PUBLIZIERBARER ENDBERICHT

A) Projektdaten

Kurztitel:	CILFAD
Langtitel:	Climate Impact on Low Flows And Droughts
Programm inkl. Jahr:	ACRP - 2nd Call for Proposals, 2010
Dauer:	01.01.2011 bis 31.12.2013
KoordinatorIn/ ProjekteinreicherIn:	Prof. Gregor Laaha Institute of Applied Statistics and Computing (IASC) University of Natural Resources and Life Sciences (BOKU), Vienna
Kontaktperson Name:	Prof. Gregor Laaha
Kontaktperson Adresse:	Gregor Mendel-Str. 33, 1180 Wien
Kontaktperson Telefon:	+43 1 47654 5066
Kontaktperson E-Mail:	gregor.laaha@boku.ac.at
Projekt- und KooperationspartnerIn (inkl. Bundesland):	Prof. Günter Blöschl, TU Vienna Dr. Wolfgang Schöner, ZAMG Vienna
Schlagwörter:	Low flows, droughts, hydrology, water scarcity, spatio-temporal statistics, downscaling, regional climate models, water resources management
Projektgesamtkosten:	316 000 €
Fördersumme:	316 000 €
Klimafonds-Nr:	B060362
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B) Project overview

1 Kurzfassung

Ziel des Projekts ist die Analyse potentieller Auswirkungen des Klimawandels auf Niederwasser und Trockenheit in Österreich. Die Studie besteht aus mehreren aufeinander abgestimmten Work Packages. In WP1 und WP2 werden die zeitlichen Charakteristiken von Niederwasserabflüssen ausgewertet. Hierzu wird eine umfassende Trendstudien durchgeführt, die stationsweise Trendanalysen, zeitliche Stabilität, Feldsignifikanz, räumliche Trendanalyse und geostatistische raum-zeit Analysen in kohärenter Weise kombiniert. In WP3 werden GCM Szenarien für die Studie erschlossen und die regionalen Klimasignale analysiert. Die Analyse verwendet verschiedene meteorologische Trockenheitsindices auf Basis regionaler Langzeitdaten (HISTALP Datensatz) und Klimaszenarien und untersucht deren Zusammenhang mit dem Niederwassersignal. In WP4 und WP5 werden Klimaprojektionen des Niederwasserabflusses durch ein mechanistisches Modell berechnet. Hier wird ein innovativer Ansatz verfolgt der Niederschlags-Abfluss Projektionen mit stochastischen Projektionen kombiniert. Während beim Delta-change Ansatz projizierte Klimareihen Eingang finden, werden beim stochastischen Ansatz die Zeitreihencharakteristiken von Niederschlag und Temperatur für die Projektion erschlossen. Durch Kombination aller innovativen Ansätze können zuverlässigere Aussagen über klimabedingte Änderungen erzielt werden als durch jeden der Ansätze alleine.

Die Ergebnisse des Projektes bestehen in Methodenentwicklungen und Aussagen für Österreich und Nachbarregionen in Bayern, Slowakei, Ungarn und Südtirol. Für die Region nördlich der Alpen ergeben Trendextrapolation der beobachteten Niederwasserabflüsse und stochastische Projektionen keine signifikanter Änderungen, RCM Szenarien einen geringen Anstieg in naher Zukunft, sowie einen etwas deutlicher erkennbare Abnahme in fernerer Zukunft. Die Kombination aller Informationen lässt somit keine signifikante Änderung in der Periode 2020-2050 (mittelharte Aussage) und eine geringe Abnahme in der Periode 2050-2080 (weiche bis mittelharte Aussage) erwarten. Die Region südlich der Alpen lässt eine Untergliederung in zwei Zonen mit unterschiedlichen Klimafolgen erkennen. Der Südwesten (weite Teile Kärntens) verhält sich ähnlich wie die Region nördlich der Alpen. Hier führen alpine Einflüsse der höhergelegenen Gewässerabschnitte zu einer Dämpfung von klimabedingen Trends zu geringeren Niederwasserabflüssen. Der Südosten (Burgenland, Weststeiermark, Ostkärnten) zeigt ein räumlich homogeneres Verhalten. Die Projektionen ergeben für 2020-2050 eine geringe Abnahme und für 2050-2080 eine stärkere Abnahme der Abflüsse. In den Alpen zeigen RCM Szenarien eine gute Übereinstimmung mit beobachteten Trends. Hier treten Niederwässer typischerweise im Winter auf und sind durch die saisonale Temperatur gesteuert, deren Entwicklung durch RCMs gut prognostizierbar sind. Die kombinierte Information der Projektionen ergibt eine Zunahme um 20-40% für 2020-2050 (harte bis mittelharte Aussage) und um 30-50% für 2050-2080 (mittelharte Aussage).

2 Executive Summary

Current climate change scenarios suggest an increasing risk of droughts and associated low streamflows for European water bodies. The possible impacts have been assessed in a number of international studies which are either based on a mechanistic or upward approach (model chain experiments of climate scenarios) or a downward approach (trend analysis of streamflow observations). The projections from these studies, however, are still highly uncertain, due to either the uncertainty of climate change scenarios, or the limited record length of streamflow observation.

The aim of the project “Climate impacts on low flows and droughts (CILFAD)” is to analyse the potential impact of climate change on low flows and droughts in Austria. The study is designed to overcome the limitations of upward and downward studies using different sources of information. The approach adopted consists of a number of complementary work packages that are designed to strengthen the credibility of the impact projections.

The purpose of WP1 is to obtain an understanding of the temporal characteristics of low flows in Austria, and WP2 extends this analysis to a spatial context. We perform one of currently most complete trend assessments by combining at-site trend analysis, temporal stability assessment, field significance analysis, spatial trend analysis and geostatistical space-time analysis in a coherent way. Results are used in a simple trend extrapolation model to prescribe observed changes to the future.

The purpose of WP3 is to provide downscaled GCM scenarios and to assess changes in the climate signal. The analysis employs various meteorological drought indices calculated from log-term regional data (HISTALP data set) and assesses their link to the low flow signal.
WP4 and WP5 perform climate projections using a mechanistic model. The innovative idea combines rainfall-runoff projections of low flows with stochastic projections of low flows and droughts. While rainfall-runoff projections are based on climatic time series on low flows, the statistical characteristics of these time series, such as time series characteristics (estimated parameters and uncertainty) of precipitation and temperature, are used for the stochastic projections. By combining all innovative ideas we believe to assess climate change impacts more reliable than it is possible with applying the usual scenario technique alone. The findings derived by the project team consist of methodological developments and conclusions from an ensemble of resulting climate projections for the extended Austrian study area.

For the region North of the Alps, extrapolation of observed low flow trends correspond well with stochastic projections and RCM scenarios show a slight increase for near future and a somewhat stronger decrease for further future would be projected. There was no field significance of the observed low flow trends in this region. From all information we expect no significant change for period 2020-2050 (medium confidence) and a slight drying trend for period 2050-2080 (low to medium confidence).

The region south of the Alps appears to be divided into two zones with differing behavior. The western zone (larger parts of Carinthia) shows a similar behavior as the North of the Alps. Here regimes reflect a contribution from mountain areas which likely dampen the climatically induced drying trends in lowlands. We expect no significant change for period 2020-2050 (medium confidence) and a drying trend for period 2050-2080 (low to medium confidence). In the eastern zone (Burgenland, W-Styria and to some degree E-Carinthia) low flow trends are strongly influenced by recent dry years, from 2000-2005. The stochastic projections yield more robust projections then low flow trend extrapolation, and RCM projections seem to overestimate low flows for the nearer future but correspond well with the projections for 2050-2080. The stations show a more consistent regional behavior as reflected by field significance analysis. We therefore conclude there is moderate confidence in a slight drying trend for period 2020-2050 and a stronger drying trend for 2050-2080.

For the Alpine region extrapolation of observed low flow trends correspond well with rainfall-runoff projections of RCM scenarios. In these regions low flows occur in winter due to snow storage processes and are mainly driven by seasonal temperature. This is obviously well captured by the RCM scenarios which project temperature with much higher confidence than precipitation. The observed low flow trends are field significant, i.e. the percentage of stations showing a trend is greater than that expected by chance. For stochastic simulations, however, the effect of increasing temperature in the Alps is not well captured. From the combined information of low flow observations and RCM projections we expect an increase in low flows by 20-40% for period 2020-2050 (high to medium confidence) and a further increase by 30-50% for period 2050-2080 (medium confidence).

While the project has led to important findings about future water resources, the meaning of projected changes remains unclear because we only have a limited knowledge of past water resources. A follow-up study shall is planned to address this important research gap, by pushing forward reconstruction of low flows from various proxies, to enhance methods and understanding of the past for better managing the future.

3 Background and objectives

3.1 Initial situation / motivation for the project:

Climate change impacts on low flows and droughts may have a significant impact on socio-economic systems. Low flows and associated streamflow droughts are caused by meteorological anomalies and modified by various catchment processes. While low flows occur regularly during typical seasons, droughts refer to regionally extensive occurrence of below average natural water availability and include meteorological, agricultural and hydrological droughts, depending on the variable concerned. Water resources are a major economic factor in all economies around the world and Austria is no exception. With climate change there are concerns of increasing risks of water shortage. A better understanding of what will be the changed risk of water demand, be it for drinking water, irrigation, industrial purposes or other water uses, not being met by water availability will allow a more prudent management of the water resources. To what extent increasing risks of water shortage would have to be expected will be addressed in this project. Changed low flow regimes and hydrological droughts may also have significant effects on the water quality and the ecological status of the water bodies. Here, the effects for small streams are of particular interest where the relative changes in streamflow can be large. Lower discharges will translate into higher water temperatures with a cascade of chemical and biological processes to follow that can lead to adverse effects on the status of the water bodies. Again, a better understanding of the risk of such changes will greatly enhance the foresight in managing the water resources. A key to making the results useful for the water management practice is a comprehensive assessment of the reliability of the results as, depending on the level of reliability, different management measures may be taken. In all cases, the results target government agencies at both state and federal levels and private businesses and the main benefit will come from reduced costs to the government budgets as well as to private stakeholders due to more efficient management decisions. The proposed project will address climate change impacts on lows flows and droughts in the context of both types of risks, water scarcity and environmental degradation, to assist in developing adaptation measures and better managing the water resources in a sustainable way.

3.2 Objectives of the project

The current project combines the upward and downward strategy in order to better understand climate impacts on low flow and drought in Austria. The combination of different approaches is a prosperous way to reduce predictive uncertainties inherent to each method. First, we will analyse space time patterns which are more meaningful than trend analysis of individual sites. This work package goes beyond the traditional single-site trend analyses and identifies spatial fluctuations and trends by exploiting the space-time correlations of low flow and drought patterns. The spatial extents of hydrological droughts and their space-time characteristics will be one of the results from this work package which allow to put the projections of future changes in low flows and droughts into context. Second we will not simply use mechanistic models for projecting climate changes on low flows. However, we will analyse how mechanisms will affect climate change. The innovative idea combines rainfall-runoff projections of low flows with stochastic projections of low flows and droughts. While rainfall-runoff projections are based by climatic time series on low flows, the statistical characteristics of these time series, such as the probability of dry spells, are used for the stochastic projections. The stochastic approach allows to analyse a much wider range of probabilities than the more traditional rainfall-runoff approach. Also, the stochastic approach allows to run partial scenarios that represent climate change effects with different levels of credibility. Future air temperatures are known with better confidence than is future precipitation and these differences are mapped onto the low flow and drought projections. By combining both innovative ideas we believe to assess climate change impacts more reliable than is possible with applying the usual scenario technique alone.

4 Project content and results

4.1 Content

The approach adopted consists of a number of complementary work packages that are designed to strengthen the credibility of the impact projections. The purpose of work package 1 is to obtain an understanding of the temporal characteristics of low flows in Austria. This is the starting point of the project and includes checking the quality of the runoff data to identify any anthropogenic effects on the low flow records. Such a quality check is important as anthropogenic activities such as reservoir operation and water transfer can significantly alter the streamflow regime, particularly at the low end of the flow duration curve. Work package 2 extends this analysis to a spatial context. This work package goes beyond the traditional single-site trend analyses and identifies spatial fluctuations and trends by exploiting the space-time correlations of low flow and drought patterns. We test spatial functional clustering as a novel technique for finding groups of stations with similar trends. The space-time characteristics of low flows and droughts and notably their trends are results from this work package which allow putting the projections of future changes in low flows and droughts into context. Work package 3 develops atmospheric drought scenarios, based on dynamic downscaling of scenarios from Global Circulation Models. These atmospheric scenarios are exploited in two ways. The first, covered in work package 4 uses air temperature and precipitation time series for grid cells to drive a rainfall runoff model for the catchments under study. The result of this work package will be projected time series of runoff which are particularly geared towards representing low flows well. From this, changes in low flows and hydrological droughts are estimated. The second, covered in work package 5, are stochastic simulations. The difference is that, instead of climatic time series, the statistical characteristics of these time series, such as the duration of dry spells, are used. Climate impact is then evaluating by changing the statistical characteristics and performing stochastic simulations. This procedure allows analysing a much wider range of probabilities than the more traditional approach of work package 4. Also, the stochastic approach allows running partial scenarios that represent climate change effects with different levels of credibility. Future air temperatures are known with better confidence than is future precipitation and these differences are mapped onto the low flow and drought projections. The results of work packages 1 to 5 are combined in work package 6 to evaluate the uncertainties by assessing the consistency of the results from the individual work packages. Important results are estimates of uncertainty bounds of the projections to understand the robustness of the project findings. The layout of the project is shown in Figure 1.

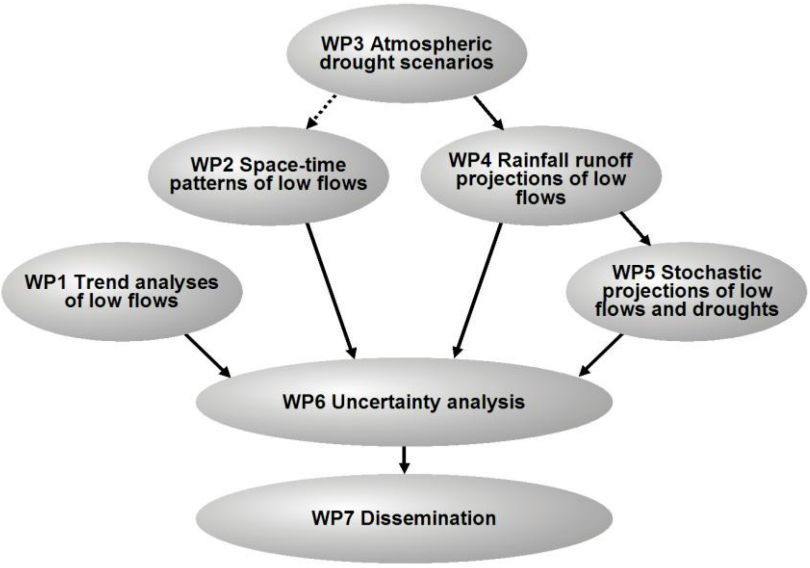

Figure 1: Schematic of the project layout.

4.2 Results

Work package 1 - Trend analyses of low flows

The data set used are annual Q95 low flows (i.e. the flows that are exceeded 95% of the time on an annual basis) of the initially 500 stream gauges in Austria. The data were quality checked and stations with major human effects due to diversions and reservoirs were excluded. Remaining 338 gauges which are classified as natural or not seriously affected by artificial influences will be used as reference data set in all further assessments. Finally, reference low flow characteristics for the remaining work packages were calculated and mapped.

For trend analysis, the study area was extended to neighboring regions of Bavaria (Germany), Slovakia and Hungary to get a more comprehensive picture for hydroclimates of border regions. The extended data set consists of 408 gauges which exhibit a common observation period of 1976-2008. Standard trend analysis was performed on a station by station basis, employing the robust Sen-Slope estimator to annual low flow time series. We did not prewhiten the data (remove first order autocorrelation effects out of time series) as proposed in some studies because (i) we found mostly insignificant serial correlations in the annual low flow series, and (ii) we considered the risk of hiding a trend much greater than detecting an autocorrelation as a trend. First, a reference map of trends in annual Q95 was produced (Figure 2). Significant positive trends (increasing discharges) were found in the Central Alps. Some negative trends (decreasing discharges) were found in Upper Austria and in the South-East of Austria, but here the trends were less significant. A field significance analysis based on the bootstrap method (Renard et al. 2008) was conduced and the analysis confirmed that trends in the Alps and southeast of Alps are significant in a regional scale while trends north of the Alps are not field significant.

In a second step, a seasonal analysis was performed (Figure 2 lower panels). Results show that positive trends in the Alps occur mainly in winter, and are likely related to a reduction of snow storage due to observed temperature increase. Negative trends of Northern Austria and SE-Austria relate to decreasing flows in summer, and are possibly related to increasing evapotranspiration according to increasing temperature. It is surprising that a similar, albeit less significant dipole effect of positive and negative trends can be observed in all seasons, so there is evidence for a general increase of flows in the Alpine region, and a general decrease of low flows in Upper Austria and SE of Austria. There is obviously a strong link of both winter and summer low flow processes to topology and climate. The trend coefficients established by the analysis give an indication of changes in the past 33 years and will serve as a reference for the remaining work packages of this study.

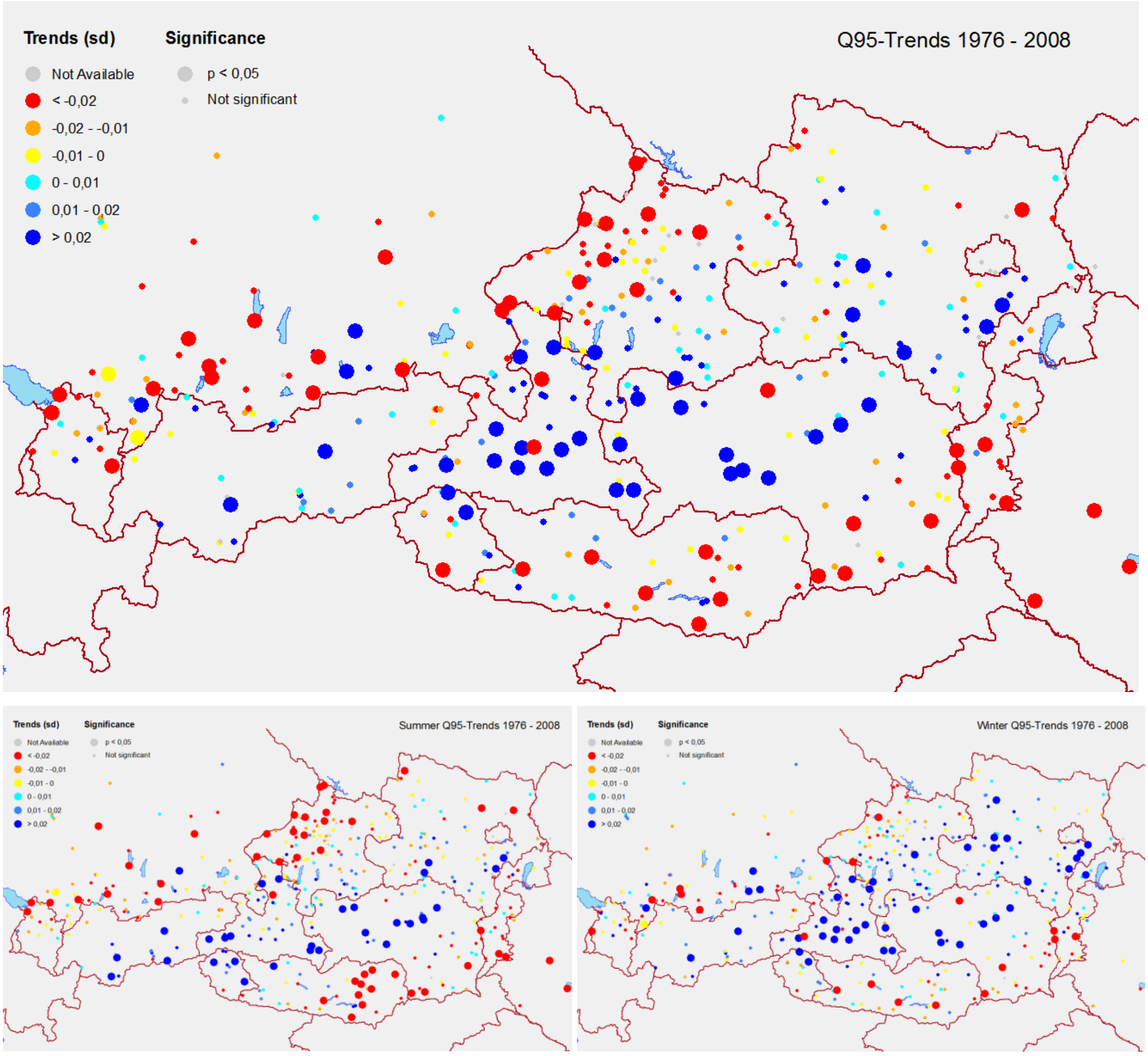

Figure 2: Trends in observed annual low flows (upper panel), summer low flows (lower left) and winter low flows (lower right).

Sensitivity to observation period: Trends as established in this study are sometimes used as a simple model for future predictions, assuming that observed time series are sufficiently long to give insight into long-term changes of the low flow regime. To get an appreciation of the temporal stability of trends we repeated the trend analysis after segmentation into three decades. The analysis showed that there is indeed a clear dependence between trends and the observational window. Short term trends varied in their sign and magnitude over the past decades, and even the time periods covered by long-term streamflow records, typically 30-50 years, appear too short. The increasing trends of Central Alps and decreasing trends of SE-Austria appear relatively stable, whereas trends north of the Alps appear less stable and should be regarded with precaution. We conclude that analyses of longer time periods would be required to get save judgments about current and future stream flow regimes. In an additional step Wavelet analysis was carried out on the data set to shed light on possible long-term fluctuations, but the connection between wavelet transformation and possible Hurst-effects as hypothesized in the proposal could not be established. Obviously, the observation periods are again too short to gain evidence for fluctuations on a longer time scale.

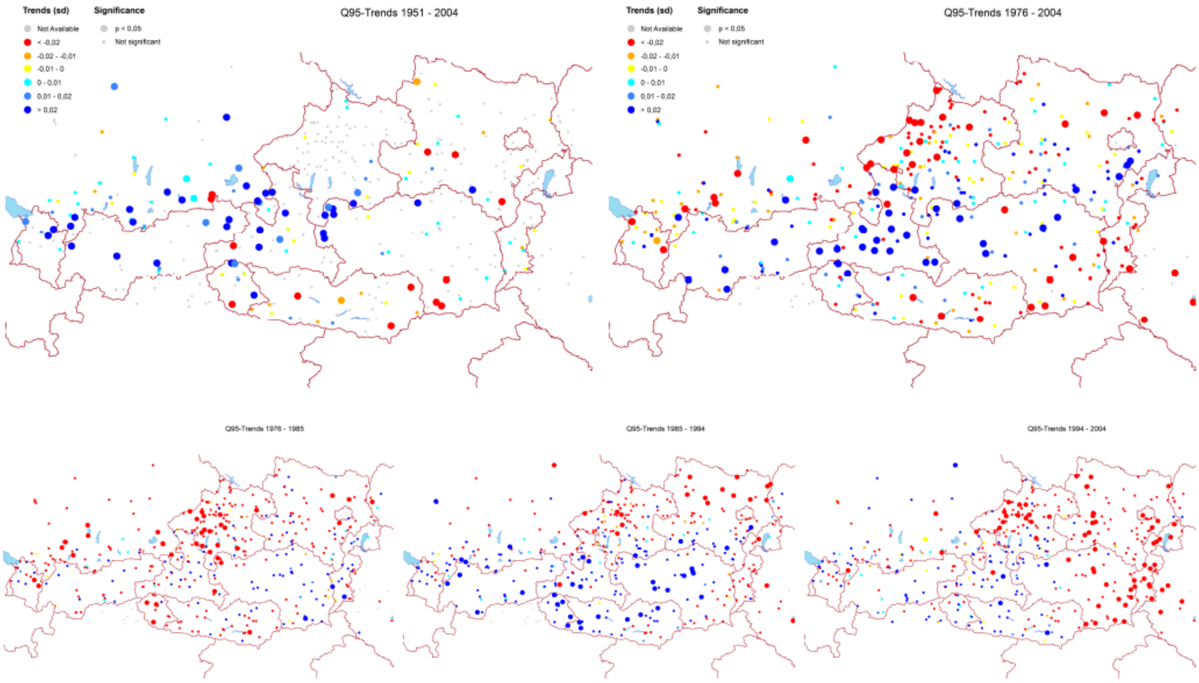

Figure 3: Temporal stability of trends in observed low flows for various observational windows: evidence from long (upper left) and standard (upper right) period, and segmentation of the standard period into trend decades (lower panels).

Comparison with HISTALP: The trends and fluctuations of observed Q95 were compared with rainfall and temperature from the HISTALP data set, which show decreasing precipitation in winter and increasing precipitation in summer. A preliminary analysis showed that the meteorological drought indices such as SPEI or Palmer Drought Index could provide a significant link between HISTALP data and low flow observations which could enable a reconstruction of historic low flows from HISTALP data

Milestones:

- Understanding of the temporal characteristics of low flows in Austria (drought decades)
- Reference low flow characteristics and representative values of trends for the remaining work packages

Work package 2 – Space-time patterns of low flows

Work package 2 extends the analyses of WP1 to a spatial context. This work package goes beyond the traditional single-site trend analyses and identifies spatial fluctuations and trends by exploiting the space-time correlations of low flow patterns. Our specific aim is to estimate trend signals representative for groups of stations, as opposed to local signals which are strongly affected by direct human impacts such as abstractions or storage. Further, to extend the analysis from linear to nonlinear trends. Because of human impacts on a local scale, at-site signals are not quite conclusive for climate induced changes, whereas regional signals are likely much more conclusive.

In a first methodological step, spatial trend analysis was performed by a novel application of spatial functional clustering (Jiang, 2012) to trend estimation. The innovative idea is to estimate and cluster average regional nonlinear trend functions in an iterative way that includes spatial information. This enables a simultaneous detection of trend regions and an estimation of the expected trend signal of these regions. As one advantage, no regions or trends need to be assumed prior to the analysis. In the functional clustering approach every time series Y at location j and year t_i is decomposed into four terms

$$Y_j(t_i) = \mu(t_i) + \mu_k(t_i) + \tau(s_j) + \varepsilon_{ij} \qquad (1)$$

where τ depends on location only and can be thought of as an space dependent intercept, μ_k is the trend of the cluster and μ is a trend component affecting all clusters. As μ could easily be misinterpreted as a global trend, we will look at $\mu + \mu_k$ only referring to it as the cluster trend of cluster k and ε refers to an error term. All trends are linear combinations of a p-spline base.

The analysis was conducted to annual series of winter (November – April) and summer (Mai – October) low flows Q95 of Austria and Bavaria over a time period from 1976 to 2008. The optimum number of clusters was set to three, based on Schwarz's Bayesian information criterion (BIC). The results are shown in Figure 4. The map on the left hand side shows the results of the functional clustering in terms of cluster membership and flags the cluster medoid as the gauge with the most typical trend signal for the region. Note that catchments are plotted at their outlet, although centers of gravity have been used in modeling. The graphs (right panels) show the estimated trend for each cluster together with the Q95 series of cluster members. Again, the signal of the medoid is highlighted. Results indicate an almost linear rising (i.e. wetting) trend along the main ridge of the Alps for both seasons (green color). The cluster corresponds well with the findings of WP1, but includes also gauges with insignificant wetting trends e.g. in the northern Pre-alps and in Waldviertel. Interestingly, the remaining gauges situated North and South-East of the Alps (WP1) are here divided into two clusters with differently decreasing (drying) signals. The red cluster contains gauges where low flows show a decrease for the 1970s to about 1995, and stabilization in summer (and even increase in winter) afterwards. These stations are situated in W-Carinthia, Vorarlberg and the North of Austria and belong to pre-alpine catchments with tributaries from the mountains; hence their trends likely reflect temperature-driven wetting. The blue cluster shows the inverse behavior, with stable regimes until the 1980s and a pronounced falling trend since ca. 1990. Cluster members typically belong to the southeast of Austria, but also some of the gauges north of the Alps show a similar signal. But here the spatial clustering is less clear than for south and southeast of the Alps.

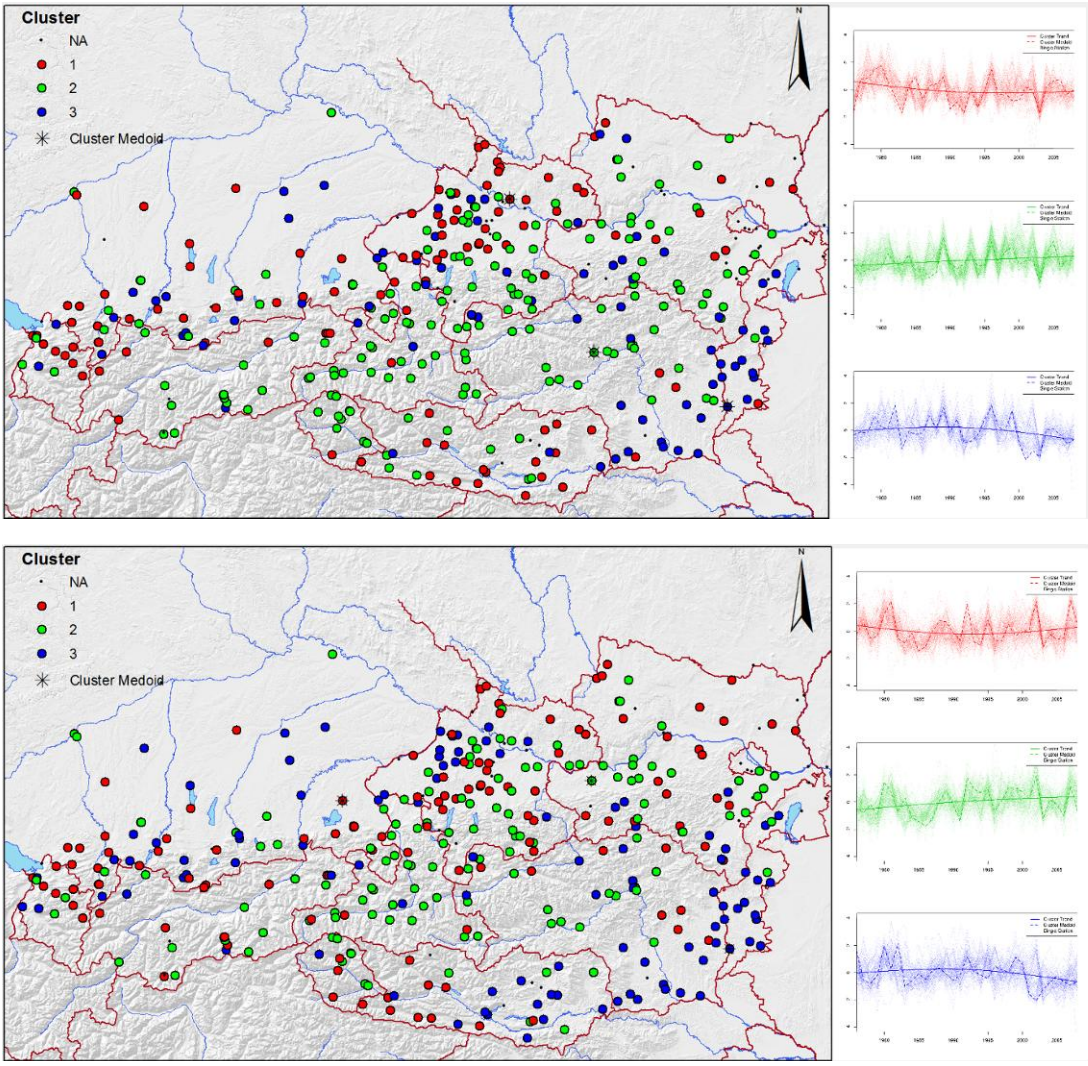

Figure 4: Cluster membership (left) and annual low flow Q95 signals for summer period (upper panels) and winter period (lower panels).

We conclude that the SE of Austria (W-Styria and Burgenland, in winter also E-Carinthia) is most critically effected by climate change as low flows show a strong decrease which might be continued in the future. Alpine catchments, however, seem to have benefited from atmospheric wetting and this trend could also be prescribed into the future.

In a second methodological step, space-time characteristics of monthly low flows are inferred from the streamflow data on the basis of geostatistical space-time modelling (Kyriakidis & Journel, 1999). The model is based on a decomposition of the spatio-temporal low flow pattern in a trend component and the residual component. Both are a function of space and time:

$$y(s,t) = \mu(s,t) + \nu(s,t) \tag{2}$$

The data can be modelled either as a set of spatially varying temporal basis functions or as spatial fields evolving in time. The approach adopted here follows the first case and uses the following model formulation for the mean field (i.e. space-time trend):

$$\mu(s,t) = \sum_{l=1}^{L} \gamma_l \mathcal{M}_l(s,t) + \sum_{i=1}^{m} \beta_i(s) f_i(t) \quad (3)$$

where the first term represents a possible effect of covariates, and the second term represents spatio-temporal trends modeled by a set of (smooth) temporal basis functions which are common to all locations but locally weighted by spatial varying coefficients. The temporal basis functions *fi(t)* are obtained by single value decomposition and represent most important components of temporal trend. The local weights *βi(s)* are treated as spatial random fields (with a spatial covariance structure) and estimated using a universal kriging estimator. Modeling was performed for time series of monthly specific low flows q95 ($ls^{-1}km^{-2}$) using the R-package SpatioTemporal. The results were checked for convergence and predictive performance and the fit was found acceptable. Hence it was used as a visualisation tool of temporal change in a spatial context. Figure 5 shows results for one gauge in Mühlviertel. It can be observed that observations are well captured by the predictions.

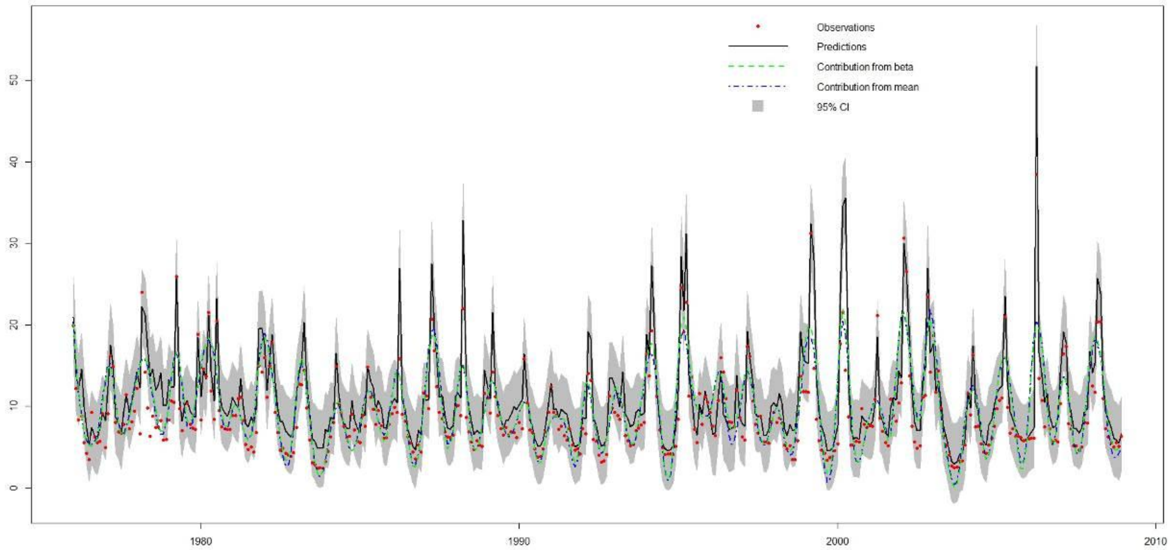

Figure 5: Space-time modelling of monthly low flows q95 ($ls^{-1}km^{-2}$) for gauge Steinerne Mühl at Harmannsdorf (Mühlviertel).

Milestones:

- Understanding of the space-time patterns of low flow in Austria
- Detection of the dynamics of spatial extents of low flow in Austria

Work package 3 - Atmospheric drought scenarios

All available scenario runs of the reclip:century regional climate simulations for the Greater Alpine Regions have been pre-processed and delivered to the TU-Wien as driving data for the hydrologic modelling. The ensemble consists of four individual runs by the Regional Climate Model (RCM) COSMO-CLM, forced by ECHAM5 (three runs, scenario A1B, A2 and B1) and HadCM3 (Scenario A1B).

RCMs offer downscaled values of GCM scenarios but their skills to estimate dry spells for topographically complex areas such as Austria needs to be questioned. As the uncertainty of RCM simulations will be mapped onto the climate projections, it is interesting to assess the skill of RCMs to simulate meteorological drought conditions of the past in order to get an appreciation of their uncertainty.

In a first step we explored the link between meteorological drought indices and streamflow and found that the Standardized Precipitation Evapotranspiration Index (SPEI, Vincente-Serrano et al. 2010) is well suited to represent dry spells in the meteorological signal as an input for streamflow models. The assessment required supplementary analyses beyond the stipulated deliverables of this project and results were published in Haslinger et al. 2014. The SPEI gives a representation of the climatic water balance (precipitation – pot. evapotranspiration) on a monthly or multi-monthly time scale. The balance term is rescaled into standard normal distribution on a monthly basis, showing dry states at negative sign and wet states at positive sign.

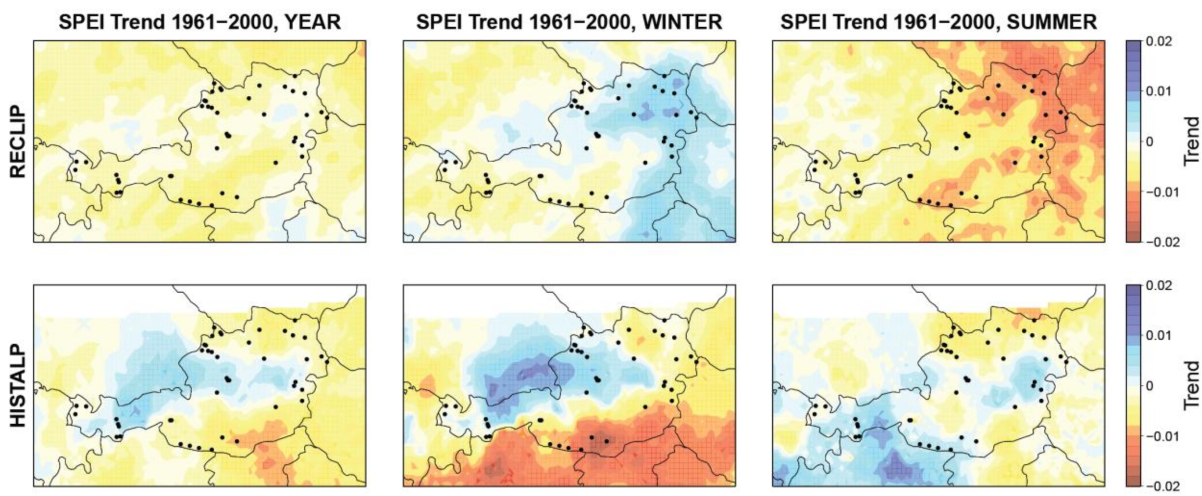

Figure 6: Trends of the SPEI from 1961-2000 from reclip:century RCM-simulations (ensemble mean, upper panel) and HISTALP observations(lower panel) stratified by the annual trend (left), winter trend (centre) and summer trend (right)

In the second step the SPEI trend for the period 1961-2000 was analyzed from both RCM simulations and observational data (HISTALP, Chimani et al. 2012, Chimani et al. 2013), and the results are shown in Figure 6. In general the trend patterns from the reclip:century runs show considerable deviations from observed trends. In winter, we see a larger dipole of drying trend in the south and a trend to wetter conditions in Central Alps in the HISTALP data. From the RCM simulations, however, drying trends would have occurred in the western half of the domain and wetting in the eastern half of the domain. In summer, the HISTALP based SPEI shows a rather patchy pattern of positive and negative trends, whereas in reclip:century a negative trend of the SPEI is apparent which enhances towards the east.

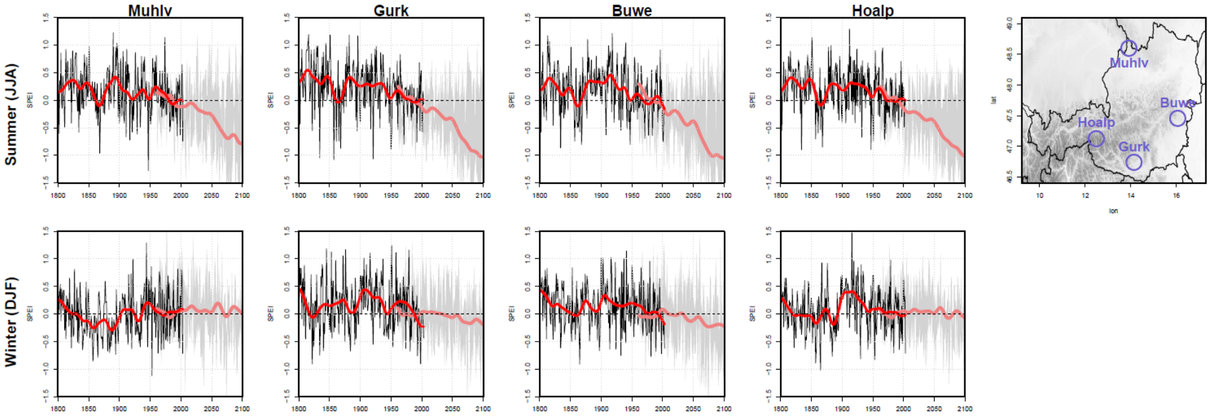

Figure 7: Past (HISTALP, black) and projected future (reclip:century ensemble spread, grey) evolution of the SPEI in summer (upper panel) and winter (lower panel) for four different climatic regions in Austria; the thick red and lightred line represents the Gaussian low-pass filter of the past and future SPEI time series respectively.

An assessment of future droughts in the context of past changes and present conditions is shown in Figure 7. For the four different climatic regions in Austria, representing different low flow trends (negative trend N-Austria – Muhlv, negative trend SE-Austria – Buwe, Gurk and positive trend – Hoalp) the SPEI evolution from 1801 to 2100 is shown, based on HISTALP observations and the reclip:century ensemble. In summer a considerable negative future SPEI trend in all regions in apparent. Deviations of the observed trend and the reclip:century trend in the overlapping period from 1961-2000 are seen in Hoalp, indicating high uncertainties of the projections in the high-alpine areas due to RCM biases (e.g. Haslinger et al. 2012. In winter no future trend is seen in the Muhlv and Hoalp regions, slight negative trends occur in Gurk and Buwe. Again, uncertainties in the high-alpine areas are expected, due to the positive SPEI trend in the observations in Ötztal, which is not confirmed by the future projections.

Apart from climate model uncertainty, the extremely negative trends in the summer SPEI have also to be treated with caution because the potential evapotranspiration calculation within the SPEI algorithm is known for overestimating climate change signals expressed by surface temperature trends, as was shown by Sheffield et al. (2012). More sophisticated methods for estimating evapotranspiration are likely to yield less extreme trends.

Milestones:

- Climate scenarios to be used in WP4
- Climatological drought characteristics to be used in WP5

Work package 4 - Rainfall-runoff projections of low flows

In WP4 the rainfall-runoff projections of low flows were estimated using a delta change approach. Conceptual hydrologic model (TUWmodel, Parajka and Viglione, 2012) was calibrated for 338 catchments selected in WP1. In order to assess the sensitivity of rainfall-runoff projections to parameter uncertainty, different variants of model calibration were performed. The model was calibrated separately in three different decades (1976-86, 1987-97, 1998-08) for assessing the impact of time stability of model parameters (Merz et al., 2011), and by using 11 variants (different weights w_Q) of the compound objective function (Merz et al., 2011) for assessing calibration sensitivity. The trade-off between median of model performance and w_Q found for three calibration periods is presented in Figure 8.

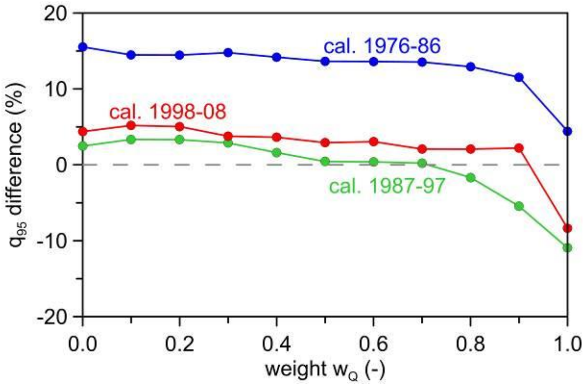

Figure 8. Tradeoff between model performance and weight (w_Q) used for hydrologic model calibration in different decades. Model performance represents median of relative difference between simulated and observed low flow index Q95 (1976-2008) over 338 catchments in Austria.

The low flow estimates and their future projections were derived from TUWmodel daily runoff simulations, both for present conditions (1976-2008) and four future climate scenarios (ECHAM5-A1, A2, B1 and HADCM3-A1) for the periods 2021-50 and 2051-2080. The final results were regionalised to the entire stream network of Austria by using the Top-kriging method (Skøien et al. in press). An example of low flows projection for different climate scenarios is presented in Figure 9. The projections for the period 2021-50 indicate an increase of low flows (Q95) in the Alps, typically in the range of 10 to 30% and a decrease in south-eastern part of Austria (Styria, Burgenland, Carinthia) mostly in the range of -5 to -20%. The change in the seasonality varies between scenarios, but there is a tendency to earlier low flows in the Central Alps and a shift to later occurrence in the Eastern Austria.

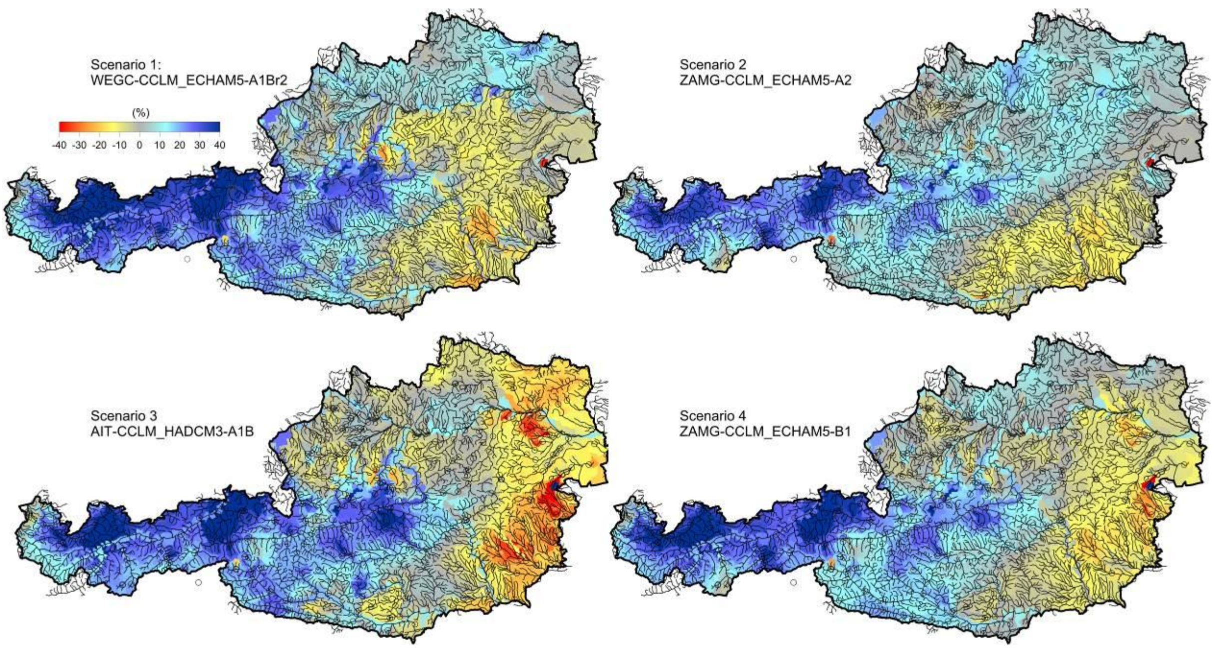

Figure 9. Low flow projections, i.e. relative difference between future (2021-50) and current estimate of Q95 (in %) for four different climate scenarios. Model simulations were performed by using model parameters obtained by the weight w_Q=0.7 (Figure WP4.1.) calibrated in the period 1987-97.

The uncertainty and range of future projections was estimated by comparing simulations from all calibration variants (different decades and objective functions) and climate scenarios. Figure 10 shows the range of low flows changes from four climate scenarios and one calibration variant (left panel) and a total range of changes from all calibration variants and climate scenarios. The uncertainty range from four climate scenarios is within 15-20% at the majority of Austria, while the total model uncertainty from climate scenarios and calibration is much higher: i.e. more than 50%, particularly in the Alps. This suggests the importance of selecting objective functions for modelling low flows projections.

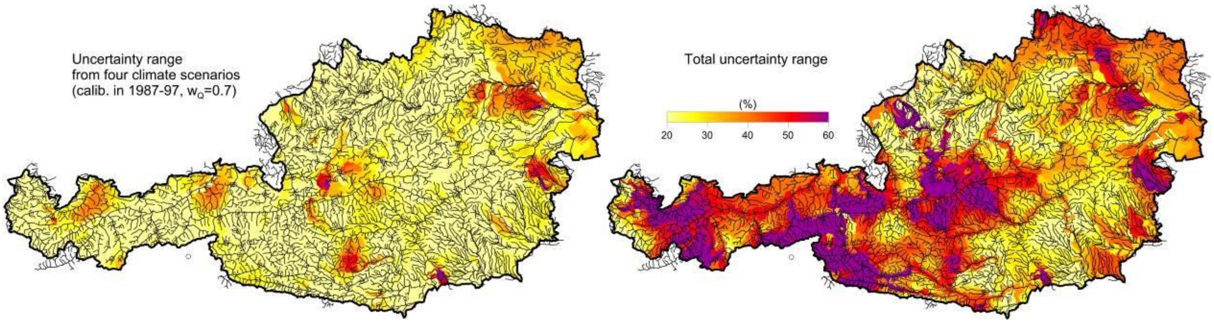

Figure 10. Range of low flows projections from four climate scenarios and one calibration variant (left panel) and from four climate scenarios and all calibration variants (right panel). Low flows projection is defined as a relative difference between future (2021-50) and current estimate of Q95.

Milestones:

- Runoff time series and low flow projections for four climate scenarios.
- Assessment of changes in low flows relative to the current situation and ranges of low flows projection uncertainties.

Work package 5 – Stochastic projections of low flows and droughts

While in WP4 (Rainfall-runoff projections of low flows) the projected future RCM scenarios are used to investigate what could be the change in low-flows in the future, here a different approach is used where no climatic scenarios are analysed. By stochastic projections we investigate what would happen if the trend of observed precipitation and temperature for the 1948-2010 period will continue in the future. This scenario is highly realistic for near future while the degree of realism for far future is more uncertain. A total of 13 hot spots have been chosen that represent the hydrological variability of the Austria (see Table 1). For each hot spot, data from a meteorological station are used to calculate trends in the past. Those trends are then extrapolated to the future and the obtained series are used to feed a rainfall-runoff model calibrated for one representative catchment of the hot spot.

Table 1 - Hot spots.

hs	Name	Name_long	Leitpegel	Leitpegel_Name	Leitpegel_Fluss	LeitMeteo	LeitMeteo_Name
1	Buwe	Bucklige Welt	210245	Altschlaining	Tauchenbach	55	Wörterberg
2	Brewa	Bregenzerwald	200287	Schönenbach	Subersach	45	Schröcken
3	Flysch	Flyschzone	209197	Lachau	Melk	34	Pabneukirchen
4	Hoalp	Hochalpen	212076	Matreier Ta	Tauernbach	48	StJakob_Def
5	Weinv	Weinviertel	208637	Zwingendorf	Pulkau	24	Laa_Thaya
6	Innv	Innviertel	204768	Osternach	Osternach	38	Reichersberg
7	Otzt	Oetztal	201376	Obergurgl	Gurgler Ache	33	Obergurgl
8	Muhlv	Muehlviertel	204925	Harmannsdorf	Steinerne Mühl	34	Pabneukirchen
9	Gail	Gailtal	212670	Rattendorf	Gail	39	Reisach
10	Dachst	Dachstein	205799	Kniewas	Steyr	6	Feuerkogel
11	Waldv	Waldviertel	207944	Zwettl (Bahnbrücke)	Kamp	50	Stift_Zwettl
12	Gurk	Gurktal	212951	Zollfeld	Glan	20	Klagenfurt
13	Leitha	Leitha	208413	Marienthal	Fischa	46	Schwechat

One peculiarity of the method is that the extrapolated trends are not those of the mean annual and seasonal precipitation and temperature. Since the generation of precipitation time series is done through a stochastic model, we have extrapolated trends affecting three parameters of the model: the mean annual storm duration, the mean annual inter-storm period and the mean annual storm intensity. In order to do so, we have applied a storm-separation algorithm to the data, and we have calculated the observed temporal trends of the mean annual storm duration, the mean annual inter-storm period and the mean annual storm intensity. Note that annual trends are calculated (and therefore extrapolated). Therefore contrasting seasonal trends that may be found in the data have not been modelled explicitly, which may be a critical assumption in some of the hot spots.

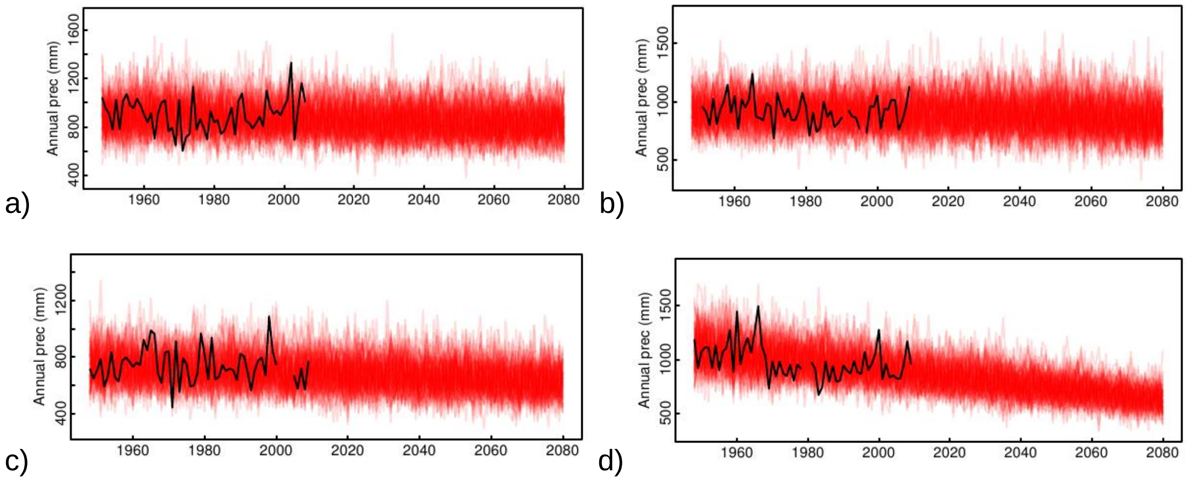

Figure 11. Simulated annual precipitation for a) Pabneukirchen (Muhlv), b) Klagenfurt (Gurk), c) Wörterberg (Buwe), d) St. Jakob im Defreggental (Hoalp)

The stochastic rainfall model has been calibrated to the observations, then has been used to simulate an ensemble of 100 possible time series affected by trends in the model parameters (see Figure 11). For the temperature, instead, the 100 possible time series have been obtained by detrending the observations, mixing randomly the years, and applying the trend on the reshuffled series. The trend in the temperatures is reflected into analogous trend in the potential evapotranspiration. A simplified lumped version of the same TUW rainfall-runoff model has been used, driven by the 100 stochastic inputs.

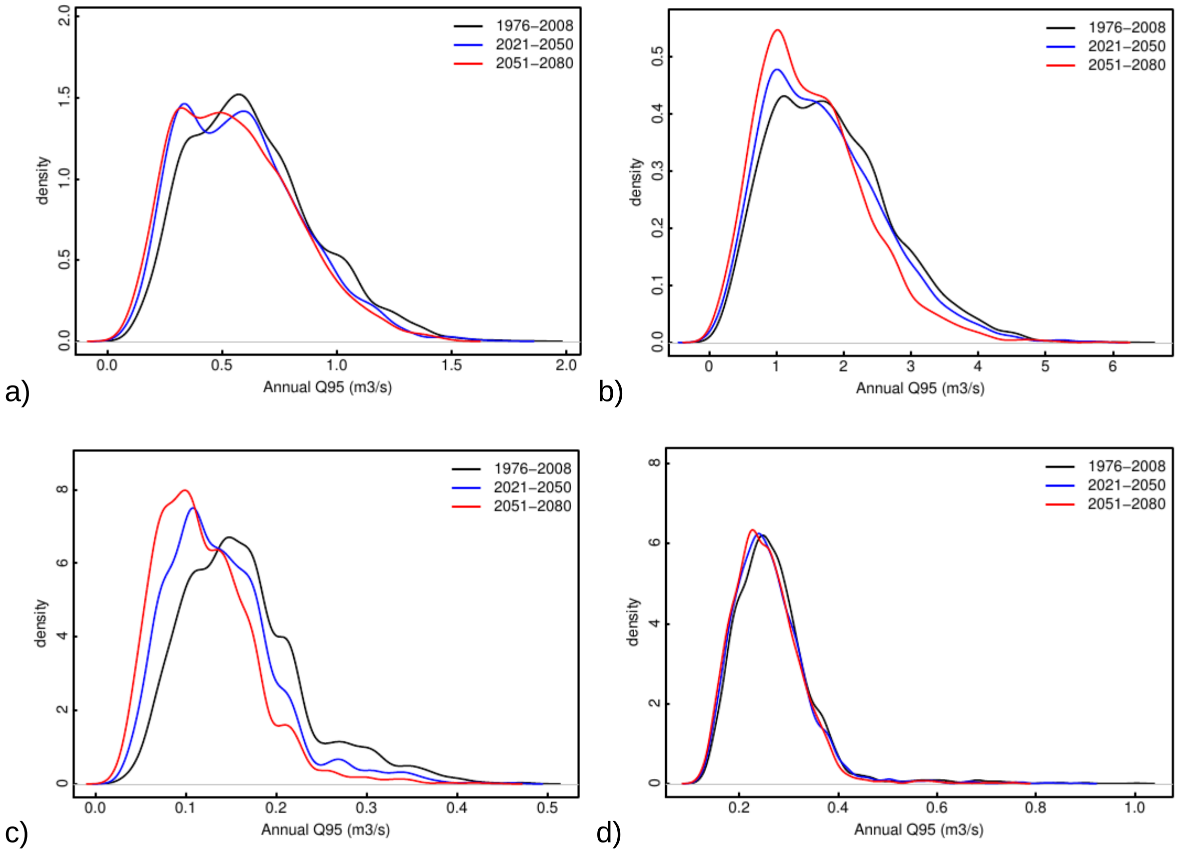

Figure 12. Simulated changes in the Q95 distributions for the rivers a) Steinerne Mühl at Harmannsdorf (Muhlv), b) Glan at Zollfeld (Gurk), c) Tauchenbach at Altschlaining (Buwe), d) Tauernbach at Matreier Tauernhaus (Hoalp)

Figure 12 shows the stochastic projections of Q95 (basis 33 years) together with the observations of the standard period. For the N-Austria (Mühlviertel region, panel a), the models extrapolate a slight reduction of Q95 in the future, even though there is not a reduction in the annual precipitation (Figure 11a), implying that the increasing temperature plays a main role. For the S-Austria (Gurk region), the models also extrapolate a slight decrease in Q95 (Figure 12b), and also in this case the cause is to be searched more in the increase of temperature than in the decrease of precipitation that, as shown in Figure 11b, does not change significantly. For the southeast of Austria (Buwe region) the extrapolated reduction of Q95 is quite important. In this case, the annual precipitation has a slight decrease, which is observable in Fig 10b which adds to the effect of increasing temperature. Interestingly, for the Hochalpen region (Figure 12c) the models do not extrapolate changes of Q95 in the future, despite the large decrease of annual precipitation (Figure 11c).

Milestones:

- Mechanisms of climate induced low flow changes and associate them with levels of confidence
- Quantification low flow changes for the mechanisms above using a stochastic model

Work package 6 – Uncertainty analysis

Previous work packages assessed climate change from different sources of information: streamflow records, rainfall-runoff projections of RCM scenarios, and projections of stochastic climate simulations. Each of the approaches has their merits and shortcomings. Trend analysis is the method with minimal assumptions as no streamflow or climate model is required. Extrapolation of trends will give future projection of the scenario that the change is prescribed to the future. This will give a realistic estimate for close future and a possibly less realistic estimate of far future. However, trend estimation strongly suffers from short observation periods and instrumentation change leading to possible biases for earlier recording periods. The second method, hydrologic projections of GCM scenarios and dynamically downscaled derivatives from RCMs exploits information of process-based simulation of future climate, taking account of different greenhous gas emission scenarios. But RCM simulations have still rather coarse spatial resolutions (10km for the reclip:century simulations) so that projections for complex terrain such as the Austrian study area are subject to considerable downscaling errors. For the study area, projections are not well compatible with long-term observations of climate drivers, as shown in WP3. The third method, stochastic projections makes best use of information in observed climate signal, and has clearly less assumptions then RCM. The weakness of the stochastic simulations is that it is difficult to capture the most relevant statistical characteristics of climate, and it is always unlear if a trend in the observation is real and if it will persist.

All methods provide uncertain projections of low flows and it is suggested here to combine the merits of all methods using the strategy of a three-pillar approach. The overlay of the three pillars, observed trend extrapolation, rainfall-runoff projections of RCM scenarios, and stochastic projections combines different sources of information. Hence, it offers possibility for better predictions as each of the methods alone. On the other hand, the degree to which methods coincide provides information about uncertainty of the future projections. This will be expressed as three (high, medium, low) levels of confidence in accordance with the uncertainty concept of IPCC report (Field et al. 2014). The results for characteristic stations belonging to the three trend zones established in WP1 are presented in Figure 13. Red lines (and fluctuating confidence limits) correspond to stochastic projections, black lines (and blue confidence limits) to observed low flows, and boxplots of rainfall-runoff projections of RCM scenarios for periods 2020-2050 and 2050-2080.

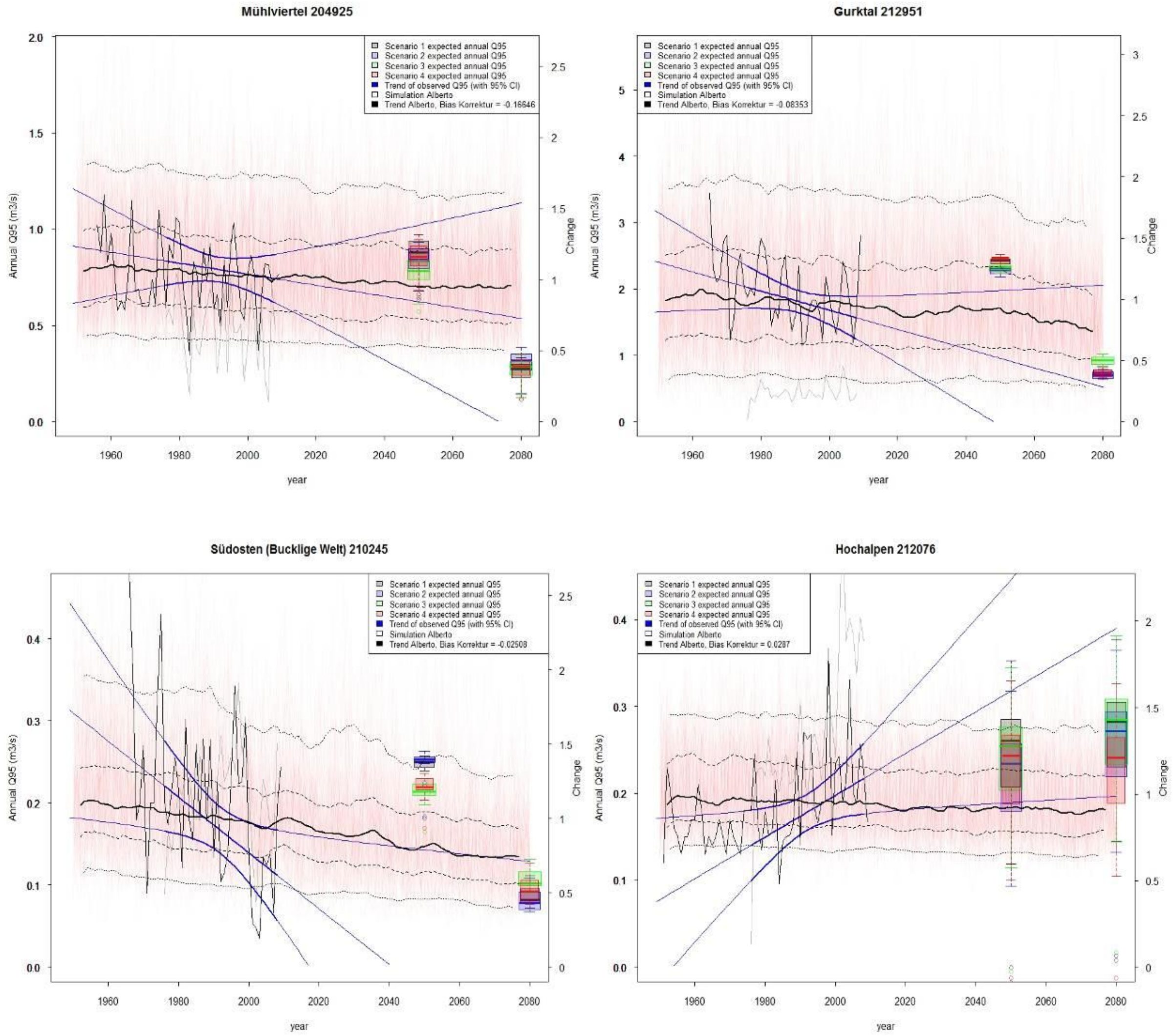

Figure 13. Three-pillar projections of low flows Q95 distributions for the rivers a) Steinerne Mühl at Harmannsdorf (Muhlv), b) Glan at Zollfeld (Gurk), c) Tauchenbach at Altschlaining (Buwe), d) Tauernbach at Matreier Tauernhaus (Hoalp)

For the region North of the Alps, extrapolation of observed low flow trends correspond well with stochastic projections (panel a). Both methods project a slight, insignificant decreasing trend, corresponding to a reduction of about 10% for period 1, and about 20% for period 2. From RCM scenarios a slight increase for near future and a somewhat stronger decrease for further future would be projected. There was no field significance of the observed low flow trends in this region. From all information we expect no significant change for period 2020-2050 (medium confidence) and a slight drying trend for period 2050-2080 (low to medium confidence).

The region south of the Alps appears to be divided into two zones with differing behavior. The western zone (larger parts of Carinthia) shows a similar behavior as the North of the Alps. Here regimes reflect a contribution from mountain areas which likely dampen the climatically induced drying trends in lowlands. We expect no significant change for period 2020-2050 (medium confidence) and a drying trend for period 2050-2080 (low to medium confidence). The eastern zone (Burgenland, W-Styria and to some degree E-Carinthia) behaves differently. As shown in Figure 13c, observed low flow trends are strongly influenced by recent dry years, from 2000-2005. This yields strong negative trends which quantity seems less reliable because the change is not linear, however pointing to a drying effect in this region. The stochastic projections yield more robust projections of a moderate drying trend which, in quantitative terms, corresponds better with the longer-term picture of low flow observations. They predict a decrease of about 15% for period 1, and about 20% for period 2, due to an increasing trend in temperature (high confidence) and a slightly decreasing trend in precipitation (medium to low confidence). In comparison, RCM projections seem to overestimate low flows for the nearer future but correspond well with the projections for 2050-2080. The stations show a more consistent regional behavior as reflected by field significance analysis. We therefore conclude there is moderate confidence in a slight drying trend for period 2020-2050 and a stronger drying trend for 2050-2080.

For the Alpine region extrapolation of observed low flow trends correspond well with rainfall-runoff projections of RCM scenarios (Figure 13d). In these regions low flows occur in winter due to snow storage processes and are mainly driven by seasonal temperature. This is obviously well captured by the RCM scenarios which project temperature with much higher confidence than precipitation and the scenarios correspond well with the observed increase of winter temperature for the Alpine region since the 1970s (Schöner et al. 2012). The observed low flow trends are field significant, i.e. the percentage of stations showing a trend is greater than that expected by chance. For stochastic simulations, however, the effect of increasing temperature in the Alps is not well captured. The model works with annual temperature parameters and this structure is obviously not well suited to predict changes for the winter season. Resulting stochastic projections show no significant decrease of low flows seeming unrealistic in view of observed changes. From the combined information of low flow observations and RCM projections we expect an increase in low flows by 20-40% for period 2020-2050 (high to medium confidence) and a further increase by 30-50% for period 2050-2080 (medium confidence).

Milestones:

- Compare of the uncertainty of changes in low flows due to climate induced changes of WP 1, 2, 4, 5
- Discussion of the changes and their uncertainty in the context of the current literature

Work package 7 – Dissemination

A number of dissemination activities were conducted. As one major activity, the International Symposium on Climate Impacts on Low Flows and Droughts was organized at the BOKU-University from 1-2 March 2012. The conference focused on the current stat-of-the-art to assess past, present and future low flows and droughts and their implications for water resources management. The following questions were discussed:

- What are the main climate drivers of hydrological change related to droughts?
- What is the state-of-the-art of drought modelling, including scenarios, downscaling and coupling models?
- What is known about the time patterns of droughts from observed, reconstructed and projected time series in streamflow and climate variables?

- What are the predictions of future low flows and droughts, and how reliable are such predictions in the light of all the uncertainties involved?
- How do regional assessments fit into Europe-wide analyses, and vice versa?
- What are the lessons on climate impacts on low flows and droughts to be learned for science and water resources management?

We could win leading scientists from hydrology (Lena M. Tallaksen, University of Oslo) and meteorology (Sonia Seneviratne, ETH Zürich and Bodo Ahrens, University of Frankfurt), and key stakeholders (Karl Schwaiger, BMLFUW – Section International Water Management and Christian Kopeinig, Hydrographical Service Carinthia) to give keynotes on current topics from science and water management perspectives.

60 Participants from 15 nations actively participated at the conference through oral talks, poster presentations and in discussion sessions organized after each topical block. The major deliverables include a conference webpage and a printed abstract book that can be downloaded from the conference webpage: http://statistik.boku.ac.at/cilfad2012. As a follow-up, the EGU Leonardo Conference 2014 “HYPER Droughts” is currently organised from the project consortium in a joint effort with EGU and the international FRIEND-Water network programme. For detailed information see http://www.eguleonardo2014.com/ .

The project led to methodological developments and new understanding of what will be the impacts of climate change on low flows and droughts and the associated uncertainty, which were presented regularly at international conferences such as annual EGU General Assembly (not listed here) and by means of publications in international peer reviewed journals. A summary paper describing the three-pillar approach of this project is currently drafted which will be submitted to HESS.

Milestones:

- Workshop to discuss results and implications of findings with a wider group of experts
- Recommendations on climate impact on low flows and droughts as a basis for adaptation strategies
- Publications in peer reviewed journals

5 Conclusions and recommendations

Within the CILFAD project we assessed the climate impacts on low flows and droughts in Austria. In terms of its structure, methods and evaluated information the project enabled perhaps the currently most complete regional study on regional climate impacts on water resources under drought conditions. The findings derived by the project team consist of (i) methodological developments and (ii) conclusions from an ensemble of resulting climate projections for western Greater Alpine Region.

Firstly, we assess climate change from different sources of information: streamflow records, of RCM scenarios, and observed climate signal. All individual assessments provide uncertain projections of low flows and it is suggested here to combine the merits of all methods using the strategy of a three-pillar approach. The overlay of the three pillars, observed trend extrapolation, rainfall-runoff projections of RCM scenarios, and stochastic projections combines different sources of information. Hence, it offers possibility for better predictions as each of the methods alone. On the other hand, the degree to which methods coincide provides information about uncertainty of the future projections.

Not only the combination of information, but also the methods providing the three pillars of projection contain innovative elements. In case of stochastic projections a completely new method was proposed by this study. An alternative approach to RCM scenarios is developed which used prescribes observed trends in the stochastic properties of climate drivers together with their uncertainty as input to catchment models. For trend analysis, we perform one of currently most complete trend assessments by combining at-site trend analysis, temporal stability assessment, field significance analysis, spatial trend analysis and geostatistical space-time analysis in a coherent way. For climate scenarios, we analyzed the reliability of downscaled scenarios in a regional long-term context provided by the HISTALP database and we specifically drought-relevant information of their signal. An additional analysis of the link between atmospheric drought and streamflow was carried out. We perform a detailed regional analysis of the link between meteorological drought indices and streamflow where four drought indices considering different components of the catchment water balance were tested. For rainfall-runoff projections we assessed the sensitivity of projections to calibration period to shed light on the temporal stability, calibration criteria (objective function) and to climate change scenarios. This yields currently one of the most complete uncertainty assessments of rainfall-runoff projections.

Secondly, from the application of all the different methods using various sourced of information a condensed picture about what will be the climate induced changes on low flows was derived. Although the projections are still subject to considerable uncertainty which indeed rises with the time horizon, the combination of different types of projections offers a more reliable assessment on changes of streamflow regimes under drought conditions.

For the region North of the Alps, extrapolation of observed low flow trends correspond well with stochastic projections (panel a). Both methods project a slight, insignificant decreasing trend, corresponding to a reduction of about 10% for period 1, and about 20% for period 2. From RCM scenarios a slight increase for near future and a somewhat stronger decrease for further future would be projected. There was no field significance of the observed low flow trends in this region. From all information we expect no significant change for period 2020-2050 (medium confidence) and a slight drying trend for period 2050-2080 (low to medium confidence).

The region south of the Alps appears to be divided into two zones with differing behavior. The western zone (larger parts of Carinthia) shows a similar behavior as the North of the Alps. Here regimes reflect a contribution from mountain areas which likely dampen the climatically induced drying trends in lowlands. We expect no significant change for period 2020-2050 (medium confidence) and a drying trend for period 2050-2080 (low to medium confidence). The eastern zone (Burgenland, W-Styria and to some degree E-Carinthia) behaves differently. As shown in Figure 12c, observed low flow trends are strongly influenced by recent dry years, from 2000-2005. This yields strong negative trends which quantity seems less reliable because the change is not linear, however pointing to a drying effect in this region. The stochastic projections yield more robust projections of a moderate drying trend which, in quantitative terms, corresponds better with the longer-term picture of low flow observations. They predict a decrease of about 15% for period 1, and about 20% for period 2, due to an increasing trend in temperature (high confidence) and a slightly decreasing trend in precipitation (medium to low confidence). In comparison, RCM projections seem to overestimate low flows for the nearer future but correspond well with the projections for 2050-2080. The stations show a more consistent regional behavior as reflected by field significance analysis. We therefore conclude there is moderate confidence in a slight drying trend for period 2020-2050 and a stronger drying trend for 2050-2080.

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Apart from the dissemination of findings, it is important to continue research on open questions arising from this project. While the project has led to important findings about future water resources, the meaning of projected changes is unclear because we only have a limited knowledge of past water resources. Interpretation of future changes is difficult without the historical context, as we do not know enough about the natural variability of low flows. This also yields uncertainties in the projections, as discussed for trend extrapolation and stochastic simulations where longer time series would be required to get a more comprehensive picture of changes in the past to build up better predictive models. In a similar vein, RCM projections need to be consistent with observed low flow and drought characteristics and a better knowledge of how they perform over a longer past would give new possibilities to with their contained information in a way to enhance projections. It appears from the project that our limited knowledge of the past is the major obstacle for a better understanding of climate change. A follow-up study shall address this important research gap, by pushing forward reconstruction of low flows from various proxies, to enhance methods and understanding for better managing the future.

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C) Project details

6 Methodology

Current climate change scenarios suggest an increasing risk of droughts and associated low streamflows for European water bodies. The possible impacts have been assessed in a number of international studies which are either based on a mechanistic or upward approach (model chain experiments of climate scenarios) or a downward approach (trend analysis of streamflow observations). The projections from these studies, however, are still highly uncertain, due to either the uncertainty of climate change scenarios, or the limited record length of streamflow observation.

The aim of the project "Climate impacts on low flows and droughts (CILFAD)" is to analyse the potential impact of climate change on low flows and droughts in Austria. The study is designed to overcome the limitations of upward and downward studies using different sources of information. The approach adopted consists of a number of complementary work packages that are designed to strengthen the credibility of the impact projections.

The purpose of WP1 is to obtain an understanding of the temporal characteristics of low flows in Austria, and WP2 extends this analysis to a spatial context. We perform one of currently most complete trend assessments by combining at-site trend analysis, temporal stability assessment, field significance analysis, spatial trend analysis and geostatistical space-time analysis in a coherent way. Results are used in a simple trend extrapolation model to prescribe observed changes to the future.

The purpose of WP3 is to provide downscaled GCM scenarios and to assess changes in the climate signal. The analysis employs various meteorological drought indices calculated from log-term regional data (HISTALP data set) and assesses their link to the low flow signal.

WP4 and WP5 perform climate projections using a mechanistic model. The innovative idea combines rainfall-runoff projections of low flows with stochastic projections of low flows and droughts. While rainfall-runoff projections are based on climatic time series on low flows, the statistical characteristics of these time series, such as time series characteristics (estimated parameters and uncertainty) of precipitation and temperature, are used for the stochastic projections. By combining all innovative ideas we believe to assess climate change impacts more reliable than it is possible with applying the usual scenario technique alone. The findings derived by the project team consist of methodological developments and conclusions from an ensemble of resulting climate projections for the extended Austrian study area.

From all analyses, we can see that for the region North of the Alps extrapolation of observed low flow trends correspond well with stochastic projections. However, RCM scenarios show a slight increase for near future and a somewhat stronger decrease for further future would be projected. There was no field significance of the observed low flow trends in this region. From all information we expect no significant change for period 2020-2050 (medium confidence) and a slight drying trend for period 2050-2080 (low to medium confidence).

The region south of the Alps appears to be divided into two zones with differing behavior. The western zone (larger parts of Carinthia) shows a similar behavior as the North of the Alps. Here regimes reflect a contribution from mountain areas which likely dampen the climatically induced drying trends in lowlands. We expect no significant change for period 2020-2050 (medium confidence) and a drying trend for period 2050-2080 (low to medium confidence). In the eastern zone (Burgenland, W-Styria and to some degree E-Carinthia) low flow trends are strongly influenced by recent dry years, from 2000-2005. The stochastic projections yield more robust projections then low flow trend extrapolation, and RCM projections seem to overestimate low flows for the nearer future but correspond well with the projections for 2050-2080. The stations show a more consistent regional behavior as reflected by field significance analysis. We therefore conclude there is moderate confidence in a slight drying trend for period 2020-2050 and a stronger drying trend for 2050-2080.

For the Alpine region extrapolation of observed low flow trends correspond well with rainfall-runoff projections of RCM scenarios. In these regions low flows occur in winter due to snow storage processes and are mainly driven by seasonal temperature. This is obviously well captured by the RCM scenarios which project temperature with much higher confidence than precipitation. The observed low flow trends are field significant, i.e. the percentage of stations showing a trend is greater than that expected by chance. For stochastic simulations, however, the effect of increasing temperature in the Alps is not well captured. From the combined information of low flow observations and RCM projections we expect an increase in low flows by 20-40% for period 2020-2050 (high to medium confidence) and a further increase by 30-50% for period 2050-2080 (medium confidence).

While the project has led to important findings about future water resources, the meaning of projected changes remains unclear because we only have a limited knowledge of past water resources. A follow-up study shall is planned to address this important research gap, by pushing forward reconstruction of low flows from various proxies, to enhance methods and understanding of the past for better managing the future.

Methodological "highlights"

- **Three-pillar approach to assess climate impacts on low flows.** All individual assessments provide uncertain projections of low flows and it is suggested here to combine the merits of all methods using the strategy of a three-pillar approach. The overlay of the three pillars, observed trend extrapolation, rainfall-runoff projections of RCM scenarios, and stochastic projections combines different sources of information. Hence, it offers possibility for better predictions as each of the methods alone. On the other hand, the degree to which methods coincide provides information about uncertainty of the future projections.
- **New spatial approach to trend analysis**: A functional clustering approach is developed which enables simultaneous trend estimation and classification in a space-time context.
- **Stability of trend:** Temporal stability of trends is assessed by a segmentation approach based on various observational windows to investigate trend decades

- **New stochastic approach to rainfall-runoff projections**: An alternative approach to RCM scenarios is developed which used prescribes observed trends in the stochastic properties of climate drivers together with their uncertainty as input to catchment models.
- **Additional analysis of the link between atmospheric drought and streamflow:** During the project scientific interest in the link between atmospheric drought and streamflow emerged and led to a supplementary assessment beyond the stipulated deliverables.
- **Poster award at the Klimatag 2013 for Haslinger et. al** presenting an novel approach to assess the link between atmospheric drought and streamflow

7 Work and time schedule

		Year 1	Year 2	Year 3
WP1	Trend analyses of low flows			
WP2	Space-time patterns of low flows			
WP3	Atmospheric drought scenarios			
WP4	Rainfall-runoff projections of low flows			
WP5	Stochastic projections of low flows & droughts			
WP6	Uncertainty analysis			
WP7	Dissemination			

8 Publication und dissemination activities

We believe dissemination of new understanding of climate change is important so we conducted a number of dissemination activities.

As one major activity, we organised the International Symposium on Climate Impacts on Low Flows and Droughts at the BOKU-University from 1-2 March 2012. The conference focused on the current stat-of-the-art to assess past, present and future low flows and droughts and their implications for water resources management. The following questions were discussed:

- What are the main climate drivers of hydrological change related to droughts?
- What is the state-of-the-art of drought modelling, including scenarios, downscaling and coupling models?
- What is known about the time patterns of droughts from observed, reconstructed and projected time series in streamflow and climate variables?
- What are the predictions of future low flows and droughts, and how reliable are such predictions in the light of all the uncertainties involved?
- How do regional assessments fit into Europe-wide analyses, and vice versa?
- What are the lessons on climate impacts on low flows and droughts to be learned for science and water resources management?

We could win leading scientists from hydrology (Lena M. Tallaksen, University of Oslo) and meteorology (Sonia Seneviratne, ETH Zürich and Bodo Ahrens, University of Frankfurt), and key stakeholders (Karl Schwaiger, BMLFUW – Section International Water Management and Christian Kopeinig, Hydrographical Service Carinthia) to give keynotes on current topics from science and water management perspectives.

60 Participants from 15 nations actively participated at the conference through oral talks, poster presentations and in discussion sessions organized after each topical block. The major deliverables include a conference webpage and a printed abstract book that can be downloaded from the conference webpage: http://statistik.boku.ac.at/cilfad2012. As a follow-up, the EGU Leonardo

Conference 2014 “HYPER Droughts” is currently organised from the project consortium in a joint effort with EGU and the international FRIEND-Water network programme. For detailed information see http://www.eguleonardo2014.com/ .

The project led to methodological developments and new understanding of what will be the impacts of climate change on low flows and droughts and the associated uncertainty, which were presented regularly at international conferences such as annual EGU General Assembly (not listed here) and by means of publications in international peer reviewed journals. A summary paper describing the three-pillar approach of this project is currently drafted which will be submitted to HESS. Below we list important publications in peer reviewed journals arising from this project:

Laaha G, Parajka J, Viglione A, Koffler D, Haslinger K, Schöner W, Zehetgruber J, and Blöschl G: A three-pillar approach to assess climate impacts on low flows. HESS (in preparation).

Haslinger K, Koffler D, Schöner W, Laaha G (2014) Exploring the link between meteorological drought and streamflow: Effects of climate-catchment interaction. Water Resources Research. doi: 10.1002/2013WR015051 (in press).

Stahl K, Vidal J-P, Hannaford J, et al. (2014) Synthesizing changes in low flows from observations and models across scales. Hydrology in a Changing World: Environmental and Human Dimensions. Proceedings of FRIEND-Water 2014, IAHS Publ. 36X. (in press).

Salinas, JL, Laaha, G, Rogger, M, Parajka, J, Viglione, A., Sivapalan, M., and Blöschl, G. (2013) Comparative assessment of predictions in ungauged basins – Part 2: Flood and low flow studies, Hydrol. Earth Syst. Sci., 17, 2637-2652, doi:10.5194/hess-17-2637-2013, 2013.

Viglione A, Parajka J, Rogger M, Salinas JL, Laaha G, Sivapalan M, and Blöschl G (2013) Comparative assessment of predictions in ungauged basins – Part 3: Runoff signatures in Austria, Hydrol. Earth Syst. Sci., 17, 2263-2279, doi:10.5194/hess-17-2263-2013, 2013.

Szolgayova E, Laaha G, Blöschl G, Bucher C (2014) Factors influencing long range dependence in streamflow of European rivers. Hydrological Processes 28:1573–1586. doi: 10.1002/hyp.9694.

Laaha G, Skøien J, Blöschl G (2014) Spatial prediction on river networks: comparison of top-kriging with regional regression. Hydrological Processes 2013. doi:10.1002/hyp.9578.

Laaha G, Skøien JO, Nobilis F, Blöschl G (2013) Spatial Prediction of Stream Temperatures Using Top-Kriging with an External Drift. Environmental Modeling & Assessment 18:671–683. doi: 10.1007/s10666-013-9373-3.

Laaha G, Koffler D (2012) Auswirkungen des Klimawandels auf Niederwasserabflüsse in Österreichs Flüssen und Bächen. In: Universität für Bodenkultur Wien, Quo Vadis, Universität(en)? Festschrift 140 Jahre Universität für Bodenkultur, ISSN: 978-3-900932-10-7.

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