Lavant Valley). Statistics over long periods show decreases in the average rainfall of 15 to 25 percent. The fact is that in this area, the amount of rainfall in autumn increased, in the same time the total precipitation in the summer declined.

The study cases analyzed in this work shows that even for the Current Conditions Scenarios the bandwidth of the peak flows and runoff-volumes dependent of the rainfall intensity is very large. The intensity of the flood events – by the same precipitation quantity - is mainly influenced by the rainfall distribution (intensity) and soil moisture conditions.

4.5.4.2 Future situation

Regarding the small-scale flooding events, climate change studies forecast an increase in precipitation intensity of thunderstorms in those regions, in which already many thunderstorms occur. The climate change study (Niedermair M.,BOKU Wien, 2006) predicts for the study area a superposing of three factors with major effects for the future runoff conditions. These are the shifting of the snowfall-level, increase in rainfall intensity and intensification of the storms. The study area is classified particularly as a region with numerous thunderstorms.

The carried out runoff-modelling tries exactly for the above possible developments of the flood events, over a qualitative assessment, to get a palpable quantification. Starting with investigations of the effect of the shift in the snow line, more case studies are examining precipitation stress scenarios their temporal distribution, as well as amending the soil moisture condition.

The results of the case study investigation is showing that under the made assumptions concerning boundary conditions the increasing of the peak flows and runoff-volumes are considerable and convenient counter measures has to be applied. The results are under chapter 4.1 summarized and in tables and diagrams under chapter 4.5.2 and under annexes in chapter 4.8.5. more detailed.

4.5.4.3 Counter measures

Based on the model results, a significant positive effect of a 10% increase of forested land areas could not be obtained, the land-use changes leaded to very small CN changes.

Another approach involved the influence of soil working direction of arable land, the retention capacity of the landscape can be this way considerable increased. This is especially possible in agricultural areas, where soil working methods can be modified for increasing water retention capacity and infiltration capacity. The surface runoff of arable land is dependent also from the soil working direction due the significant retention and infiltration effects of small landscape depressions.

The passive flood protection measures must be in addition to active measures strengthened. This means all measures, which are using natural retention areas. The importance of a wide measure complex concerning increasing of infiltration and retention in the landscape has to be promoted.

4.5.4.4 Model limits and usability of the results

The precipitation runoff model is a mathematical representation on the physical processes that occur in the Lavant Valley. The quality of the model results depends of the accuracy of the mathematical representation of the physical processes (model error), the quality and accuracy of the precipitation and air temperature input time series and the stream flow calibration/testing time series (data error), and the accuracy of the calibrated model parameters (parameter error). Model calibration and testing could be made for high water events until HQ_{30} (Fischering). The studied cases conduct partially to considerable peak flows over 3-times the calibrated highest flood event. Thus the obtained values have to be seen in these cases more as a qualitatively expectation.

The principal reason for this is the fact that the historical records of precipitation and stream flow are limited and particularly the 2 gauge stations for the Lavant tributaries recorded just high water events until HQ5. For the St. Jakob gauge station, the stream flow records are delivering even for the high water events peak flows which are under the estimated channel capacity; the assumption that the stream flow record underestimates the historical events by this station is confirmed by the Flood Report from 2005 (Amt der Kärntner Landesregierung, Abteilung 18 – Wasserwirtschaft / Hydrographie, 2005).

The applied SCS-CN method has strong limitations by simulation of multiple peak hydrographs and for calculation of hydrographs over longer simulation period. This concerning, the single calibration event with a double peak (HEW 2), due to the relatively short duration, had been very well reconstructed. The other scenarios are calculated on very short simulation times (4-5 days).

Regarding model simulations concerning sensitive changes in land use, the complex relationships of parameters of rainfall (intensity, duration, the amount of rain), snowmelt (air temperature and snow) and the catchment area (land form, land use, soil moisture, etc.), are currently only partially known and investigations and computer models in this direction are subject of scientific research. The results obtained are therefore more of a qualitative nature.

4.6 Summary

Strengthened by climate change and urban extensions, which lead to decreasing of the discharge capacity of the rivers, on the historical scale, the flood risk grows up. The project objective of the INTERREG IIIB Alps program of the EU deals with the issues of climate change and is deriving the resulting impact on the prevention of natural hazards. In the framework of this project, the rainfall-runoff modelling deals with natural hazards events.

The analysis of the tributaries of the middle Lavant Valley is using a state-of-the-art rainfall-runoff model. As a first step, the runoff-model, based on the in catchment area existing gauge stations, was calibrated. The existing historical records and reviews of past flood events were used in their entirety. In collaboration with the Regional Hydrographical Service, all existing observations, insights and experiences from past floods has been involved. The model parameters were calibrated using historical flood events. Due the sparse density of the stream flow gauging stations, for calibration and validation purposes, the model was extended at a total of 483.4km² and this way could be used three stream flow measuring stations instead just one. Including the gauge station the St. Gertraud (inflow boundary condition), now the whole catchment area of Lavant Valley between St. Gertraud and Fischering could be calibrated.

Based on this calibrated model, several cases study handling with current and possible future conditions scenarios has been performed. The model results and comparative graphical representation are described under Chapter 4.5.2; more detailed tables with model results can be found under Appendix 4.8.5.

Finally, the possible impacts were quantified and discussed in the light of mentioned literature, based on the simulation results and assuming changes of the land use and meteorological conditions.

4.7 Literature

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4.8 Appendices

4.8.1 Appendix A – Gauge Stations

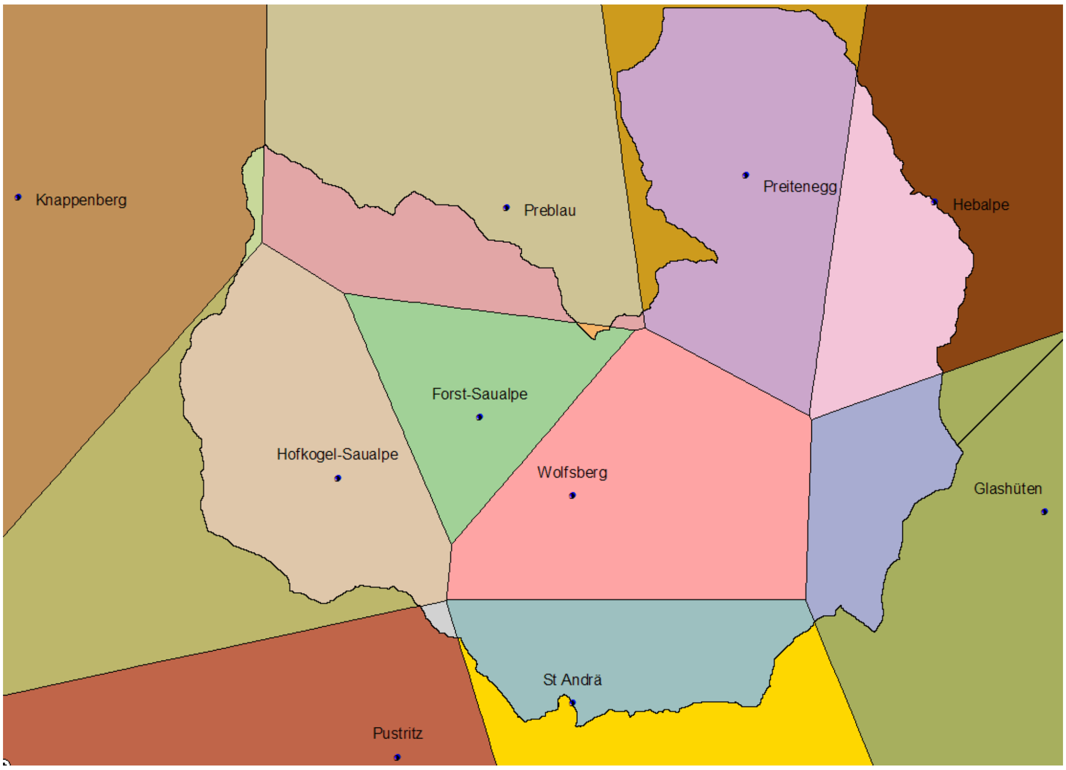


Figure 62: Thiessen Polygon of the precipitation gauge stations

The Figure 62 Thiessen Polygon has just an informative character. The model simulations were computed with the inverse-distance method

4.8.2 Appendix B – Hydrologic Soil Group

Soils are classified into hydrologic soil groups (HSG's) to indicate the minimum rate of infiltration obtained for bare soil after prolonged wetting. The HSG's, which are A, B, C, and D, are one element used in determining runoff curve numbers. The infiltration rate is the rate at which water enters the soil at the soil surface. It is controlled by surface conditions. HSG also indicates the transmission rate—the rate at which the water moves within the soil. This rate is controlled by the soil profile. Approximate numerical ranges for transmission rates shown in the HSG definitions were first published by Musgrave (USDA 1955).The four groups are defined by SCS soil scientists as follows:

Group A soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (greater than 7.62mm/hr).

Group B soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (3.81-7.62mm/hr).

Group C soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (1.27-3.81mm/hr).

Group D soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0-1.27 mm/hr).

HSG Soil	textures
A	Sand, loamy sand, or sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay

Disturbed soil profiles

Source: United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, 1986

Class	Rainfall over the last 5 days	
	Fallow period	Vegetation period
I – (AMC1)	<12mm	<36mm
II – (AMC2)	12-28mm	36-53mm
III – (AMC3)	>28mm	>53mm

Table 26: Definition of the Antecedent Soil Moisture Condition

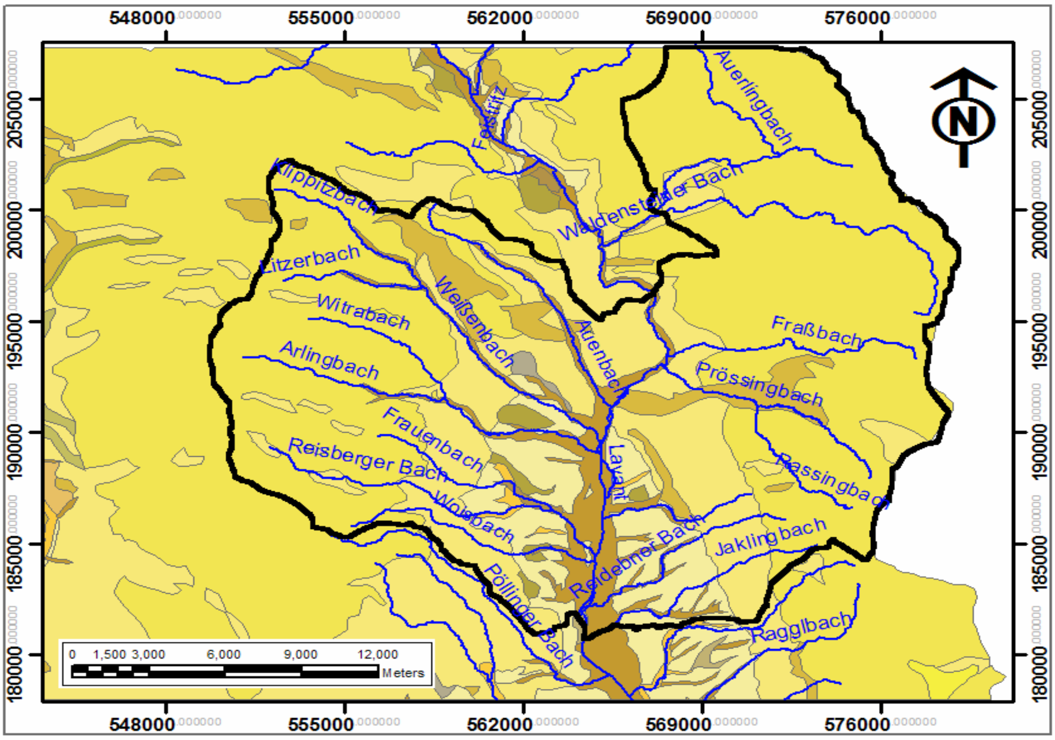


Figure 63: Soil type Map used for HSG classification

Soil	Soil Group
Anmoor	D
Soil complex: ranker brown earth	B
Brown meadowland	B
Rock brown earth	B
Skeletal soil	C
Gley	D
Grey – meadowland	D
Limestone brown clay	D
Permissively sediment brown earth over fluviatile sediments	B
Permissively sediment brown earth over glacial drift	B
fen (low land)	C
Pararendzina	B
Podsol rock brown earth	B
Pseudogley	C
Rendzina	B

Table 27: Soil table

4.8.3 Appendix C – Historical Stream flow records

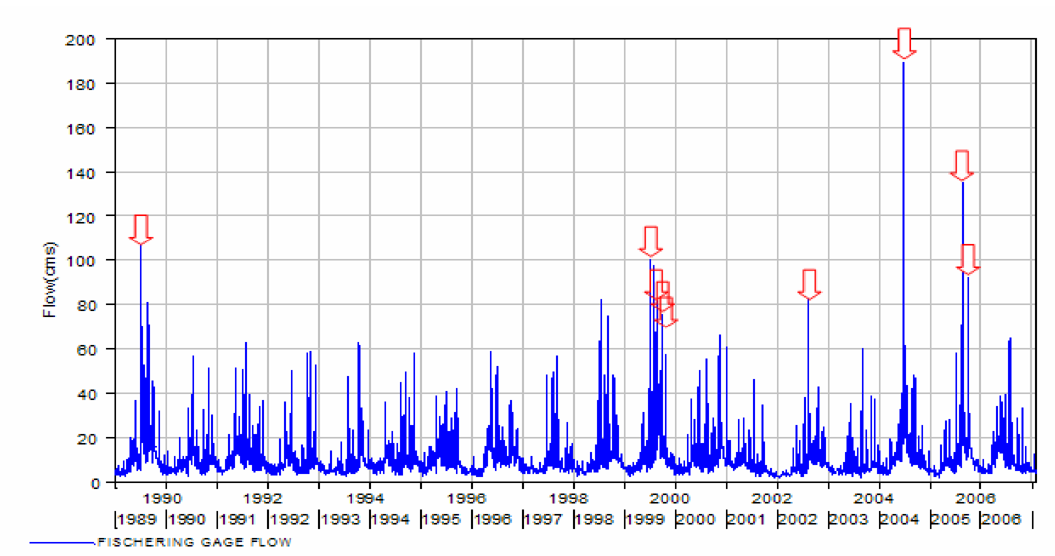


Figure 64: Historical record at the stream flow gauge station Fischering (Lavant)

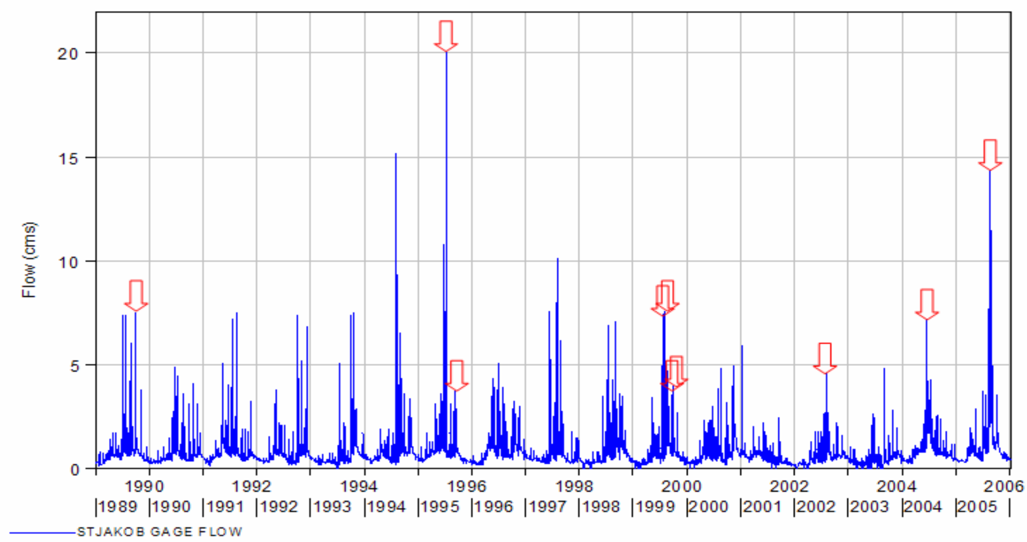


Figure 65: Historical record at the stream flow gauge station St. Jakob (Weißenbach)

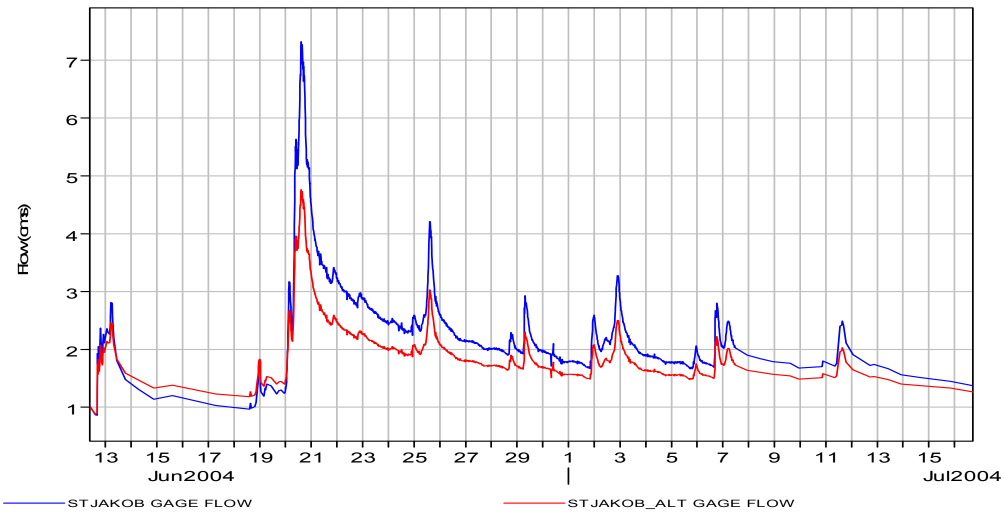


Figure 66: Stream flow gauge station St. Jakob – Bandwidth of measurements

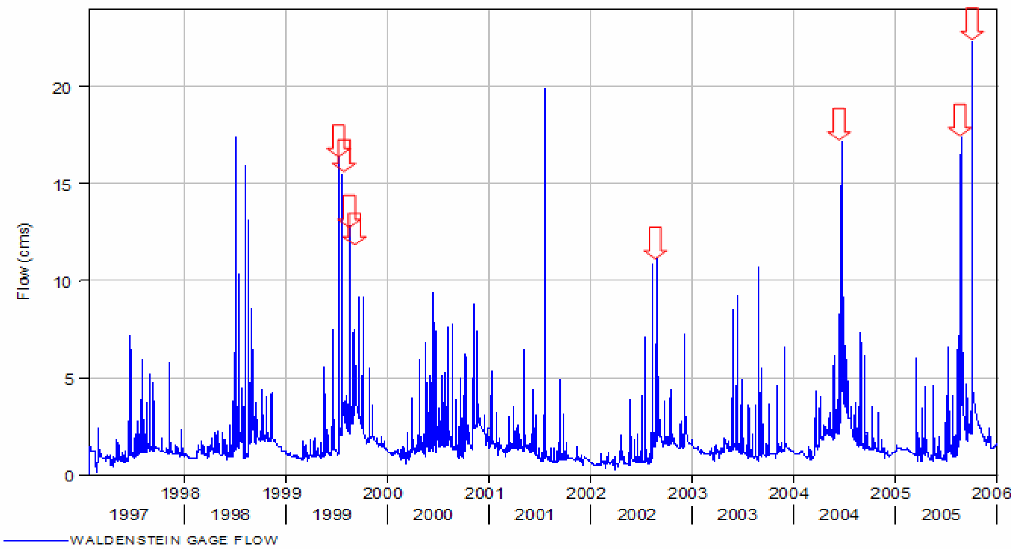


Figure 67: Historical record at the stream flow gauge station Waldenstein (Waldensteiner Bach)

4.8.4 Appendix D – Calibration and Testing Events

			Precipitation measurement station											VN5 weight value [mm]
			Knappenberg	Preblau	Preitenegg	Hebalpe	Kloster	Glashütten	Wolfsberg	Forst-Saualpine	Hofkogel-Saualpe	St. Andrä	Pustritz	
Nr.	HWE		VN5 [mm]											
1	18-24	Jun.04	0	0	0	0.2	0.2	0	2	18	19	2	2	6
2	19-26	Aug.05	41	43	46	56	16	0	43	40	42	12	7	38
3	30.06-10.07	Jul.89	17	13	27	47	0	31	21	0	0	8	12	17
4	9-16	Jul.99	7	10	5	5	0	14	0	12	0	5	7	5
5	21-28	Jul.99	2	2	5	5	0	10	2	2	0	1	2	3
6	2-9	Oct.05	15	26	19	25	2	0	26	28	28	22	25	23
7	10-17	Aug.02	46	25	27	24	15	0	29	38	0	29	34	22
8	16-20	Aug.99	18	22	14	17	0	42	11	13	0	11	13	13
9	20-24	Aug.99	42	38	45	42	0	46	37	49	0	33	36	34
10	13-18	Sep.95	6	2	2	2	0	8	6	0	0	5	10	3
relative to stream flow station			St.Gertraud	St.Gertraud	Waldenstein	Waldenstein	St.Gertraud	Fischering	St.Jakob	St.Jakob	Fischering	Fischering	Fischering	

Table 28: Rainfall in the 5-days before the calibration events (VN5)

Nr.	HWE		Knappenberg	Preblau	Preitenegg	Hebalpe	Kloster	Glashütten	Wolfsberg	Forst-Saualpine	Hofkogel-Saualpe	St. Andrä	Pustritz	VN21 weight value [mm]	VN21 [mm]	VN5 [mm]	VN5/VN21
			VN21 [mm]														
1	18-24	Jun.04	106	124	139	141	102	0	96	78	66	75	73	**95**	94.55	5.71	0.06
2	19-26	Aug.05	128	174	139	139	112	0	138	138	149	121	134	**132**	131.65	37.96	0.29
3	30.06-10.07	Jul.89	41	60	84	105	0	112	0	0	0	42	44	**42**	41.95	17.37	0.41
4	9-16	Jul.99	34	40	43	59	0	89	44	58	0	42	54	**41**	41.34	4.80	0.12
5	21-28	Jul.99	72	95	122	175	0	246	93	113	0	79	113	**101**	100.64	2.93	0.03
6	2-9	Oct.05	68	81	94	87	125	0	69	77	97	59	69	**76**	76.21	22.80	0.30
7	10-17	Aug.02	58	59	71	72	105	0	69	65	0	66	120	**51**	51.34	21.53	0.42
8	16-20	Aug.99	87	123	68	52	0	118	92	104	0	63	80	**70**	70.21	13.30	0.19
9	20-24	Aug.99	128	160	110	91	0	163	129	143	0	96	116	**102**	102.22	33.78	0.33
10	13-18	Sep.95	58	40	43	59	0	150	54	0	0	43	78	**42**	42.16	2.96	0.07

Table 29: Rainfall in the 21-days before the calibration events (VN21, VN21/VN5)

4.8.4.1 Calibration events

1) 18-24 Jun 2004

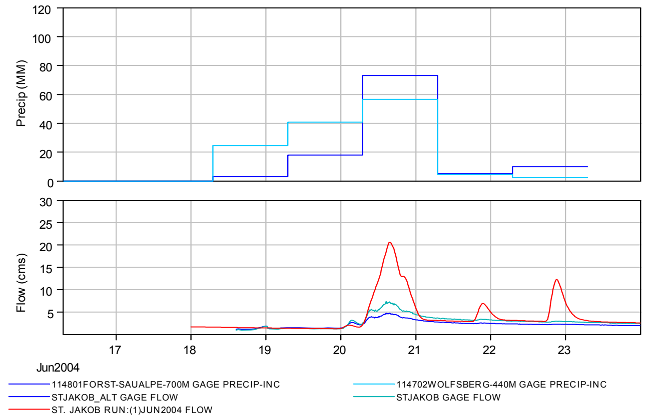
fp=1, AMC1

Rainfall:
missing data: Glasshütten, Knappenberg, Preitenegg
daily total for: Hebalpe, Hofkogel

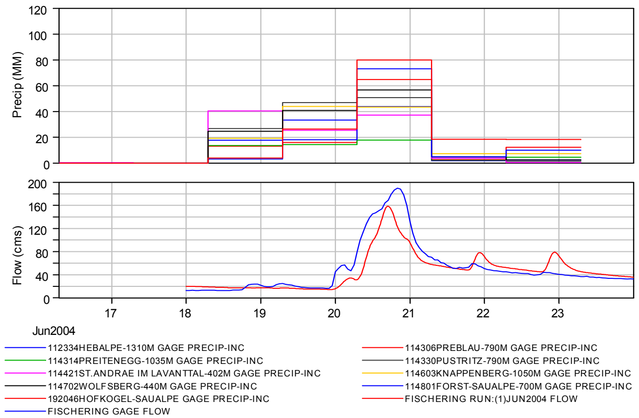
Distribution by neighbour station: Hebalpe, Hofkogel

max. VN5 =19mm - Hofkogel
max. VN21=141mm - Hebalpe
VN5/VN21=6%

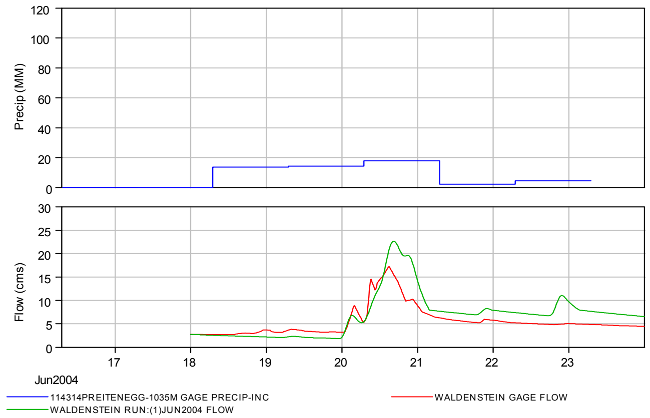
St. Jakob



Fischering



Waldenstein



2) 19-26 Aug 2005

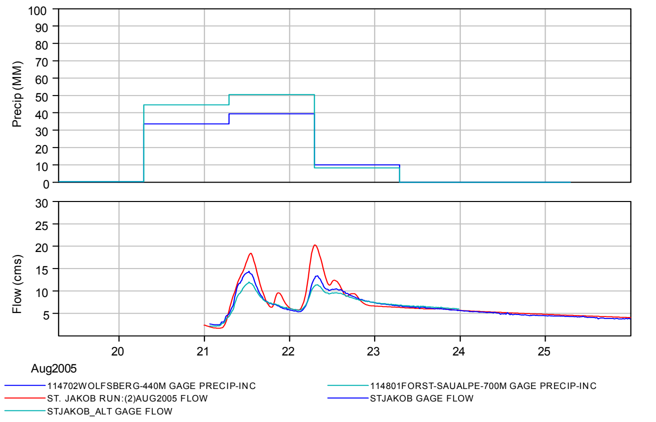
fp=1.1, AMC2

Rainfall:
missing data: Glasshütten
daily total value: Hebalpe, Hofkogel

Distribution by neighbour station: Hebalpe, Hofkogel

max. VN5 =56mm - Hebalpe
max. VN21=174mm - Preblau
VN5/VN21=25%

St. Jakob



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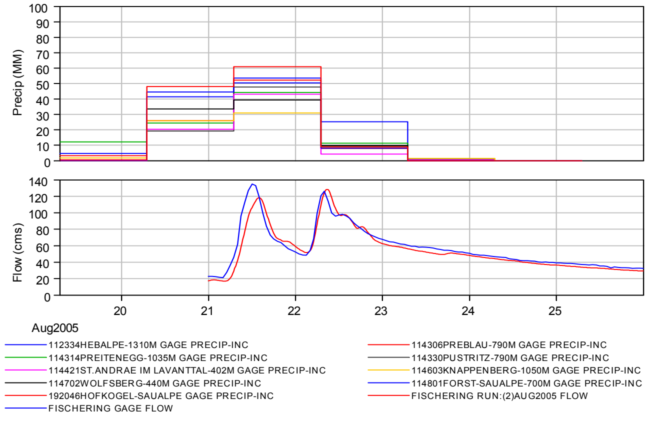

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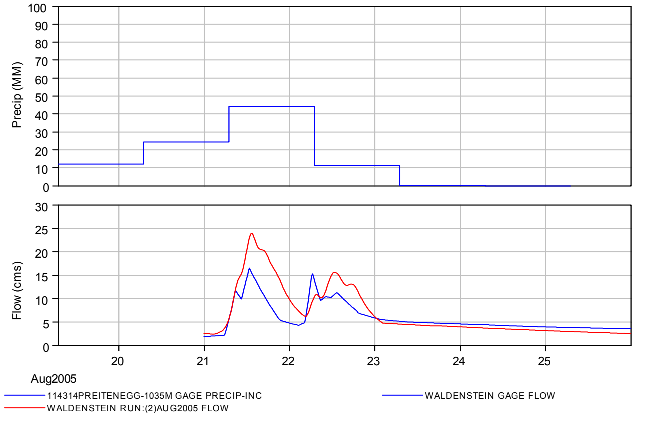


3) 01-07 Jul 1989

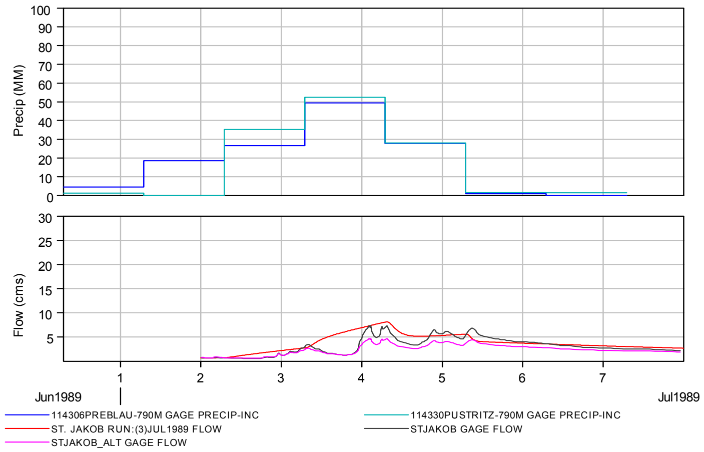
fp=1, AMC1

Rainfall:
missing data: Forst-Saualpe, Hofkogel, Kloster-Rettenbach, Wolfsberg
daily total value: Hebalpe, Preblau, Preitenegg, Pustritz, ST. Andrä

Distribution by neighbour station: no

max. VN5 = 47mm - Hebalpe
max. VN21= 112mm - Glasshütten
VN5/VN21=21%

St. Jakob



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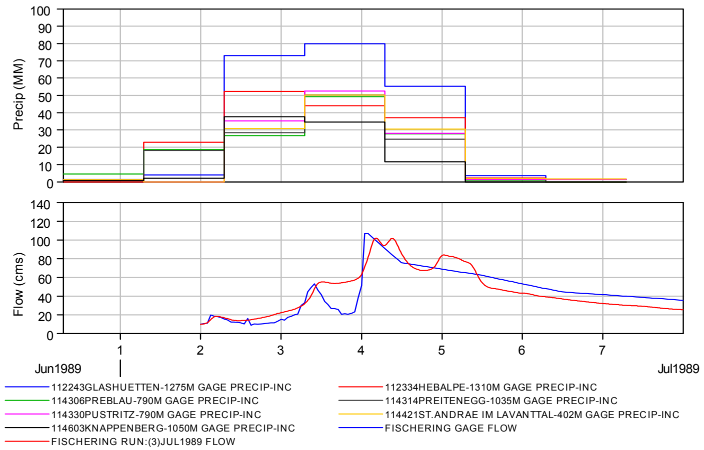

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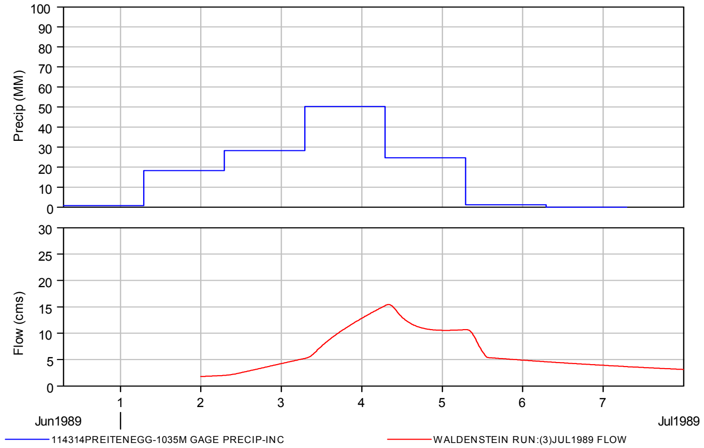


4) 09-16 Jul 1999

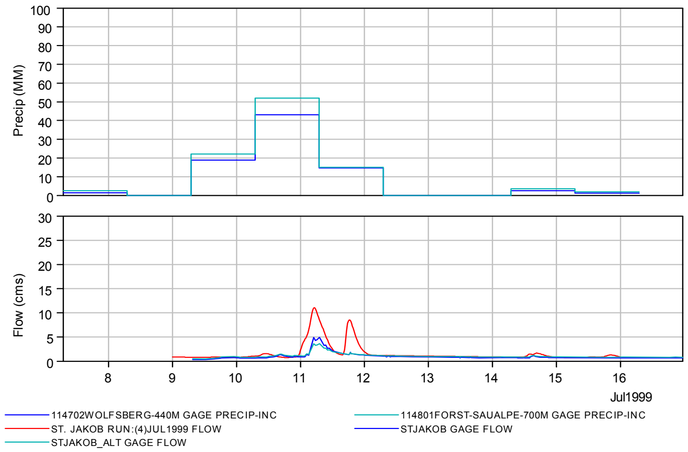
fp=0.9, AMC1

Rainfall:
missing data: Hofkogel, Kloster-Rettenbach,
daily total value:

Distribution by neighbour station: no

max. VN5 =12mm – Forst-Saualpe
max. VN21=59mm - Hebalpe
VN5/VN21=14%

St. Jakob



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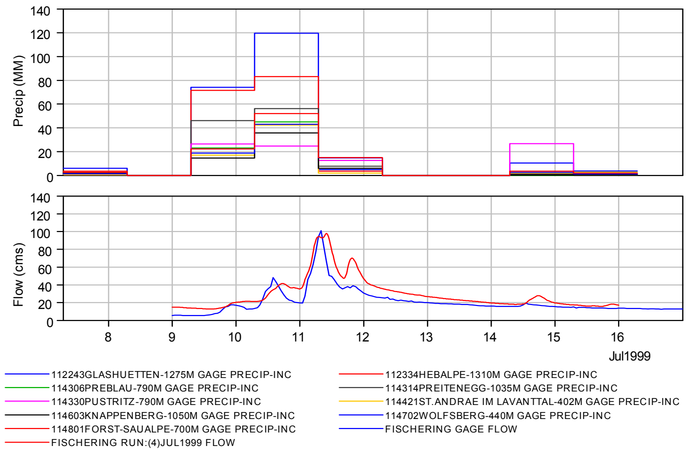

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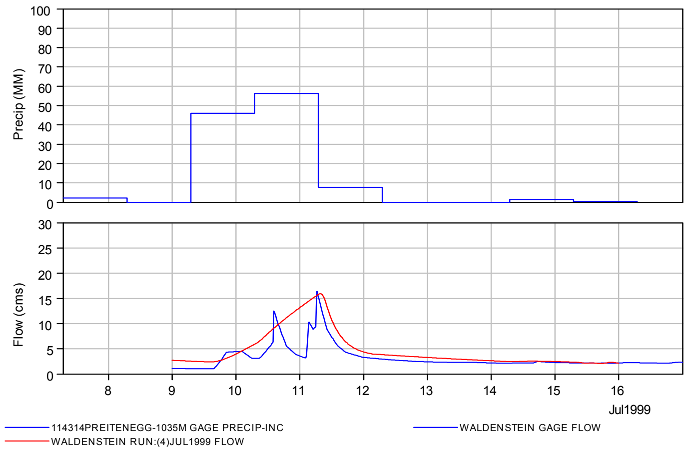


5) 21-28 Jul 1999

Fire brigade operation in Wolfsberg

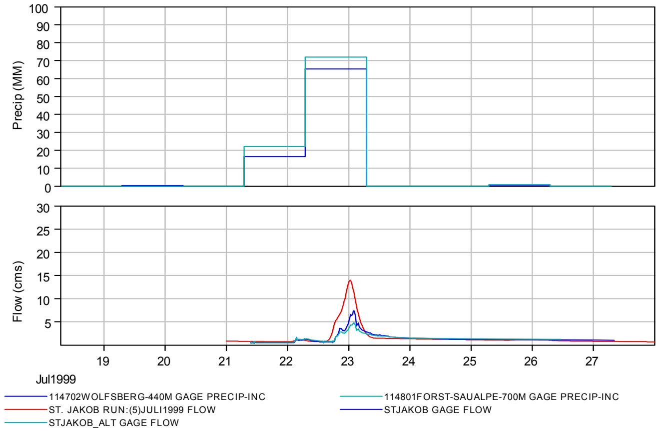
fp=0.8, AMC1

Rainfall:
missing data: Hofkogel, Kloster-Rettenbach
daily total value: Hebalpe, Preitenegg, St. Andrä

Distribution by neighbour station: no

max. VN5 =10mm - Glasshütten
max. VN21=246 mm - Glasshütten
VN5/VN21=3%

St. Jakob



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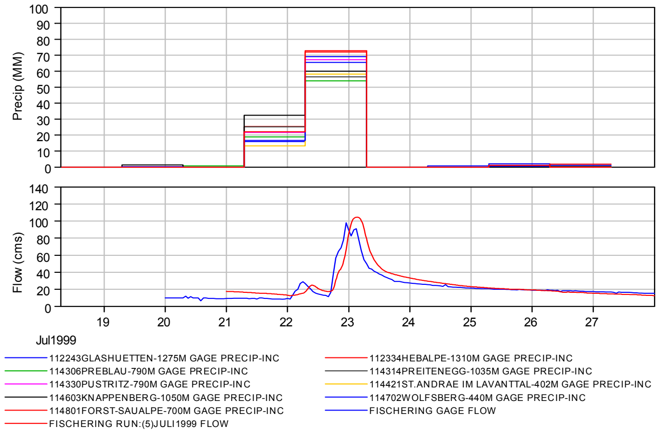

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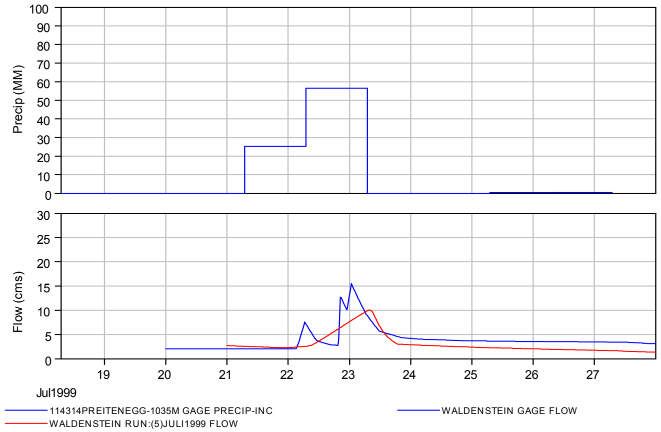


6) 02-09 Okt. 2005

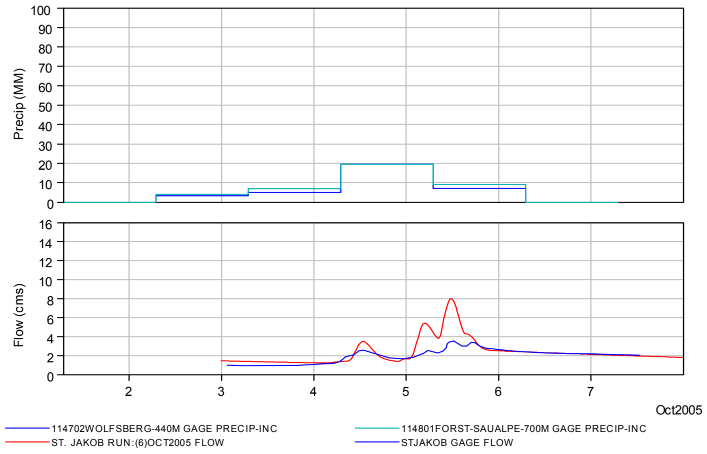
fp=1.15, AMC2 (3 days before 5°C)

Rainfall:
missing data: Glashütten
daily total value: Hebalpe, Hofkogel

Distribution by neighbour station: Hebalpe, Hofkogel

max. VN5 =28mm – Hofkogel, Forts-Saualpe
max. VN21=125mm – Kloster-Rettenbach
VN5/VN21=20%

St. Jakob



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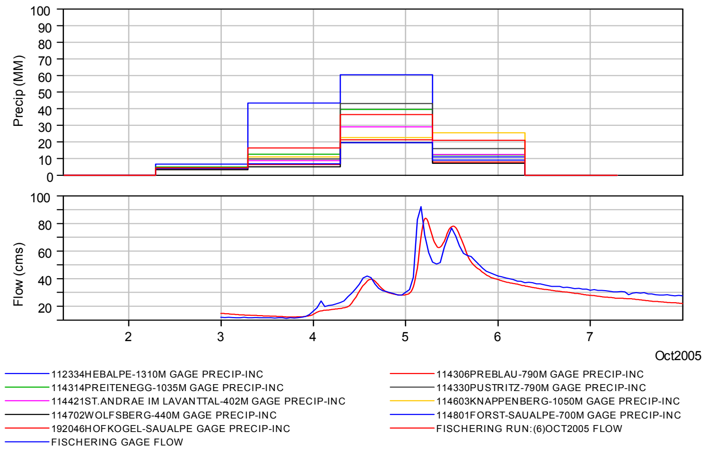

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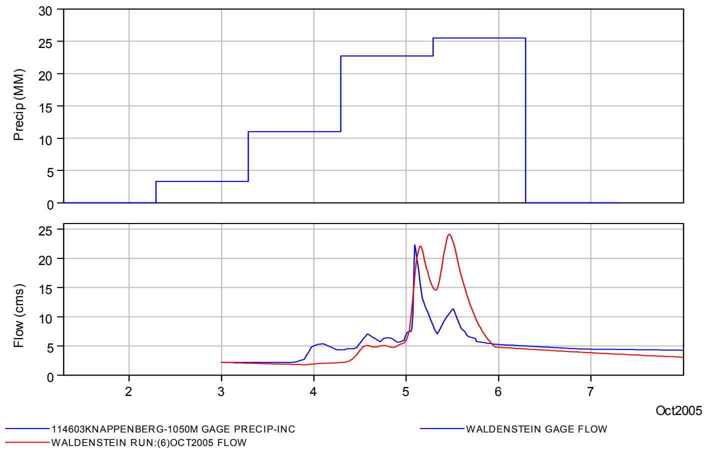

4.8.4.2 Test and Validation events

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7) 10-17 Aug 2002

fp=1, AMC1

Rainfall:
missing data: Glasshütten, Hofkogel
daily total value: Hebalpe, Hofkogel, Preitenegg, St. Andrä

Distribution by neighbour station: Preitenegg, Hebalpe, St. Andrä

max. VN5 =46mm - Knappenberg
max. VN21=125mm – Kloster-Rettenbach
VN5/VN21=39%

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St. Jakob (record missing)

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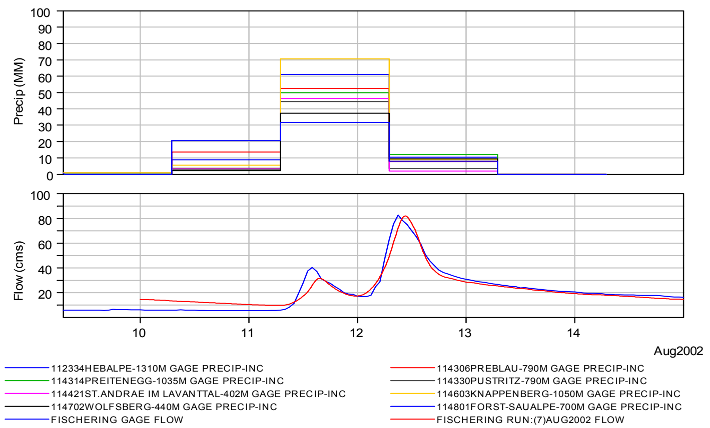
Fischering



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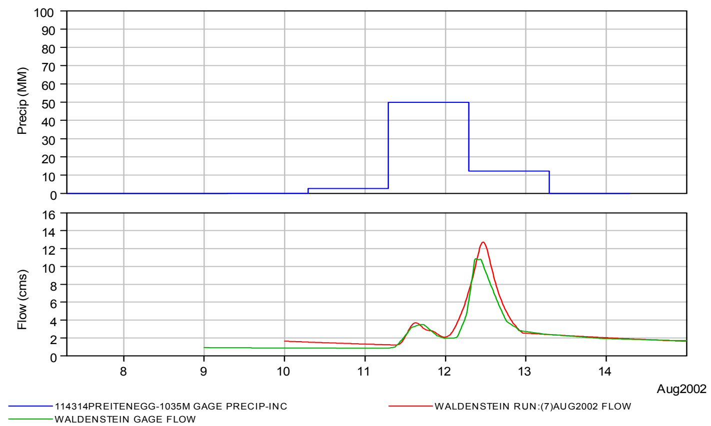

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8) 16-20 Aug 1999

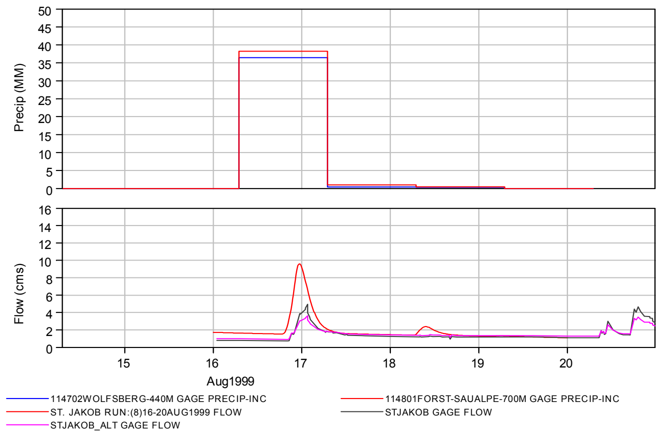
fp=1.1, AMC2

Rainfall:
missing data: Hofkogel
daily total value: Hebalpe, Preitenegg, St. Andrä

Distribution by neighbour station: no

max. VN5 =42mm - Glasshütten
max. VN21=123mm - Preblau
VN5/VN21=20%

St. Jakob



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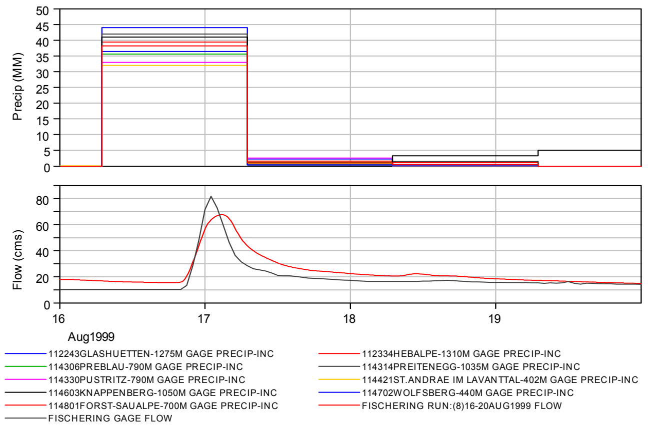

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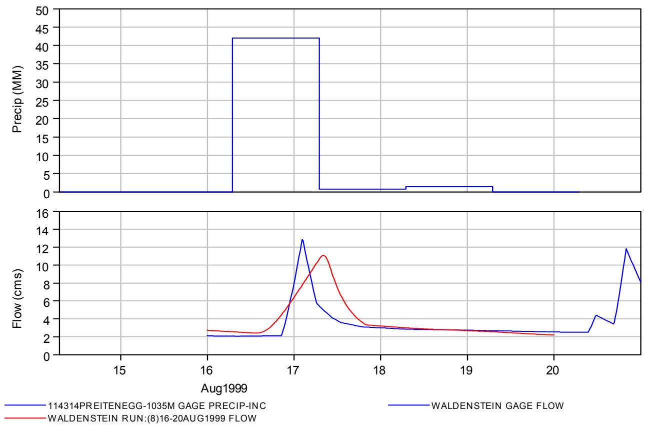


9) 20-24 Aug 1999

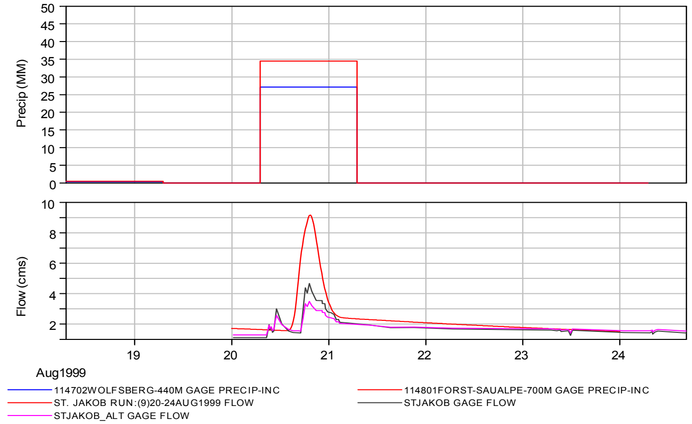
fp=1.1 , AMC2

Rainfall:
missing data: Hofgogel, Kloster-Rettenbach
daily total value: Hebalpe, Preitenegg, St. Andrä

Distribution by neighbour station: no

max. VN5 =49mm – Forst-Saualpe
max. VN21=160-163mm – Preblau, Glasshütten
VN5/VN21=32%

St. Jakob



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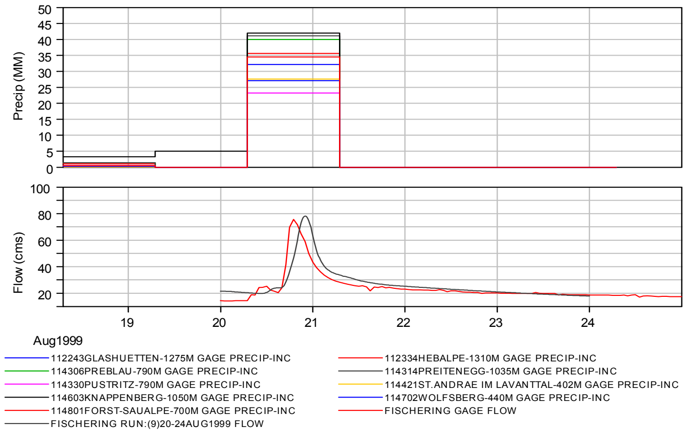

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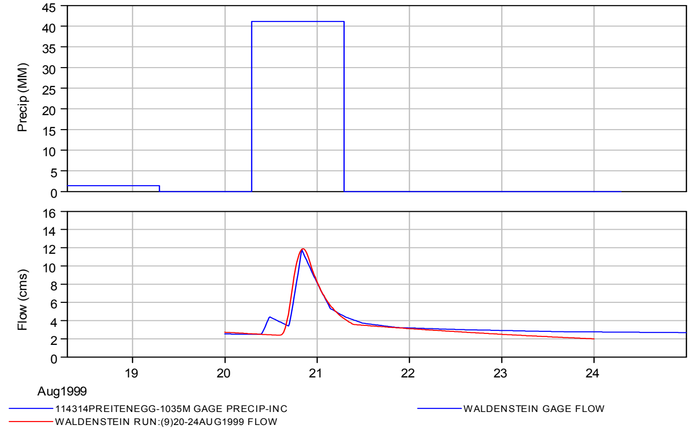


10) 13-18 Sep 1995

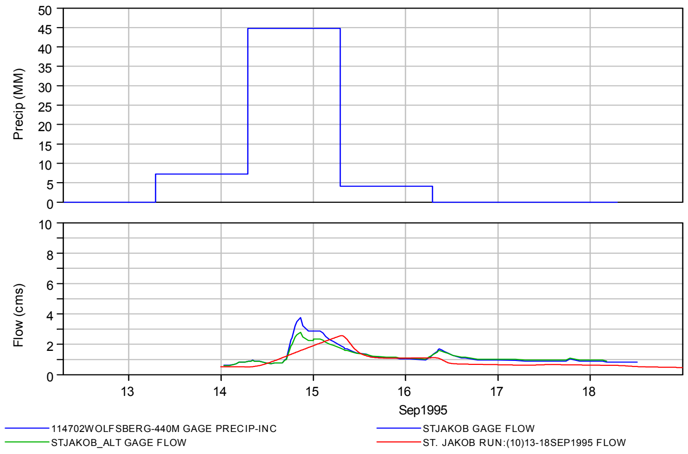
fp=1, AMC1

Rainfall:
missing data: Forst-Saualpe, Hofkogel, Kloster-Rettenbach
daily total value: Hebalpe, Preblau, Preitenegg, Pustritz, St. Andrä, Wolsfberg, Knappenberg, Glasshütten

Distribution by neighbour station: no

max. VN5 =6mm - Knappenberg
max. VN21=150mm - Glasshütten
VN5/VN21=7%

St. Jakob



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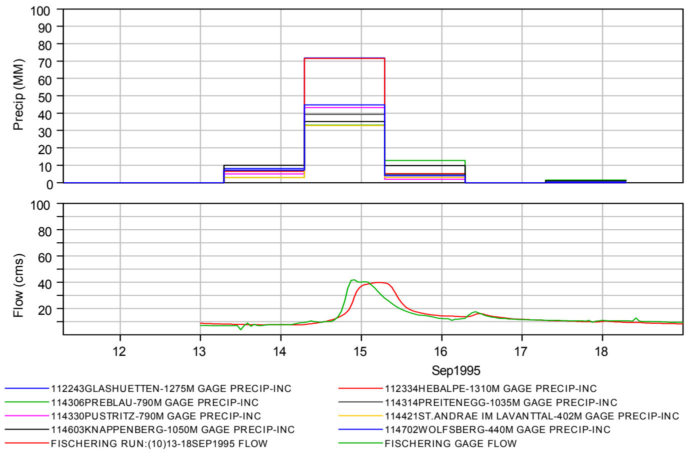

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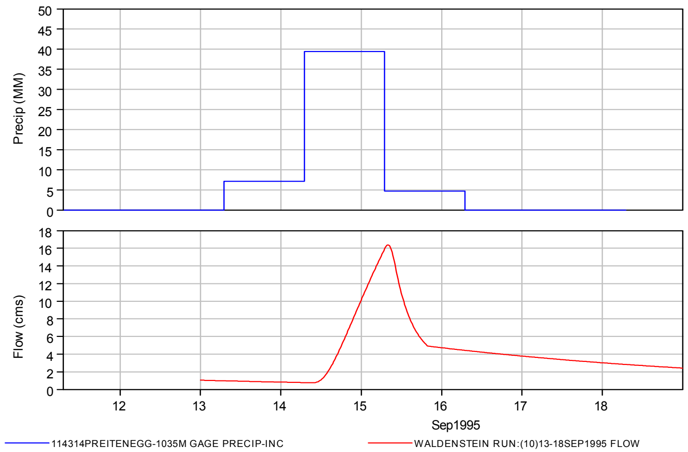

							Observed			*Simulated*		Result	
HWE	VN5 [mm]	VN21 [mm]	VN5/VN21 [-]	Month	AMC Class	fp [-]	Return period (J)	Qb [m³/s]	Vb [1000m³]	*Qc* *[m³/s]*	*Vc* *[1000m³]*	Qc/Qb [-]	Vc/Vb [-]
1-cal	5.71	94.55	0.060	June	1	1	27	189.68	26337	*157.9*	*23609*	0.832	0.896
2-cal	37.96	131.65	0.288	August	2	1.1	12	135.07	28139	*128.4*	*26670*	0.951	0.948
3-cal	17.37	41.95	0.414	July	1	1	4	106.84	29798	*101.9*	*29075*	0.954	0.976
4-cal	4.80	41.34	0.116	July	1	0.9	4	100.79	13320	*98*	*17783*	0.972	1.335
5-cal	2.93	100.64	0.029	July	1	0.8	3	97.81	14310	*104.4*	*15590*	1.067	1.089
6-cal	22.80	76.21	0.299	October	2	1.15	3	92.21	17365	*83.8*	*16491*	0.909	0.950
7-val	21.53	51.34	0.419	August	1	1	2	82.78	12154	*82*	*11878*	0.991	0.977
8-val	13.30	70.21	0.189	August	2	1.1	2	81.67	6603	*68*	*8170*	0.833	1.237
9-val	33.78	102.22	0.330	August	2	1.1	2	75.59	8654	*78.1*	*9267*	1.033	1.071
10-val	2.96	42.16	0.070	September	1	1	1	41.79	9087	*40.3*	*9840*	0.964	1.083

Table 30: Calibration and testing results for the stream flow gauge Fischering

							Observed			*Simulated*		Result	
HWE	VN5 [mm]	VN21 [mm]	VN5/VN21 [-]	Month	AMC Class	fp [-]	Return period. (J)	Qb [m³/s]	Vb [1000m³]	*Qc [m³/s]*	*Vc [1000m³]*	Qc/Qb [-]	Vc/Vb [-]
1-cal	5.71	94.55	0.06	June	1	1	2	17.21	2840	*22.6*	*3049.9*	1.313	1.074
2-cal	37.96	131.65	0.29	August	2	1.1	2	16.49	2850	*24*	*3364*	1.455	1.180
3-cal	17.37	41.95	0.41	July	1	1	-	-	-	*15.4*	*4193*	-	-
4-cal	4.80	41.34	0.12	July	1	0.9	2	16.39	2014	*15.9*	*2833*	0.970	1.407
5-cal	2.93	100.64	0.03	July	1	0.8	2	15.48	2503	*10.1*	*1839*	0.652	0.735
6-cal	22.80	76.21	0.30	October	2	1.15	4	22.29	2786	*24.1*	*2842*	1.081	1.020
7-val	21.53	51.34	0.42	August	1	1	1	10.87	1327	*12.7*	*1430*	1.168	1.078
8-val	13.30	70.21	0.19	August	2	1.1	1	12.85	1141	*11*	*1313*	0.856	1.151
9-val	33.78	102.22	0.33	August	2	1.1	1	11.82	1287	*11.9*	*1208*	1.007	0.939
10-val	2.96	42.16	0.07	September	1	1	-	-	-	*16.4*	*25.12*	-	-

Table 31: Calibration and testing results for the stream flow gauge Waldenstein

							Observed			*Simulated*		Result	
HWE	VN5 [mm]	VN21 [mm]	VN5/VN21 [-]	Month	AMC Class	fp [-]	Return period. (J)	Qb [m³/s]	Vb [1000m³]	*Qc* *[m³/s]*	*Vc* *[1000m³]*	Qc/Qb [-]	Vc/Vb [-]
1-cal	5.71	94.55	0.06	June	1	1	5	7.2	1392	*20.1*	*1620*	2.792	1.164
2-cal	37.96	131.65	0.29	August	2	1.1	5	14.25	3120	*20.3*	*3294*	1.425	1.056
3-cal	17.37	41.95	0.41	July	1	1	2	7.36	2018	*8.1*	*2502*	1.101	1.240
4-cal	4.80	41.34	0.12	July	1	0.9	1	4.9	587	*11*	*967*	2.245	1.647
5-cal	2.93	100.64	0.03	July	1	0.8	2	7.28	791	*14*	*949*	1.923	1.200
6-cal	22.80	76.21	0.30	October	2	1.15	-	3.5	241.3	*8*	*1296*	2.286	5.371
7-val	21.53	51.34	0.42	August	1	1	1	4.5	1219	*10.8*	*821.8*	2.400	0.674
8-val	13.30	70.21	0.19	August	2	1.1	1	4.87	450	*9.6*	*667*	1.971	1.482
9-val	33.78	102.22	0.33	August	2	1.1	1	4.64	623	*9.2*	*798*	1.983	1.281
10-val	2.96	42.16	0.07	September	1	1		3.8	740	*3.2*	*683*	0.842	0.923

Table 32: Calibration and testing results for the stream flow gauge St. Jakob

4.8.5 Appendix E – Model Results

4.8.5.1 Scenario A

	AMC1			AMC2					
	Current G	Future G	Future R	Current G		Future G		Future R	
	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[x1000m³]	[m³/s]	[x1000m³]	[m³/s]	[x1000m³]
Kl.Weissenb.	1.9	2.7	6.8	3.8	313.0	4.8	593.3	12.1	845.8
Jaklingbach	3.9	5.6	13.1	7.6	921.7	9.8	1267.2	22.8	1770.5
Pailbach	3.1	4.9	9.5	6.3	554.1	9.1	1160.8	17.4	1448.4
Woisbach	3.5	5.4	11.1	7.3	852.7	10.2	1194.0	20.9	1597.2
Reidebner Bach	4.6	6.3	13.1	8.4	1079.5	10.8	1363.4	22.8	1831.8
Auenbach	8.2	8.6	17.2	16.3	1821.7	16.5	2018.6	31.5	2482.2
Reisberger Bach	12.4	16.7	30.9	23.3	2430.8	29.1	3472.0	52.5	4520.8
Arlingbach	9.0	14.1	21.1	17.9	2030.7	26.6	3385.8	38.8	3706.6
Weissenbach	12.7	16.9	27.7	25.0	2530.7	31.0	3628.2	50.6	4566.8
Waldenstein	18.2	25.0	31.7	37.7	5002.0	48.4	7046.9	61.2	6929.3

Table 33: Model results for Scenario A

HWE from 8.-9. October 1980

„G"- uniform distribution, „R" - positively skewed distribution, "AMC" - Antecedent Moisture Condition Class

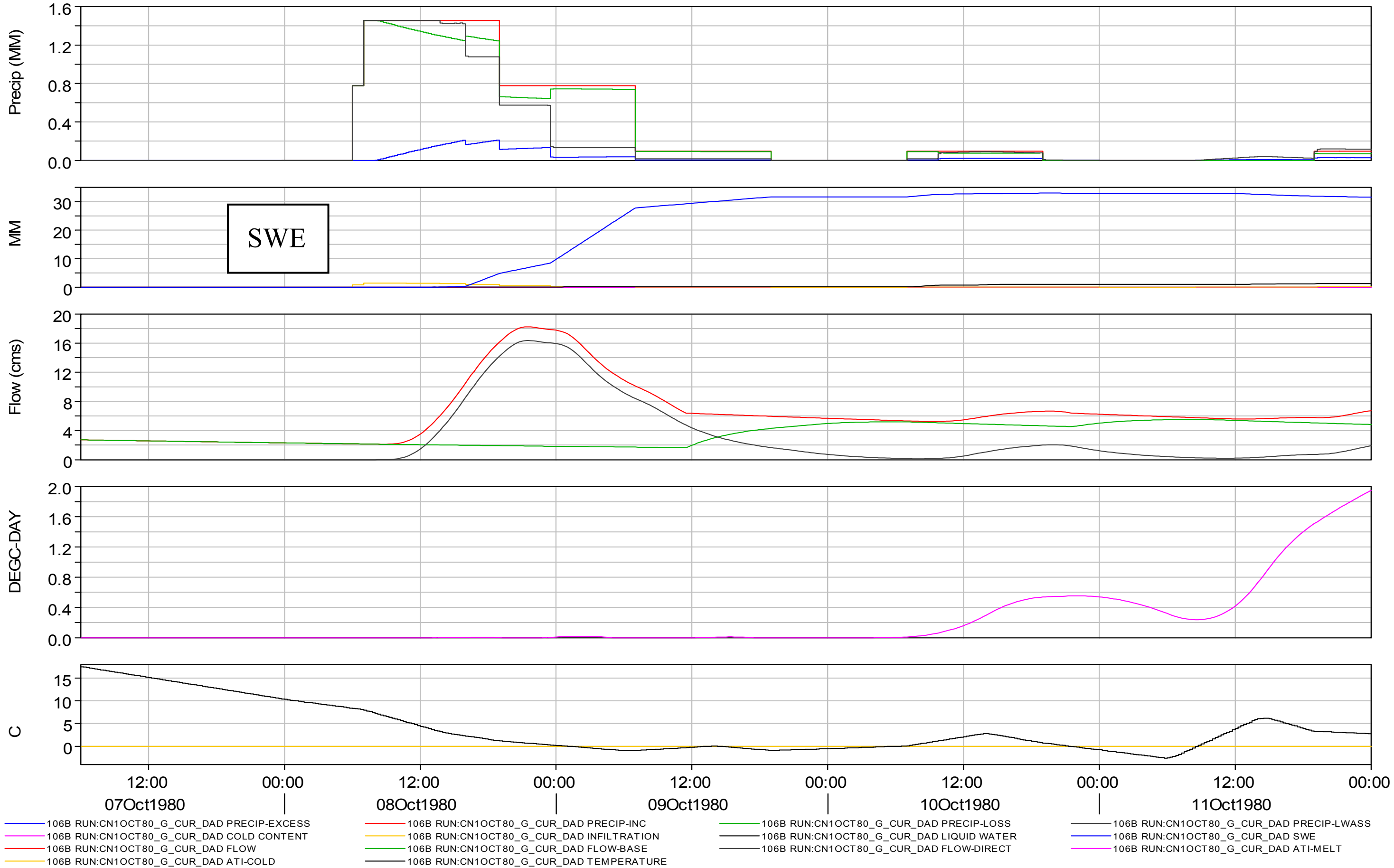

Figure 68: Model results Scenario A - Current Conditions at Waldensteiner Bach

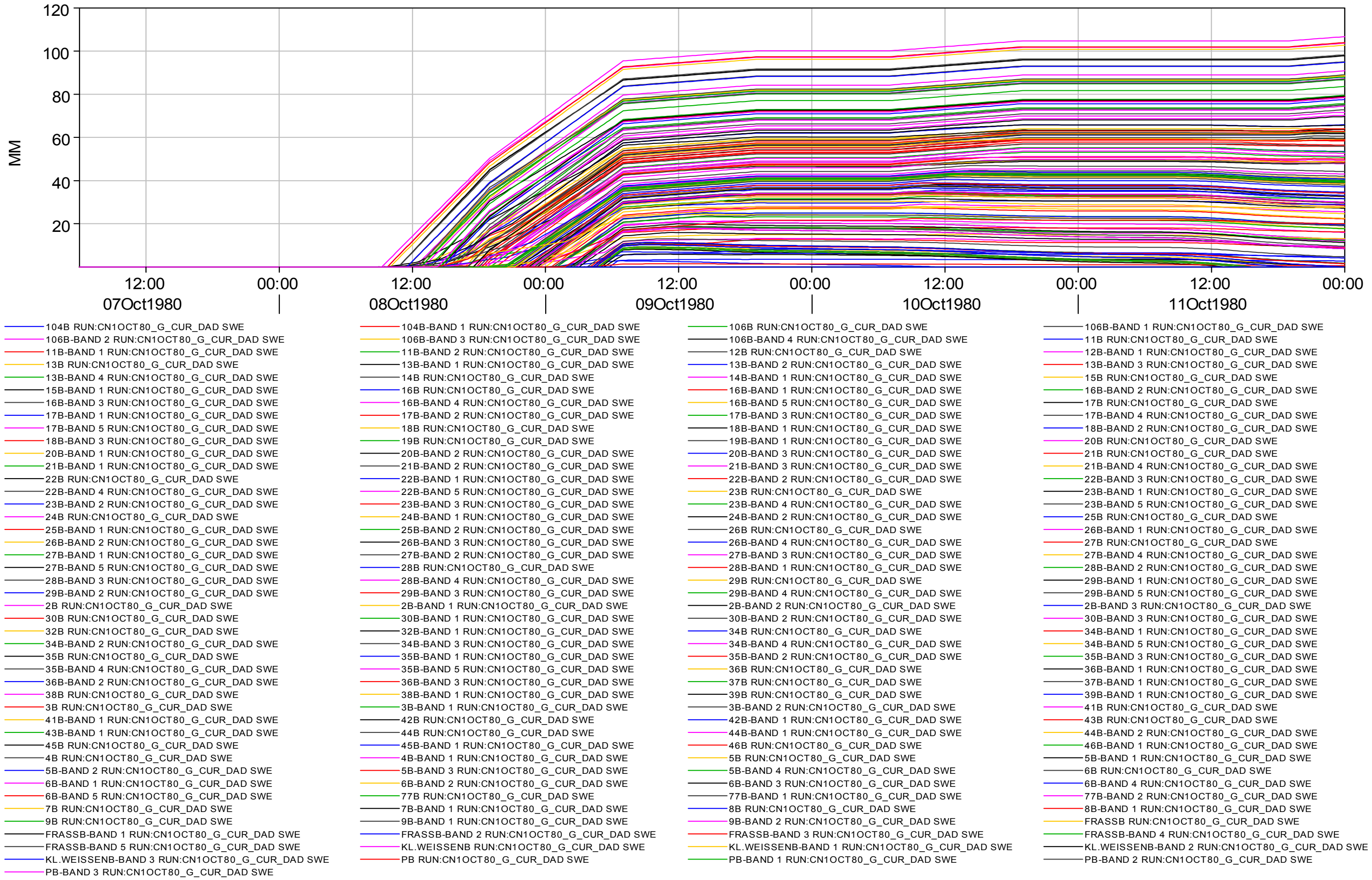

Figure 69: Model results Scenario A, Current Condition – Snow water equivalent (SWE)

all MRU, all height Bands

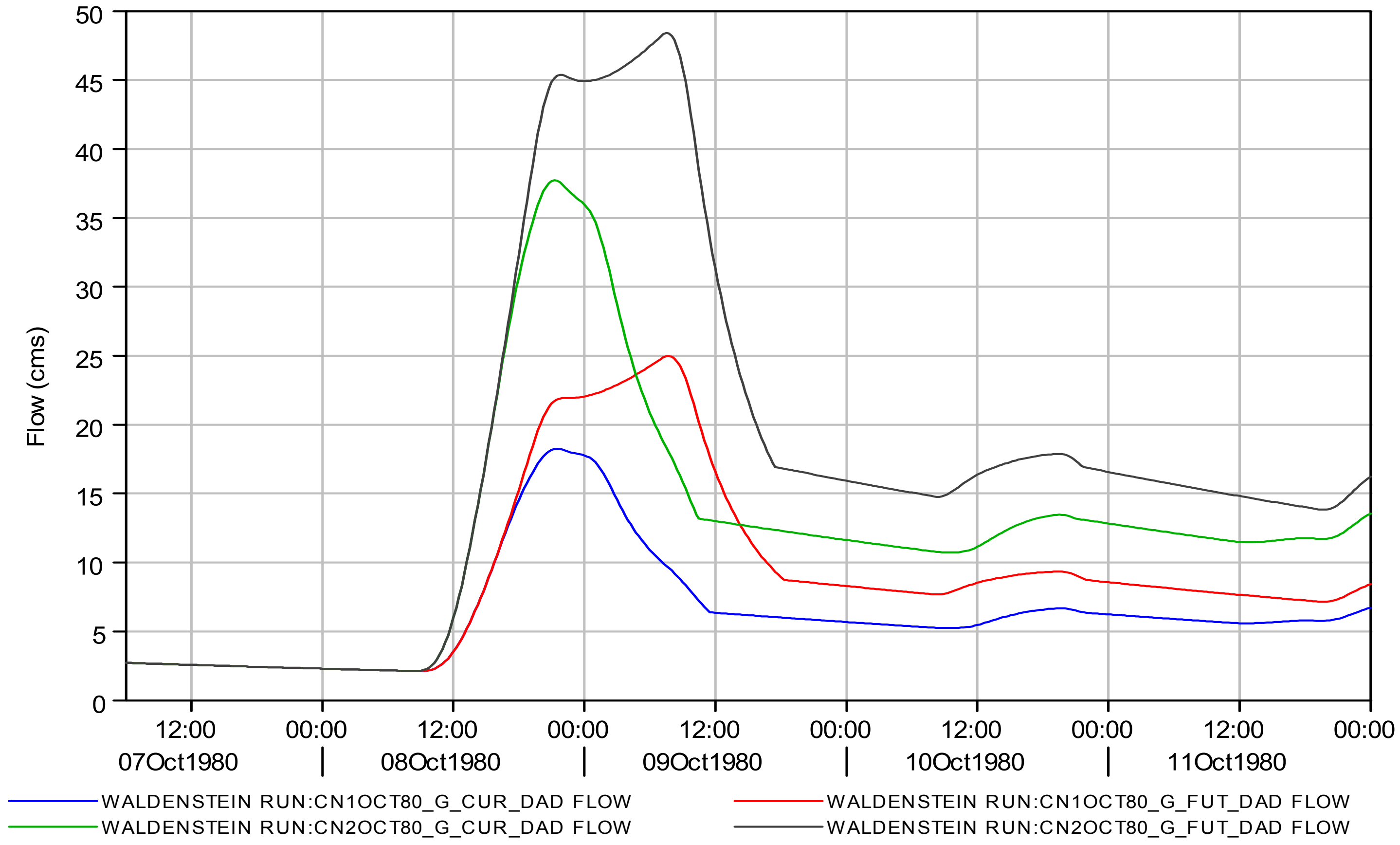

Figure 70: Model results Scenario A, Current and Future Conditions at Waldensteiner Bach for AMC1 and AMC2 by uniform rainfall distribution

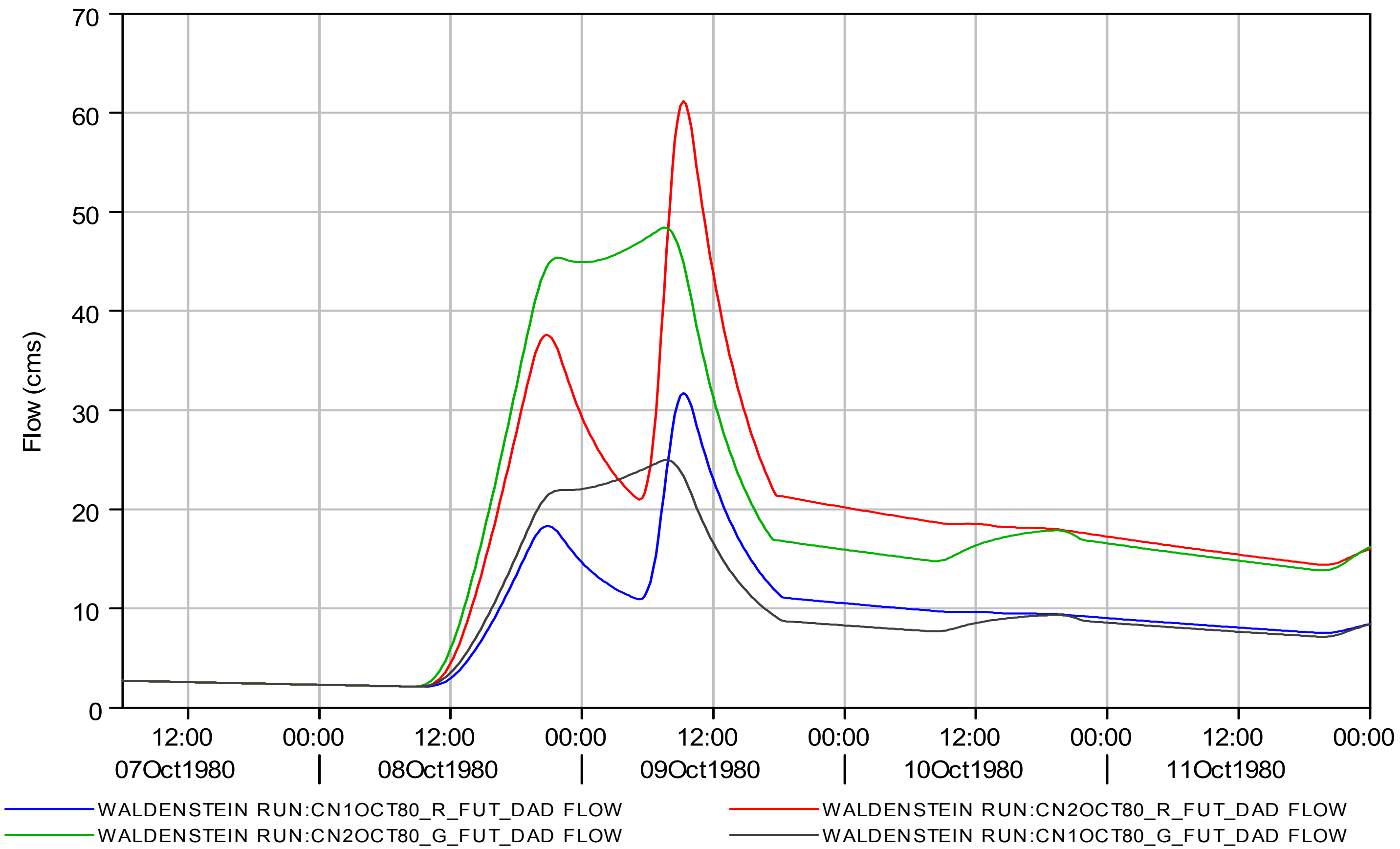

Figure 71: Model results Scenario A, Current and Future Conditions Waldensteiner Bach)

for AMC1 and AMC2 by uniform and right skewed rainfall distribution

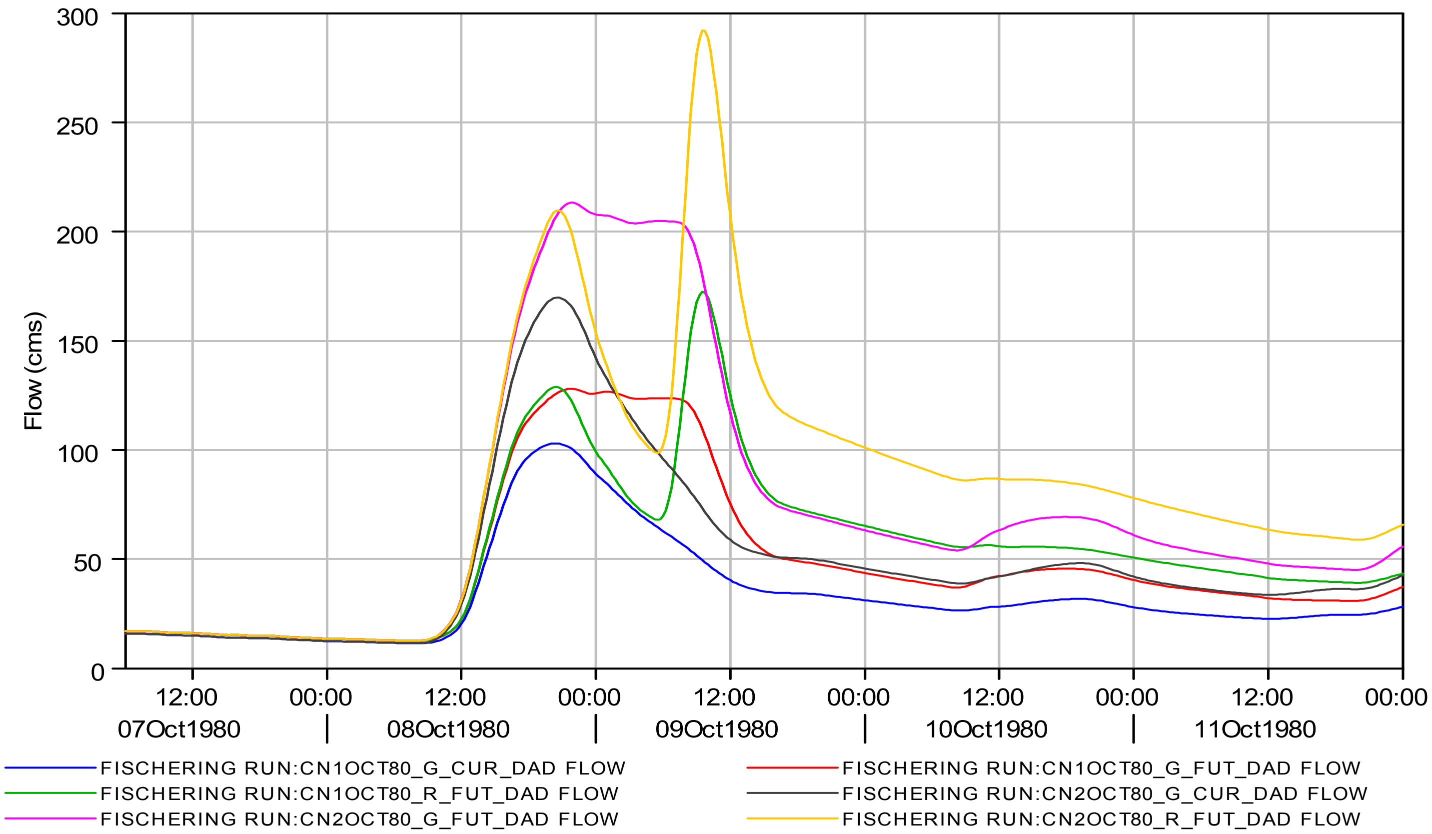

Figure 72: Model results Scenario A, gauge station Fischering

Current conditions and Climate change conditions for AMC1 and AMC2. Uniform and right-side skewed distribution

<u>Peak flows for this station are with max. 10% overestimated. (Conditioned by DAD-factor; model set up for tributaries)</u>

4.8.5.2 Scenario B1

A [km²]	River	Q [m³/s] 15min	1h	3h	Vol. 3h [x1000m³]	*Wundt* Q_{wundt} [m³/s]	$f_{w,15MIN}$	$f_{w,1h}$	$f_{w,3h}$	Statistic HQ100 [m³/s]	HHQ100 [m³/s]
8	Kl.Weissenb.	14.1	38.6	49.4	1585.9	48.05	0.29	0.80	1.03	-	-
16.3	Jaklingbach	28.0	77.3	98.3	3515.6	73.65	0.38	1.05	1.33	50	60
16.4	Pailbach	23.6	66.3	85.8	3036.1	73.92	0.32	0.90	1.16	40	50
16.6	Woisbach	20.8	60.3	80.5	2876.2	74.46	0.28	0.81	1.08	38	50
17.4	Reidebner Bach	22.3	62.0	81.6	3013.4	76.60	0.29	0.81	1.07	40	48
25.8	Auenbach	36.2	98.6	129.0	4620.4	97.02	0.37	1.02	1.33	46	60
47.4	Reisberger Bach	60.2	130.6	180.9	7565.6	139.75	0.43	0.93	1.29	60	75
54.7	Arlingbach	59.2	134.8	192.0	7881.5	152.29	0.39	0.89	1.26	75	95
58.7	Weissenbach	61.8	137.8	197.5	7301.5	158.88	0.39	0.87	1.24	75	95
108.8	Waldenstein	70.6	162.8	244.7	11945.5	230.07	0.31	0.71	1.06	100	120

Table 34: Model results for Scenario B1 (AMC1)

Heavy torrential rains

A [km²]	River	Q [m³/s] 15min	Q [m³/s] 1h	Q [m³/s] 3h	Vol. 3h [x1000m³]	Wundt Q_{wundt} [m³/s]	Wundt $f_{w,15MIN}$	Wundt $f_{w,1h}$	Wundt $f_{w,3h}$	Statistik HQ100 [m³/s]	Statistik HHQ100 [m³/s]
8	Kl.Weissenb.	23.1	57.9	70.8	2286.4	48.05	0.48	1.20	1.47	-	-
16.3	Jaklingbach	45.9	116.1	141.4	5049.0	73.65	0.62	1.58	1.92	50	60
16.4	Pailbach	40.0	103.7	128.7	4555.7	73.92	0.54	1.40	1.74	40	50
16.6	Woisbach	35.7	94.2	120.3	4305.7	74.46	0.48	1.27	1.62	38	50
17.4	Reidebner Bach	36.4	93.7	117.4	4335.6	76.60	0.48	1.22	1.53	40	48
25.8	Auenbach	60.4	150.6	188.3	6777.8	97.02	0.62	1.55	1.94	46	60
47.4	Reisberger Bach	95.6	195.3	258.3	10817.6	139.75	0.68	1.40	1.85	60	75
54.7	Arlingbach	100.3	215.3	291.3	11911.6	152.29	0.66	1.41	1.91	75	95
58.7	Weissenbach	103.5	218.4	299.2	10868.8	158.88	0.65	1.37	1.88	75	95
108.8	Waldenstein	121.5	264.2	378.2	18510.8	230.07	0.53	1.15	1.64	100	120

Table 35: Model results for Scenario B1 (AMC2)

Heavy torrential rains

4.8.5.3 Scenario B2

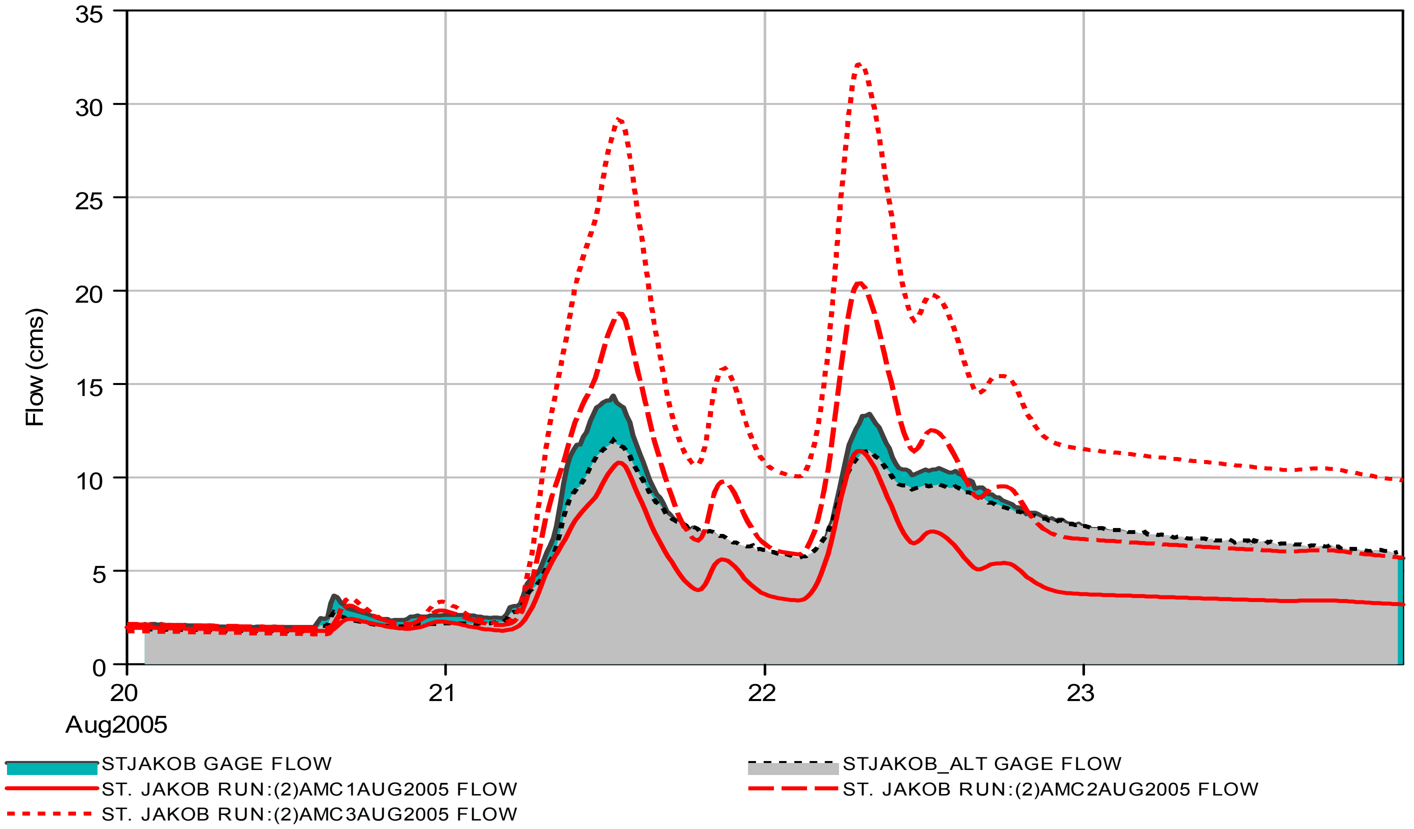

Figure 73: Model results for Scenario B2, gauge station St. Jakob

HWE from Aug. 2005 by AMC1, AMC2, AMC3

	HWE2 Aug 2005 - Peak flow - Q [m³/s]			$Q_{HW\text{-}Report}$		Runoff Volume [x1000m³]			Statistic
	AMC1	AMC2	AMC3	min	max	AMC1	AMC2	AMC3	HQ100
	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[x1000m³]	[x1000m³]	[x1000m³]	[m³/s]
Stream flow gauge St.Jakob	11.4	20.4	32.1	20	24	2092	3433	5335	75

Table 36: Model results for Scenario B2

HWE from Aug. 2005 – Weissenbach

4.8.5.4 Scenario C

A	River	Peak flow [m³/s]			Vol. 3h	Wundt-Values				Statistic	
[km²]		15min	1h	3h	[x1000m³]	Q_{wundt}	$f_{w,15MIN}$	$f_{w,1h}$	$f_{w,3h}$	HQ100	HHQ100
8	Kl.Weissenb.	6.9	21.2	35.0	1083	48.05	0.14	0.44	0.73	-	-
16.3	Jaklingbach	13.7	42.2	69.9	2438	73.65	0.19	0.57	0.95	50	60
16.4	Pailbach	11.6	35.6	60.1	2064	73.92	0.16	0.48	0.81	40	50
16.6	Woisbach	10.1	32.4	55.3	1926	74.46	0.14	0.44	0.74	38	50
17.4	Reidebner Bach	11.1	33.5	56.6	2051	76.60	0.14	0.44	0.74	40	48
25.8	Auenbach	18.4	54.5	90.5	3131	97.02	0.19	0.56	0.93	46	60
47.4	Reisberger Bach	30.9	70.3	125.2	5160	139.75	0.22	0.50	0.90	60	75
54.7	Arlingbach	29.5	70.5	129.7	5256	152.29	0.19	0.46	0.85	75	95
58.7	Weissenbach	31.0	72.4	132.9	4955	158.88	0.20	0.46	0.84	75	95
108.8	Waldenstein	34.9	84.3	161.6	7730	230.07	0.15	0.37	0.70	100	120

Table 37: Model results for Scenario C

Peak flows by 100-years heavy precipitations (Lorenz-Skoda).

Maximum from uniform and positively skewed distribution for 15, 60 and 180 min. Disseminations. Soil moisture condition AMC1

4.8.5.5 Scenario D

A [km²]	River	Peak flow [m³/s] 15min + 20%	1h + 20%	3h + 20%	Vol. 3h [x1000m³]	*Wundt-Values* Q_{wundt} [m³/s]	$f_{w,15MIN}$	$f_{w,1h}$	$f_{w,3h}$	Statistic HQ100 [m³/s]	HHQ100 [m³/s]
8	Kl.Weissenb.	10.0	29.8	48.2	1493.7	48.05	0.21	0.62	1.00	-	-
16.3	Jaklingbach	19.9	59.2	96.1	3349.1	73.65	0.27	0.80	1.30	50	60
16.4	Pailbach	16.8	50.2	83.1	2851.9	73.92	0.23	0.68	1.12	40	50
16.6	Woisbach	14.7	45.5	76.2	2652.4	74.46	0.20	0.61	1.02	38	50
17.4	Reidebner Bach	16.0	46.8	77.8	2811.3	76.60	0.21	0.61	1.02	40	48
25.8	Auenbach	26.2	75.6	123.6	4272.9	97.02	0.27	0.78	1.27	46	60
47.4	Reisberger Bach	43.6	97.2	172.0	7077.5	139.75	0.31	0.70	1.23	60	75
54.7	Arlingbach	42.3	98.6	180.2	7282.2	152.29	0.28	0.65	1.18	75	95
58.7	Weissenbach	44.4	101.1	184.6	6837.1	158.88	0.28	0.64	1.16	75	95
108.8	Waldenstein	50.1	118.3	225.5	10773.3	230.07	0.22	0.51	0.98	100	120

Table 38: Model results for Scenario D

Increasing of the heavy precipitations by soil moisture conditions AMC1

4.8.5.6 Comparative Study – counter measures

A	River	Q [m³/s]	Vol. 3h	*Wundt*		Statistic	
[km²]		3h	[x1000m³]	Q_{wundt} [m³/s]	$f_{w,3h}$	HQ100 [m³/s]	HHQ100 [m³/s]
8	Kl.Weissenb.	45.6	1413.6	48.05	0.95	-	-
16.3	Jaklingbach	91.2	3165.4	73.65	1.24	50	60
16.4	Pailbach	81.4	2788.4	73.92	1.10	40	50
16.6	Woisbach	70.5	2452.2	74.46	0.95	38	50
17.4	Reidebner Bach	75.9	2635.0	76.60	0.99	40	48
25.8	Auenbach	116.2	4016.6	97.02	1.20	46	60
47.4	Reisberger Bach	155.5	6404.7	139.75	1.11	60	75
54.7	Arlingbach	175.7	7059.7	152.29	1.15	75	95
58.7	Weissenbach	179.6	6619.0	158.88	1.13	75	95
108.8	Waldenstein	222.6	10634.0	230.07	0.97	100	120

Table 39: Model results for counter measures

Correlates to Scenario D with soil working direction across the slope -- Soil moisture conditions AMC1

5. GRANDES JORASSES SITE: A CASE STUDY

5.1 Abstract

Glaciers are known as realiable indicators of climate changes, as they change their size in a more or less quickly way in order to balance climate conditions. The purpose of this study is to test the different technologies to let us know in a better way the glacier morphology and in which way it changes. In order to get results, two case studies have been chosen. The first site is the Grandes Jorasses hanging glacier (Val Ferret-Courmayeur-Italy) on which we focused on collecting data usefull for finding the relationship between the rock substratum temperature and the displacement rate field of the serac. The second site is the Pré de Bar glacier (Val Ferret-Courmayeur-Italy) on which we focused on the evaluation of morphology variations using some experimental technics (in glaciological field) as LIDAR and photogrammetry assisted by GPS.

5.2 Grandes jorasses site

5.2.1 Geographic and glaciological description

5.2.1.1 Introduction

Considering the high pertinence of glacier monitoring as an indicator of climate change, we can note the infrequency of research work and the absence of a coordination project for the activities carried out by various bodies involved in achieving common targets. The study of glacial mass instability and its related hydraulic and geomorphic apparatus can be considered a useful means of distinguishing not only global warming effects and subsequent reduction of glacial masses, but also of improving forecasts for territorial planning and management of possible emergencies. The damage and hazard study on the south face of the Grandes Jorasses hanging glacier, situated in the municipality of Courmayeur, appeared as a natural optimal laboratory where specific methods of study were applied both for risk assessment and for the application of monitoring methods concerning the dynamic evolution of hanging glaciers.

More specifically, the project targets were:

- To improve and update our knowledge of the evolutive dynamics of hanging glaciers;
- To define a monitoring procedure for hanging glaciers.;
- To assess melting, geometric and planoaltimetric variations on hanging glaciers using different techniques;
- To identify traces indicating collapse;
- To identify threshold alert (variation of glacial mass horizontal acceleration, the slope of the cliff, basal fracture);
- To assess the risk of hanging glaciers;
- To value dangerousness;

- To manage risk (risk management).

5.2.1.2 The Geographic and Morphologic setting of the south slope of Grandes Jorasses

The hanging glacier examined in this study is located along the southern slope of the Grandes Jorasses (Aosta Valley side) immediately downhill from the Summit crest, at an altitude of about 4000 m . The glacier covers a surface of 25.000 sq m and is characterised by a conspicuous serac from which ice masses of various sizes detach regularly. The glacier lays on a 30° sloping bedrock surface that is connected to the valley below covering a vertical drop of about 2600 m.Because of steep slopes and vertical drops and a lack of tall trunk trees, the detachment of glacial mass, especially in the winter when there is snow on the whole slope, can generate large avalanches that can interfere with human activity at the bottom of the valley.

Figure 74: Grandes Jorasses peak (2007)

5.2.1.3 A description of the Grandes Jorasses hanging glacier

A classic, geomorphologic classification of the Grandes Jorasses glacier describes the glacier itself as a hanging glacier that is to say a glacier portion delimited at the bottom of the valley by a cliff.

A more recent classification of hanging glaciers is based on a primary appreciation of the danger inherent to these glaciers

A glacier is classified according to its bed surface geometry, on its state of balance, on its type of fracture, on the possibility that an eventual collapse would fall on the glacier itself.

The Grandes Jorasses , following this classification, is defined as a Hanging Glacier and more precisely, a Ramp Avalanching glacier unbalanced with Slab Fracture.

A Hanging Glacier is simply a hanging glacier. An avalanching glacier is a dry calving glacier lying on a steep slope (a slope which is sufficient to allow debris to fall away from the calving zone) or terminating on a bedrock cliff. The definition excludes glaciers with unstable seracs which fall on the glacier itself.

The bedrock geometry is another characteristic used to classify a hanging glacier which, in the case of the Grandes Jorasses, is called ramp (a slope without evident changes of incline or terraces).

Ramp glaciers are avalanching glaciers lying on a uniform, even, steep bed, which leads to major instabilities. The calving area represents a significant portion of the glacier. The unstable part is supplied principally by direct snow accumulation. Therefore, after a collapse, a long period (usually one to several decades) is required to reach another critical state.

The final characteristic to consider for a classification of the glacier is the break off process that is directly connected with bedrock topography in the calving zone. As we said previously, in the case of the Jorasses glacier the “ramp” bed surface aids the isolation.

Figure 75: Grandes Jorasses hanging glacier

5.2.2 Glacier's monitoring activity

5.2.2.1 Potential risk of serac fall

5.2.2.1.1 Historical analysis of icefalls

In order to understand the phenomenology of collapse better and to set in the territorial context in which it falls, it is fundamental to make an accurate historical analysis of past damage.

- December 21 1952: a large ice and snow avalanche reached the village of Plampincieux causing a lot of damage. It is not clear if the snowfall was generated by the glacial collapse from serac;
- August 2 1993: collapse of approximately 80.000 sq m overwhelms and kills 8 climbers who were climbing the Grandes Jorasses normal slope;
- July 11-14 1996: repeated collapse for a total of approximately 24,000 sq m trigger an avalanche;
- January 23 1997: repeated collapse for a total of approximately 1715 sq m trigger an avalanche;
- January 25 1997: repeated collapse for a total of approximately 24000 sq m;
- June 1 1998: collapse of the whole serac.

5.2.2.1.2 Past monitoring activities realized on Grandes Jorasses hanging glacier

In the summer of 1996 some mountain guides, during a climb to the top, noticed two new cross-sectional cracks and put the regional technicians on alert. The first fissure, a few metres from the edge of the serac, was reduced to the natural evolution of the serac front or rather to the superficial traction effort caused by the continuous release of ice pieces due to the steep slope of the front.

The central cross fissure was considered atypical and it indeed probably reflects a general instability of the whole ice mass. Since 1996, studies have been conducted by ETH on commission from the Aosta Valley Autonomous Region, to monitor studies to understand the evolution of the glacier.

The temperature was taken on all thicknesses of ice by drilling and laying "thermometers" and the speed of movement was measured after laying 6 snow-poles on the surface of the serac.

Thanks to the information obtained by the readings it was possible to exclude the fact that hanging glacier instability was caused by the ice warming in contact with the bedrock. The data show temperatures, within the ice baseline, of about -4,-5° C , therefore temperatures characterizing "cold" ice .

Research in the last few years has shown that below zero temperatures in contact with the bedrock substrate (from-7 to -3 °C), at least on the glacier front, guarantee a certain stability. Laboratory studies have shown that the ice in temperatures of-10°c presents a breaking load of about 400 kPa while in temperatures of around 0° C the breaking load is halved to 200 kPa.

The problem of being able to predict the time of release of a large ice mass in a hanging glacier has led us to propose the empirical equation for the ice speed before the "breakoff" in order to obtain a critical threshold to use in the field of risk management (Flotron A. 1977).

$$V(t) = Vo + a\,(tf-t)^{-m} \quad m>0$$

The speed V (t) increases from its initial Value V0 infinitely to the time of break off Tf The measurements of speed have illustrated the progressive increase of velocity prior to break-off.

To assess the potential instability of the hanging glacier, another fundamental aspect to take into consideration is the progressive deterioration in the properties of ice baseline and the growth of the crevasse. Models tested manifest that the most important feature of the increase in depth of the crevasse h in a glacier of thickness H is the increase of the force of traction. In other words, the overhanging serac induces a locally unbalanced stress $\tau 0$ at the glacier front which is the driving force of crevasse formation and growth. The relative depth of the crevasse $\acute{\omega} = h/H$ is a measurement of material deterioration, or damage. Further we assume that the ice velocity v and crevasse growth depend on the stress state τ in the vicinity of the crevasse bottom (the "working zone" where fracturing or damage occur).

Direct observation of the evolution of instability in hanging seracs showed that the worsening rheological properties of ice baseline were visible about a year before the collapse.

5.2.2.1.3 Methodological approach to assessment and risk management

The final aim and future target of the study and monitoring of the Jorasses hanging glacier is the definition and management of risk induced by the glacier itself

The methodology that led to the definition of risk was particularly complex, since the factors that compose it are complex and articulate. Essentially, risk includes the outcome of the susceptibility of the territory and its socio-economic structure.

Territorial susceptibility, involving all the natural factors, is governed by the planoaltimetric geometry of the Jorasses south slope (inclinations and elevated gradients), by the morphometrical characteristics of the hanging glacier and by rheologic characteristics of ice

In order to define risk, it is necessary to consider the following factors (UNESCO, 1984):

Dangerousness (H): probability that a potentially damaging (Hazard) phenomenon of a certain intensity can happen in a limited period and in a specific area and for given trigger causes.

Elements at risk (E): population, ownership, economic activity at risk.

Vulnerability (V): degree of loss expected on a specific element or group of elements at risk from a potentially destructive phenomenon of fixed intensity. Vulnerability is expressed on a scale between 0 (no loss) and 1 (total loss).

Specific risk (Rs): degree of loss expected because of a fixed natural phenomenon of specific intensity; which can be expressed as the result of H by/x V.

Total (R) risk: degree of losses expected in terms of human life, injuries, damage to ownership and to infrastructure, direct and indirect damage to the economy because of one given geological danger. It is the result of the specific risk Rs and elements to risk (E).

Therefore the total risk is the result of the following:

$$R = H\ V\ E = Rs\ E$$

5.2.2.1.4 Qualitative risk analysis

Qualitative risk analysis is the easiest methodology to apply in our case, and it involves the acquisition of factors contributing to risk assessment (Dangerousness, Elements at risk, Vulnerability) assigning to each of these elements a select qualitative parameter inside determined classes of values, substantially through an experienced judgement.

An important factor to consider is the indication of the trigger causes of the phenomena, also in terms of critical thresholds (i.e.. critical values of the horizontal acceleration of the serac, appearance of sectors fractured at the base).

In order to mitigate the risk of the serac, the reduction of risk factors (dangerousness, elements at risk, vulnerability) is a possible strategy

We can achieve a reduction of danger in our case study by maintaining a critical threshold and by limiting the access to given areas which have exceeded that threshold

5.2.2.2 Rock surface temperature measurement of the Grandes Jorasses serac

5.2.2.2.1 Final aim

Characterize the temperature of the rock substratum in proximity of the Whymper glacier serac and its temporal variability in order to estimate possible variations in the thermal regime of the contact zone ice -rock.

5.2.2.2.2 Introduction

One of the factors that can condition a hanging glacier's stability is the thermal characteristics of the ice that constitutes the suspended portion, whose variations could notably modify the rheologic features of the ice. The distinction between cold glaciers and temperate glaciers, which have completely different dynamics, is well known.

A further element that influences the conditions of stability of the hanging glacier is the temperature of the interface ice-substratum rock which is responsible for the modification of the mechanical properties of resistance and the variation of the same towards temperature. Moreover, if we consider the fact that global warming could affect the thermal state, continuous monitoring and measuring of these parameters are of utmost importance as a means of knowing more about the management of eventual risks.

Therefore, two thermologgers were installed for the continuous measurement of rock temperature near the wall of the hanging glacier. Both the implementation and final results of the activity were conditioned by the singularity of the site (a 4000 metre glacier) and by the meteorological conditions during the summer of 2007 that caused delays in the installation of sensors and limited, consequently, the availability of data collected. However we consider the action very important for future activities.

5.2.2.2.3 Preliminary activities

Predisposition of the instrumentation. For the measure of the surface temperature of the cliff , a device previously experimented by ARPA for the Interreg ALCOTRA n. 196 "PERMAdataROC". Project was employed. The instrumentation included a 3 channel minidatalogger (a Geoprecision) with 3 temperature sensors (PT1000) inside a support (diameter 10 ml.) which was placed at different distances (from the beginning o f the support), at a depth of 55cm. ,30cm. and 3 cm. from the surface of the cliff. 55 cm represented the best compromise between the need to find superficial temperatures not too influenced by direct solar radiation (so high variability) and the possibility of installation in rock by means of a battery drill.

Monitoring sites. In order to understand the abovementioned dynamics , the data of greatest interest, was the surface temperature of the cliff under the serac. The impossibility of achieving this within the project, in spite of the remarkable economic resources and the necessity to predispose prototype instrumentation, led to alternative solutions. Substratum rock with the same features as the serac was chosen and which included the following characteristics:

- safe working conditions for the installation;
- low probability of snow cover;
- low probability of damaging the instrumentation by means of rock/ice falls
- the chosen site was highly representative of the surrounding area;
- easy comparison between serac rock and the area of interest. (lithologic, morphologic and structural characteristics)

Figure 76: Optimal position for the logging of substratum rock temperatures (2007)

Figure 77: Ultimate position chosen for the instruments to monitor superficial rock temperature (2007)

Figure 78: Minilogger. Dowload and setup function via infrared com (2007)

5.2.2.2.4 Measurements

In the table below we have plotted the series of data now available (hourly frequence) for the period between 07/09/2007 and 24/10/2007 for the point DX and 07/09/2007 – 17/09/2007 for the point SX. A battery breakdown caused a loss in data from SX sensor.

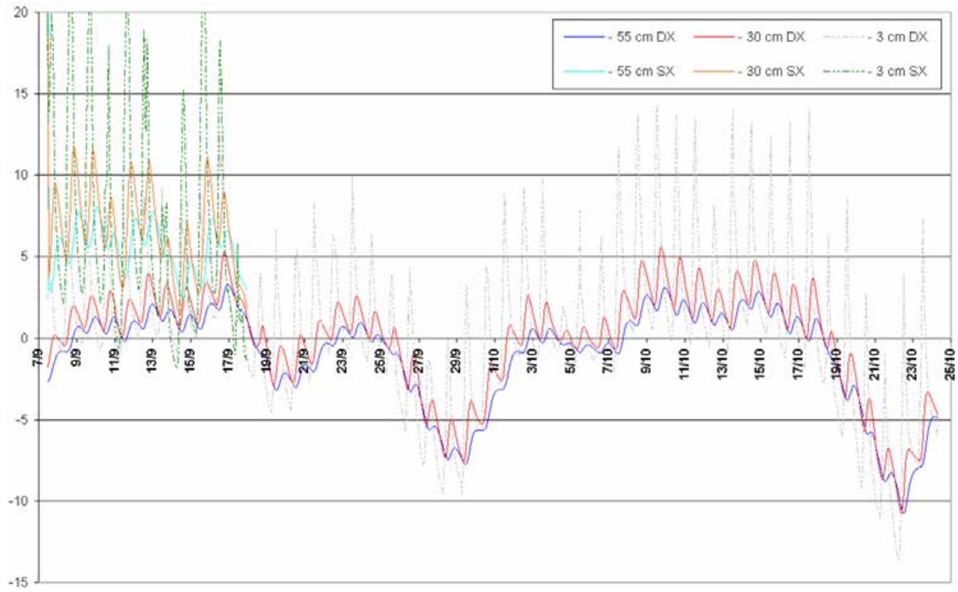

Figure 79: Temperatures logged by t° DX e t° SX at 3, 30 e 55 cm depth (2007)

Although we have only limited data, we can observe some interesting behaviour regarding the characterization of the thermal state o f the rock.

First of all the -3cm. surface temperature will not be considered because of its extreme variability due to the high frequency of the sample. The same effect could be found in the comparison between DX and SX sites and in particular we have for -30 cm sensor 9°C and for the -55 cm sensor 5,5°C. This difference is caused by the different aspect of the rock in which sensors were put: SX is south-west and DX is approximately east.

In the table below there is a comparison between data logged at different depths and for different sensors (DX anc SX).

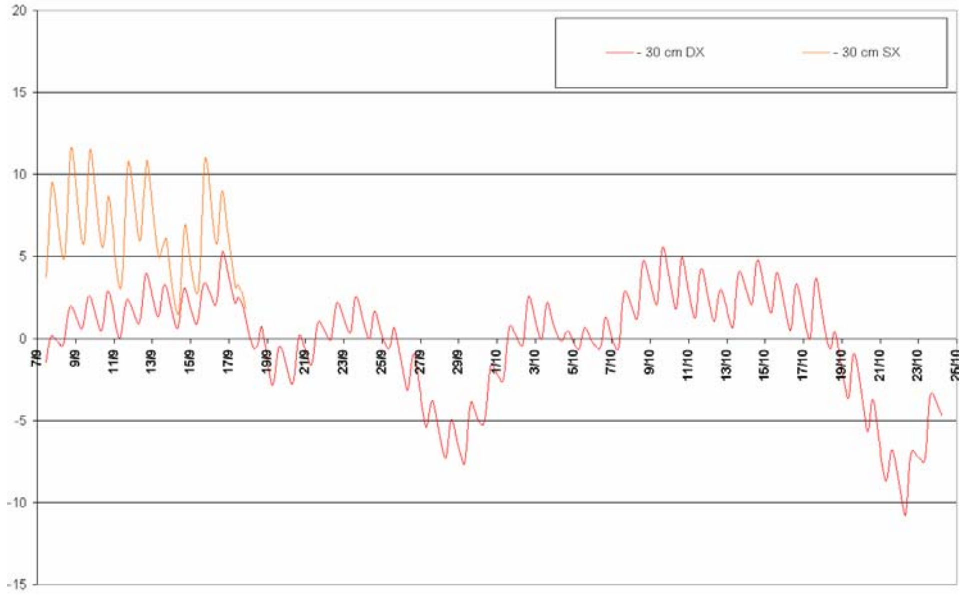

Figure 80: Temperature time series of logger putted at -30 cm (2007)

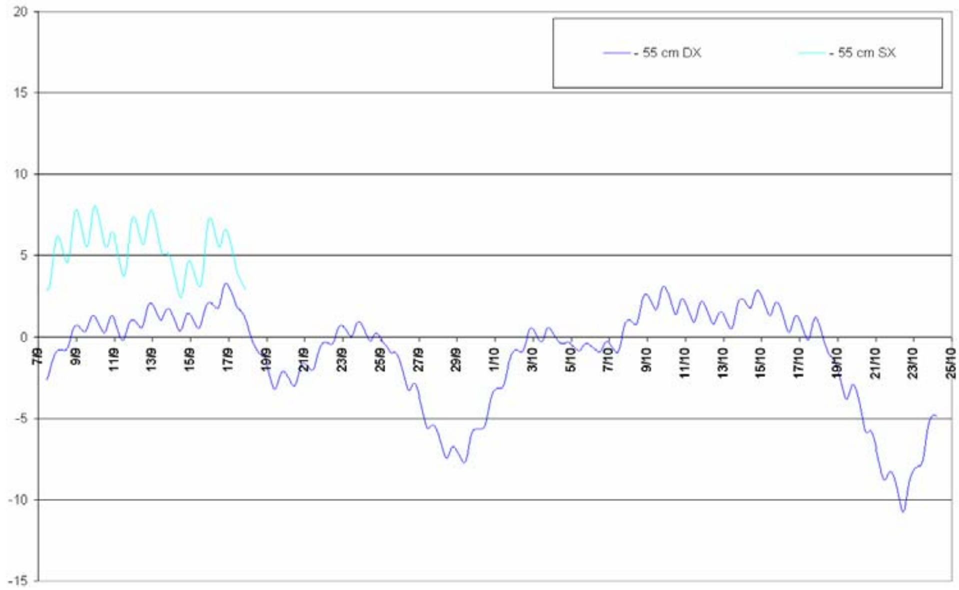

Figure 81: Time series of logger putted at -55 cm (2007)

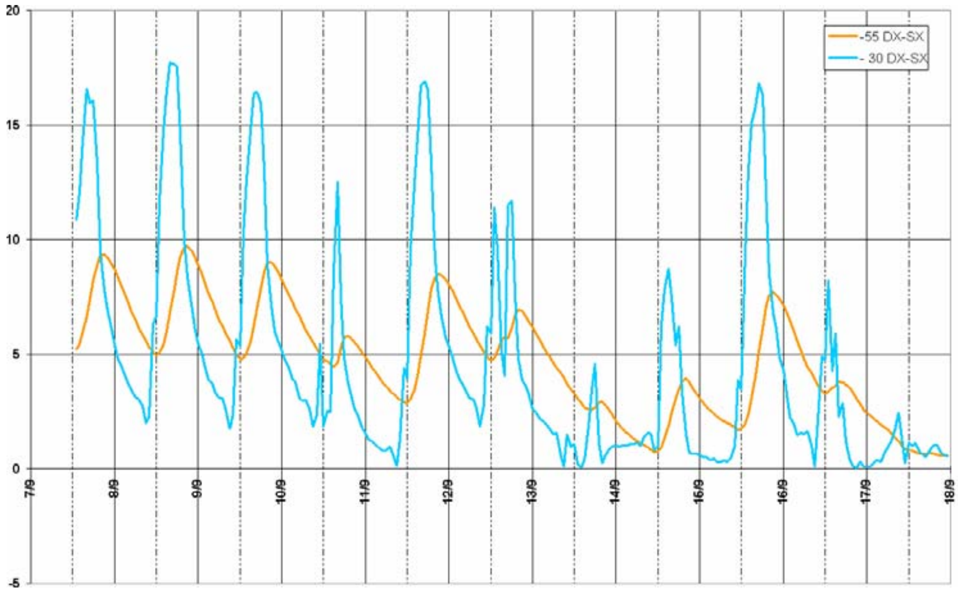

Figure 82: Plot of the temperature difference between two logger at -30 e -55 cm (2007)

In the table below, we have plotted average values for different sensors

- 55 cm DX	- 30 cm DX	- 3 cm DX
-1,02	-0,06	0,66

- 55 cm SX	- 30 cm SX	- 3 cm SX
5,63	6,703	7,153

Table 40: Average values (2007)

In the table below we have included mean daily temperatures (in the period examined). We have also plotted mean daily temperatures logged at different depths.

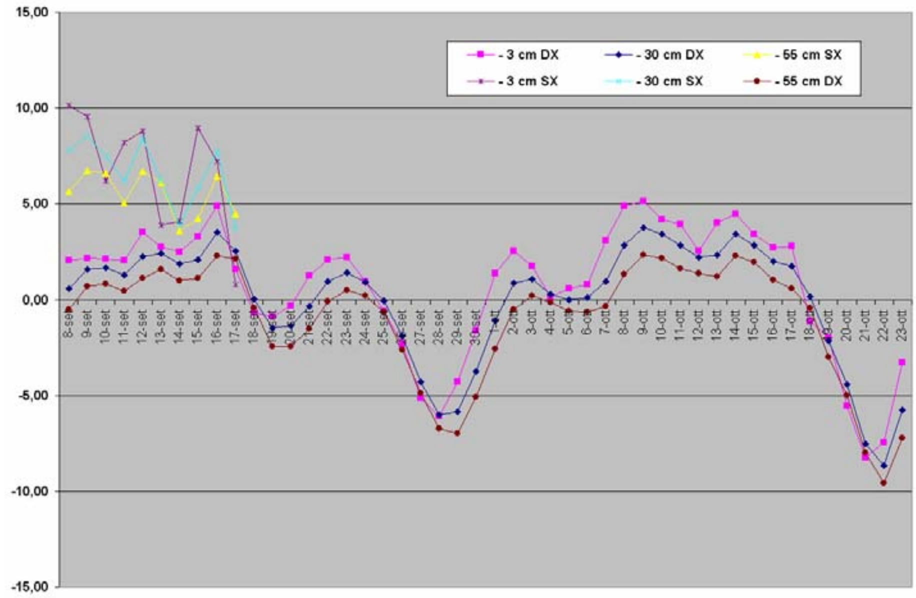

Figure 83: Plot of the temperature difference between logger at different depth (2007)

5.2.2.3 Grandes Jorasses glacier displacement rate fields measurement:

5.2.2.3.1 Final aim

Study of displacement rate of Whymper hanging glacier serac in non-critical condition

5.2.2.3.2 Introduction

As a method for hanging glacier displacement rate measurment, periodic comparison between position of benchmarks, placed on serac surface, has been chosen. The exact

benchmarks position, in a relative coordinate system, has been determined by means of indirect theodolite measurement, taken from a point in front of the serac.

One constraint was the necessity of compare new data with mesurements taken after 21/12/1996, in the circumstance of the critical event occurred in january 1997; moreover, it was necessary to ensure results even in critical environmental conditions and with available financial resources. Thus, this method was preferred to other technologies - such as the comparison between laser-scanning 3d surface models taken in different times or continuous GPS measurement on glacier's surface. Moreover, ther same techician who realised measurement of Serac Whymper in 1997 (on charge of A.V.A.R.-Service of Hydraulics and Soil Protection) was involved in the activity.

5.2.2.3.3 Preliminary works

Reference frame. For the above reason, the same local reference frame and the position of measurment station as in 1997 was maintained. The station has been positioned on a small rock eminence on the Pra Sec ridge, at 3930 m asl, where the theodolite support used in 1997 is still functional. In fact, no errors were found in the repetition of measurment of the reference point (the Madonna on summit of Aiguille Noire), so one can assess that no displacement of the measurment base has occurred.

Benchmarks on serac's suface. Metallic stakes with a reflecting surface were chosen as benchmarks; this on the basis of previous experiences by ARPA in the glacial environment and other technicians in glacier's monitoring.

Benchmarks network. Considering the present serac's geometry and the necessity of measure the whole seracs displacements, 12 stakes have been positioned, divided into two different alignements of 4 and 8 stakes respectively. Stakes were positioned during the first measure session.

5.2.2.3.4 Measurements

Topographic measurements performed are listed in the tables below

measure 1: 07/09/2007				
point	**coord. X**	**coord. Y**	**altitude**	**description**
100	**0,000**	**0,000**	**0,000**	**Station (tool)**
104	**334,295**	**-172,683**	**228,740**	**Stake1**
105	**336,580**	**-128,690**	**203,940**	**Stake2**
106	**339,047**	**-102,394**	**184,118**	**Stake3**
107	**340,625**	**-72,930**	**162,802**	**Stake4**
108	**413,694**	**-65,316**	**185,645**	**Stake5**
109	**337,274**	**-44,665**	**141,751**	**Stake6**
110	**400,231**	**-44,647**	**166,466**	**Stake7**
112	**334,607**	**-22,172**	**124,438**	**Stake8**
113	**386,162**	**-22,889**	**142,817**	**Stake9**
114	**375,751**	**-5,881**	**124,807**	**Stake10**
115	**327,680**	**-3,475**	**106,277**	**Stake11**
116	**334,255**	**6,690**	**100,462**	**Stake12**
124	**416,509**	**113,875**	**83,804**	**Fix target**

Table 41: Stakes coordinates measured on 07/09/2007

Measure 1: 24/10/2007				
point	**coord. X**	**coord. Y**	**altitude**	**description**
2-100	0,000	0,000	0,000	Station (tool)
2-104	334,298	-172,209	228,088	Stake1
				Stake2
2-106	338,970	-100,443	182,618	Stake3
2-107	340,044	-71,184	161,192	Stake4
2-108	412,376	-64,360	183,477	Stake5
2-109	336,201	-42,754	140,007	Stake6
2-110	399,028	-43,171	164,739	Stake7
				Stake8
2-113	384,986	-21,280	141,095	Stake9
				Stake10
				Stake11
				Stake12
2-124	416,506	113,873	83,819	Fix target

Table 42: Stakes coordinates measured on 24/10/2007

By comparing the local coordinates measured in the different sessions, sigle points horizontal, vertical and total displacements were determined. Displacements are reported in tables and graphs below (Hor: horizontal component, Vert: vertical component, 3d: total vector).

Displacement (47 gg)			
description	**Hor (m)**	**Vert (m)**	**3D (m)**
Station (instrument)	0,000	0,000	0,000
Stake1	0,474	-0,652	0,806
Stake2			
Stake3	1,953	-1,500	2,462
Stake4	1,840	-1,610	2,445
Stake5	1,628	-2,168	2,711

Stake6	**2,192**	**-1,744**	**2,801**
Stake7	**1,904**	**-1,727**	**2,571**
Stake8			
Stake9	**1,993**	**-1,722**	**2,634**
Stake10			
Stake11			
Stake12			
target fixed	**0,004**	**0,015**	**0,015**

Table 43: Stakes displacements between 07/09/2007 and 24/10/2007

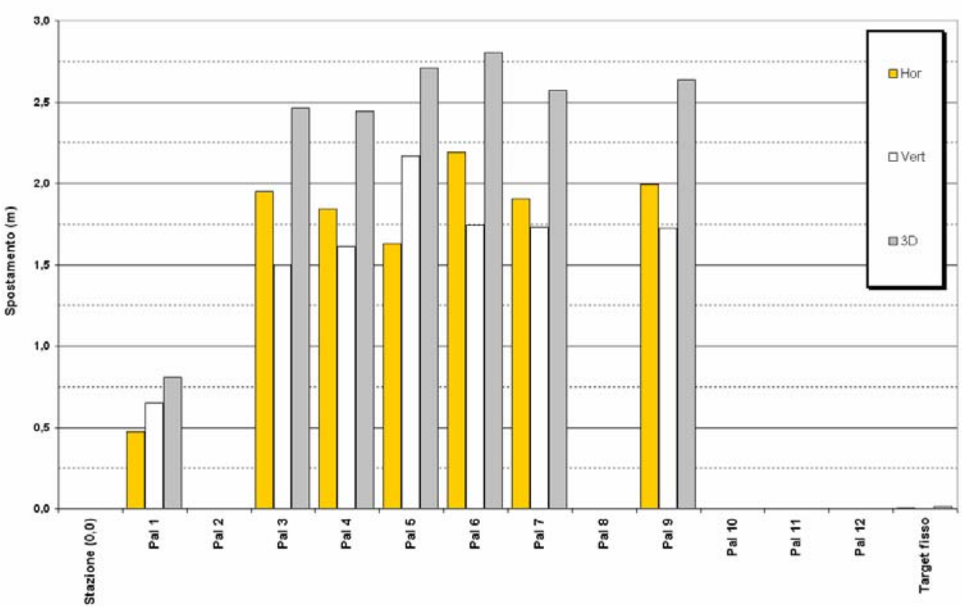

Figure 84: Stakes displacements between 07/09/2007 and 24/10/2007

From a brief displacement analysis, in the analised period, a different behaviour of stake 1 - at the maximal altitude- from the whole of other stakes can be assessed. Stakes 2,8,10,11,12 could not be measured on 24th october, so the displacement values are not reported in tables above. Minimal displacement for the taget control point (less of 2 cm) confirms the precision of methods and the accuracy of the measurements.

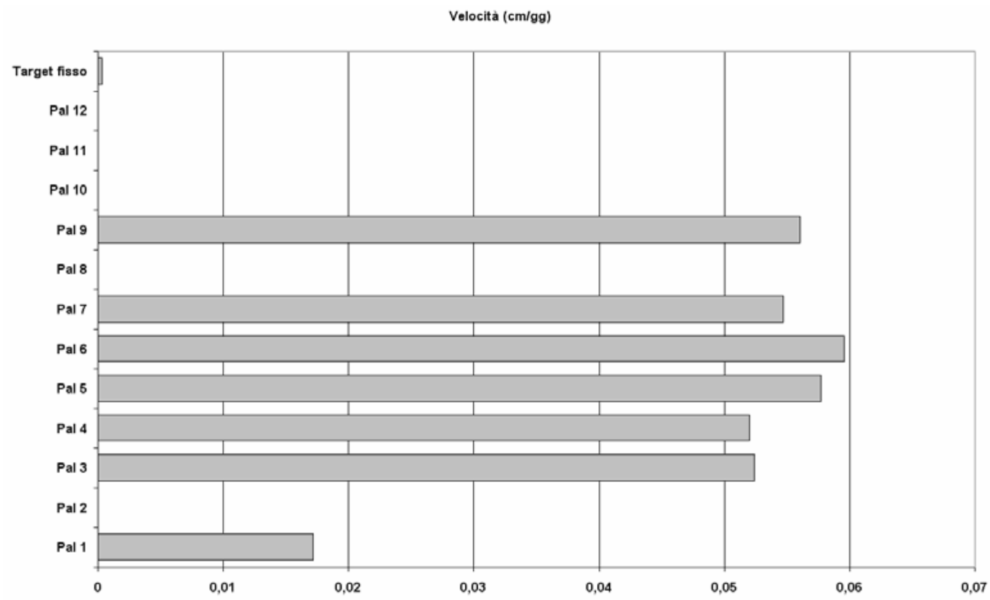

Figure 85: Mean displacement rate of stakes between 07/09/2007 and 24/10/2007; values have been calculated as (total 3d displacement/days) ratio.

Displacement rate (lowering and approaching of benchmarks with respect to station point) was determined as a ratio between whole displacement and number of days between two session.

From the image, a mean diplacement rate between 5.2 e 5.9 cm/day can be pointed out for all stakes (with two session data available). A significant different from stake 1 displacement rate is pointed out. The displacement rate of the target control point is very near zero.

5.2.2.3.5 Outlook

- quantification of snow accumulation on serac (continuous measurement with a purpose station);
- comparison of results with measurement of winter 1996-1997;
- analysis of the whole serac geometry by means of ice thickness and bedrock morphology assessment.

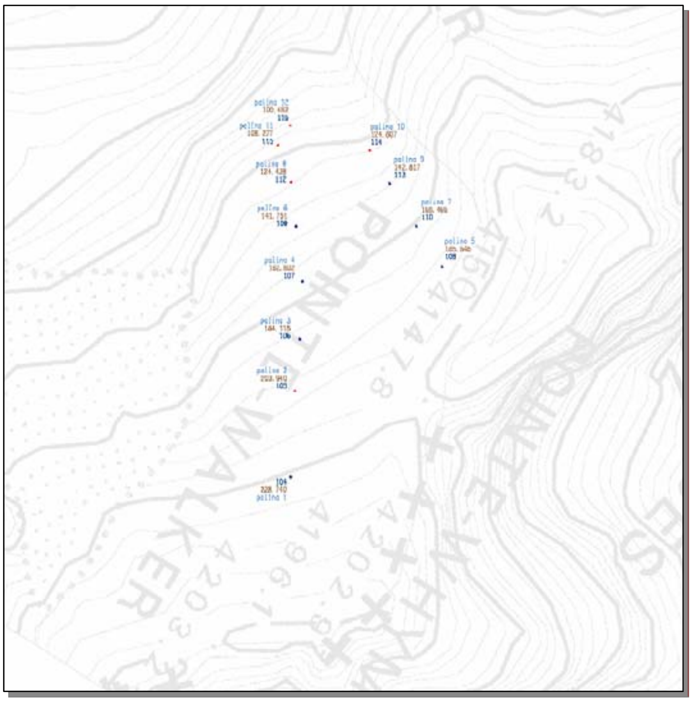

Figure 86: Stakes geographic position (2007)

5.3 Pre de Bar site

5.3.1 Innovative technologies for glacier monitoring

5.3.1.1 Introduction

Topographical relief in the environmental field has had a remarkable development thanks to the introduction of instruments that are more precise and allow an automation of the acquisition procedures. There remain, however, some fields of survey in which the techniques, consolidated in other fields, must still be tested. In this case we don’t mean tests only from a scientific point of view but from an operational and logistic one. In fact there are many techniques used frequently in a lot of fields of application that have to be experimented in other situations in which the environmental conditions are highly unfavourable and which influence the relief procedures noticeably.

5.3.1.2 The Pré de Bar site

Pré de Bar was the site chosen in order to carry out all the tests of the techniques. The site is in the high Val Ferret (Courmayeur – Aosta Valley - Italy). The entire glacial body has an extension of approximately 3 sq km and covers a vertical height of 1000 meters. All the surveys covered only the most frontal portion of the glacier called the ablation tongue, the area where we have more morphological variations. The extension of the area is approximately 0,2 sq km. The glacier has some peculiarities, which is the reason why we chose it:

- no need to use a helicopter to reach it;
- morphologic complexity that allowed us to highlight the limits and the potentialities of the different techniques adopted;
- uncovered ice just near a debris covered ice, differential ablation phenomenon;
- presence of rock cliff in order to find GCP;
- presence of scientific activities, sources of useful data for the validation of the techniques.

On the test site we experimented two techniques in particular:

- terrestrial photogrammetry assisted by GPS;
- terrestrial LIDAR.

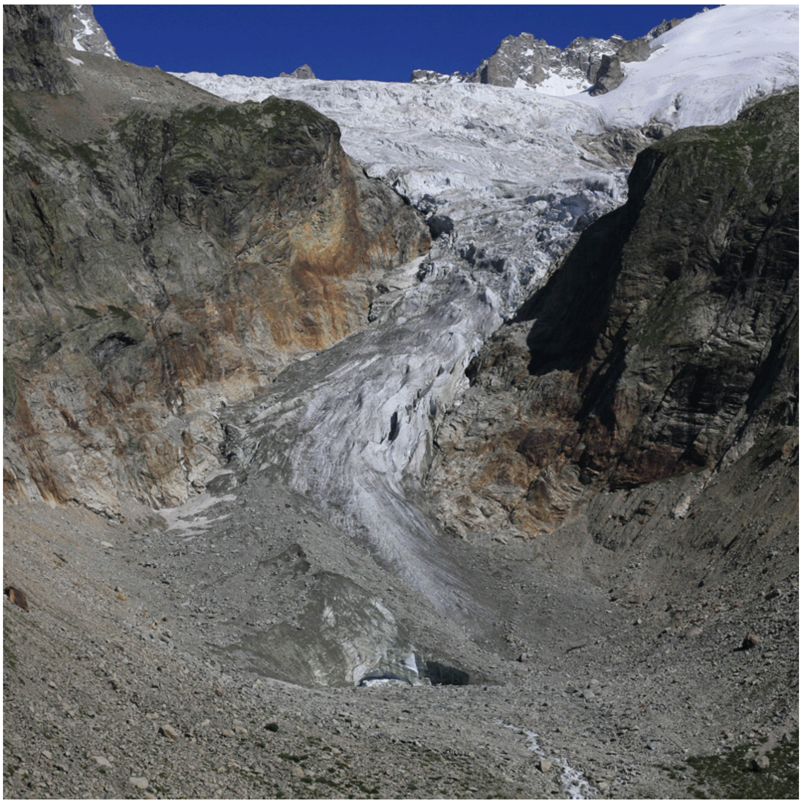

Figure 87: Pré de Bar site, ablation tongue (2007)

Figure 88: Particular of the ablation tongue (2005)

5.3.1.3 Terrestrial photogrammetry assisted by GPS

Photogrammetry assisted by GPS, called photo-GPS , was applied thanks to our collaboration with the University of Parma, Department of Civil Engineering (Prof. G. Forlani, Prof. M. Ferrero, Ing. PhD R. Roncella). This technique implements the classic photogrammetry joined to a GPS receiver directly linked to the camera. The obvious advantage of this technique resides in the fact that it is not necessary to materialize GCP in order to achieve external orientation of the photographs, an aspect that is particularly useful where there are dangerous or inaccessible places. The interior orientation (camera principal point) is known in a geographic coordinate system thanks to the employment of the GPS and it becomes a GCP.

5.3.1.3.1 The system

The system is composed of a hardware that allows the acquisition .of data in the field and by a software that has, at the present time, almost complete automation of the procedures of exterior orientation and restitution for the creation of the DSM (Digital Surface Model).

The hardware includes a double frequency GPS receiver, an external geodetic antenna mounted on a stake, a reflex digital camera with calibrated optical lenses and a support to link the camera with the antenna rigidly. The instrumentation is particularly lightweight and so it can be transported for hours.

The software has been written in C# and nowadays provides for an automatic exterior orientation of the photogrammetric block and a semi-automated procedure for DSM creation. A future development of the software will include the complete automation of the process.

The execution of the photogrammetric project must be done with great care in order to achieve two results:

- generate a sequence of images that can be oriented in an automatic (or semi-automatic) way;
- choose the camera position of the camera so as to guarantee the precision of the relief in the most uniform way possible (for example the positions of the shots should not be aligned).

Figure 89: System components

5.3.1.3.2 Field activities

We carried out two surveys with an interval of 76 days ,a period in which the glaciers melted and moved a lot. The relatively low altitude of the ablation tongue causes the extreme summer temperatures to melt the glacier, so the process is rapid and evident. We have a graph showing the temperatures near the ablation tongue of the glacier.

The main problem throughout the survey was GPS precise positioning. In the area there are in fact many orographical occlusions that made satellite visibility discontinuous and caused a longer time of acquisition. From an operational point of view it was very important to guarantee a survey capable of supporting the desired precision, 50 cm error in the worst case. For that we chose a configuration as indicated in the picture below.

We calculated (within centimetres) the coordinates of the master station (a hundred metres from the glacier tongue) thanks to the permanent GPS station located in Val Ferret. The master station has collected many raw data useful to post process the data collected by the rover station on which the camera is mounted. During the first acquisition a theodolite with a GPS was also used to determine with great precision the position of some points on the surface of the glacier so as to calibrate and verify the data calculated with the photogrammetry.

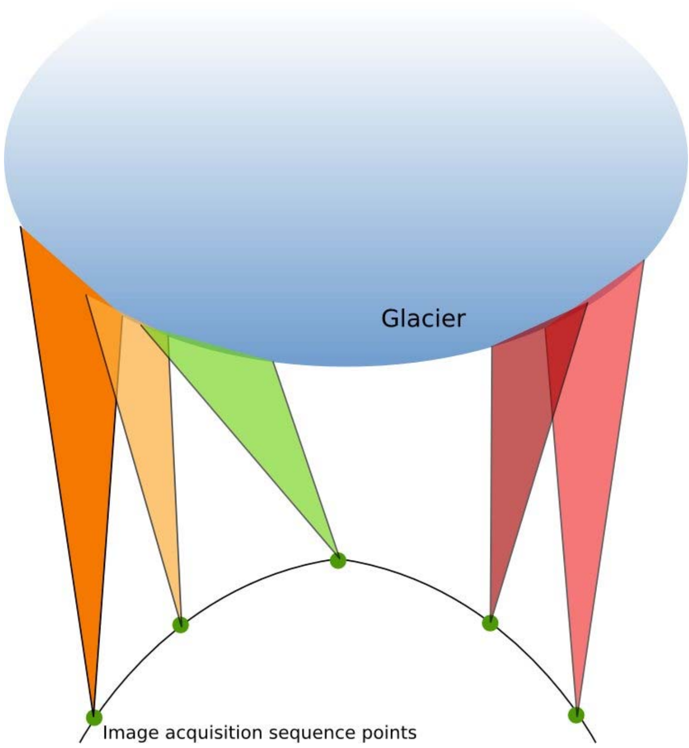

Figure 90: Description of the topographic project

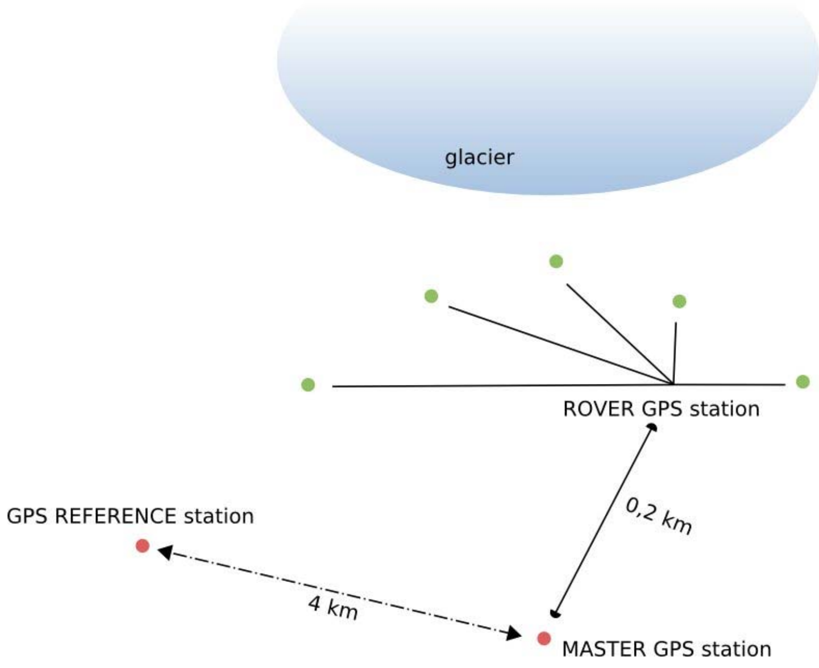

Figure 91: GPS frame description

5.3.1.3.3 Software data computation

Once the images and the GPS positions were acquired the field activities were complete. We could now proceed to the phase of data processing according to the following outline:

- inner guideline of the photograms with calibration certificate;
- external guideline of the photograms with typical algorithms of the reconstruction of the "structure and motion", in a semi-automatic way;
- automatic generation of DSM through typical dense matching algorithms;
- comparison of the two DSM generates (multitemporality) and extraction of useful glaciological parameters valid for the appraisal of morphological changes in the apparatus.

5.3.1.3.4 Digital surface models

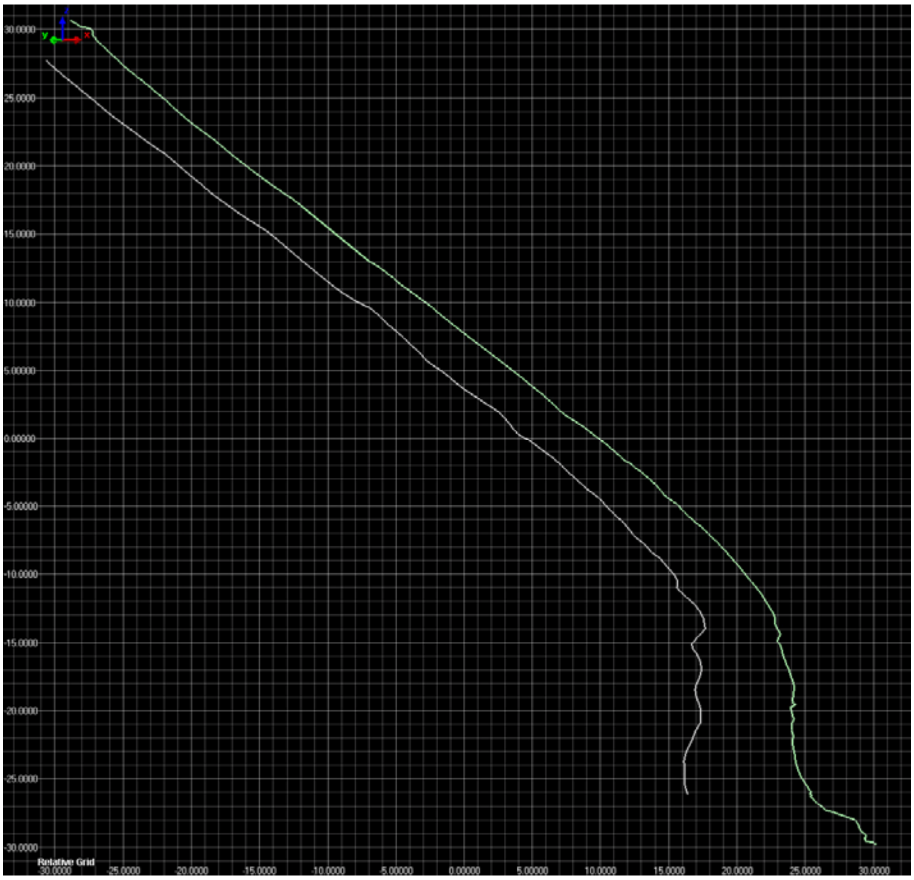

Figure 92: Section of glacier tongue in two different epoch (two differents DSM); the difference in x component is approximately about 10 m in 76 days. (2007)

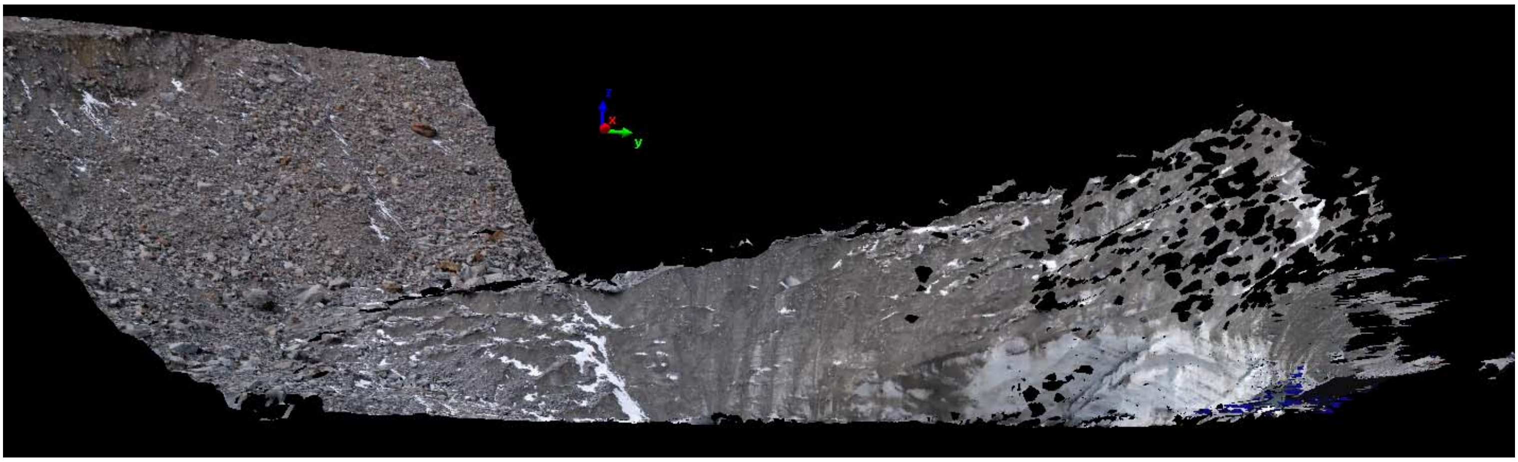

Figure 93: Particular of DSM with RGB values (glacier tongue) (july 2007)

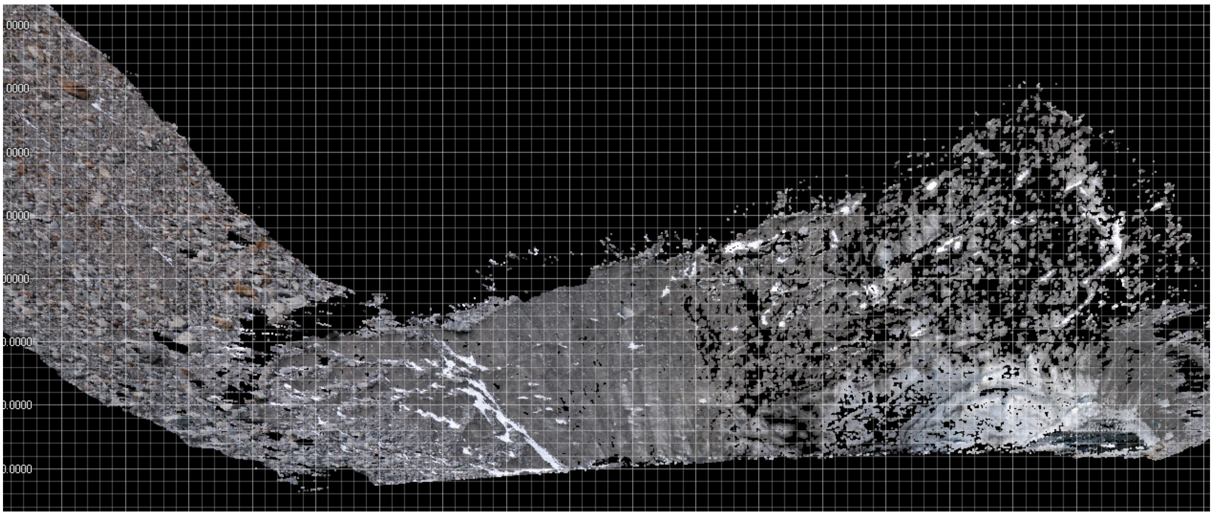

Figure 94: Particular of DSM with RGB values (glacier tongue) (october 2007)

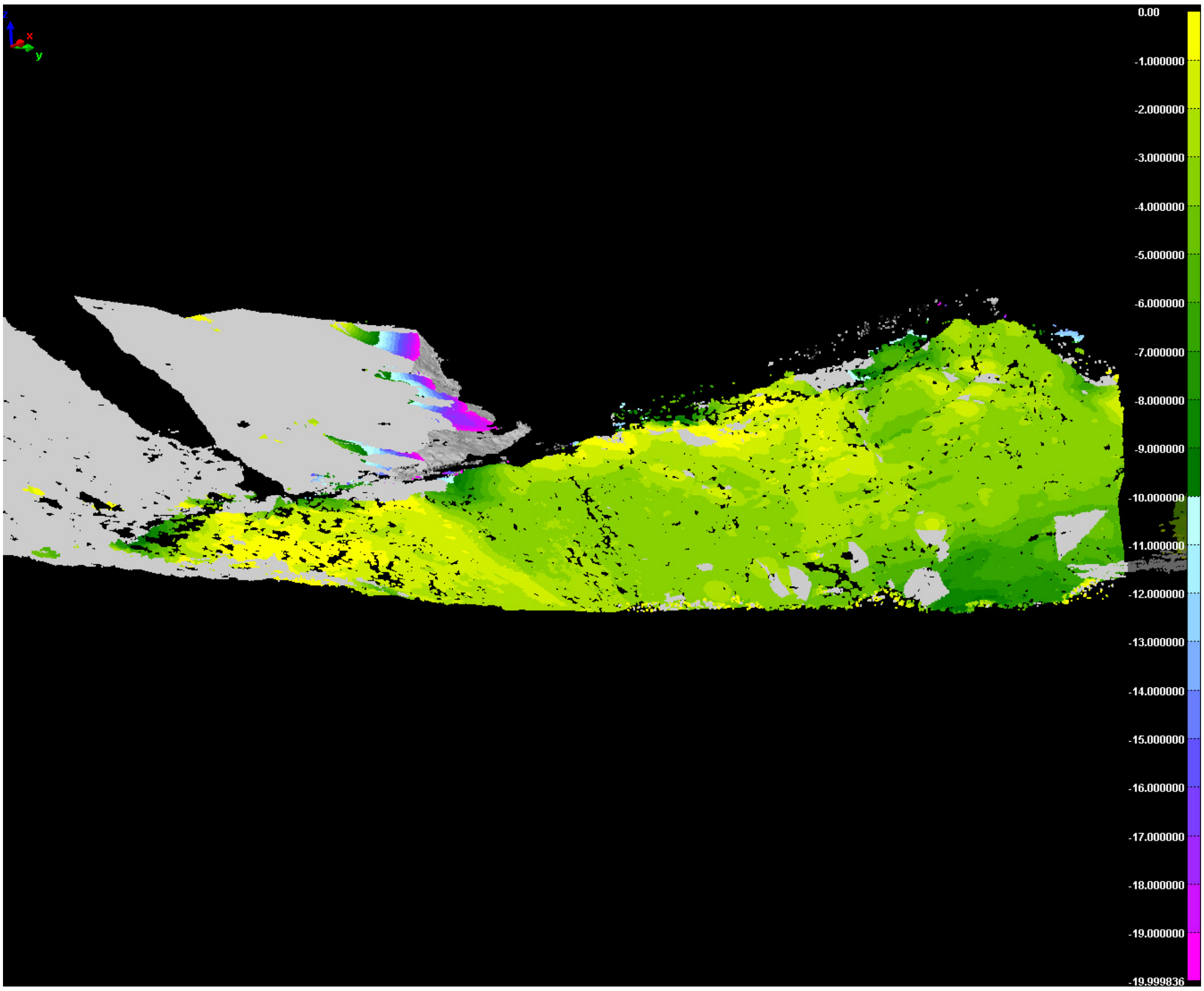

Figure 95: Morphologic variations in glacier tongue during 76 days of summer ablation

5.3.1.4 LIDAR

LIDAR was applied thanks to our collaboration with the Politecnico di Torino, DITAG (Prof. F. Rinaudo, Ing. PhD L. Bornaz). LIDAR technique allows a three-dimensional survey of the surfaces with high accuracy and resolution reducing scanning time. The laser scanner is a typical laser ranger that is able to scan all the 3D positions in space and returns the distance, azimuth and zenith of all the points scanned into an instrumental coordinate system. The results of the scan session is a dense point cloud that describes the objects with high accuracy. In order to transform the coordinates of the points from the instrumental system to a geographic system, GCP are needed.

5.3.1.4.1 Scanning system

The system is composed of different modules:

- power supply: rechargable battery, portable petrol powered generator;
- driver scanner: notebook with dedicated software;
- scan instrument: laser scanner , digital reflex camera, topographic tripods;
- georeferencing instrumentation: 3 GPS with tripods.

Figure 96: LIDAR system (2005)

5.3.1.4.2 Field activities

The glacier tongue was scanned twice: the first time in 2005 and the second in 2007. The delay between the scan times was 706 days. During this period the glacier changed its morphology a lot. Many preliminary activities were done: marker positioning on stable points, GPS positioning in order to reach the geographic position of some markers, total station point measurement. It's very important in laser scanner relief to achieve high precision by finding coordinates of the points. As regards laser acquisitions, we choose three scan points in order to describe the geometry of the glacier tongue as completely as possible. The point clouds resulting from the scan points are merged thanks to the GCP. 30 – 45 minutes of scanning were sufficient to get all the points needed with a resolution of 50 cm for the most distant points. The precision of the scanner, on the contrary, was constant: 10 cm.

5.3.1.4.3 Data computation

The phases of processing the data were the following:

- GPS topopgraphy reconstruction;
- marker (GCP) individuation for merging;
- point clouds filtering;
- point cloud georeferencing and transformation of the heights from ellipsoidical ones to orthometric ones;
- DSM generation with 50 cm regular grid resolution;
- multitemporal comparison between two DSM.

5.3.1.4.4 Digital surface models: DSM

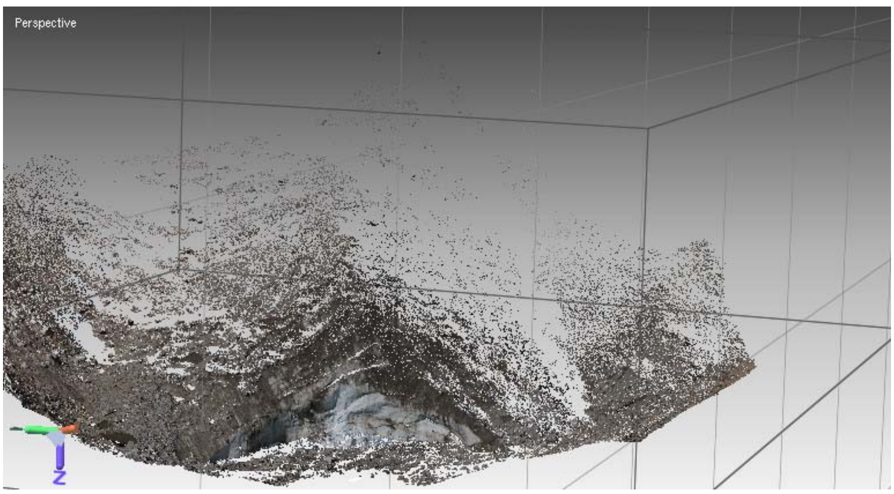

Figure 97: LIDAR DSM model with RGB values (october 2005)

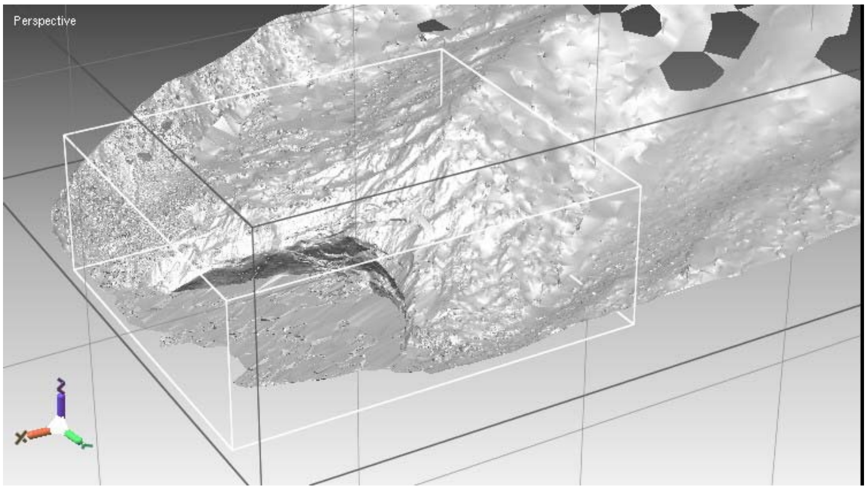

Figure 98: Triangulated mesh from LIDAR DSM (2005)

5.3.1.5 Comparison of the two systems of data acquisition

Photogrammetry and the LIDAR system are used a lot in architectural, mechanical and archaeological fields, but they have yet to be experimented in glacial surveys. So we have tried to highlight the pros and cons of the two techniques:

Photogrammetry.

Pros: the system is lightweight, compact and very resistant, with reduced acquisition time, non need of GCP; It's a low-cost system using economic software/hardware for computation.

Cons: highly dependent on GPS performance, inconstant accuracy (range dependent).

LIDAR.

Pros: constant accuracy, direct DSM generation, data computation simpler

Cons :heavy and cumbersome system, which is not inexpensive but sensitive to low temperatures

5.4 Literature

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CHAPTER 4

FUTURE SCENARIOS OF NATURAL HAZARDS

G. Prudent (ONERC, France), J-M. Vengeon (RhôneAlp, France)

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1. FLOODS – FUTURE SCENARIOS

1.1 Flood sensitivity and links with climate

The floods sensitivity and links to climate have already been developed in the CH1 – 1 Floods – historical processes chapter.

1.2 Potential impacts of climate change on floods

1.2.1 Flood intensity/frequency and seasonality

The simulated winter precipitation increase and the expected limited buffer effect of the snow cover (due to a higher rain/snow limit) should lead to favourable situations for floods in winter (both for intensity and frequency). These impacts would be of major importance for the basin presenting large zone at high altitude with a consequent snow cover. But on the other hand, as a consequence of the graduate snow cover melting, the intensity of the spring flood peaks would be reduced.

The river flood peak due to snow cover melting could occur a month earlier in the year.

On a global scale, during summer, diminished low waters and even droughts should be more frequent because of reduced summer precipitation and stronger evapotranspiration. Nevertheless, the rivers fed by glaciers (which represent important water stocks) may experience a flow increase in the short term with stronger glacier melting in summer. In the long term, once the glacier would have lost most of its volume (and / or surface), and so its potential water stock, the flows of these rivers would decrease. The summer flow increase has already been observed while the decrease on long term is only a strong assumption at the moment.

2. DEBRIS FLOWS – FUTURE SCENARIOS

2.1 Debris flows sensitivity and links with climate

The debris flows sensitivity and links to climate have already been developed in the CH1 – 2 Debris flows – historical processes chapter.

2.2 Potential impacts of climate change on debris flows

2.2.1 Debris flows intensity

The material availability is the critical factor that could lead a change in the future debris flows intensity. This intensity variation could lead to increased volume and stopping distance. Thus, even if the debris flows intensity can be assessed in a general manner, it is important for policy makers and technical services to also know the evolution for particular sites. The hazard areas that are linked with the periglacial area may potentially experience marked intensity changes (even if such changes have not already been observed).

Despite the important number of hypothesis proposing debris flows intensity increase with climate change, no trends has been observed, nor modelled.

2.2.2 Debris flows frequency

Model results are in good accordance with the observations in some areas (debris flows frequency decrease) because they simulate a decrease of debris flows events for a warmer climate. The often evoked increase of debris flows frequency in a climate change context, seems to be hypothetic and is confirmed neither by the observations, nor by the modelling. However, on the Alpine scale the frequency could increase in particular regions and decrease elsewhere depending on local situations and driving parameters.

2.2.3 Debris flows seasonality

Some hypotheses are also proposed concerning the debris flows activity evolution if the precipitation would increase during the transition periods (as suggested by climatic models). But this precipitation seasonal shift should not have consequences because the mean temperature during these periods would remain lower (from 4 to 7°C) than the mean temperature during the summer season (summer is the main season for debris flows occurrence).

2.2.4 Debris flows localisation

The deglaciated area and the permafrost degradation process are supposed to furnish more available materials for future debris flows activity. Moraines and active talus slopes can furnish debris flows; some dismantled rocky glaciers can also be affected by this kind of phenomenon. The trigger could occur more easily if the slope is steep in these areas. High mountain area in the periglacial zone could be more favourable to debris flows events than in the past.

3. AVALANCHES– FUTURE SCENARIOS

3.1 Avalanches sensitivity and links with climate

The avalanches sensitivity and links to climate have already been developed in the CH1 – 3. Avalanches– historical processes chapter.

3.2 Potential impacts of climate change on avalanches

Some authors propose a potential increase of the wet-snow avalanches due to more frequent and intense melting periods and an elevated snow/rain limit, but the same authors also guess that, looking at the annual mean, these changes would be almost imperceptible. Other hypotheses propose that the avalanche activity would decrease at low and middle altitudes because of reduced snow-cover while it could increase at high altitude (because of an expected snow cover increase at high altitude, as a consequence of strong precipitation increase counterbalancing the temperature rise).

Thus, it seems quite impossible to provide an overview of the evolution of avalanche activity in regards to intensity, frequency, location and seasonality in a climate change context. Some hypotheses have been proposed but the evolution proposed are not quantitative and could actually not been detected in the available data.

4. MASS MOVEMENTS – FUTURE SCENARIOS

4.1 Abstract for all classes of mass movements

The landslide activity evolution seems to be very much impacted by any change in the precipitation patterns. Intense precipitation variations would tend to impact the shallow landslides (trough the surface water runoff and stream actions), while the long term precipitation variations would impact the deep landslides (trough underground water action). The summer precipitation decrease may have a positive effect by reducing the deep and shallow landslides activity.

The rock falls seems to be insensitive toward precipitation, their activity is much more influenced by freezing/defreezing cycles. Thus, a potential temperature increase would lead to less frequent rock falls at low and middle altitude (with less freezing days) but these rock falls may also increase at high altitude (with more defreezing days).

4.2 Mass movements / Shallow landslides – future scenarios

4.2.1 Shallow landslides sensitivity and links with climate

The shallow landslides sensitivity and links to climate have already been developed in the CH1 – 4.1. Mass movements / Shallow landslides – historical processes chapter.

4.2.2 Potential impacts of climate change on shallow landslides

Shallow landslides intensity : some hypotheses propose that increased heavy rainfall, permafrost degradation and marked glacier retreat may increase the shallow landslides intensity (especially the mudflows trough increased available materials). These hypotheses have neither been confirmed nor infirmed by global observations in the Alps.

Shallow landslides frequency : the hypotheses developed in the intensity chapter (based on glacier retreat and permafrost degradation) are also valid for the event frequency. The vegetation cover disappearing after a forest fire or a storm is a cause for shallow landslide triggering. In a climate change context, such cases may be more frequent. In general, the scientists propose a shallow landslide frequency increase with a warmer climate, but these scenarios of “indirect impacts” are difficult to model and lack of sufficient time-series to calibrate and validate the models.

The scree slopes and rock chaos re-vegetation may lead to decreased slopes instabilities trough better slope cohesion. But there are not observations for the moment to validate this hypothesis.

4.3 Mass movements / Deep landslides – future scenarios

4.3.1 Deep landslides sensitivity and links with climate

The deep landslides sensitivity and links to climate have already been developed in the CH1 – 4.2. Mass movements / Deep landslides – historical processes chapter.

4.3.2 Potential impacts of climate change on deep landslides

Deep landslides intensity : each deep landslide has its own characteristics (lithology, hydrogeology, topography, vegetation, etc.) and regime of deformation. Some of them will react to precipitation increase with an acceleration of their movements. This reaction will not be systematic and will be strongly influenced by local conditions.

Deep landslides frequency : for the movements presenting sensitivity to short term meteorological parameter, an increase of acceleration phases can be expected (as a consequence of the expected intense precipitation increase).

Deep landslides localisation : as a consequence of new climatic conditions, and more especially changes in precipitation patterns, there would rather be a re-activation of old deep landslides than an activation of new deep landslides.

4.4 Mass movements / Rockf falls – future scenarios

4.4.1 Rock falls sensitivity and links with climate

The rock falls sensitivity and links to climate have already been developed in the CH1 – 4.3 Mass movements / Rock falls – historical processes chapter.

4.4.2 Potential impacts of climate change on rock falls

Rock falls intensity : some hypotheses propose a link between permafrost degradation and future rock falls intensity increase in the zones affected, but it remains difficult to propose trends for future events intensity.

Rock falls frequency : the assumptions for the rock falls propose a frequency increase in the permafrost area influenced by freezing/defrezzing cycles. Thus it is very likely the frequency would increase in theses zones but is also very likely that the frequency would decrease in lower zones.

5. GLACIAL HAZARDS – FUTURE SCENARIOS

5.1 Abstract for all classes of glacial hazards

By and large, with the general glacier retreat (and even their disappearance in some cases), potential glacial hazards should decrease in the long term. Many glacial hazards and the parameters governing their formation and their triggering remains poorly understood, thus their evolution in a climate change context is hypothetic. However, pro-glacial lakes and sérac falls from hanging glaciers are the two main glacial events that could lead to glacial hazard situation in the next years.

5.2 Glacial hazards / Glacial Lakes Outburst Floods– future scenarios

5.2.1 Glacial Lakes Outburst Floods sensitivity and links with climate

The Glacial Lakes Outburst Floods sensitivity and links to climate have already been developed in the CH1 – 5.1. Glacial hazards / Glacial Lakes Outburst Floods – historical processes chapter.

5.2.2 Potential impacts of climate change on Glacial Lakes Outburst Floods

Some hypotheses propose that climate warming (with accelerated glacier retreat and heavy precipitation increase at high altitude as expected consequences of this warming) may lead to a potential increase of the glacial lake formation, without distinction.

These conjectures are based on weak arguments because the influence of climatic conditions on supra-glacial, peri-glacial, drainpipe and confluence lakes is not clear. Only the evolution of pro-glacial lakes is clear and there would be a multiplication of these lakes with a strong glacier retreat.

5.3 Glacial hazards / Glacial water pocket – future scenarios

5.3.1 Glacial water pockets sensitivity and links with climate

The glacial water pockets sensitivity and links to climate have already been developed in the CH1 – 5.2. Glacial hazards / Glacial water pockets – historical processes chapter.

5.3.2 Potential impacts of climate change on glacial water pocket

Considering the lack of knowledge mentioned in the CH1 – 5.2 chapter, the evolution of glacial water pockets in a climate change context is impossible to assess.

5.4 Glacial hazards / Sérac falls– future scenarios

5.4.1 Sérac falls sensitivity and links with climate

The sérac falls sensitivity and links to climate have already been developed in the CH1 – 5.3. Glacial hazards / Sérac falls – historical processes chapter.

5.4.2 Potential impacts of climate change on serac falls

Serac falls frequency should not increase. There are few direct observations of this phenomenon and the predisposition evolution for this natural event is mainly hypothetical. Even if a local short term serac fall frequency increase can be extrapolated on some sites, the ice volume decrease and general glacier retreat should attenuate this increase.

6. STORMS – FUTURE SCENARIOS

6.1 Storms sensitivity and links with climate

The storm sensitivity and links to climate have already been developed in the CH1 – 6. Storms – historical processes chapter.

6.2 Potential impacts of climate change on storms

6.2.1 Tempest intensity

The water steam increase may have two diverging impacts : facilitate the water steam condensation during the clouds and precipitation formation, or help the energy tempest transfer to the high latitudes. So, the hypotheses for the tempest intensity evolution are contradictory for the moment.

6.2.2 Tempest frequency

The atmosphere warming may have contradictory consequences with a North-South gradient increased or decreased (depending on the warming if either the high or low atmosphere is more impacted) and thus a tempest frequency increased or decreased.

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CHAPTER 5

DETERMINATION OF CRITICAL FACTORS OF CLIMATE CHANGES AND THE IMPACTS TO THE FUTURE NATURAL HAZARDS AND RISK POTENTIAL IN THE ALPINE SPACE

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ABSTRACT

The methods for the description and characterization of the natural hazards in the Alps are based on the intensity and frequency of events. The planning and design of permanent countermeasures are based on specific design events with a fixed return period and the relating process intensity. Because of this practice in risk management, the deduction of the most critical factors for hazard assessment under changing environmental 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 and in the course of precipitation events.

In this study, the sensitivity of the alpine torrent catchments against climatic changes was analysed on the regional scale. The focus of this study lied on the identification of the torrent catchments in which the future hazard scenarios described in the previous chapters will modify the hazard situation. The sensitivity of the mountain torrent and torrential river catchments was characterised qualitatively by analysing the topographical and geomorphological characteristics of the catchments.

The analyses pointed out that the impacts of climate changes to the hazard situation of torrential and river systems are varying spatially and seasonally. The 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. Thus, the 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 and could therefore support the discussion about the future strategies for adaptation to alternated climate conditions.

1. INTRODUCTION

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 extent of damage, the latter specified by the damage potential and the vulnerability of the endangered object.

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

In accordance with the definition of United Nations (2004), the specifications for the probability of the defined scenario (p_{Si}), the 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 methodological concept for the determination of the critical factors and of the future risk potentials for the natural hazards in the Alpine Space due to climate changes is based on this risk equation. For assessing the impacts of climate changes to natural hazards and risks, the authors of this chapter tried to synthesize and generalize the conclusions made in the previous chapters and synthesize the observed and modeled impacts of climate changes to natural hazards and risk.

The previous chapters of this report described some of the expected changes in the environmental systems in the Alps. For the assessment of hazards, the following changes are the most important ones regarding the hazardous processes:

- 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
- Changes in extreme precipitation events

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. The relative consequences for the land use and the corresponding 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 fixed return period and the relating process intensity.

Because of these practices in risk management, the deduction of the most critical factors for hazard assessment under changing environmental 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).

The evaluation of climate simulations enables the precipitation extremes for return periods of between 5 and 50 years to be quantified. The probability and geographical distribution of extreme events will alter gradually with the change in climate. The extent and character of the changes will differ depending on the location and character of the extreme events (Fig. 1).

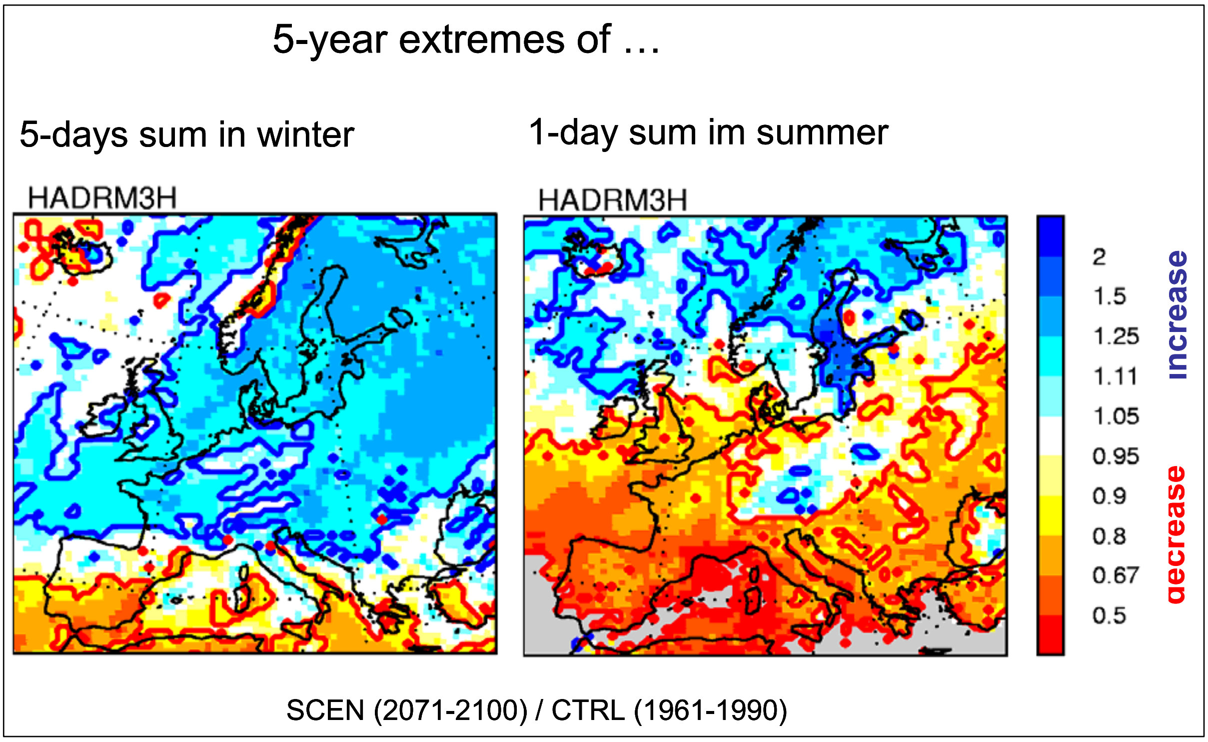


Figure 14: Changes in 5 years extreme precipitation over Europe for 5-day precipitation in winter (left) and for 1-day rainfall in summer season (right) (Frei et al., 2006).

Seasonal and regional changes in precipitation are to be expected as follows: In Autumn, extreme values 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. Under the most unfavorable conditions, a 100-year event of today could in the future become a 20-year event (Fig. 2). In winter and spring, the precipitation volumes are expected to increase as a result of greater extremes and longer durations. Because of highly variable results and the uncertainty of the model simulations, no predictions can be made for summer. At most, a tendency towards an increase in the northern Alps and a decrease in the Southern Alps is indicated.

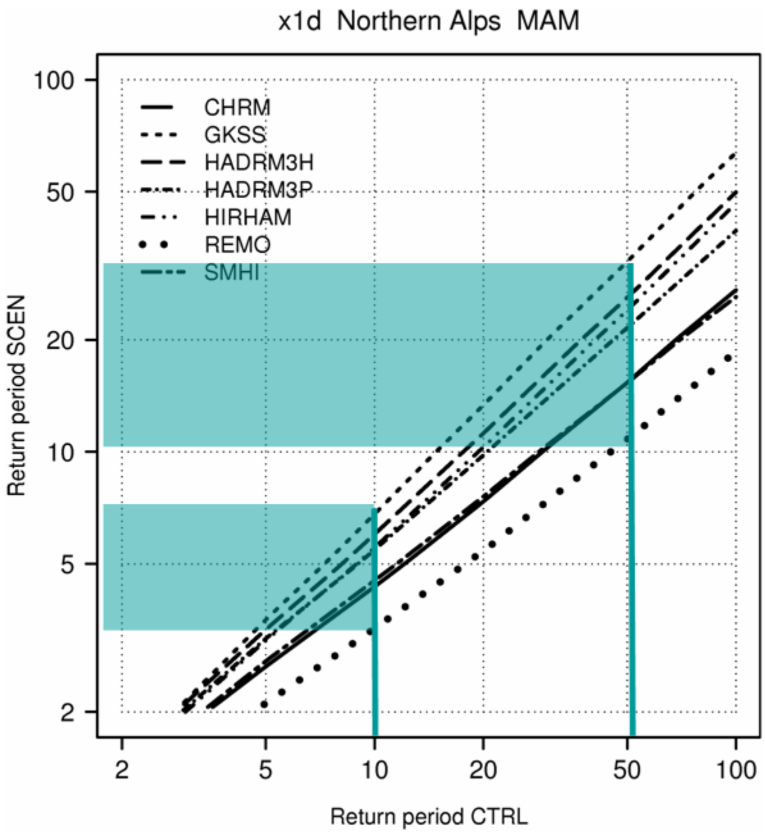


Figure 15: Change of frequency distribution of 1-day precipitation in spring for the region in the northern Swiss Alps. Values of present time (CTRL) are compared with results for the 2050 scenario for different regional climate models (Frei et al. 2006).

Impacts of climate change can have positive or negative effects for the human environment. In interaction with the potential future development of the Alpine Space, the impacts of climate changes to the resulting future risk potential could be the following trends (Stötter et al. 2003): Under changing environmental conditions, the development of the risk for persons and human infrastructures caused by natural hazards is depending on the impacts of climate change to the probability of occurrence of dangerous processes and the extent of damage potential. Assumed that climate changes do not impact on the spatial development, the impacts of climate changes can either increase or decrease the hazard potential. In combination with a constant extent of damage potential, an increase in the hazard potential results in an increase in the resulting risks. Under this assumption, a decrease in the hazard potential results in a decreasing risk.

		VALUES AND PROBABILITY OF PRESENCE OF PERSONS AND GOODS		
		DECREASE	CONSTANT	INCREASE
INTENSITY AND PROBABILITY OF NATURAL HAZARDS	INCREASE	risk development: tends to result constant	risk development: tends to increase	risk development: tends to remarkably increase
	CONSTANT	risk development: tends to decrease	risk development: tends to result constant	risk development: tends to increase
	DECREASE	risk development: tends to remarkably decrease	risk development: tends to decrease	risk development: tends to result constant

Figure 16: Possibilities of the development of future risk potential due to climate changes and due to changes in spatial development (modified, after Stötter et al. 2001)

In the previous chapters of this report, the trends of future hazard potentials were pointed out. For a few case studies, the consequences of potential climatic changes for the natural hazard situation were described. These case studies demonstrated that the knowledge of the potential changes in the natural hazard situation is a basic requirement for the implementation of adaptation measures in natural hazard and risk management.

But, for authorities responsible for natural hazard and risk management is important to know **WHERE** these changes will be relevant for land use planning and risk management. In this study, the Department for Hydraulic Engineering of the Autonomous Province of Bolzano South Tyrol developed an approach for the identification and localization of alpine torrents which are sensitive against climate changes.

2. METHOD

In this study, the sensitivity of the alpine torrent catchments against climatic changes was analysed on the regional scale. The focus of this study lied on the identification of the torrent catchments in which the future hazard scenarios described in the previous chapters will modify the hazard situation.

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 against assumed climatic changes was developed. The results of the study were the delineated catchments classified by the sensitivity against the changes in the selected environmental parameters. The sensitivity analysis was made in a pilot area.

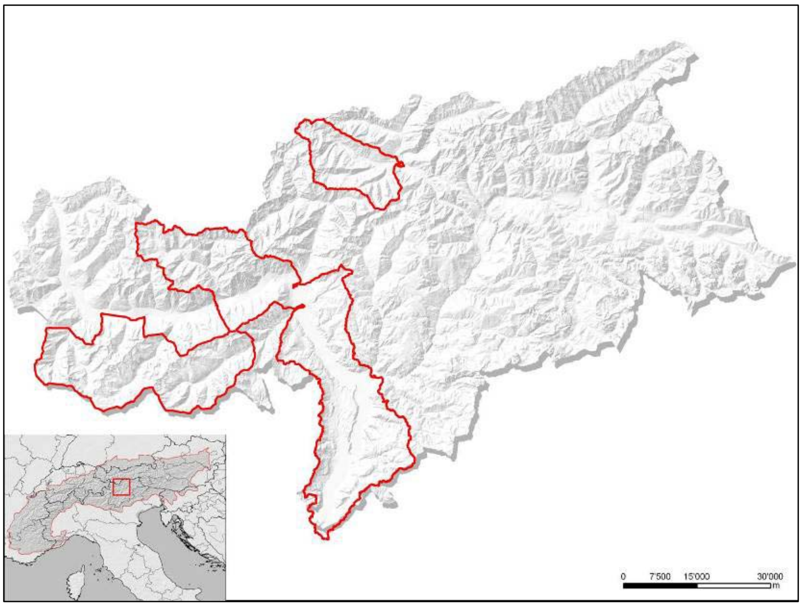


Figure 17: Study area in the Autonomous Province of Bolzano South Tyrol, Italy.

The alpine torrent catchments were classified into three catchment classes:

Torrent classification	Catchment area	Description
a) mountain torrents	< 20 km2	torrential processes, mainly driven by discharge and bed load transport processes
b) torrential rivers	20 - 100 km2	torrential rivers, processes mainly driven by hydrology and partially by bed load transport
c) Alpine rivers	100 - 1000 km2	rivers, processes mainly driven by runoff processes

Table 1: Classification of alpine torrent catchments.

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 mean sum of precipitation in summer is decreasing
- The intensity and frequency of short extreme rainfall events in summer is increasing
- The mean sum of precipitation in winter is increasing of about 20%
- The daily mean temperatures in summer and winter are increasing

It was assumed that the following factors are varying spatially and are relevant for the sensitivity of the torrent catchments against climate changes (geo7 2007):

- Percentage of areas located between 1000 and 2000 m above sea level:

  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). As threshold value was chosen a percentage of 50 % of these areas respective to the total catchment area.

- 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 sediment delivery processes and the period between extreme discharge events transporting the weathered material downstream. 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 %, the torrent catchments were classified as torrents eroding older deposits, otherwise as torrents eroding recent deposits. If the percentage of areas with landslides respective to the total bed load source area exceeds 30 %, the torrent catchments were classified as torrents mainly influenced by landslide activity.

- 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. The sensitivity of torrent activity against climate changes increases with a higher proportion of bed load source areas respective to the total catchments area.

- Permafrost degradation areas:

  Thawing permafrost destabilizes scree slopes in unconsolidated material. With the existence of such areas in the bed load source areas of the torrent catchments, the sensitivity of torrent activity against climate changes increases.

- Areas with elevated surface runoff:

  Areas with reduced water storage capacities increase the surface runoff. The sensitivity of torrential rivers and rivers against climate changes increases with a higher proportion of areas with reduced water storage capacities respective to the total catchments area.

The delimitated torrent and river catchment areas were classified by the combination of these factors influencing the sensitivity of mountain torrents and rivers against climate changes. The classification was made by means of a decision tree implemented into a GIS-based procedure. The results of the classification procedure are different classes of torrent and river catchments reacting in a different way to potential climate changes. The whole procedure is described in geo7 (2007).

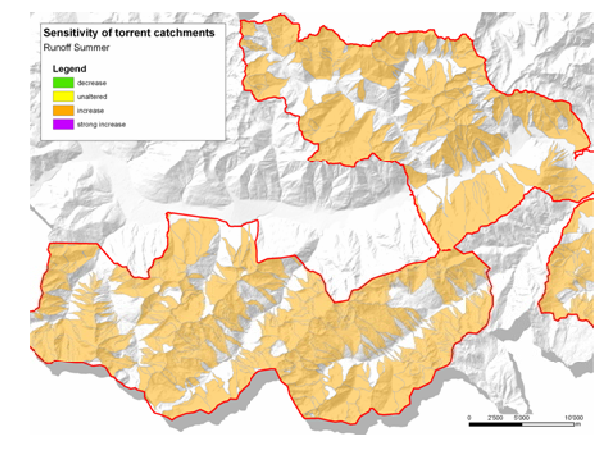
The following spatial datasets were used for this study:

- mountain torrents and rivers dataset
- landslide inventory
- geological map
- digital terrain model
- land use map
- hazard index map for debris flows and overbank sedimentation processes of the Autonomous Province of Bolzano (geo7 2006)
- modeled permafrost areas representing the permafrost distribution in 1850, 1994, 2100 (Zischg 2007, see WP6 report)

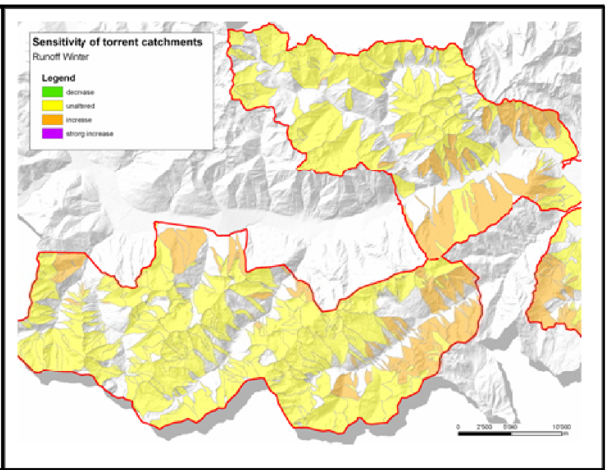
3. RESULTS

The main results of the procedure were the classification of the catchments into different reaction typologies and the classification into different sensitivity typologies. The datasets could be queried under different aspects.

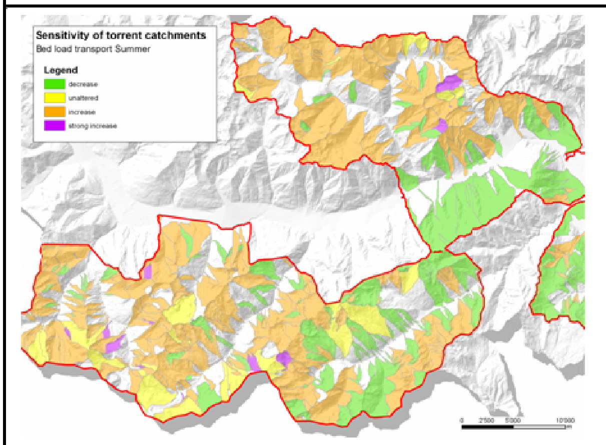
The procedure was made also for torrential river and river catchments. The results showed that the runoff of nearly all torrent catchments is expected to increase in summer. The runoff in winter is expecting to increase only in torrent catchments having a high percentage of their total surface area below 2000 m. The bed load transport in summer is expected to increase in high mountain areas and is expected to decrease in catchments at submontane levels. The bed load transport in winter increases in a few mountain torrent catchments and does not change in the most catchments. The frequency of small scale debris flow and sediment transport processes is expected to increase in most of the torrent catchments.



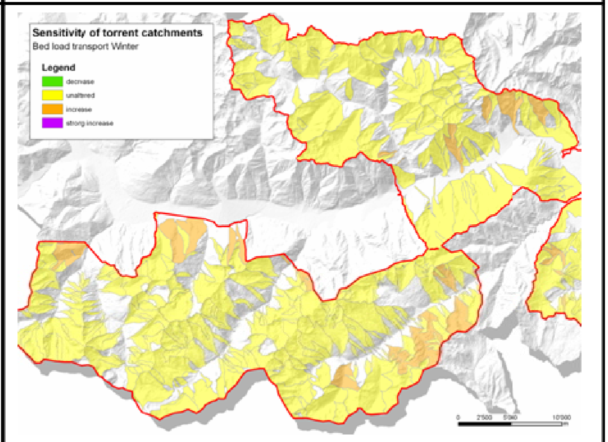
Sensitivity of torrent catchments against climate changes. Runoff in Summer.



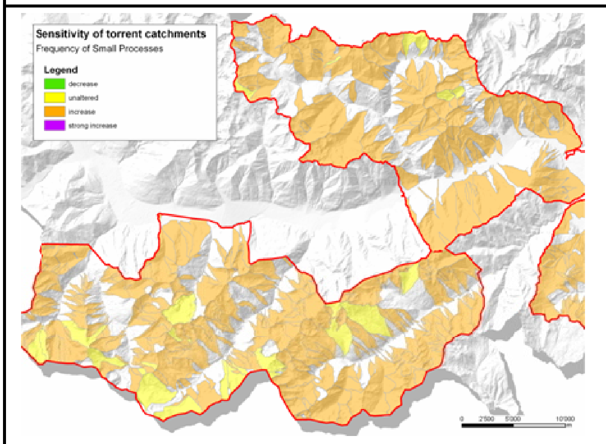
Sensitivity of torrent catchments against climate changes. Runoff in Winter.



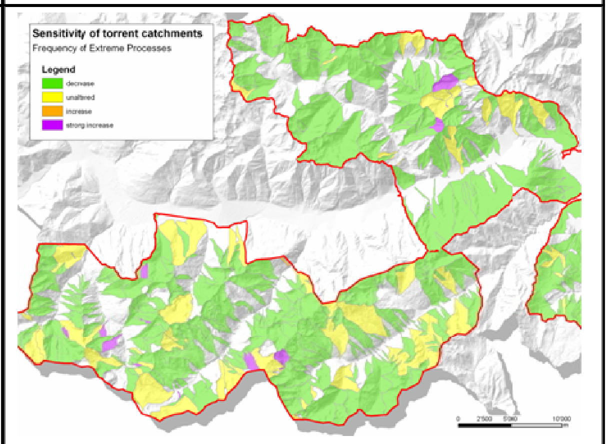
Sensitivity of torrent catchments against climate changes. Bed load transport in Summer.



Sensitivity of torrent catchments against climate changes. Bed load transport in Winter.



Sensitivity of torrent catchments against climate changes. Frequency of small scale processes.



Sensitivity of torrent catchments against climate changes. Frequency of extreme events.

Figure 18: Classified torrent catchments and their qualitative sensitivity to the assumed changes in the environmental parameters influencing the hazard situation.

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 expected 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 are varying spatially. The 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. Thus, the procedure could support the discussion about the future strategies for adaptation to alternated climate conditions.

At the moment, the procedure does not consider future climate scenarios (e.g. regional climate models) quantitatively. This weakness in fact may be eliminated, 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 against climatic changes provides the basis for the assessment, where increases in the future risk potential have to be expected. In this study, this step could not be made because of the narrow timetable of the project.

The previous chapters in the natural hazards report of WP5 of the ClimChAlp project showed that the positive effects of climate changes to the natural hazard situation are only a few. Thus, in the simplified assessment of the development of the future risk potential the option for a decrease of the intensity and occurrence of natural hazards seems not to be plausible. At the other side, a decrease in the extent of damage potential seems also not to be plausible. As different studies showed, the natural hazard risk increased from 1950 to 2000 due to an increase of the number of endangered buildings and due to an increase of their values (Fuchs et al. 2004, Keiler 2004, Fuchs et al. 2005). Assuming, that the spatial development in the Alpine Space is following the trends of the last decades, there are remaining the following options for the development of the future risk potential:

- in the best case, the development of the risk potential tends to be constant,
- in most cases the development of the risk potential tends to increase slightly,
- in the worst case, the development of the risk potential tends to increase remarkably.

		VALUES AND PROBABILITY OF PRESENCE OF PERSONS AND GOODS		
		DECREASE	CONSTANT	INCREASE
INTENSITY AND PROBABILITY OF NATURAL HAZARDS	INCREASE	not plausible	risk development: tends to increase	risk development: tends to remarkably increase
	CONSTANT	not plausible	risk development: tends to result constant	risk development: tends to increase
	DECREASE	not plausible	not plausible	not plausible

Figure 19: : Possibilities of the development of future risk potential due to climate changes and due to changes in spatial development under the assumption that a decrease in the hazard potential and a decrease in the damage potential are not plausible (modified, after Stötter et al. 2001).

The previous chapters showed that in general an increase in the intensity and frequency of natural hazards has to be expected as a consequence of climate changes. But, the effects of these changes in the hazard situation to the risk situation depend also to the 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 equivalently 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 event management activities. In WP8 of this project, a strategy for the optimization of the risk management by considering and combining all risk management tasks is shown.

The conceptional approach for assessing qualitatively the impacts of climate changes 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 the risk reduction. With the reduction of the vulnerability of endangered buildings against the dangerous processes, a remarkably increase in the hazard potential as an impact of climate changes in combination with a further increase in the extent of damage potential must not stringently conduct in an increase in risk potential.

Finally, 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, the procedure provides a basis for further refinement and enhancement of the consideration of the effects of climate changes in natural hazards and risk management.

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CHAPTER 6

GAPS AND RESEARCH NEEDS

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1. FLOODS – GAPS AND RESEARCH NEEDS REGARDING CLIMATIC ISSUES

1.1 Gaps:

- Data and studies mainly concern peri-alpine large rivers, e.g. Rhône or Rhine Rivers. Tributaries of those rivers are less studied; when they are studied it is mainly as small part of a larger basin and not considering the area where they have consequences (such as Isère, Doubs and Durance, smaller tributaries basins in the larger Rhône basin). Thus, focus has to be given to the river having direct consequences for the Alpine area.

1.2 Research needs:

- Historical reconstructions of the river floods have already been developed in many countries. Such analyses provide homogeneous and quality information. European networks need to be develop to provide analysis at the alpine scale; such working groups would have to collect the data chronicles for each river and then compare them, calibrate them, to provide comparative analysis.
- Probabilistic approach based on non-stationarity (like those developed by the French Cemagref) have to be further developed. These new approaches are necessary to take into account the reference events fluctuation of river flow regimes with new climatic conditions.
- Take into account the precipitation/flows models for a better assessment of the links between precipitation evolutions and expected future floods situations.
- Hydrological models have to be developed in the future for the Alpine area. These hydrological models have to integrate as much features as possible (vegetation cover, erosion, topography, orientation, etc.) and also have to be developed with quite small space grids (few kilometres at best).

2. DEBRIS FLOWS AND TORRENTIAL FLOODS – GAPS AND RESEARCH NEEDS REGARDING CLIMATIC ISSUES

2.1 Gaps:

- The historical documents assessment for debris flows at the alpine scale is quite rare and the different event reconstruction techniques (e.g. dendromorphology) are not sufficiently developed to provide significant chronicles. Even considering a particular debris flows catchment in a particular valley, the available information (considering any event's characteristic) do not enable researchers to propose potential future evolution of the events for this area.

2.2 Research needs:

- Needs for a better hydro-meteorological measure network covering various altitude ranges and various sites.
- Needs for quantitative information concerning the unstable volumes that might be transformed in debris flows in case of heavy precipitation events (sedimentary budgets method).
- Build up homogeneous data base for the sediment volume storage in the deposit area.

Develop sensitivity indicators for both meteorological and climatic parameters (precipitation thresholds for debris flows triggering, data concerning the precipitation amounts during the days preceding the event, soil moisture, etc.).

3. AVALANCHES – GAPS AND RESEARCH NEEDS REGARDING CLIMATIC ISSUES NEEDS

3.1 Gaps:

- The avalanche data chronicles are not systematic and concern mainly the area where human stakes are threatened by the avalanche activity. They are not enough accurate to allow a trend detection (particularly because the occurrence frequency of avalanches are generally relatively low – "return periods" from some years to some decades).
- Even for the places where avalanches are observed, there is a lack of data in the triggering zone and on the avalanche trajectory. The mechanisms of avalanche triggering and flowing are not well known and the present models still need further development.
- Furthermore, there are no climatic observations connected with the avalanche data for restrained area. Thus the links between any changes in the avalanche activity and the corresponding changes in the climatic parameters are not possible to directly assess.
- Climatic parameters can be obtained from model analysis for long periods (several decades) and allow to explain trends for snow pack data. But the scale of these data is actually too large to use them for avalanches studies.

3.2 Research needs:

- Needs for a better measurement network (snow pack, meteorology and avalanches) with a good spatial density (particularly in triggering zones) and long term observations (allowing statistical modelling).
- Needs for new observation tools for a better avalanche observation (complementary to human ground network). Research should be done or continued on seismic or sonic detection, ground or spatial remote sensing, etc. Mechanical snow properties need also to be more studied in order to improve avalanche dynamics and snow pack models.

- As the avalanche activity assessment is closely linked to the snow cover and solid precipitation characteristics, it would be efficient to create shared and homogeneous data bases for both snow and avalanche parameters.
- The protection forest rule has to be further studied as it represents a “natural” and very efficient protection measure. This kind of research is already under development in different alpine countries.
- The development of models combining both the snow falls evolution, the vegetation evolution (especially the tree line altitudinal location), and the avalanche triggering/flows would help to understand in a better way the future avalanche activity.

4. MASS MOVEMENTS – GAPS AND RESEARCH NEEDS REGARDING CLIMATIC ISSUES

4.1 Gaps:

- As for the avalanche, the existing data base (at the national level) mainly deals with the event characteristics, rather than with the conditions leading to the event’s triggering. Only some experimental sites can provide a full range of indicators (e.g. climatic parameter, geological conditions, etc.) that would enable scientists to assess any links between a change in the in situ conditions and any potential activity changes.
- Regarding the potential changes in the permafrost distribution and pattern in high altitude rock walls (> 2500 m a.s.l), there is a lack of observations for the rock falls occurring at such altitudes.

4.2 Research needs:

- Develop even more the existing data base and include some in situ information (i.e. climatic conditions before and during the event, human activities that may have consequences in the vicinity of the movement, etc.). This data base should be carried on by regional services under trans-national supervising.
- Develop the meteorological indicators that are relevant for the considered hazards (precipitation triggering threshold for both shallow and deep landslides, data for the monthly and daily precipitation falls preceding the mass movement, soil moisture…).
- As the empiric approach can not solely be used to assess the mass movement activity, it is important to develop numerical model in a way to implement attenuation measures for high altitude mass movements. Such kind of movement would be closely linked to permafrost degradation and glacier retreat. Thus the consequences of the evolution of both glacier and permafrost soils should be monitored considering mass movement issues.

4.3 Mass movements / Shallow landslides – Gaps and research needs regarding climatic issues

4.3.1 Research needs:

- As shallow landslides are closely related to short term precipitation patterns and daily rainfalls characteristics, the identification of precipitation thresholds for shallow landslides triggering would enable a better management of such hazards.
- The impacts of changes in factors that are not primary linked to climatic conditions, such as tree line altitudinal limit, permafrost evolution, vegetation cover evolution (especially the effect of root system to stabilize the superficial part of the slopes…) would be also interesting to assess.
- Such changes would take place in longer terms than the climate related changes but could aggravate the slope destabilisation.

4.4 Mass movements / Deep landslides – Gaps and research needs regarding climatic issues

4.4.1 Research needs:

- There is a need for a state of knowledge concerning the deep movement sensitivity to both superficial and deep hydrological characteristics (precipitation, snow falls, superficial runoff, underground runoff, etc.).

4.5 Mass movements / Rock fall – Gaps and research needs regarding climatic issues

4.5.1 Gaps:

- There is a lack of measurement in the steep slopes and rock walls presenting permafrost occurrence (most of these area are located above 2500 m a.s.l in the Alps); the evolution of permafrost patterns in such slopes is particularly relevant regarding the future rock falls activity in high altitude.

4.5.2 Research needs:

- Some links between the freezing-defreezing cycles have already been highlighted by scientific research. Such links need to be further studied for different altitude range (the studies concern mainly the middle mountain level, < 2000 m a.s.l).

5. GLACIAL HAZARDS – GAPS AND RESEARCH NEEDS REGARDING CLIMATIC ISSUES

5.1 Gaps:

- Glacial hazards in the Alps did not lead to major catastrophes during the last decades (despite existing potentially hazardous situations in the Alps). Thus the research did not focus on such natural events. However, considering the on-going climate change and its already striking consequences on glaciers, it would be very useful to develop glacial hazards monitoring and research.

5.2 Research needs:

- The "Gridabase" database developed in the frame of the FP5 GLACIORISK program (2001-2003), including 4 alpine countries (Austria, Italy, France, and Switzerland) has to be continued. This data base is a unique piece considering glacial hazards events. However, there are still some glaciers which need to be integrated and the information forms for each glacier could be improved with maps, localisation, pictures, technical reports, etc. In other terms, such a database should evolve from an "events" database, to a "potentially dangerous glaciers" database.
- As the empiric approach can not solely be used to assess the glacial hazard activity, it is important to further develop numerical model in a way to implement attenuation measures for this kind of hazards.

5.3 Glacial hazards / Glacial Lake Outburst Flooding (GLOF) – Gaps and research needs regarding climatic issues

5.3.1 Gaps:

- The mechanisms leading to pro-glacial lakes formation are quite well understood. But all the other kind of glacial lakes formation mechanisms are not very well understood and their links with climatic parameter are not very clear.
- The processes of ice erosion under the effect of water runoff are still not well known at this moment.

5.3.2 Research needs:

- The conditions leading to the formation of most types of glacial lakes (except for pro-glacial lakes) need to be better understood.
- The behaviour of ice channel during supra-glacial lakes emptying operation needs to be better understood.
- The reaction of glacial lakes after emptying operations needs to be studied to check the state of the lake bank, of the lake dikes and emptying channel years after the emptying operation and thus the potential actions to implement (reinforcement of the emptying channel, monitoring the banks evolution to avoid sudden bursting, etc.).

5.4 Glacial hazards / Glacial water pocket – Gaps and research needs regarding climatic issues

5.4.1 Gaps:

- There is very little knowledge concerning the glacial water pockets. No methods enable yet scientists or technical services to detect this kind of phenomena. Thus, the study of glacial water pockets does not exist at the moment.
- Liquid water flows in the glacier remain very poorly understood at the moment. Some hypotheses are proposed but none of the suppositions has been scientifically demonstrated.

5.4.2 Research needs:

- The glacier liquid water runoff needs to be better understood. Some liquid water releases have already been observed but the origin of such water release has never been clearly identified.
- The data concerning the rivers fed by glaciers should be made accessible for scientific use (from hydro-power plants managing companies by example).

5.5 Glacial hazards / Ice avalanche – Gaps and research needs regarding climatic issues

5.5.1 Gaps:

- The monitoring of ice avalanches is not developed enough considering that this phenomenon is the main ablation mode for hanging glaciers and also represents a high intensity potential hazard that could be enhanced by climate change.
- Potential consequences of ice avalanches downstream (i.e. when it triggers snow avalanches or debris flows) are not fully understood.

5.5.2 Research needs:

- A numerical model has been successfully developed to predict the breaking of ice avalanches from glaciers by Swiss scientists. It would be useful to share this knowledge and accurate even more the model with other countries scientist team.
- The future development of hanging glaciers could be a key topic for future hazards in the periglacial area. Thus temperature measurements in hanging glaciers (both in surface and inside the glacier, up to the bedrock) would help scientists to evaluate the potential hazardous situations due to warming hanging glaciers.

6. STORMS – GAPS AND RESEARCH NEEDS REGARDING CLIMATIC ISSUES

6.1 Gaps:

Even if it is possible to build and analyse relevant natural events chronicles, the conclusions based on these instrumental and historical data sources would be of limited use considering the "hazardous" occurrence of natural events (the occurrence of catastrophic situations does not mean that such situations would occur in the future and catastrophic situations can occur without previous activity). However, such research work and findings is of great help to assess the potential "hazardous level" of some areas and give precious reference values (intensity, frequency, localisation and seasonality) for natural hazard management.

6.2 Research needs:

- Strengthen the phenomenon monitoring to better understand the complexity and heterogeneity of the natural systems, in order to better anticipate their evolution (for different altitude ranges for example).
- Develop the approaches based on systemic models. Such a systemic approach can highlight the relation between different types of natural hazards and also help to implement "integrated management" of natural hazards.
- Needs to further develop natural hazards observatories and experimental sites:
- With identified manager, resources, action plans
- By straightening the existing structures
- With action plans, funding institutions, operational organisations well defined and included in long term programs.
- By taking into account the propositions corresponding to these objectives in the thematic groups of the strategic project "Natural Hazards " of INTERREG IV ALCOTRA.
- Continue and improve the projects aiming to propose common data bases and common research programs at the alpine scale. Considering the important systemic interrelation and the importance of systemic approaches, such projects need also to be developed in a multi-disciplinary scheme, involving hydrologists, glaciologists, botanists, etc. The results obtained for the alpine region should be compared with the results obtained from other European mountain ranges (Pyrénées, Scandinavian Alps, Sierra Nevada, etc.).
- Improve regional precipitation thresholds knowledge considering hydro-gravitational phenomena (landslides, river floods, torrential events, etc.), especially by collecting all the information on different natural events triggered during a single heavy precipitation event.