PUBLIZIERBARER ENDBERICHT

A) Projektdaten

Kurztitel:	SeRAC-CC
Langtitel:	**Se**nsitivity of the **R**unoff Characteristics of Small **A**lpine **C**atchments to **C**limate **C**hange
Programm inkl. Jahr:	ACRP 3rd Call (2010)
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Schlagwörter:	Abfluss, Disposition, Systemzustand, kleine alpine Einzugsgebiete, Klimawandel, Extremereignisse
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Projektübersicht

1 Kurzfassung

Die Abflussreaktion kleiner alpiner Einzugsgebiete (< 10 km²) auf Niederschlagsereignisse und damit die Magnitude des Abflussereignisses hängt ab von

- den Eigenschaften des Niederschlagereignisses (Dauer und Intensität, Ausmaß der Überregnung des Einzugsgebiets, Schneefallgrenze)
- der naturräumlichen Ausstattung der Teileinzugsgebiete (geologische Eigenschaften, Relief, insbesondere Anbindung an das Gerinnenetzwerk, Boden, Vegetation, Landnutzung) und
- ihrem aktuellen Systemzustand (z.B. Bodenwassergehalt, Existenz einer hydrophoben Auflage, Bodenverdichtung durch Beweidung, Bodenfrost, Schneedecke).

Das Projekt SeRAC-CC zielte darauf ab, den Einfluss des Klimawandels auf die Abflussreaktion von kleinen alpinen Einzugsgebieten in Abhängigkeit von ihrer Höhenlage und ihrem Niederschlagsregime zu untersuchen, in dem kritische Kombinationen von Systemzuständen und meteorologischen Bedingungen identifiziert und ihre zukünftigen Eintrittswahrscheinlichkeiten analysiert wurden.

Um die erwarteten Abhängigkeiten von der Höhenlage zu berücksichtigen, wurden drei Einzugsgebiete untersucht, die niedrige, mittlere und höhere Lagen repräsentieren:

1) Einzugsgebiet des Ruggbachs (7 km², 400-1100 m), in der Molassezone (Bregenzer Wald) am Alpennordrand (Vorarlberg, Österreich),
2) Einzugsgebiet des Brixenbachs (9 km², 900-2000 m), in der Grauwackenzone (Kitzbüheler Alpen) nördlich des Alpenhauptkamms (Tirol, Österreich),
3) Einzugsgebiet des Längentals (9 km², 1900-3000 m), in den kristallinen Stubaier Alpen am Alpenhauptkamm (Tirol, Österreich).

Die verwendeten Methoden umfassten:

- Feldmessungen, insbesondere Starkregenversuche, um die Niederschlags-Abflussreaktion repräsentativer Standorte bei verschiedenen Systemzuständen hinsichtlich Bodenfeuchtegehalt, Beweidungszustand und Existenz einer isothermen Schneedecke zu bestimmen,
- Aufbereitung von Klimaszenarien: einerseits wurden regionale Klimamodelle (ALADIN – ARPEGE, REMO und RegCM3 – ECHAM5) fehlerkorrigiert sowie räumlich und zeitlich disaggregiert. Zu Vergleichszwecken wurden andererseits mit Hilfe des Expanded-Downscaling Verfahrens die globalen Modelle MPI-ESM-MR, CNRM-CM5 and IPSL-CM5 für die Testgebiete aufbereitet.
- kontinuierliche hydrologische Simulationen mit dem Niederschlags-Abflussmodell HQsim, angetrieben durch Klimaszenarien, um zu ermitteln, wie sich saisonale Systemzustandsmuster verändern.
- Ereignisbasierte hydrologische Simulationen mit dem Niederschlags-Abflussmodell ZEMOKOST, um die Bandbreiten aktueller und zukünftiger Spitzenabflüsse zu simulieren
- Sensitivitätsstudien zur Abschätzung von Eintrittswahrscheinlichkeiten.

Die wichtigsten Projektergebnisse sind:

- Die Abflussreaktion kleiner alpiner Einzugsgebiete (< 10 km²) auf Niederschlagsereignisse verändert sich in Abhängigkeit vom Systemzustand und den Niederschlagseigenschaften. Im Rahmen des Projekts wurden der Einfluss des Bodenwassergehalts zu Ereignisbeginn, der Beweidungsintensität und der Existenz einer isothermen Schneedecke untersucht. Der Grad der Empfindlichkeit hängt von der Größe jener Einzugsgebietsteilflächen ab, die bei mittlerem (nicht kritischem oder günstigem) Systemzustand eine mittlere

Infiltrationskapazität haben. Während sich die Abflussreaktion von Flächen mit sehr hoher (z.B. Wald) bzw. sehr niedriger (z.B. Sättigungsflächen) Infiltrationskapazität bei mittleren Bedingungen bei Systemzustandsänderungen kaum verändert, reagieren Flächen mit mittlerer Infiltrationskapazität sehr sensitiv auf Veränderungen im Bodenwassergehalt oder Oberbodenverdichtung aufgrund von Beweidung.

- Aussagen zur zukünftigen Entwicklung von Starkniederschlagsereignissen müssen wegen der Limitierungen in den Klimamodellen und den statistischen Auswertungen mit Vorsicht interpretiert werden. Analysen der Intensität von Starkniederschlagsereignissen zeigen aber einen klaren Anstieg im Ausmaß von bis zu 10%. Analysen der vertikalen Stabilität der Luftmassen (Showalter Index) deuten auf eine Zunahme der Eintrittswahrscheinlichkeit von Starkniederschlagsereignissen mit sehr hoher Intensität. Die Deutlichkeit des Klimasignals und die physikalische Plausibilität der Zunahme der Starkniederschlagsintensität auf der lokalen Skale (konvektive Zellen), zeigen, dass die Befunde bei der Ermittlung von Bemessungsereignissen trotz der bekannten Modellunsicherheiten berücksichtigt werden müssen.
- Die Abnahme der Schneedecke in Ausdehnung und Dauer sowie die steigende Evapotranspiration aufgrund der höheren Lufttemperaturen führen unabhängig von der exakten Festlegung des Schwellenwerts für kritische Zustände zu einer Abnahme der Tage mit kritischem Systemzustand im Sommer (Juni – August) um die Hälfte oder mehr. Im Frühling (März bis Mai) kann für das Einzugsgebiet des Ruggbachs kein Trend, für das des Brixenbachs eine Abnahme und für das des Längentalbachs eine Zunahme der Tage mit kritischem Bodenwassergehalt festgestellt werden. Diese Unterschiede sind in der differierenden Höhenlage der Einzugsgebiete begründet. Für den Herbst und Winter zeigten die Simulationen unterschiedliche Ergebnisse je nach Klimaszenario, es zeichneten sich keine belastbaren Trends zur Veränderung der Eintrittshäufigkeit von kritischem Bodenwassergehalt ab.
- Somit sind teilweise gegensätzliche Entwicklungen zu erwarten: Auf der einen Seite zeigen die Projektergebnisse eine Zunahme der Intensität von Starkregenereignissen und eine Verlängerung der Periode, in der Gewitter wahrscheinlich auftreten. Auf der anderen Seite deuten die Simulationen auf die Vorverlegung der Perioden mit hohem Bodenwassergehalt in Abhängigkeit von der Höhenlage im Frühling und auf eine Verringerung der Tage mit kritischem Bodenwassergehalt im Sommer hin. Derzeit kann keine verlässliche Aussage getroffen werden, welche Auswirkungen das auf die Eintrittswahrscheinlichkeit extremer Niederschlags-Abflussereignisse hat.
- Die Projektergebnisse legen jedoch eine Erweiterung der Bandbreite zukünftiger Spitzenabflüsse nahe. Nimmt man nach dem Clausius-Clapeyron-Gesetz eine Zunahme der Regensumme für jedes Ereignis um 7% pro Grad Temperaturzunahme (Temperatur zu Ereignisbeginn) an, erhöht sich der Spitzenabfluss um ca. 11% ± 2,5% (untersuchter Bereich 1° bis 5°C Temperaturanstieg).

2 Executive Summary

Runoff reaction of small Alpine catchments (< 10 km²) to precipitation events and therewith the magnitude of the event depend on

- the precipitation characteristics (rainfall duration and intensity, spatial coverage by the rainfall cell, snow line),
- the properties of the sub-catchments (geological characteristics, relief – especially connection to the channel network, soil, vegetation, land use) and
- their system states (e.g. antecedent soil moisture content, existence of hydrophobic layers, bulk density, soil frost, snow layer) which vary episodically owing to precipitation events, seasonally as a function of radiation intensity, grazing intensity, soil frost and snow cover and other factors and in the long term due to climate and land-use changes.

SeRAC-CC aimed at evaluating climate change impacts on the runoff reaction of small Alpine catchments depending on their altitude and precipitation regime by

- identifying the critical combinations of system states and meteorological conditions and
- investigating their future, climate change driven occurrence probability.

In order to consider the expected dependencies on their height above sea level, three catchments representing low, medium and high altitude were investigated:

1) Ruggbach catchment (7,2 km², 400–1100 m), situated in the Molasse zone (Bregenzer Wald) at the northern border of the Alps (Vorarlberg, Austria);
2) Brixenbach catchment (9,3 km², 900–2000 m), situated in the Grauwackenzone (Kitzbüheler Alps) north of the main ridge of the Alps (Tyrol, Austria);
3) Längental catchment (9,2 km², 1900–3000 m), situated in the crystalline Stubaier Alps (main ridge of the Alps, Tyrol, Austria).

Methods used comprised

- field measurements, especially sprinkling experiments in order to explore the precipitation-runoff reaction of representative sites at different system states regarding antecedent soil moisture, grazing and the existence of an isotherm snow cover,
- preparation of climate change scenarios: on the one hand with the aid of bias-correction and temporal and spatial disaggregation of regional climate models (ALADIN – ARPEGE, REMO and RegCM3 – ECHAM5) and on the other hand for comparative purposes by Expanded Downscaling (XDS) of the global climate models MPI-ESM-MR, CNRM-CM5 and IPSL-CM5.
- a continuous hydrological simulation with the precipitation-runoff model HQsim, driven by climate change scenarios in order to assess how seasonal patterns of system states of catchment subareas change,
- event based hydrological simulations with the precipitation-runoff model ZEMOKOST in order to assess bandwidths of future peak runoffs;
- sensitivity studies for the assessment of changes in occurrence probabilities.

The most important project results are:

- Runoff reaction of small catchments (< 10 km²) to precipitation events is sensitive to changes in system states and event characteristics. Within the project the effect of antecedent soil moisture content, grazing and the existence of an isotherm snow cover were investigated. The degree of sensitivity depends on the size of areas with medium infiltration capacity at medium (not critical or favourable) system conditions. While areas with very high infiltration capacity (e.g. forests) and very low infiltration capacity (e.g. wetlands) at medium system conditions do hardly change their reaction at changing system conditions, those with medium infiltration capacity at medium system conditions are very sensitive to variations in antecedent soil moisture content and changes due to soil compaction by grazing.
- Statements on the future development of heavy precipitation events have to be interpreted with caution due to the limitations of the state of the art climate models itself and also the

statistical post processing. Analyses of the intensity of heavy precipitation events indicate a clear increase up to 10 %. The analyses of the vertical stability (Showalter index) indicate an increase of the probability of very strong thunderstorms in the investigated region. The clear climate change signal and the physical plausibility for the scenarios for extreme precipitation on local scale (convective cells) indicate that we should take these scenarios seriously even though we know the limitations of our models.

- The reduction of snow cover in extension and duration and the raised evapotranspiration because of the higher temperatures lead to a reduction of days with critical antecedent soil moisture content in summer (June to August) to the half or even more independently of the exact definition of the threshold for critical system conditions. In spring (March to May) no trend can be found in Ruggbach catchment, in Brixenbach catchment the number of critical days decreases, in Längentalbach the number increases. These disparities may be contributed to the different altitude of the catchments. For autumn and winter the simulations showed different results for different climate scenarios, no reliable trends according to the occurrence probability of critical soil water contents could be obtained.
- Thus contrary developments have to be expected: On the one hand the project results show an increase of the intensity of torrential rain events and a prolongation of the period, in which thunderstorms occur. On the other hand simulations point at a pre-ponement of periods with high soil water content in dependence of the altitude in spring and a decreasing occurrence probability of days with critical antecedent soil moisture in summer. At the moment no reliable answer can be given, how these developments affect the occurrence probability of extreme precipitation-runoff events.
- Project results suggest an extension of the bandwidths of possible peak runoffs: Assuming an increase of the rainfall sum of each event by 7% per degree rise of air temperature at the beginning of the rainfall according to the Clausius-Clapeyron scaling, catchment peak discharge will rise by ~ 11% (/1°C, standard deviation 2,5%, for 1°-5°C).

3 Hintergrund und Zielsetzung

Numerous settlements in the Alps are situated on alluvial fans at the exit of small torrent catchments. Thus they are threatened by floods and/or debris flows usually caused by local thunder cells (convective intense precipitation) with very short lead times due to the short distance between the runoff controlling areas and the endangered objects. This is why tools for flood estimation and forecasts are of eminent importance for planning authorities and engineering offices.

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- the precipitation characteristics (rainfall duration and intensity, spatial coverage by the rainfall cell, snow line),
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- their system states (e.g. antecedent soil moisture content, bulk density, existence of hydrophobic layers, soil frost, snow layer) which vary episodically depending on precipitation events, seasonally depending on radiation intensity, grazing intensity, soil frost and snow cover and other factors and in the long term due to climate and land-use changes.

Climate change may therefore have a strong influence on the magnitude-frequency-relationship of floods in small Alpine catchments, not only by possible changes in precipitation characteristics, but also by shifting or extending the bandwidths within which system state variations take place.

Up to now only few systematic studies exist that examine

a) the relationship between system state conditions within the catchment area at the time of the precipitation event and the runoff reaction that follows and
b) the effects of climate change on the system state conditions and the consequent runoff reactions.

However, research on this topic is of considerable importance as it leads to an improved evaluation of flood risk. Resulting tools for the assessment of the runoff disposition of Alpine soil/vegetation complexes under different system states with regard to future developments can be used for the dimensioning of flood prevention measures, which allows a more focused employment of scarce public financial means.

Thus SeRAC-CC aimed at evaluating climate change impacts on the runoff reaction of small Alpine catchments depending on their altitude and precipitation regime by

- identifying the critical combinations of system states and meteorological conditions and
- assessing their future, climate change driven occurrence probability.

In order to consider the expected dependencies on their height above sea level, three catchments representing low, medium and high altitude were investigated:

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4 Projektinhalt und Ergebnis(se)

4.1 Activities performed within the framework of the project, including methods employed

WP1 – Project management

Within this work package all necessary contracts between the consortium partners as well as between the applicant and the subcontractor (University of Potsdam) were developed. Several meetings of the project partners were organised and took place, namely a kick-off workshop (8 February 2011), yearly project workshops (30 January 2012, 14 March 2013, 6-7 February 2014, 2 April 2014), joint field surveys in Brixenbach catchment (15 June 2011), Längentalbach (16 June 2011) and Ruggbach catchment (3 July 2012) and secured smooth collaboration within all work packages in order to reach the project goals as well as possible. At the end of the project two stakeholder workshops were organized (1 April 2014 in Innsbruck and 12 May 2014 in Bregenz). All reports were compiled in time.

WP2 – Data acquisition and preparation for hydrological modelling

Areal data (geological, soil, vegetation and land use characteristics of the three catchments) were collected and prepared. Meteorological and discharge time series were collected, quality checked, corrected if necessary and statistically analysed. Methods used comprised interpretation of orthophotos, field surveys, analysis with Geographic Information Systems and time series analysis.

WP3 – Field measurements

Surface runoff maps and surface roughness maps were elaborated for all three catchments based on the code of practice for assessment of surface runoff coefficients of alpine vegetation/soil units in torrential rain (Markart et al. 2004). Therefore units with a comparable hydrological response (HRUs) were identified and defined. Maps of the channel network including the estimation of channel roughness were made. Furthermore maps of the hydrogeological situation of the catchments were created based on the technical guidebook for a qualitative and quantitative survey of subsurface flow processes in torrential catchments (Pirkl and Sausgruber, in preparation).

For the characterization of the runoff and infiltration behaviour of different HRUs, representative research plots were chosen. They were irrigated by a transportable spray irrigation installation for large plots (40 m² – 80 m², Fig. 1). As torrential rainfalls are known to be the flood triggers in small catchments like the test watersheds and in order to compare measurement data with the large pool of irrigation measurement data collected at the BFW, the applied water intensity which can be set by the kind and amount of sprinkling nozzles was chosen to be about 100 mm h^{-1}. Surface runoff occurring inside the irrigated plot was collected in a horizontal trench equipped with a rain drain at the bottom side of the investigation area. Discharge from the site was measured in a calibrated tank. In general irrigation was carried out during 60 minutes per experiment. Due to the danger of triggering landslides, some experiments in the Ruggbach catchment were done with lower rain intensities (53 - 74 mm h^{-1}). At some forested sites the duration of the experiments was extended up to three hours.

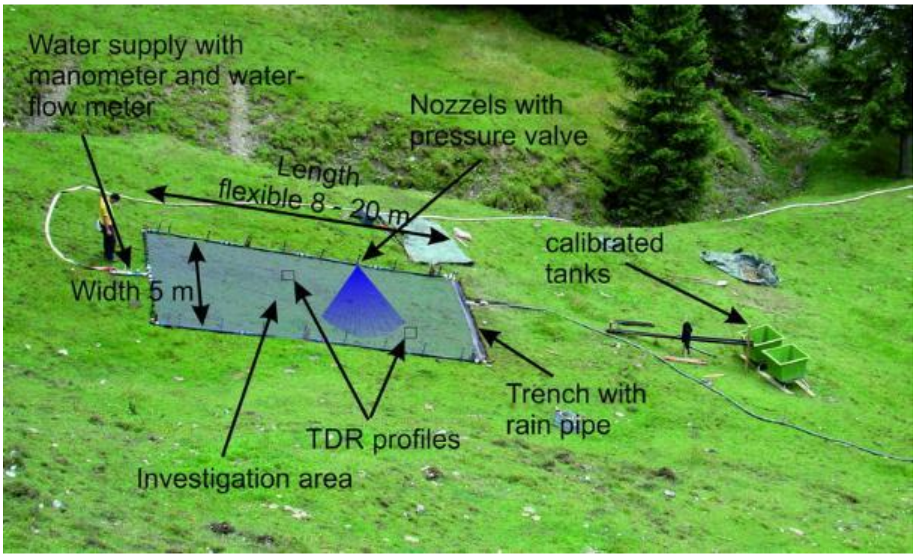

Fig. 1: Arrangement of the large spray irrigation installation

To investigate the influence of soil water content (e.g. pre-event rain) on surface runoff, a multiple experiment design was developed. After a first experiment at a research site, one or two further experiments were conducted similarly with a time lag of 30 to 60 minutes between the irrigations. In this way defined system conditions could be generated for each experiment. In the Brixenbach catchment also the impact of grazing was investigated by conducting sprinkling experiments on a research plot in May straight before the start of the grazing season and in September immediately after the end of the grazing season.

The main specific values deducted from each sprinkling experiments were:

- the time of initial loss (IA) between the start of the irrigation and the first surface runoff describing the capacity of a site to buffer rain;
- the volumetric surface runoff coefficient Ψ_{vol} which is the quotient of the irrigated water and the runoff volume;
- the surface runoff coefficient at constant discharge Ψ_{const} which describes the runoff state at a stable infiltration/runoff situation, thus its value is normally higher than the volumetric runoff coefficient.

To match also the interests of the project "Shallow Interflow" funded by the Austrian Academy of Sciences (ÖAW), the number of rain simulation experiments in the Ruggbach catchment was increased and additionally occurring interflow was measured at several sites. Velocities of the subsurface flow are published in Markart et al. (2014). During the sprinkling experiments soil moisture was recorded in (usually) two profiles in different soil depth (usually 5, 15, 25, 40 cm) using the Time Domain Reflectometry (TDR) method (length of the probes: 8 cm). On some plots in the Ruggbach catchment also geoelectrics was used to document the propagation of the water front in the soil (Markart et al. 2014).

In order to support the interpretation of the sprinkling experiments´ results, soil samples from all sprinkling plots were taken for the analysis of physical soil properties. Therefore loose soil material and cylinder samples were extracted from different soil depth levels (0-10, 10-20, 20-30, 30-50 cm). The main values of the soil analysis were: distribution of the pore volume including high permeable coarse pores; distribution of grain size and soil texture, soil density, content of skeleton and organic matter and hydraulic conductivity at saturated conditions.

All sprinkling experiments took place between July 2011 and September 2012: 19 experiments were conducted at nine different sites in the Ruggbach catchment, 14 experiments at eight sites in the Brixenbach catchment.

Due to boundary effects, plot size of sprinkling experiments influences the reliability of their results: the larger the experimental plot, the more representative the measured runoff coefficients.

As sprinkling experiments on the large plot are very time-consuming the opportunity was taken to combine the experiments carried out within SeRAC-CC with a methodical study. Within a diploma thesis (Mayerhofer 2012) 33 small-plot rainfall simulations (1 m², Fig. 2) were conducted in Ruggbach and Brixenbach catchment parallel to the large-plot simulations in order to identify conditions under which small-plot experiments might also give reliable results.

Fig. 2: Irrigation experiments on an isotherm snow cover in Längentalbach catchment (10.05.2012)

In the Längentalbach catchment large talus slopes are damping runoff reaction. Due to the large pore volume antecedent rainfall has only a small influence on a rainfall-runoff event. However the existence of an isotherm snow-cover might significantly change runoff reaction to a rainfall event. Thus two experiments were done in the Längentalbach catchment in order to characterise runoff behaviour of an isotherm snow cover. For this purpose a 20 cm snow layer (top layer) was separated from the snow column using a plastic canvas cover. The parted snow volume was irrigated by a small sprinkling device (1 m², Fig. 2) and the runoff was measured at the artificial plane. Thus the retention effect of snow (temporally storage of liquid water into the pore volume of the snow cover) and the following snowmelt process could be investigated. The design of the experiment represented the situation of a shallow snow cover over an impermeable surface (e.g. solid rock). However, runoff behaviour after infiltration into the ground, which occurs on the large areas covered by talus slopes, could not be simulated with this experimental setup.

In supplementation of the sprinkling experiments, double ring infiltrometer measurements were conducted in the Brixenbach catchment. In order to repeat the experiments at different antecedent soil moisture conditions at exactly the same plot and thus to determine the temporal variability of the infiltration, an adaptation of the double-ring infiltrometer device was used. The main feature was the splitting of the inner ring into two parts. While the lower part remained in the soil during the whole investigation period (July 2009 – September 2011), the upper part was fixed to the lower one just before the infiltration experiment. At eight representative plots in Brixenbach catchment which have also been equipped with soil moisture and soil temperature sensors three infiltration rings were installed in order to get also the spatial variability of the infiltration rate. Measurements were then conducted at dry, medium and wet conditions regarding soil water content.

With the aid of field mapping and measurement activities, profound process knowledge was collected which was applied for the set-up of the hydrological models and the verification of the modelling results.

WP4 – Hydrological modelling

Two hydrological models were used: HQsim in order to identify changes of seasonal patterns of system conditions in the test catchments and ZEMOKOST to specially analyse rainfall-runoff-events.

HQsim (Kleindienst 1996, Achleitner et al. 2011) is a semi distributed rainfall-runoff model especially designed for simulating flow peaks in mesoscale Alpine catchments. The model has been applied for several Alpine catchments and is currently part of the flood forecasting model for the river Inn in Tyrol (HoPI). HQsim uses homogeneous areas (HRUs), which were created by processing and intersecting various datasets (surface runoff classes, slope and aspect) by a Geographical Information System (GIS). HQsim calculates the runoff of each HRU by the combination of four storages: the unsaturated soil zone, the saturated soil zone, the interception storage and the snow cover (Dobler et al. 2010). The model was automatically calibrated for the three test catchments by changing the parameter values (by latin hypercube sampling, Dobler & Pappenberger 2012). In a second step the optimal runs were manually recalibrated using process knowledge gained in WP3. The model simulations were evaluated by the comparison of the modelled and measured water balance and the usage of the Nash-Sutcliffe Efficiency coefficient. The input variables of the model were temperature and precipitation data with a temporal resolution of 15 minutes derived from INCA analysis data set. In each of the three catchments, the model was calibrated from 01 January 2008 to 31 December 2010. Subsequently the model was validated during the period from 01 January 2004 to 30 September 2008 (Längentalbach, Ruggbach) and 01 January 2005 to 30 September 2008 (Brixenbach, according to the length of the discharge time series), respectively.

The event based rainfall-runoff model ZEMOKOST (Kohl 2011) was designed for the estimation of the peak runoff in ungauged torrential basins and has been intensively used by the Austrian Authorities for Torrent and Avalanche control. The semi distributed model is based on a two layer concept with a surface and a subsurface runoff module. ZEMOKOST needs the portions of surface runoff classes (Ψ_{const}) and surface roughness classes for each subcatchment (Markart et al. 2004) and the channel roughness mapped in WP3. Contribution areas of the interflow and its runoff velocity were estimated using the map of the hydrogeological situation (see WP3, Pirkl and Sausgruber, in preparation). Precipitation intensities from design events ("Bemessungsniederschläge" at ehyd.gv.at) were included in the model for the three test catchments in order to simulate different torrential rain events. The model was validated by the comparison of the modelled and measured runoff of selected rainfall-runoff-events.

WP5 – Climate change scenarios

For the purpose of comparison climate change scenario data for the three catchments were produced in two ways:

a) by project partner 2 (Institute of Meteorology, University of Natural Resources and Life Sciences):

Three regional climate models from the EU research project ENSEMBLES were used: ALADIN driven by the global climate model (GCM) ARPEGE, REMO and RegCM3 both driven by the GCM ECHAM5. This data, originally on a grid with a resolution of 25 km x 25 km and a time step of one day from 1951 to 2100, was spatially downscaled to a 1 km x 1 km grid for the area encompassing the three catchment areas under investigation (Ruggbach, Brixenbach, Längentalbach catchments). Temporal disaggregation of this climate scenario data was carried out from a time step of 1 day to 15 minutes. Temperature was disaggregated based on the daily maximum and minimum temperatures using three piecewise continuous cosine curves – midnight to sunrise, sunrise to the time of maximum temperature, time of maximum temperature to midnight. It was assumed that the minimum temperature occurs at local sunrise and the maximum at 3 pm local time. An exception to this was when the minimum temperature of the following day was greater than the maximum of the current day. In this case the time of maximum for the current day and the time of minimum of the following day were set to midnight.

Precipitation was disaggregated using stochastic functions whose distributions are based on 10-minute precipitation statistics from stations close to the target areas (Koutsoyiannis 2003, Goler & Formayer 2012). First the number of wet periods for the day was randomly chosen based on the observational statistics. Then for each wet period (continuous 15-minute intervals with a non-zero rain amount), a random fraction of the daily precipitation was assigned. The starting time and duration of the wet period were stochastically chosen based on the observational statistics. The precipitation amount was then randomly distributed over this wet period with the requirement that the sum was equal to that originally assigned to the wet period. Physically unrealistic precipitation intensities were avoided by imposing a temperature-dependent upper bound which was determined from the monthly temperature and precipitation intensity statistics from the original station. Due to the stochastic nature of this disaggregation method, it was only applied to one grid point within the catchment area. The precipitation for the remaining grid points was calculated based on this generated 15-minute time series and subsequently scaled by a factor determined by the daily precipitation totals from the original climate scenario. This ensures a spatial consistency with the timing of the rainfall across the catchment.

b) by the subcontractor of the applicant (Institute of Earth and Environmental Sciences, University of Potsdam):

For all stations contained in the three study areas of SeRAC-CC, daily temperature and precipitation was downscaled from three GCMs, MPI-ESM-MR, CNRM-CM5 and IPSL-CM5. The GCMs were forced using historic concentrations and a representative concentration pathway (RCP) of 8.5 W/m² (IPCC 2013). The downscaling was calibrated and validated using the ECMWF ERA interim reanalysis fields. The method of Expanded Downscaling (XDS, Bürger 1996, Bürger 2009, Bürger et al. 2013) was used to derive the local scenarios. This is a well-tested method that is particularly suited to the downscaling of extreme events. Besides these simulations, a rough estimate of future extreme 15 min-precipitation was provided, based on future temperature estimates and the Clausius-Clapeyron scaling.

The results of both approaches were compared regarding their climate change signals (see 4.2 WP5).

WP6 – Sensitivity and probability analysis

In a first step continuous hydrological model runs with HQsim based on the climate change scenarios (1950 – 2100) were performed which allowed to assess run-off relevant changes of the seasonal patterns in the catchments with regard to snow cover and soil moisture content. For this purpose frequency duration curves and plots of annual courses (daily mean and standard deviation) for three time slices (1981 – 2010, 2031 – 2060, 2071 – 2100) were analysed.

In a second step the comparison of soil water contents and precipitation sums for discharge classes led to the identification of thresholds defining critical (even small precipitation sums may produce high runoff amounts) and favourable system states (even high precipitation sums may lead to only small runoff amounts) regarding antecedent soil moisture content. Their occurrence probability was calculated for the three time slices in order to detect changes.

In a final step input data of ZEMOKOST were sequentially varied in order to determine a bandwidth of possible future precipitation-runoff reaction of the catchments. Different system conditions were modelled by using different surface runoff maps representing a critical and favourable state regarding soil moisture content and soil compaction by grazing. In the Längentalbach catchment, the system conditions were changed assuming the existence of an isotherm snow cover during the rain event. The assumed volume of existing ice was equivalent to the amount of ice which can be melted during a rain event. The snow melting process is implemented in ZEMOKOST by an increase of the precipitation value. Temperature of rain at the time when it reaches the surface of the snow cover was increased stepwise. For the runoff calculations at the present climate situation design, rainfall event data (weighted mean values) provided by the Austrian Hydrographic Service (ehyd.gv.at) with a return period of 100 years was used. For modelling the runoff at climate change conditions, the rainfall design events were modified by increasing the rainfall sum of each event by 7% per degree temperature rise (air temperature during rain event, according to Clausius-Clapeyron scaling, Trenberth et al. 2003, Lendering et al. 2008, Calvano 2014, Fritz 2014). The runoff modelling was carried out for all system-state-scenarios and warming scenarios up to a temperature rise of 5°C.

Additionally to the analyses of the results of the hydrological model, two meteorological indicators for extreme precipitation were analysed. The first is the exceedance of a specific percentile (99.5 and 99.9) of the daily precipitation sum. For calculating the percentiles only days with a catchment averaged daily precipitation sum of more than 0.1 mm are considered. As an example the 99.5 percentile on annual base is ~ 37 mm in the Brixenbachtal catchment and the 99.9 percentile ~ 50 mm.

The second indicator is the Showalter Index (Showalter 1947). It is defined as: S = (T_{500}-T_L). T_{500} is the temperature at the 500 hPa level (~5500 m a.s.l.) and T_L is the temperature of an air parcel lifted from 850 hPa (~1500 m a.s.l.) to 500 hPa according to the try adiabatic lapse rate till reaching the dew point temperature and according to the wet adiabatic lapse rate afterward. Showalter index values below zero indicate the possibility of thunderstorms and values below -4 indicate heavy thunderstorms.

WP7- Evaluation of climate change impacts on the runoff reaction of small Alpine catchments

Within this work package results were merged and intensively scientifically discussed, both internally within the partner network and externally with international scientific experts. See chapter 8 for detailed information on the dissemination activities and especially for the stakeholder workshops.

4.2. Description of the results and project milestones (also on work package basis)

WP1 – Project management

M 1.1 – M 1.4 workshops and reports

See chapter 4.1

WP2 – Data acquisition and preparation for hydrological modelling

M 2.1, M 2.2, M 2.3: Areal data and meteorological/discharge time series prepared

Prepared areal data, meteorological and discharge time series were provided via ftp-server to all project partners in order to serve as common data base.

Runoff data for the Ruggbach (catchment size 7,2 km², 400 – 1100 m a.s.l.) has been available since 1967 (analogously) and 1976 (digitally) respectively (precipitation and runoff data provided by the Vorarlberg Federal Office for water management). The highest peak runoff was measured on 18 July 1974 and reached 65 m^3s^{-1}. Event analysis showed that high discharge rates are mainly produced by thunderstorms with high precipitation intensity and antecedent soil moisture plays an important role for the runoff reaction.

The discharge time series of the Brixenbach (catchment size 9,3 km², 900 – 2000 m a.s.l.) is rather short, as the discharge gauge at the catchment's outlet was erected by the Hydrographic Service of Tyrol in 2004. The highest discharge until the end of the SeRAC-CC project was measured on 2 June 2013 (7,7 $m^3 s^{-1}$) during a Vb-situation with high rainfall sums (68,9 mm in 19 h) after a wet spring season (HD 2013). Data analysis revealed that high antecedent soil moisture plays an important role in the runoff reaction of Brixenbach catchment, as is for example shown by the comparison of two thunder storm events which took place after project end (29 July 2014 and 3 August 2014) with very similar duration (1-2 h), precipitation sum (44,7 and 30,3 mm resp.) and maximum intensity (18,6 and 15 mm/15 min resp.). The first event took place after a dry week with only three short thunderstorms and a 7-days-antecedent precipitation sum of 41,1 mm. Peak discharge of the event on 29 July 2014 was 2,9 $m^3 s^{-1}$. The event was the begin of a rainy period leading to a 7-days antecedent precipitation sum of 196,5 mm for the second event on 3 August 2014. Although measured precipitation sum and intensity were slightly lower than at the first event, peak discharge raised up to 17,5 $m^3 s^{-1}$ (precipitation and discharge data provided by the Hydrographic Service of Tyrol, see Gruber 2011 for detailed information on rainfall-runoff-events). Although rain distribution possibly differed between the two events, they clearly show the strong influence of antecedent soil moisture.

The discharge time series of the Längentalbach (catchment size 9,2 km², 1900 – 3000 m a.s.l.) starts in 1981 thanks to the water reservoir for power generation at the catchment outlet (precipitation and discharge data provided by the Tyrolean Water Power TIWAG). The highest peak discharge took place during a Vb-situation on 22 August 2005 (7,1 m³ s^{-1}). This is a rather small amount compared to the other test catchments which is owed to the catchments characteristics with large talus slopes retarding runoff reaction to rainfall events. Due to their large storage capacity the role of antecedent soil moisture is limited. Runoff reaction however is controlled by the existence of a snow cover and the height of snowline during the event (see Lusser 2014 for detailed information on rainfall-runoff events).

WP3 – Field measurements

M 3.1 completion of the rainfall experiments at different system states

Sprinkling experiments indicated that in general surface runoff is clearly affected by the kind of land cover / land use and the type of soil. On forested sites, no surface runoff occurred at the major number of experiments. Only at one site in Ruggbach catchment moderate surface runoff was measured due to the partially wet zone inside the investigation area. Grassland sites (Ruggbach catchment) showed surface runoff coefficient at constant discharge (Ψ_{const}) values between 0.1 and 0.7. In the Ruggbach catchment in addition quick reactions of shallow interflow and high contributions from interflow to catchment runoff have been observed (17 - 62 m h^{-1}). The frequent occurrence of high runoff on grassland is contributed to the soils mostly rich in silt and clay. On pasture sites (Brixenbach catchment), the Ψ_{const} is differing between 0.2 and 0.96 depending on the intensity of grazing as well as on the soil material.

All investigated system states, which comprise the amount of antecedent soil moisture, the impact of grazing and the existence of an isotherm snow cover, show a clear influence on the runoff behaviour of grasslands and pastures. In general the amount of surface runoff increases, and the time of initial loss decreases in case of unfavourable system conditions. Runoff behaviour of forested sites however is only marginally influenced by the system conditions.

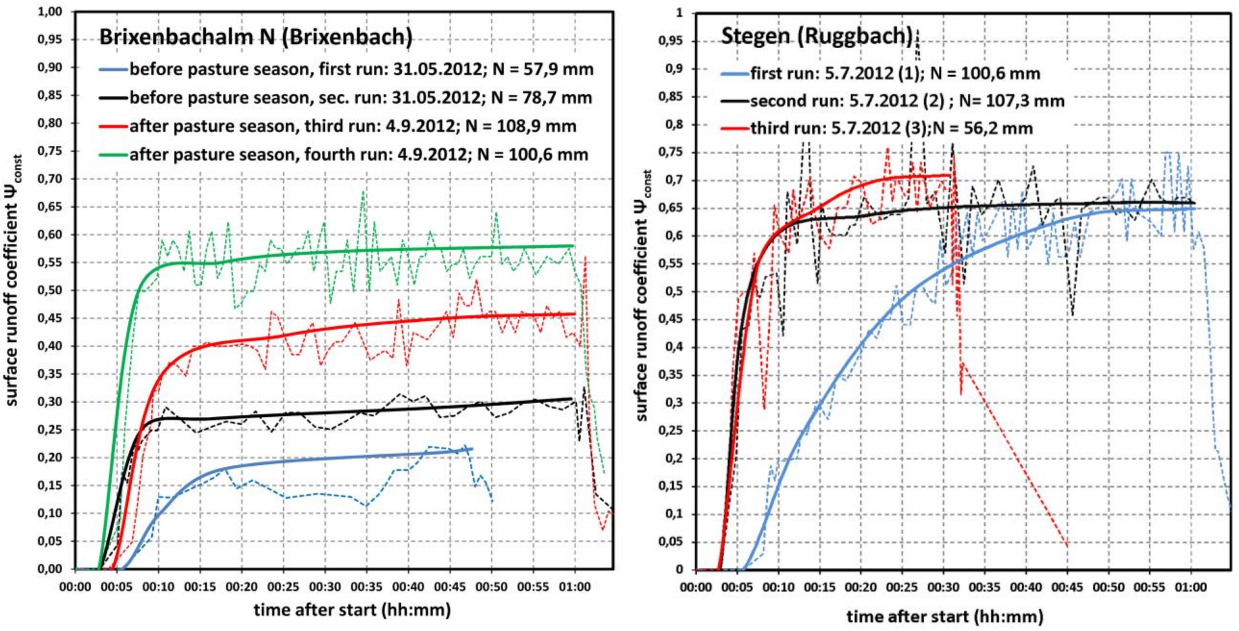

Fig. 3: Surface runoff coefficient at site Brixenbachalm (Brixenbach catchment, left) and site Stegen (Ruggbach catchment, right) and at different system conditions

Regarding the influence of the antecedent amount of soil moisture, different kinds of behaviours were found.

1) Sites whose surface runoff reaction is extremely sensitive to antecedent soil moisture content: There the time of initial loss (IA) decreases as well as the amount of runoff increases, thus both the total volumetric (Ψ_{vol}) and the runoff coefficient at a constant level (Ψ_{const}) are higher at moist conditions comparing to dry conditions. This type of reaction was particularly found in the Brixenbach catchment (experiments Brixenbachalm North, see Fig. 3 left or Rechentalalm)

where pastures on soils rich in skeleton are predominant, also at Ruggbach (experiment Lutzenreute).

2) Sites whose surface runoff reaction is sensitive to antecedent soil moisture content: The time of initial loss (IA) decreases, the runoff coefficient at a constant level (Ψ_{const}) reaches the same height comparing to dry conditions. Due to the reduced time of initial loss, the total amount of runoff increases moderately. This type of runoff behaviour was found in the Ruggbach catchment (experiments Stegen, Fig. 3 right) as well as in the Brixenbach (experiments Brixenbachalm South).
3) Sites whose surface runoff reaction is hardly sensitive to antecedent soil moisture content: The surface runoff behaviour of many forested sites is not or only marginally influenced by the wetness state as the loose soil is able to route great amounts of water vertically and laterally.

Grazing showed a clear influence on the surface runoff amount. At the investigated site (Brixenbachalm North in Brixenbach catchment) the time of initial loss as well as the runoff coefficient increased after pasturing, similarly to type 1 described above. Impact of grazing proved to be substantially higher than the influence of soil moisture (Fig. 3 left). Thus, at a worst case, if a torrential rain occurs at the end of the grazing season with high antecedent soil moisture content, the pasture site may show surface runoff amounts three times higher than at the best case. Lower surface runoff values in spring before the pasturing season showed that due to freezing and thawing soil partly recovers from pasturing during the winter time.

The results of the Längentalbach experiments on a snow covered plot showed that an isotherm snow cover is not able to retain torrential rain for a relevant lag of time. Immediately after begin of the irrigation, surface runoff started and increased very fast to a runoff coefficient of 1.15 (1.19 during the second run). The experiment demonstrated the increasing runoff due to melting snow on a snow covered impermeable surface. Contrarious effects, e.g. the storage of precipitation or at least a damping of the runoff peak of an isotherm snow cover during heavy rain were negligible.

The small-plot sprinkling experiments carried out in the catchments of Ruggbach and Brixenbach due to methodical reasons revealed that at sites with intensive grazing, due to topsoil compaction and the shortened flow path, the small-plot device delivered significantly higher runoff coefficients than the large-plot device. At mainly mowed grassland sites with at most a short grazing period in autumn both sprinkling devices showed similar results. At sites with a high amount of macropores/pipes the small-plot simulator showed even lower runoff coefficients comparing to the results of the large-plot simulator. Thus the reliability of the results of the small-plot device strongly depends on the characteristics of the irrigated plot.

<u>M 3.2 completion of the double ring infiltration measurements</u>

At the investigated pasture sites in Brixenbach catchment correlations between total infiltrated water and initial soil moisture conditions were identified – independently of the underlying soil type. High initial soil water content led to reduced infiltration rates. By contrast, no correlation was found for forest sites with high infiltration rates in any case or wetlands with always low infiltration rates.

WP4 – Hydrological modelling

<u>M 4.1 – M 4.3 Models calibrated and validated, model performance assessed for the Ruggbach, Brixenbach and Längentalbach catchments</u>

a) Continuous hydrological model HQsim

Table 1 shows the Nash-Sutcliffe-Efficiency coefficients for the model parameterisations of the three catchments. The values are not very high, but acceptable taking into account that they were calculated for 15 min-time steps. Only the calibration period for the Ruggbach catchment could not be simulated satisfactorily despite time consuming attempts to adapt parameters in order to better reproduce the runoff processes within the model.

Tab. 1: Nash-Sutcliffe-Efficiency values for the HQsim parameterization

Nash-Sutcliffe-Efficiency	Calibration period (2008 – 2010)	Validation period (2004/2005 – 2007)
Ruggbach	0.32	0.57
Brixenbach	0.57	0.64
Längentalbach	0.84	0.81

Yearly and monthly water balances were reproduced satisfactorily in all three catchments. Comparison between observed and simulated discharge values showed that in the Ruggbach and Brixenbach catchment low flows in spring and summer are overestimated, high flows in winter, spring and summer are underestimated by the model. In the Längentalbach catchment low flows are underestimated in winter and spring. Summing up it can be stated that the parameterisations of HQsim allowed analysing seasonal changes of the system conditions states with climate change. Due to the underestimation of peak runoffs singular events could only be interpreted with caution.

b) Event-based hydrological model ZEMOKOST

The ZEMOKOST model was validated by calculating several measured rainfall/runoff events. For the Ruggbach catchment several rainfall/runoff events, especially two big events in 2010, which had a discharge of about 30 $m^3 s^{-1}$, could be recalculated with a good conformance. For long rain events, the setting of the subsurface flow parameters had to be modified by expanding the contribution area. So, the event from June 2013 could be recalculated with good conformance. With the current model setting and the available precipitation data (only the rain gauge in Bregenz was able to measure rain intensity in high time resolution), the event from 1974 (65 $m^3 s^{-1}$ observed) could not be recalculated. Thus the data reliability of the highest known event for the catchment will be discussed again. The recalculation of a series of three rain events between 17 and 19 June 2010 confirmed the approach of different runoff behaviour at different system states. While the first event showed the best fit with the "best case scenario" for dry conditions, the further events could only be recalculated with the "worst case scenario" for wet conditions (Klebinder et al. 2014).

Due to the short runoff-measurement series for the Brixenbach catchment, the ZEMOKOST model was primarily checked for plausibility. Based on information of a technical report from the Austrian avalanche and torrent control (WLV 1976), a huge event from July 1975 could be recalculated. Furthermore some small events with measurements of the precipitation and the discharge could be recalculated with good conformance (Klebinder et al. 2012)

For the Längentalbach catchment the ZEMOKOST model was already validated by Kohl (2011). The highest measured discharge for the catchment, which occurred in August 2005, could be recalculated with good conformance. Furthermore a short torrential event with a high intensity of precipitation could be simulated satisfactorily.

WP5 – Climate change scenarios

M 5.1 Evaluation of the skill of RCMs to reproduce heavy precipitation events in small scale Alpine catchments

The statistical methods applied by BOKU-Met (see 4.1 WP5) secured that the temperature and precipitation statistics from the bias corrected climate scenarios have the same range as the in situ measurements within the catchments. However, statistical bias correction has limitations in case of extreme events and this especially for precipitation data on daily base. Thus the behaviour of the localized daily precipitation for the extreme precipitation of the 99.5 percentile was analysed. In Fig. 4 the annual cycle of the precipitation intensity of the 99.5 percentile is shown for the Brixenbach catchment. In the observation data the precipitation intensity has a minimum in April with 21.2 mm and a maximum in July with 54.7 mm. The REMO and ALADIN scenario show a very good agreement in the maximum values in summer with values of 56.1 and 57.8 mm, but the minimum occurs in December and is underestimated. The RegCM3 scenario in general shows little too low values and also underestimates the annual cycle of the extreme precipitation intensity.

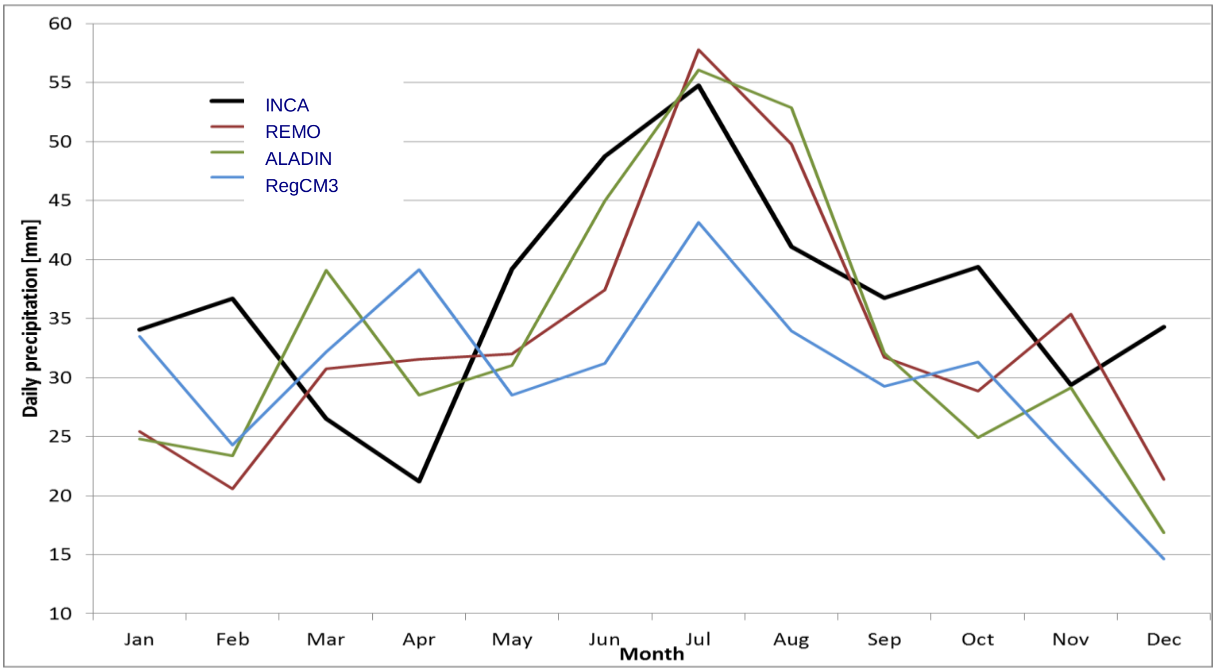

Fig. 4: Annual cycle of the daily precipitation of the 99.5 percentile for the Brixenbachtal observed (black) and the three localized scenarios for regional climate models (colour) (reference period 1981 – 2010).

These results increase the confidence in the localized scenarios in terms of heavy precipitation events especially for the REMO and ALADIN scenario. The other two catchments show similar results. The quality of the localized precipitation scenarios within the catchments is sufficient for the application in the hydrological model.

M 5.2 Quantitative and qualitative information of the change in the probability of critical meteorological conditions for the three catchments

An indicator for the frequency of critical meteorological conditions is the development of the inter-annual variability. All models indicate an increase in the inter-annual variability of the winter precipitation. In summer in RegCM3 the variability remained constant and in the other models it increased.

The three climate scenarios (ALADIN, REMO, RegCM3) based on regional climate models show clear increasing trends for heavy precipitation events in all three catchments in the order of 10 to 15 %. The statistically derived scenarios from GCMs show a higher variability. The scenario from MPI-ESM-MR is quite similar to the results of the regional models. CNRM-CM 5 shows an even stronger increase in the order of 20 % and the absolute values are higher. IPSL-CM5 reacts differently and indicates an intensity reduction in the order of 10 %. The reason for this might be the strong precipitation reduction of more than 30 % in summer in this model. As an example for these results the development of the precipitation intensity of the 99.5 percentile is shown in Fig. 5.

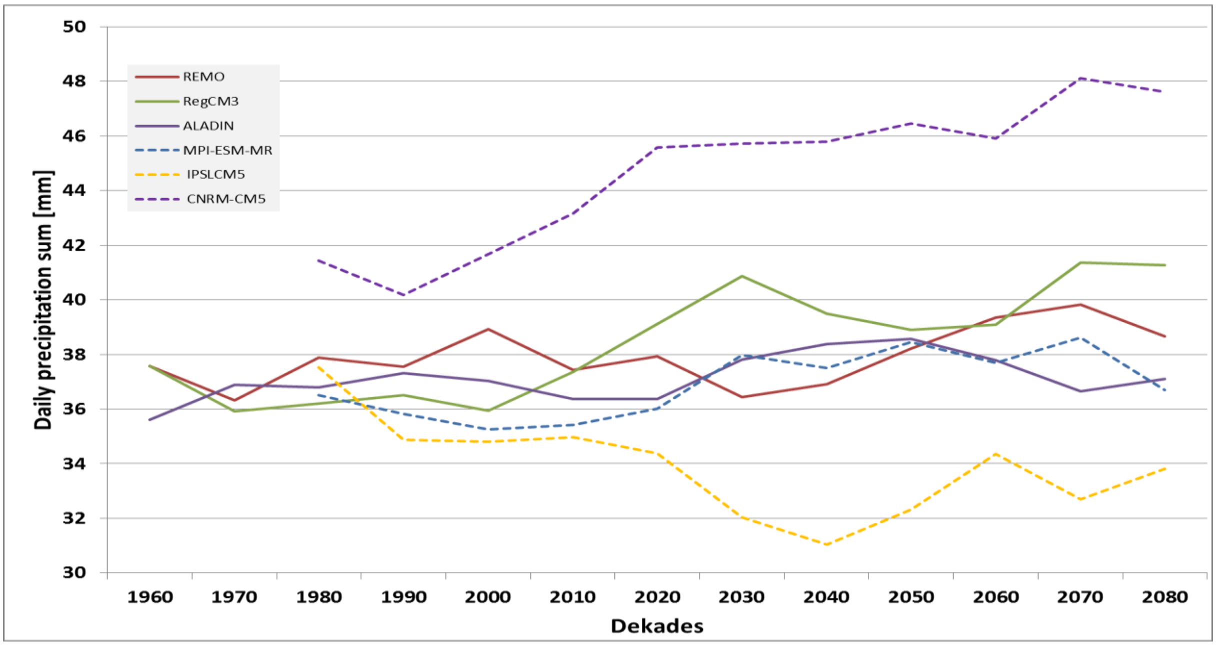

Fig. 5: Development of the daily precipitation sum with a probability ≥ 99,5 % for the Brixenbachtal. Dotted lines indicate scenarios derived statistically from GCMs forced with RCP 8.5. Bold lines are based on RCMs forced with SRES A1B.

A very important factor for the runoff situation in Alpine catchments is the existence of a snow cover. Within the 21st century extension and duration of a snow cover will be strongly reduced. In Fig. 6 the share of snow fall in precipitation of the whole Brixenbach catchment is shown. During winter the fraction of snow will be reduced from now 75 % to 55 % and in spring there will be a shift of approximately two months. This means that the future situation in March will be similar to the situation now in May.

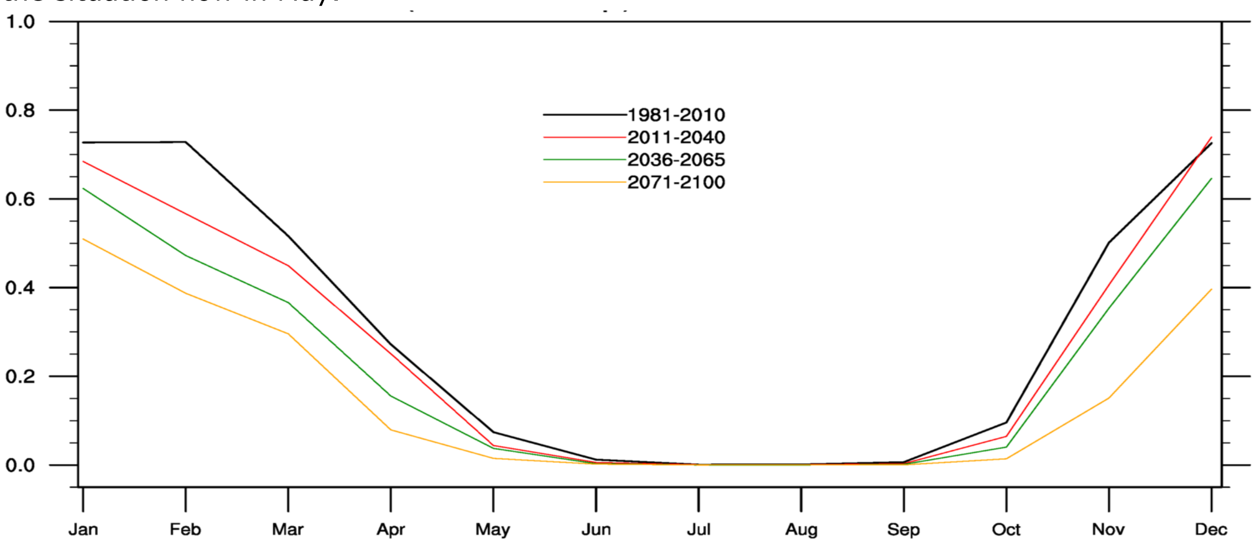

Fig. 6: Development of the fraction of snow on total precipitation for the whole Brixenbach catchment observed (black) and three time frames within the 21st century according to the REMO scenario.

Besides the direct effect of snow on runoff additionally indirect effects might occur. Snow cover on mountains acts as a switch for convection. As long as the mountains are snow covered, surface induced convection is reduced. Due to the reduced accumulation and earlier melt the mountain peaks will become snow free and thus convective processes will be induced earlier and longer within the annual cycle. A more detailed analysis on convective processes is given in 2.2.6.

M 5.3 Quantitative and qualitative information of the change in the probability of critical system state conditions for the three catchments

See M6.1 – M6.3

WP6 – Sensitivity and probability analyses

Seasonal patterns of system conditions

Continuous hydrological model runs with HQsim based on the climate change scenarios (1950 – 2100) allowed to estimate how seasonal patterns of system conditions change with climate change. Analysis of frequency duration curves for discharge (daily mean values) and soil water content for the three time slices (1981 – 2010, 2031 – 2060, 2071 – 2100) showed:

- for the catchments of Ruggbach and Brixenbach an increase of winter runoff (December – February), a slight decrease of the spring values (soil water content and runoff, March – May) and a more pronounced decrease of the summer values (June – August). In autumn (September – November) low flows may decrease, which is indicated to a varying extent depending on the climate change scenario.
- for the Längentalbach catchment an increase in the winter values, especially for the high flows, also a distinct increase of spring values (soil water content and runoff) and a pronounced decrease in the summer values. The signal for autumn values differs between the scenarios and is contradictory.

Plots of the mean course of the year of the snow water equivalent (catchment mean) for the three time slices show that the duration of the snow cover, mean snow water equivalent and its standard deviation will decrease distinctively. Begin of snow melt will shift

- in Ruggbach catchment from mid-February (1981 – 2010) to the second half of January (2071-2010),
- in Brixenbach catchment from mid-March (1981 – 2010) to mid-February (2071 – 2100),
- in Längentalbach catchment from the second half of May (1981- 2010) to the begin of May (2071 – 2100).

All changes are attributable to the temperature increase leading to less snowfall and increased evapotranspiration. Although high flows are not reproduced well by the continuous simulation with HQsim, it can be stated that the bandwidths of future peak runoffs will not become narrower. ZEMOKOST results (see below) showed that peak runoffs will rather increase.

M 6.1 – M 6.3 Identification of the critical input parameter combinations for the Ruggbach, Brixenbach and Längentalbach catchments

Time series analysis of precipitation-runoff-events, field mapping and measurements, especially the sprinkling experiments and hydrological modelling indicated that Ruggbach and Brixenbach catchment react to torrential rainfalls with high precipitation intensity. Antecedent soil moisture conditions strongly influence runoff reaction. High antecedent soil water content enforces runoff reaction significantly. Due to extensive talus slopes the Längentalbach catchment shows a retarded reaction to rainfall events resulting in substantially lower peak runoffs comparing to the other two catchments. An isotherm snow cover lying in large parts of the catchment could increase peak runoff, antecedent soil moisture has a smaller effect due to large pore volumes in the talus slopes.

Plotting soil water contents against precipitation sums for different discharge classes showed specific distribution patterns which allowed to identify thresholds, i.e. critical (small precipitation sums are sufficient to produce high runoff amounts) and favourable system states (even high precipitation sums may lead to only small runoff amounts) regarding antecedent soil moisture content. A sensitivity analysis showed that the identified trends described below do not depend on the exact definition of the thresholds for critical and favourable system conditions.

Fig. 7 shows the number of days per year on which the defined threshold for the critical system conditions is exceeded using the example of the hydrological model runs driven by the climate scenario REMO. Regarding the median (red line), data indicate a decrease of days with critical antecedent soil moisture conditions towards the end of the century in summer (June to August), which is also confirmed by the model runs driven with ALADIN and RegCM3. In spring (March to

May) no trend can be found in Ruggbach catchment, in Brixenbach catchment the number of critical days decreases, in Längentalbach the number increases. These disparities may be contributed to the different altitude of the catchments. No trend can be identified for all catchments for the winter and autumn months. The boxplots illustrate the interquartile range and outliers indicating that the inter-annual variability decreases towards the end of the century.

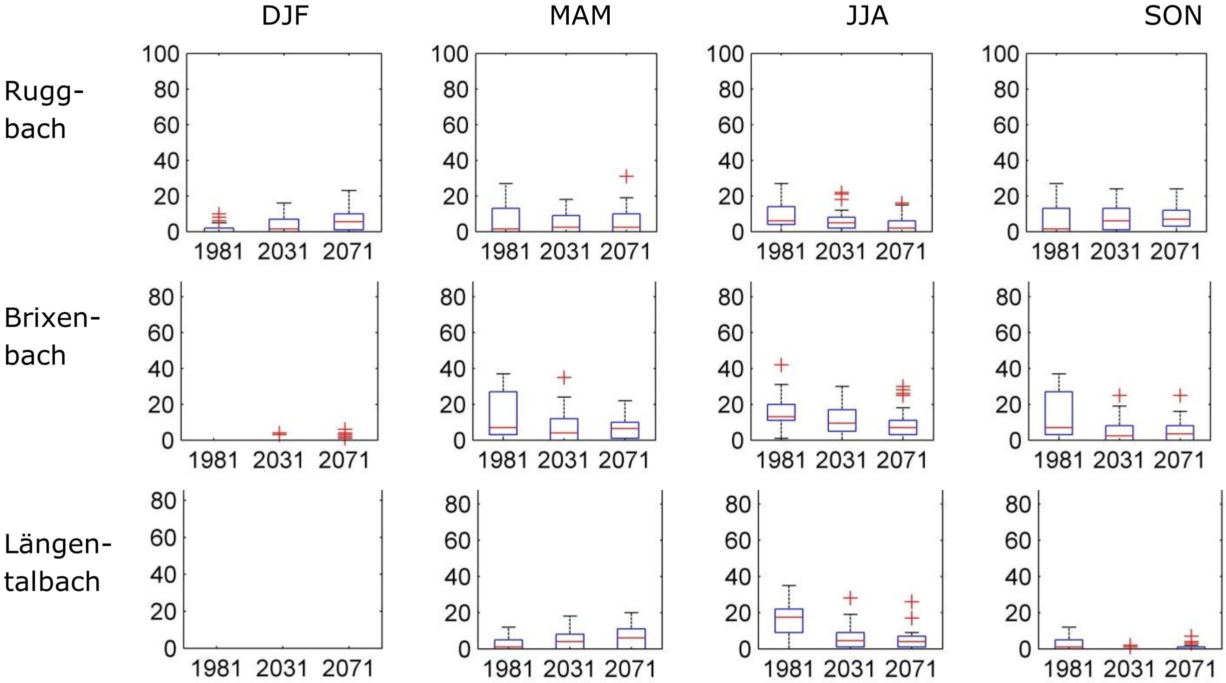

Fig. 7: Boxplots showing the number of days per year on which the defined thresholds for the critical system conditions regarding soil water content are exceeded (y-axis) in the hydrological model HQsim, driven by the climate scenario REMO. Years on the x-axis indicate start of the considered time-slices (1981 – 2010, 2031 – 2060, 2071 – 2100). Red line = median value of the 30years-data, box = interquartile range (Q1 - 25% to Q3 - 75%) of the 30years-data, whisker = Q1 - 1.5 times the interquartile range and Q3 + 1.5 times the interquartile range, crosses = beyond 1.5 times the interquartile range, DJF = December – February, MAM = March to May, JJA = June to August, SON = September to November.

Based on results from the ZEMOKOST model, the estimated peak runoff at the Ruggbach catchment for the base-scenario at current climate conditions is about 65 $m^3 s^{-1}$. If unfavourable system conditions are assumed (parameterized by higher surface runoff values representing high antecedent soil moisture and/or soil compaction due to cattle grazing), the peak runoff increases up to 104 $m^3 s^{-1}$ (factor 1.6 of the base-scenario), otherwise if favourable conditions are assumed, the peak runoff decreases to 39 $m^3 s^{-1}$ (factor 0.6). The influence of the system conditions is smaller in the Brixenbach (factor 1.3/0.75 regarding the influence of antecedent soil moisture and/or soil compaction due to cattle grazing) and in the Längentalbach (factor 1.14 for rain with a temperature of 5°C on an isotherm snow cover) catchment.

Modelling with higher precipitation intensities related to climate change induced rising temperatures leads to significantly increased peak runoffs. The influence of temperature rise is higher for the Längentalbach (factor 1.53 at temperature rise of 3°C) than for Brixenbach (factor 1.4) and Ruggbach (factor 1.36). For temperature increases (air temperature at the event) up to 5°C of the peak runoff can be described with a value of roughly 11% (standard deviation 2.5%) per one degree of temperature rise.

WP7 – Evaluation of climate change impacts on the runoff reaction of small Alpine catchments

Project results show opposite trends: While there is strong evidence that the precipitation intensity of torrential rainfalls will rise due to higher water vapour content in a warmer atmosphere, wet system conditions will appear less frequently due to intensified evapotranspiration and decreasing of snow cover in time and depth. A final statement, if these trends cancel each other out resulting in unchanged occurrence probabilities of extreme runoff events, cannot be given at present due to uncertainties in climate change models and hydrological modelling.

M 7.1 Workshop with external experts (= M 1.3) and M 7.2 Final evaluation report
See chapter 2.2.3 and chapter 4

4.3 Description of the project "highlights"

Field measurements (sprinkling and double ring infiltrometer measurements) showed that sensitivity of hydrological units to changes of the system state depends on the infiltration capacity at "medium" (neither favourable nor critical) system conditions of the site:

- Units with a very low infiltration capacity (high surface runoff potential) show a low sensitivity to changes of the system state, they always produce a high amount of surface runoff, such as sites with very dense or cohesive soils, soils rich in silt or clay.
- Units with a high infiltration capacity (low surface runoff potential) also have a low sensitivity to changes of the system state, they rarely produce surface runoff, such as sites with very pervious soils and a high fraction of permeable coarse pores.
- Units with medium infiltration capacity (medium surface runoff potential) however are very sensitive to changes of the system state. Thus the percentage of these areas on the total catchment area determines to which degree the catchment as a whole is sensitive to changes in system states.
- 36% of the area of the Ruggbach catchment is assessed to be sensitive against changes of the system state. Not sensitive areas are dominantly covered by forest or are sealed. For the Brixenbach catchment the share of sensitive areas is about 20%. These areas are predominantly used for pasturing. Due to the very high fraction of uncovered or slightly covered rock and talus the Längentalbach catchment is hardly sensitive against land use effects and antecedent rain.

Grazing strongly effects the infiltration and storage potential of soils. Compaction of the top soil layer strongly raises surface runoff in case of torrential rains. At the end of the pasture season (September) deterioration of intensive grazing is significantly stronger than the effect of high antecedent soil moisture.

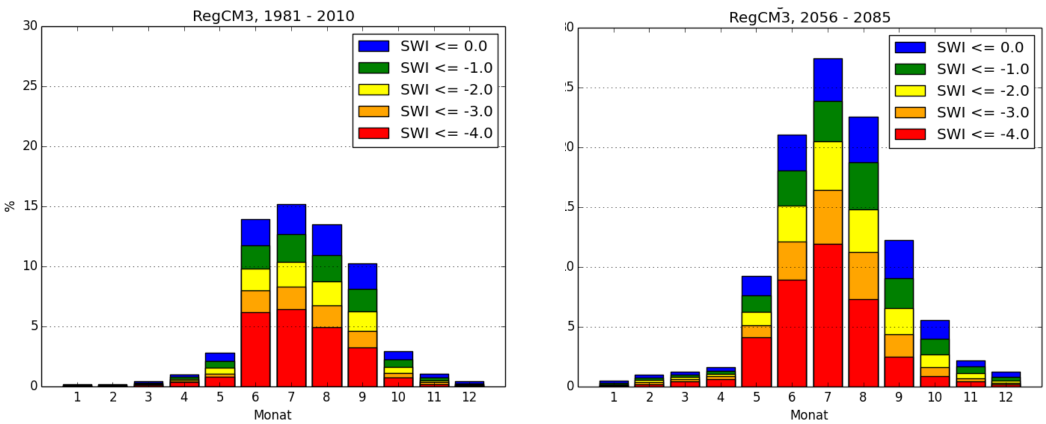

Fig. 8: Development of Showalter index values indicating thunderstorms derived form RegCM3 for the periods 1981-2010 (left) and 2056-2085 (right). The probability of very strong thunderstorms (≤-4) more than doubles during the summer months.

Because climate models have no explicit representation of convective processes and also statistical methods have limitations for extreme events, some analyses of the vertical stability within the atmosphere and its development within the 21st century were made. The Showalter Index was used as an indicator for heavy convective processes. Although the comparison of the statistics of the Showalter Index of the regional model with the reanalyses model ERA-INTERIN indicates some deficiencies in the representation of the vertical stability in the surrounding of Alps, a clear trend can be seen in the future development. In Fig. 8 the statistics of the Showalter Index during the reference period 1981-2010 (left) and for 2070 (right) are shown. Showalter values below zero indicate the possibility of thunderstorms. Values below -4 indicate very strong thunderstorms. It clearly can be seen that the thunderstorm season broadens and the probability of heavy thunderstorms more than doubles.

Although only one regional climate model was considered in this analyses and the model indicates some weaknesses in the representation of the vertical stability in the Alpine region, the climate change signal of the Showalter index is so strong that it should be considered as a plausible development. This method for the analysis is really promising and should be transferred in future to high resolution reanalyses data sets and an ensemble of regional climate model with very high resolution (e.g. 12.5 km runs of EURO-CORDEX).

5 Schlussfolgerungen und Empfehlungen

Project results correspond to the results presented in Austrian Assessment Report (Ahrens et al. 2014, Nachtnebel et al. 2014) and supplement them because of the special focus on small Alpine catchments (< 10 km²).

The following conclusions can be drawn from project results:

Runoff reaction of small catchments (< 10 km²) to precipitation events is sensitive to changes in system states and event characteristics. Within the project the effect of antecedent soil moisture content, grazing and the existence of an isotherm snow cover were investigated. The degree of sensitivity depends on the size of areas with medium infiltration capacity at medium (not critical or favourable) system conditions. While areas with very high infiltration capacity (e.g. forests) and very low infiltration capacity (e.g. wetlands) at medium system conditions do hardly change their reaction at changing system conditions, those with medium infiltration capacity at medium system conditions are very sensitive to variations in antecedent soil moisture content and changes due to soil compaction by grazing.

Regarding climate change within the Alpine catchments the following can be stated:

- Temperature increase is a very robust climate change signal. All used climate projections indicate a warming of at least 1.5 to 2 °C till the mid of the century. The development in the second half of the century highly depends on the emission scenarios used.
- Temperature induced changes relevant for runoff include:
    - Reduction of the share of snow in total precipitation in all seasons
    - Change in snow accumulation and melt (amount and seasonality)
    - Increase in evapotranspiration due to longer vegetation period and higher water vapour deficits
    - Increase in precipitation intensities due to increase of precipitable water content in a warmer atmosphere (Clausius–Clapeyron relation)
- The precipitation scenarios are comparatively not so robust and vary stronger between the different climate projections. Most models show a precipitation increase during the winter half year and a moderate decrease during the summer half year. One model forced with the RCP 8.5 scenario even showed a strong decrease in the order of 30 %. Four of six models indicate an increase in the inter-annual variability.
- Statements on the future development of heavy precipitation events have to be interpreted with caution due to the limitations of the used climate model itself and also the statistical post processing. Analyses of the intensity of heavy precipitation events indicate a clear increase up to 10 %. The analyses of the vertical stability (Showalter index) indicate an increase of the probability of very strong thunderstorms in the investigated region.
- The clear climate change signal and the physical plausibility for the scenarios for extreme precipitation on local scale (convective cells) indicate that we should take these scenarios seriously even though we know the limitations of our models.
- Beside the direct meteorological effects on catchment runoff indirect effect of climate change on the landscape and the land use (shifts in vegetation, disastrous events like forest fires, bark beetle,…) might modify the behaviour of the catchment runoff.

Modelling with the continuous hydrological model HQsim showed:

- Regarding the runoff relevant system state of the catchments, climate induced temperature rise leads to a reduction of the snow cover in depth and duration and to an shift of the melting period which will start two weeks to one month earlier at the end of the century comparing to the reference period 1981 – 2010 (this statement refers to the 30years mean snow water equivalent).
- Raised evapotranspiration and reduced amount of snow lead on the average to dryer system states in summer and autumn (all three catchments) and to wetter system states in winter

(Ruggbach catchment), winter and early spring (Brixenbach catchment) and spring (Längental catchment) respectively. The variations between the catchments can be attributed to their differing altitudes.

- Thus the number of days with critical antecedent soil moisture content will halve or be reduced even stronger in summer (all catchments, independent of the exact definition of the threshold). In Längentalbach catchment the number increases in spring (see Fig. 7). In all catchments the number of days with favourable antecedent soil moisture content increases in summer and decreases in winter. Spring and autumn show no clear trends and partly differing results between the three runs driven by the three climate scenarios used.
- Although mean runoff values will decrease in summer as the system states tend to become dryer, extreme peak runoff values will not decrease, thus bandwidths of possible peak runoffs will not become narrower.

Modelling with the event-based model ZEMOKOST showed:

- A significant response to changes in the system conditions can be found for all catchments. Peak discharge of the Ruggbach reacts stronger on changes of system states (with regard to antecedent soil moisture) than peak runoff of the Brixenbach (system state changes with regard to antecedent soil moisture and grazing) as the sensitive areas in the Ruggbach watershed cover a larger percentage of the catchment area.
- The existence of an isotherm snow cover increases the peak discharge of the Längentalbach catchment only moderately. For longer rain events, the effect of the snow becomes more important.
- Short torrential rain events with a duration of less than one hour are the critical events for all catchments.
- The highest impact of rising precipitation intensity according to temperature increase on peak discharge was found for the Längentalbach catchment, the lowest for the Ruggbach catchment.
- The increasing of the catchment peak discharge (~ 11%/1 °C, standard deviation 2.5% for 1 – 5°C rise of air temperature at the event) is higher than the increasing of the precipitation intensity/sum (7% / 1°C).

Assessment of possible extreme runoff value in small Alpine catchments is already in presence subject to considerable uncertainty due to limited knowledge on the characteristics of soil and geological substrate which strongly effect runoff reaction and due to possible threshold controlled processes. For the future there is strong evidence that the precipitation intensity of torrential rainfalls will rise due to higher water vapour content in a warmer atmosphere. On the other side wet system conditions will appear less frequently due to intensified evapotranspiration and decreasing of snow cover in time and depth. A final answer, if one of these trends equalizes the other out resulting in unchanged occurrence probabilities of extreme runoff events, cannot be given because of uncertainties of state of the art climate change models and hydrological modelling.

B) Projektdetails

6 Methodik

Regarding the uncertainties of climate change projections on small Alpine catchments SeRAC-CC pursued a novel and innovative approach by feeding the hydrological models with bias corrected climate change scenarios to generate information on the future seasonal patterns of system state conditions (soil moisture content, intensity of grazing, snow cover). For the single extreme events, however, the critical combinations of meteorological and system state conditions were identified by sensitivity analysis as part of hydrological modelling.

The chosen workflow is presented in Fig. 9.
Work package 1 was dedicated to project management, thus to the organisation of project meetings, communication between the project partners, the production and maintenance of the homepage and the elaboration of all necessary reports. Within work package 2 all necessary data were collected and prepared. Work package 3 contained field mapping and measurement activities, especially the conduction of sprinkling experiments with the large and small plot device and double ring infiltration measurements in order to measure runoff reaction at different system states. Within work package 4 the hydrological models HQsim and ZEMOKOST were calibrated and validated respectively for three test catchments. Climate change scenarios were elaborated within work package 5: on the one hand regional climate models were bias-corrected, and spatially and temporally disaggregated. On the other hand global climate models were downscaled (Extended downscaling). Both methods were compared regarding their ability to represent torrential rainfalls. Within work package 6 continuous hydrological model runs with HQsim, driven by climate scenarios, provided information on changes in seasonal patterns of the system states of the catchment subareas. Sensitivity studies with ZEMOKOST showed bandwidths of future peak runoffs. Work package 7 contained final evaluation of the results, uncertainty analysis and communication to stakeholders.
See chapter 4 for detailed description of the chosen methods and the work packages.

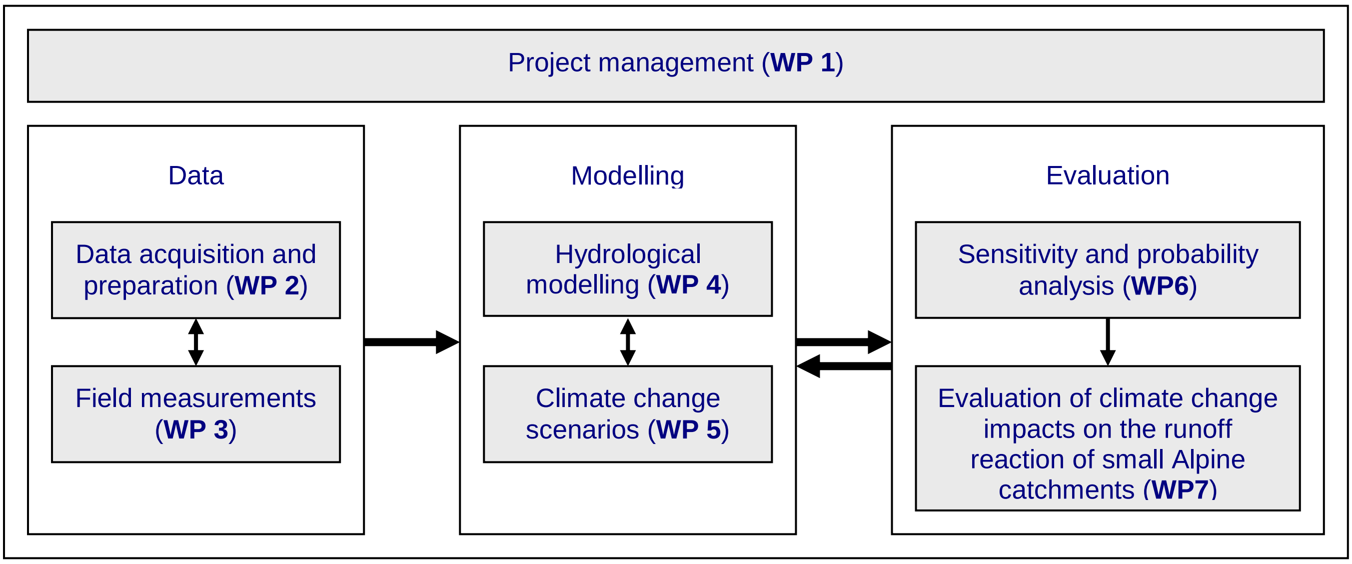

Fig. 9: Work packages – methodical steps

7 Arbeits- und Zeitplan

Fig. 10 shows the final work and time schedule of the project. SeRAC-CC was designed for a period of 36 months. Due to demands of the climate and energy fund, project end was determined to be 31 December 2013. As project start took place on 1 February 2011, this led to a reduction of project duration to 35 months. Owing to delays because of unforeseen personal turnovers an extension of the project duration until 30 June 2014 which was applied for and approved. Thus finally the project duration was 41 months.

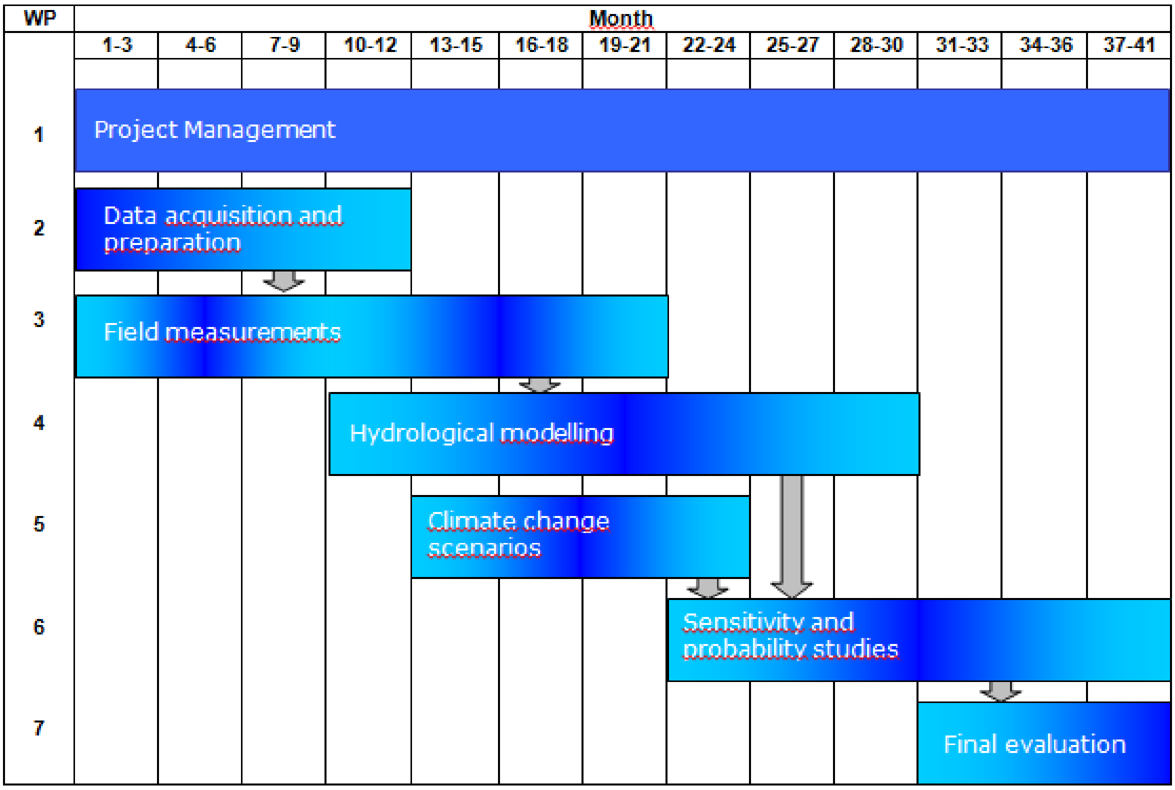

Fig. 10: Final work and time schedule

8 Publikationen und Disseminierungsaktivitäten

Papers and Extended Abstracts

Bürger, G., M. Heistermann & A. Bronstert (2014): Towards Subdaily Rainfall Disaggregation via Clausius-Clapeyron. Journal of Hydrometeorology vol. 15, pp. 1303 - 1311. http://journals.ametsoc.org/toc/hydr/15/3

Klebinder, K., B. Kohl, G. Markart, G. Meißl & B. Sotier (2014): Hochwasserabfluss in alpinen Einzugsgebieten - hydrologische Standortsfaktoren und deren Bewertung. In: Bericht 4. Umweltökologisches Symposium am 18. und 19. März 2014 am LFZ Raumberg-Gumpenstein, pp. 37 - 42.

Klebinder, K., G. Meißl, B. Kohl, G. Markart, C. Geitner & F. Schöberl (2014): Sensitivität der Abflussreaktion kleiner alpiner Wildbacheinzugsgebiete auf Änderungen des Systemzustands. Zeitschrift für Wildbach-, Lawinen-, Erosions- und Steinschlagschutz, 78. Jg. Heft 171, pp. 268 - 279.

Meißl, G., K. Klebinder, C. Geitner, R. Schader, F. Kerl & G. Markart (2013): Räumliche Differenzierung der Abflussbildungsprozesse im Brixenbachtal (Tirol). Innsbrucker Jahresberichte 2011 - 2013, Innsbrucker Geographische Gesellschaft, pp. 24 - 44. http://www.uibk.ac.at/geographie/igg/berichte/2013/pdf/meissl.pdf

Meißl, G.,K. Klebinder, C. Geitner, F. Schöberl, B. Kohl, G. Markart, H. Formayer, Th. Gorgas & A. Bronstert (2012): Sensitivität der Abflussprozesse kleiner alpiner Einzugsgebiete auf Klimaänderungen. In: Weiler, M. (2012): Wasser ohne Grenzen. Beiträge zum Tag der Hydrologie am 22./23. März 2012 an der Albert-Ludwigs-Universität Freiburg. Forum für Hydrologie und Wasserbewirtschaftung Heft 31.12, pp. 121 - 126. http://tdh2012.uni-freiburg.de/download/tagungsband

Ruggenthaler, R., G. Meißl, C. Geitner, G. Leitinger, N. Endstrasser & F. Schöberl (submitted): Investigating the impact of initial soil moisture conditions on total infiltration by using an adapted double-ring infiltrometer. Submitted to Hydrological Sciences Journal.

Abstracts

Meißl, G., K. Klebinder, F. Kerl, Ch. Dobler, C. Geitner, F. Schöberl, B. Kohl, G. Markart, B. Sotier, H. Formayer, R. Goler, Th. Gorgas, G. Bürger & A. Bronstert (2014): Sensitivity of runoff behaviour of Alpine catchments to system conditions - looking at the current and future situation. Geophysical Research Abstracts Vol. 16, EGU2014-10672, 2014. http://meetingorganizer.copernicus.org/EGU2014/EGU2014-10672.pdf

Meißl, G., K. Klebinder, C. Dobler, C. Geitner, F. Schöberl, F. Kerl, B. Kohl, G. Markart, B. Sotier, H. Formayer, R. Goler, Th. Gorgas, G. Bürger & A. Bronstert (2013): SeRAC-CC - Sensitivität der Abflussprozesse kleiner alpiner Einzugsgebiete auf Klimaänderungen. Tagungsband zum 14. Klimatag, 4.-5. April 2013, Wien, pp. 32-33. http://ccca.boku.ac.at/wp-content/uploads/2012/12/Seiten-aus-Tagungsband_klimatag_v10_27032013_TeilVortraege1.pdf

Meißl G., K. Klebinder, C. Dobler, C. Geitner, F. Schöberl, B. Kohl, G. Markart, B. Sotier, H. Formayer, Th. Gorgas, R. Goler & A. Bronstert (2012): Sensitivität der Abflussprozesse kleiner alpiner Einzugsgebiete auf Klimaänderungen. Tagungsband zum 13. Klimatag, 14.-15. Juni 2012, Wien, P 17 (2 pages). http://www.austroclim.at/fileadmin/user_upload/13._Klimatag2012/Tagungsband.pdf

Goler, R.A. & H. Formayer (2012): Temporal disaggregation of daily meteorological data to 15-minute intervals for use in hydrological models. EMS Annual Meeting Abstracts, Vol. 9, EMS2012-174-1. http://meetingorganizer.copernicus.org/EMS2012/EMS2012-174-1.pdf

Reports

Klebinder, K., B. Kohl, G. Markart, B. Sotier & K. Suntinger (2012): Hochwasserabfluss-bemessung Brixenbach. Unpublished report by order of the Torrent and Avalanche control.

Project workshops for stakeholders

- A stakeholder workshop within the frame of the "Innsbrucker Hofburggespräche" was organised on 1 April 2014 in the assembly hall of the University of Innsbruck in order to present project results and put them into the context of international research results. About 70 participants from science, local authorities and engineering offices took part in intensive discussions. (http://www.bfw.ac.at/rz/bfwcms.web?dok=9827)

- On 12 May 2014 results from the project with a focus to the Ruggbach catchment were presented to external experts from the government of Vorarlberg and the Austrian avalanche and torrent control. Because of a current revision of the hazard maps for the communities of Lochau and Hörbranz including the design of technical measures for the lower channel of the Ruggbach, the results of the current project were in the centre of interest. Furthermore a presentation of results took place for the mayors of the communities Lochau, Hörbranz and Eichenberg on this day.

Presentations

- Oral presentation by G. Meißl: "Sensitivität der Abflussprozesse kleiner alpiner Einzugsgebiete auf Klimaänderungen." at the Day of Hydrology in Freiburg, Germany (22-23 March 2012)
- Poster presentation by C. Dobler "Sensitivität der Abflussprozesse kleiner alpiner Einzugsgebiete auf Klimaänderungen." at the 13th Austrian Climate Day, Vienna, Austria (14-15 June 2012)
- Poster presentation by R. Goler "Temporal disaggregation of daily meteorological data to 15-minute intervals for use in hydrological models" at 12th EMS Annual Meeting and 9th European Conference on Applied Climatology in Lódz, Poland (10-14 September 2012)
- Oral presentation by G. Meißl "Sensitivität der Abflussprozesse kleiner alpiner Einzugsgebiete auf Klimaänderungen." at the 14th Austrian Climate Day, Vienna, Austria (4-5 April 2013)
- Oral presentation by K. Klebinder "Sensitivität der Abflussreaktion kleiner alpiner Wildbacheinzugsgebiete auf Änderungen des Systemzustands." at the 4. Umweltökologisches Symposium at LFZ Raumberg-Gumpenstein, Austria (18-19 March 2014)
- Oral presentation by H. Formayer "Eintrittswahrscheinlichkeiten extremer meteorologischer Bedingungen jetzt und in der Zukunft" at Innsbrucker Hofburggespräche „Systemzustände – Ausgangsbedingungen für Hochwasserereignisse jetzt und in der Zukunft", University of Innsbruck, Austria (1 April 2014)
- Oral presentation by K. Klebinder "Abhängigkeit der Abflussreaktion alpiner Einheiten vom aktuellen Systemzustand" at Innsbrucker Hofburggespräche „Systemzustände – Ausgangsbedingungen für Hochwasserereignisse jetzt und in der Zukunft", University of Innsbruck, Austria (1 April 2014)
- Oral presentation by A. Bronstert "Möglicher Wasserrückhalt im Einzugsgebietsmaßstab in Abhängigkeit von Niederschlagsintensität, Bodeneigenschaften und Landnutzung" at Innsbrucker Hofburggespräche „Systemzustände – Ausgangsbedingungen für Hochwasserereignisse jetzt und in der Zukunft", University of Innsbruck, Austria (1 April 2014)
- Oral presentation by G. Meißl "Identifizierung kritischer Kombinationen von Systemzustände und Ereigniseigenschaften und deren zukünftige Eintrittswahrscheinlichkeiten" at Innsbrucker Hofburggespräche „Systemzustände – Ausgangsbedingungen für Hochwasserereignisse jetzt und in der Zukunft", University of Innsbruck, Austria (1 April 2014)
- Poster presentation by G. Meißl "Sensitivity of runoff behaviour of Alpine catchments to system conditions - looking at the current and future situation." at the European Geosciences Union, General Assembly 2014, Vienna, Austria (27 April – 2 May 2014)
- Oral presentation by G. Meißl "Auswirkungen des Klimawandels auf die Eintrittswahrscheinlichkeit kritischer Niederschlagsereignisse und Systemzustände in kleinen alpinen Einzugsgebieten" at the Tri-national Workshop – Hydrological Processes in High-altitude Mountains" of the hydrological societies of Germany, Switzerland and Austria in Obergurgl, Tyrol (28 - 30 September 2014)
- Poster presentation by K. Klebinder "Systemzustandsfaktoren in Wildbacheinzugsgebieten und deren Einfluss auf die Abflussbemessung" at the Tri-national Workshop – Hydrological

Processes in High-altitude Mountains" of the hydrological societies of Germany, Switzerland and Austria in Obergurgl, Tyrol (28 - 30 September 2014)

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