AdaptAlp
Adaptation to Climate Change in the Alpine Space

Bayerisches Landesamt für Umwelt

KLIWA

Klimaveränderung und Wasserwirtschaft

Alpine Space
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Water Balance Modelling for the Inn River Basin

Water Balance Modelling for the Inn River Basin and Improved Precipitation Regionalisation for Southern Tributaries to the Danube in Bavaria using the Physically Based, Fully Distributed Water Balance Model WaSiM-ETH

Based on a report by Pöhler, H., Wendel, S. Schultze, B., Karl, S., Scherzer, J. (Pöhler et al., 2010) commissioned by the Bavarian Environment Agency (LfU), abridged and edited to protect the rights of data owners. The unabridged version of Pöhler et al., 2010 can not be published on the internet for copyright reasons. For more information please contact: jane.korck@lfu.bayern.de

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1 Introduction

Since a change in precipitation pattern is expected due to global warming, the question arises which consequences on the water cycle can be projected regarding water management. Within the cooperation project KLIWA („Klimawandel und Wasserwirtschaft“: Climate change and consequences for water management www.kliwa.de) this question is addressed. In this context there is a need for runoff-models that have a physical basis and manage to simulate actual and future hydrological processes in complex river basins on a wide range of scales. Those runoff-models or water balance models allow an analysis not only of discharge at defined gauges but also the evaluation of the distribution of precipitation, evapotranspiration, groundwater recharge or other parts of the water balance and their changes in space and time. In Bavaria, the model WaSiM-ETH is used for this purpose (Schulla 1997, Kleeberg 1999, Schulla and Jasper 2007).

KLIWA and the Interreg IVb project AdaptAlp (Adaption to Climate Change in the Alps), which started in September 2008, share the aim to simulate the effects of different climate scenarios on the water regime of the Inn River basin. For this purpose, spatially distributed numerical catchment projects, modelling the water balance in different subcatchments of the Inn River basin, have to be established.

The study consists of four sections examining following issues: First, the projects for the upper course of the Inn ending at gauging station Oberaudorf/Inn and the upper course of the Salzach (gauge Golling/Salzach) had to be established. As major discrepancies were detected in interpolated precipitation compared to several indicators, WaSiM-ETH needed to be upgraded regarding the methodology of precipitation interpolation (section 2). Section 3 presents detailed investigations in precipitation interpolation, which were not only conducted for the catchment area of the Inn, but for all southern inflows of the Danube in Bavaria, starting at the gauging station Ulm (Table 1). In a further step, the new models had to be calibrated and the already existing model for the lower course of the Inn had to be recalibrated owing to the new precipitation input data (section 4). The last step is a long model run (1971-2000) and the analysis of the spatial and temporal distribution of several components of the water cycle (section 4.2).

Table 1: Models with WaSiM-ETH within the project

Region	Abbreviation
Danube from inflow of Iller to gauging station Donauwörth, including rivers Iller and Lech	Danube 1
Danube from gauging station Donauwörth to Deggendorf	Danube 2
Danube from gauging station Deggendorf to Johenstein, including river Vils	Danube 3
Isar	Isar
Lower Inn with rivers Alz and Rott	LoInn
Upper Inn	UInn
Upper Salzach	Salz

2 Upgrading WaSiM-ETH

The grid-based **Wa**ter Flow and Balance **Si**mulation **M**odel WaSiM-ETH is a well-established tool for investigating the spatial and temporal variability of hydrological processes in complex river basins. The model can be seen as a reasonable compromise between detailed physical basis and minimum data requirements. Previous applications demonstrated that WaSiM-ETH is able to address successfully very different hydrological problems on a wide range of scales (Schulla and Jasper 2007, Schulla 2009). The model is documented in German and English and can be used free of cost (http://www.wasim.ch).

WaSiM-ETH was continuously improved in order to be used for the evaluation of impacts of climate change. Since 2005 several modules in the model were developed. That is, in detail, the possibility to compute models with layered soils (van Genuchten), to compute a dynamic time step control, and macro-pore discharge. Further, a possibility was implemented to simulate dynamic vegetation development (phenological model). An internal link to groundwater models was added. Furthermore, the module in WaSiM-ETH for lakes, reservoirs and abstractions was improved with regard to a more detailed description of different rules for abstractions and reservoirs and the model now considers evaporation from water surface more precisely. Those improvements were finished 2008 and led to model version WaSiM-ETH v. 8.5.06.

To assess the quality of simulated runoff compared to measured runoff, the performance criterion R^2 as suggested by Nash and Sutcliffe (1970) is used. Because runoff data usually does not fulfil the theoretical requirement of normal distribution the impact of flood peaks is overestimated. Therefore, a second performance criterion (R^2 log) is calculated using the logarithms of the runoff values (Nash and Sutcliffe 1970, Schulla and Jasper 2007).

By an upgrade of the model within this project, the interpolation of meteorological data from station data to surface data may be performed more flexibly than before. Since the new module "RegionalSuperposition" was introduced (WaSiM-ETH version 8.05.00), different methodologies of interpolation can be used now in subregions within the catchment area. The spectrum of interpolation methods in WaSiM is a very broad one: Inverse Distance Interpolation (IDW), elevation dependent regression with external or internal pre-processing, a linear combination of IDW and elevation dependent regression, bilinear interpolation using gridded time series, bilinear interpolation using both gradients and residuals and a linear combination thereof, bicubic interpolation of gridded data or using gradients and residuals, or input of externally interpolated input as grids for each time step. Those interpolation methods can now be used independently in defined subregions of a model area. To avoid boundary effects, a region transition distance can be defined which induces a smooth transition between subregions.

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3 Precipitation

Precipitation is one of the most important input parameters in water balance simulation models. Systematic measuring errors due to evaporation losses and wind drift are known to distort measured precipitation data. Also, given the high variability of precipitation in space and time within a catchment, its interpolation is still a matter of discussion. Realistic interpolated precipitation is needed to achieve simulation accuracy. In previous related studies interpolated precipitation was found to be underestimated along the northern Alpine rim and overestimated in the lowlands between the Danube and Alps (e.g. catchment areas of Zusam, Paar, Vils or Rott; Pöhler et al., 2009).

3.1 Methods

It is common practice to use correction procedures to compensate for systematic measuring errors. In order to compare corrected with uncorrected data, precipitation was corrected for the whole investigation area (catchments of the southern tributaries to the Danube in Bavaria) after Richter (1995). In contrast to a previous study in the same region (Pöhler et al., 2009), station data for the upper valleys of the Inn and Salzach were also included, leading to some minor changes in the interpolated data which affects simulated runoff in the regions Danube1, Danube2, Danube3, Isar and Inn (see Table 1 and Table 2 (appendix)).

In order to improve precipitation interpolation, the new WaSiM-tool "RegionalSuperposition" was used (chapter 2) and regions were defined by different methods. In these regions the ratio between the interpolation methods Inverse Distance Weighting (IDW) and altitude dependent regression (EDREXT) can be weighted differently.

Regions were defined by the following methods:

a. altitudinal belt ("alt.")
b. continentality ("cont.")
c. exposition ("expos.")
d. difference between the interpolated precipitation by IDW and a linear combination of IDW and EDREXT ("IDW/combi")
e. residuals of the altitude dependent regression ("Residuals")
f. difference between the interpolated precipitation by IDW and extern precipitation records ("IDW/REGNIE")

To interpolate precipitation in the defined regions, the following steps were performed: First, all rain gauges and weather stations in the specified region were identified. Second, the meteorological data of these stations were transformed to meteorological input data for WaSiM-ETH. Third, mean annual precipitation was considered in relation to the altitude of the specified rain gauge. The obtained regression coefficient indicates the fraction that can be explained by altitude. For example, a regression coefficient of 0,33 suggests a relative weight of 33% for EDREXT and 67% for IDW in a specified region, respectively. To avoid boundary effects between the defined regions within a project area, the maximum transition distance was introduced. First interpolation results suggested the need for a transition distance also between project areas where boundary effects were found to have occurred. The transition distance was set to 10 km. This width represents a compromise between the total avoidance of boundary effects and the effectiveness of relatively small interpolation regions.

Best results were achieved with the method based on the residuals of the altitude dependent regression (based on Weilguni, 2006). Compared to the other methods, this method led to satisfyingly high precipitation interpolation results in the Alpine foothills. The application of this method required several steps: The mean annual precipitation and the altitude of the measurement stations were related by linear regression. Theoretical precipitation amounts at the stations were calculated with the obtained linear model. Subsequently, the difference between measured and calculated averaged annual precipitation (the residuals) were calculated. Afterwards, residuals were interpolated in ArcMap 9.1 using IDW. Regions were then defined according to the interpolation of the residuals.

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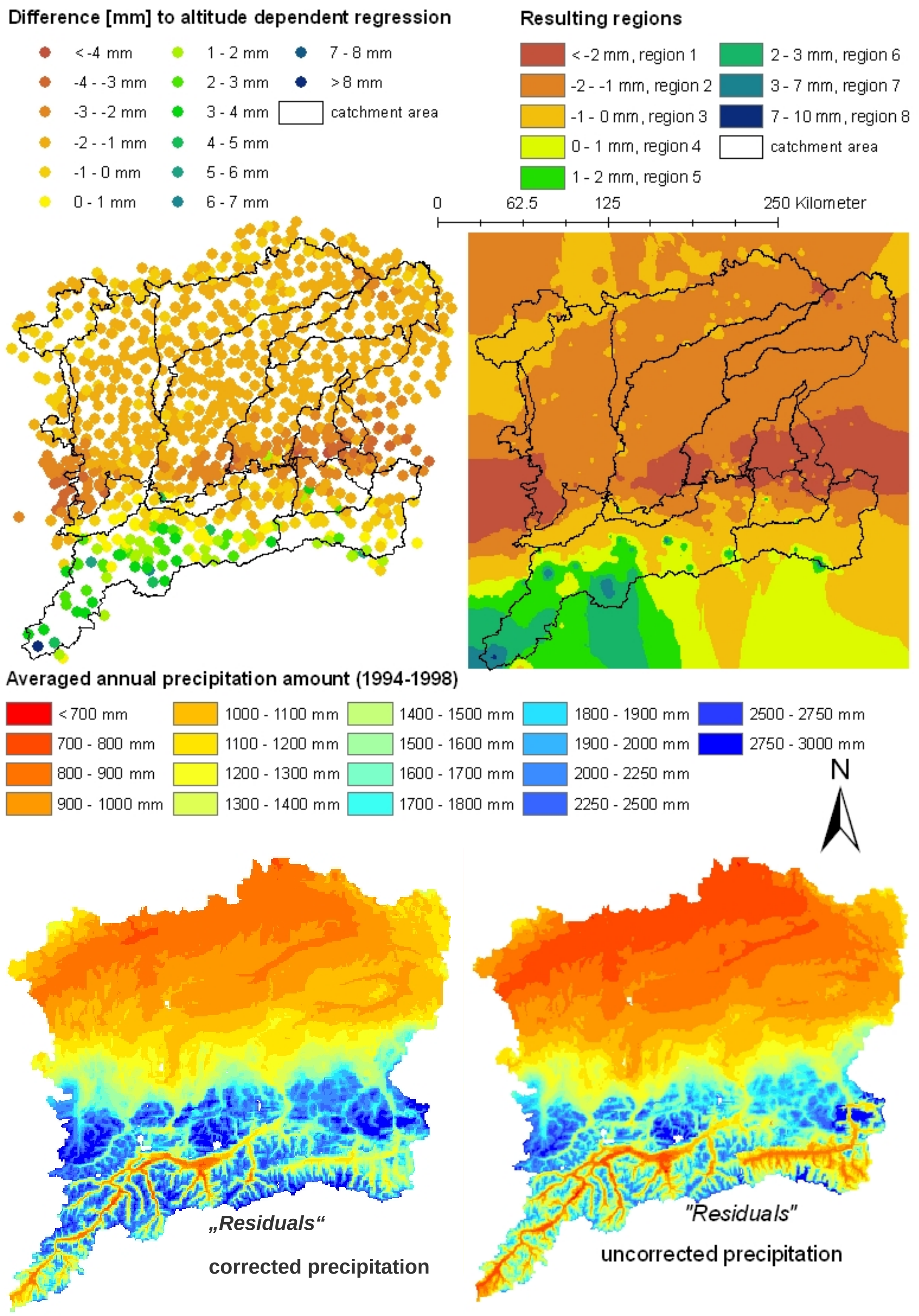

Figure 1: *Method “Residuals”. Top left: Residuals at the individual rain gauges (uncorrected precipitation). Top right: Interpolation via IDW of the residuals (uncorrected precipitation) Bottom left: Precipitation interpolation based on method “Residuals” with <u>corrected</u> precipitation data. Bottom right: Precipitation interpolation based on method “Residuals” with <u>uncorrected</u> precipitation data.*

3.2 Results

3.2.1 Comparison with other hydrometeorological datasets

The precipitation obtained by applying the different “zoning” methods was compared with several existing precipitation datasets. Among them a provisional version (2010) of the so-called “HYRAS” Dataset of the German Weather Service (DWD) and the observational reference dataset used in the GLOWA-Danube Project (Mauser and Strasser 2004, 2007; http://www.glowa-danube.de). The regionalised precipitation data in the HYRAS and the GLOWA datasets cover the whole investigation area. In addition the three independent precipitation datasets REGNIE and HAÖ, that only cover parts of the area of interest, and the Frei and Schär (1998) dataset were included in the study. The HYRAS record was only available for the period 1971-2000 as averaged annual precipitation amount. The GLOWA record was available as monthly averaged precipitation covering the time period from 1971 to 2000.

The precipitation interpolation results based on the different “zoning” methods were similar to one another and did not yield the amount of precipitation in the HYRAS record, except for the method “Residuals”. The GLOWA record clearly differs from any precipitation data simulated by WaSiM-ETH. In general, the interpolated precipitation by WaSiM-ETH shows a more differentiated pattern and is higher compared to the GLOWA-record in the northern part of the investigation area. Alpine precipitation in the GLOWA-record is less altitude dependent than the interpolated precipitation by the method “Residuals” in the specified area.

A comparison of the precipitation interpolated according to the different methods described above (chapter 3.1) with the three different precipitation datasets REGNIE, HAÖ and Frei and Schär shows similar results to the comparison with the HYRAS-data. The different resolutions in the three datasets do not, however, allow a detailed comparison. This applies especially to the Swiss and Austrian parts of the investigation area where the lower resolution of the HAÖ and Frei and Schär precipitation record compared to the REGNIE dataset is evident.

3.2.2 Water balance

In order to compare regionalised precipitation based on different “zoning” and interpolation methods objectively, both with and without the application of precipitation correction, water balance simulations were carried out (Table 2, Appendix). Altogether, 80 simulation runs were performed including seven “zoning” methods with corrected precipitation and three with uncorrected precipitation. A further ten control runs were completed. Measured catchment runoff was compared to simulated runoff for the period 1971-2000. Catchments influenced by reservoirs and/or (external) diversions were not taken into account. Implausible discharge measurements were not considered either. The emphasis of the comparison was on the headwaters, as these are generally less

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exposed to anthropogenic influence. A feasibility evaluation for the mass balance was introduced, based on the assumption that actual evaporation is not strongly affected by the different methods to interpolate precipitation.

In a first step, the influence of the model version of WaSiM-ETH was tested because the modules in WaSiM-ETH had been upgraded. Further, the effect of precipitation correction had to be assessed, because significant differences were identified between precipitation interpolated on the basis of externally corrected precipitation and the correction after Richter (1995) conducted within this study (Table 2, Appendix). Both, the new correction of precipitation data and the new WaSiM-ETH version resulted in slightly higher runoff.

Second, the effect of the different methods to define regions ("zoning" methods) on the water balance was evaluated. It could be shown that small differences between subcatchments occurred between different methods ("alt.", "cont.", "expos", "IDW/combi" and "IDW/REGNIE"). However, a general pattern for the investigation area could be determined. South of the northern Alpine rim, the water balance shows a deficit of between 10 and 50%, whereas north of the Alps about double the amount of water was available in the system. In contrast, the method "Residuals" applied to corrected data induced a clear water surplus all over the investigation area except the headwaters of Inn, Salzach and Ilz.

Due to the systematic overestimation of precipitation in the investigation area induced by the correction after Richter (1995) when combined with the method "Residuals", the interpolation was also performed with uncorrected precipitation input. For comparison, a simulation run with no division of the investigation area into regions and a run combining the method "IDW/combi" with uncorrected data were performed. Both induced an error of less than 10% in wide parts of the northern investigation area. However, as expected, the water deficit in the Alps intensified. The most equalised water balance resulted form the application of the method "Residuals" with uncorrected precipitation input. Nearly the whole investigation area, north of, south of and directly along the northern Alpine rim, is characterised by a more or less even water balance when precipitation is interpolated by this method (Figure 2).

Nevertheless, two main areas can be identified where a definite water surplus and deficit remain respectively: the Isar in the northern Alpine rim and the Ilz in the Bavarian Forest. The water surplus for the upper course of the Isar is partly owing to a hydrogeological peculiarity at the headwaters of Ammer, Loisach and Isar. Most probably, runoff partly bypasses the gauge station as groundwater (compare Pöhler et al. 2009). Moreover, the results of the method "Residuals" might not be appropriate for the climatic characteristics in this specific area. The project GLOWA Danube suggests discharge amounts that are comparable with those derived in this study (compare http://www.glowa-danube.de/atlas/atlas.php, „Simulationsmodelle der Teilprojekte", category „Hydrologie/Fernerkundung", subcategory „Abflussbildung"). The comparatively small number of rain gauges and weather stations at the north-eastern edge of the investigation area results in inadequate runoff simulation causing the deficit at the headwater of the Ilz in the Bavarian Forest. The method “Residuals” by Weilguni (2006) was developed to improve interpolation of alpine precipitation. Hence, this method possibly does not yield optimal simulation results in the Bavarian forest.

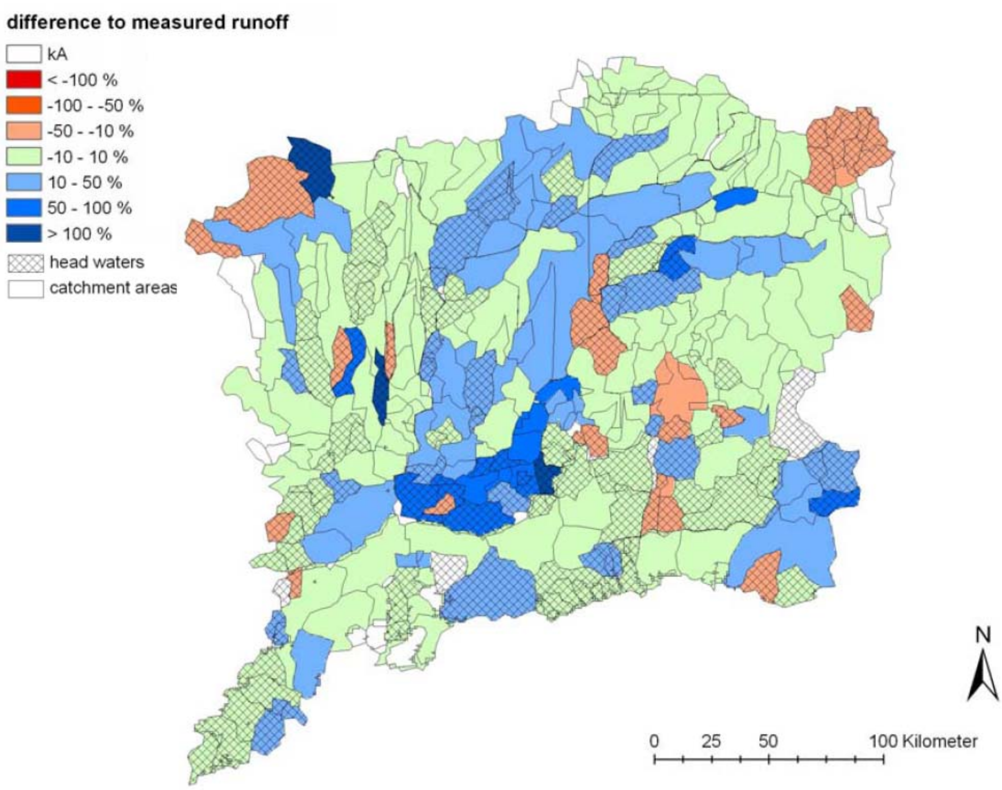

Figure 2: Water balance for the whole investigation area (catchments of the southern tributaries to the Danube in Bavaria).Differences between simulated and measured runoff (1971-2000).

The method „Residuals” with uncorrected precipitation input was chosen for further water balance modelling in the study area because of its even water balance. Before beginning the calibration of the model, the model version was changed from WaSiM-ETH 8.0.10 to WaSiM-ETH 8.5.06. Additional meteorological data, e.g. temperatures, were obtained from weather stations in the investigation area. Furthermore, the parameters for evapotranspiration in the new projects were adjusted to likely values.

Even before calibration, the water balances for the catchment area Upper Inn and Upper Salzach were, to a large extent, even. Only catchment areas which are highly influenced by water management showed greater deviations between simulated and measured data (e.g. Punt dal Gall/Spöl, Hart/Ziller). In the Upper Salzach region only one tributary showed great differences between the modelled and measured quantities of water: Fritzbach (gauge Kreuzbergmaut). The results for the rivers Mangfall and Rott were also not satisfactory at this point. Subsequent optimisation performed within KLIWA led to further improvements for the upper parts of the Isar and Ilz catchments.

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4 Water balance simulation with WaSiM-ETH

4.1 Preprocessing

Preprocessing was conducted separately for two projects: the upper basin of Inn River (UInn, 9715 km²) and the upper basin of the River Salzach (Salz, 3561 km²). The model for the lower Inn basin (LoInn), reaching from the Austrian-Bavarian border to the Danube, was taken from Pöhler et al. 2009 (Figure 3).

To run WaSiM-ETH, various spatially distributed data, time series of meteorological and hydrological data are needed (Schulla and Jasper 2007). For this project, meteorological data from 235 weather stations with data for temperature, relative humidity, sunshine duration and wind speed were used. Also, measured daily precipitation amounts from 1059 rain gauges in the investigation area were available (Figure 4). The model resolution is 1 km². Most spatial data was derived from three basis data sets: the digital elevation model, the land use data and the soil type data. This information was provided by the Bavarian Environment Agency and other partners in the AdaptAlp project.

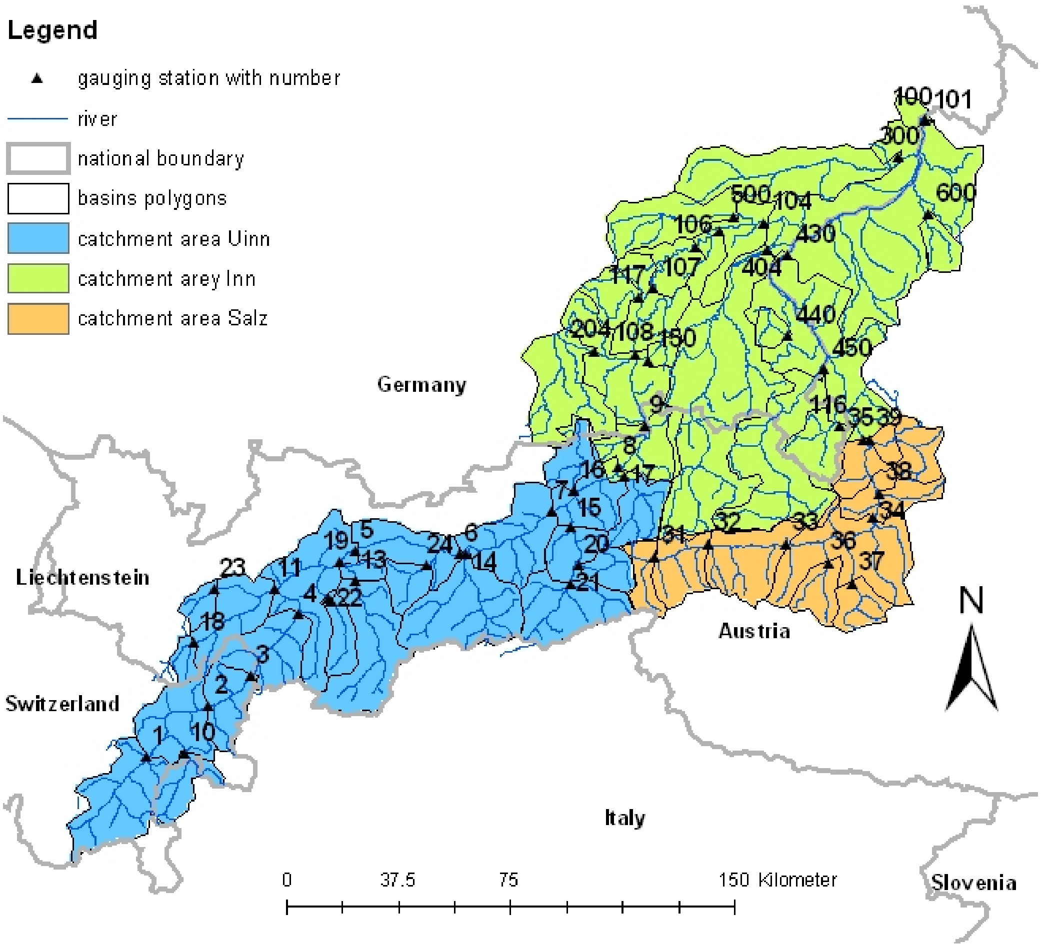

Figure 3: Modelling regions Upper Inn (blue), Salzach (orange), Lower Inn (green). The names of the stations corresponding to the numbers can be found in Table 3- Table 5 (Appendix).

Discharge data from 26 gauging stations in the catchment areas UInn and Salz and from 47 gauging stations in the catchment area LoInn was used. Additional observational data for the model area Upper Inn was included for the tributaries Sanna (gauging stations Galtür-Au and St. Anton), Ziller (gauging stations Mayrhofen and Rohr), Pitzbach (gauging station Ritzenried), Ötztaler Ache (gauging Station Brunau), Vernagt (Vernagtbach), Vent o.N. (Rofenache) and for Vent u.N. (Venter Ache).

The catchment area of the Upper Inn includes the headwaters in the Swiss Engadin with Swiss and Italian tributaries such as Flaz, Spöl and Clemgia. Further Austrian tributaries such as Faggenbach, Sanna, Pitzbach, Ötztaler Ache, Sill, Ziller, Brandenberger Ache and Brixentaler Ache contribute to the runoff considerably. Most upper courses of the tributaries and the headwater of Inn River are characterised by a complex system of reservoirs, inflows, abstractions and bypasses as a part of the extensive use of hydropower. The river Inn receives water from the catchment area of river Isar (before gauge Rotholz) and Salzach (reservoir Durlaßboden) and delivers water from the catchment area of Sanna to the catchment area of the river Ill which is a tributary to the river Rhine. The discharge of the river Salzach and its tributaries Stubache, Kapruner Ache, Rauriser Ache, Gasteiner Ache are influenced by reservoirs, inflows and abstractions similar to the Upper Inn. The Salzach receives water from the catchment area of river Drau and delivers water to the basin of Ziller (UInn). To facilitate the calibration of abstractions and reservoirs, further “pour points” were added in both models (UInn and Salz) and information provided by the AdaptAlp Partners was supplemented with extensive research in available literature. In the catchment area “LoInn”, reservoirs and abstraction-rules were estimated and adjusted if necessary.

In the mountainous regions of the investigation area, low vegetation and mountain forest dominate. However, the valleys in the northern limestone Alps show a different land use than most parts of the Central Alps with a high proportion of pasture land. To the north of the Alpine rim, coniferous forests, pastures and lakes characterise the countryside. The lower valley of the Inn basin north of the Chiemsee and the northern tributaries, especially the catchment area of the Rott, are characterised by agriculture and meadows.

The runoff regimes in some sub-basins, e.g. Cinuos-chel/Inn, Tumpen/Ötztaler Ache, Ritzenried/Pitzbach are highly influenced by glacier discharge. In order to calibrate glacier runoff, additional information from gauging stations Vernagt (Vernagtbach), Vent o.N. (Rofenache) and Vent u.N. (Venter Ache) were included. These stations are either situated directly underneath a glacier (Vernagtbach) or are influenced highly by glacier runoff. To use the glacier-module in WaSiM-ETH, each glacier must have its own basin. Hence some additional pour points had to be integrated.

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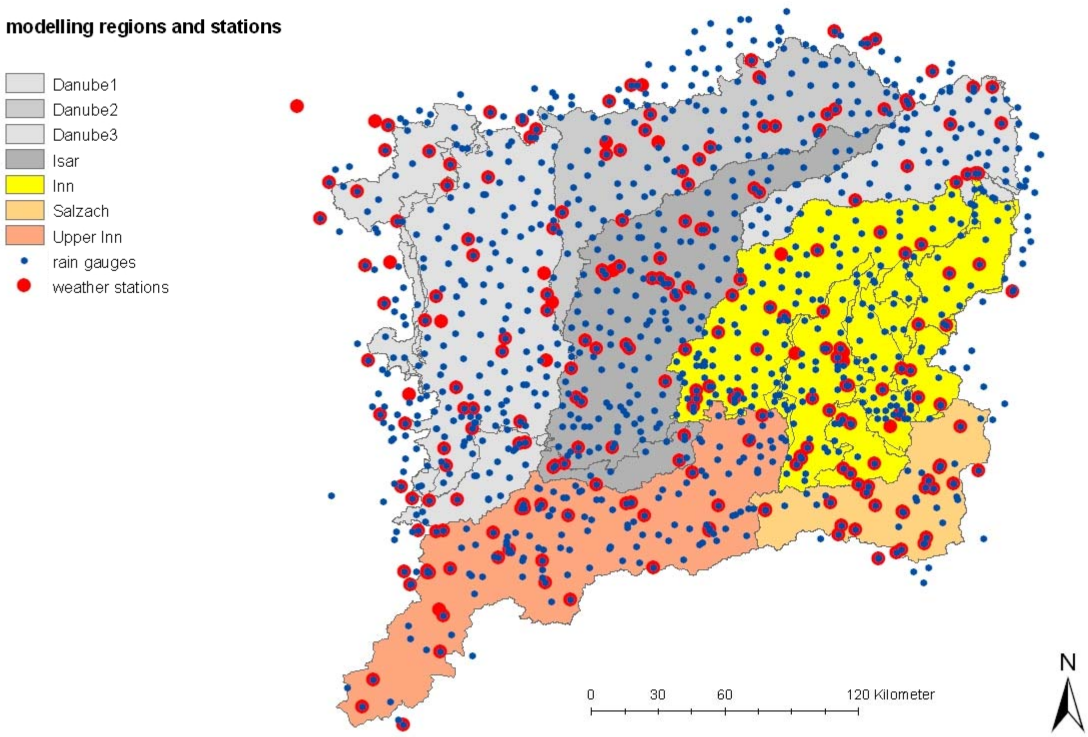

Figure 4: Modelling regions with precipitation and weather stations in the whole investigation area.

4.1.1 Method

A special calibration concept, developed by UDATA for the application of WaSiM-ETH in mesoscale catchment areas, was used. The calibration and validation periods are defined in a first step. The calibration period covers the years from 1994-1998 followed by the validation period 1999-2003. To equilibrate the model, the starting date was set to January 1st 1993 (calibration) and 1998 (validation), respectively.

The second step is the calibration of evapotranspiration regarding the water balance by adjusting the parameters *rsc*, *rs_evaporation* and *intercepCap*. These specific parameters are used to calculate the evapotranspiration after Penman-Monteith in the model (Schulla and Jasper, 2007). The calibration takes difference between measured and modelled runoff for every catchment area with a gauging station into account, considering the discharge averaged over several years and individual years.

Then the parameters of the Richards-equation (Richards 1931) are checked. This third step is conducted for all soil types which are found in the model and for the most important land use types. If unrealistic values for hydraulic head or theta (water content of soil) are found, the parameters are adjusted. The same holds if the interannual dynamic of hydraulic head of theta does not show plausible behaviour. After adjusting those parameters, the water balance is again checked to avoid negative feedbacks to the model.

The fourth step is the calibration of the soil module in WaSiM-ETH (unsatzon_model) and of the parameters which affect the form of runoff. This includes the parameters k_d and *fr* for direct runoff, k_i and d_r for subsurface runoff and k_b and Q_0 for base flow. Also, runoff from glaciers is calibrated by using the parameter k_{ice}, k_{snow}, f_{ice} and f_{snow}. Simultaneously the rules for reservoirs and abstractions are checked, and if necessary adjusted, by using measured data from the respective gauging stations.

Finally, the model is validated and a long simulation run is performed (1999-2003, 1971-2000).

The described calibration concept was applied in principle to the recalibration of the already existing model part for the Lower Inn (LoInn) as well as to the newly set up model parts Upper Inn and Salzach (projects UInn and Salz).

4.1.2 Results

4.1.2.1 Water balance

According to the calibration concept, evapotranspiration parameters and parameters in the glacier module were adjusted in the projects UInn and Salz considering a consistent parameterisation. Further, abstraction rules and volume-runoff-relations of reservoirs were checked and the snow module was adjusted for the projects UInn and Salz separately. Hence, a consistent parameterisation in the snow module is suspended, by taking into account regional peculiarities in the Upper Inn and Salzach valley, respectively (also see chapter 4.1.2.3).

In both projects (UInn and Salz), the water balance can be simulated on a good level (Figure 5). Strong deviations between measured and modelled runoff occur in catchment areas influenced by water management (e.g. Punt dal Gall/Spöl, Hart/Ziller). Though annual runoff amount is produced generally well, the clear water surplus at the gauging station Kreuzbergmaut/Fritzbach is remarkable. This evident difference may be due to discrepancies in the interpolation of precipitation owing to a low number of rain gauges in the specified area (compare Figure 4) or the deviation in the size of the catchment area. The water balances in the eastern subbasins in Salz show a positive trend, indicating pronounced discrepancies in the interpolation of precipitation or impacts of inflows and intensive water management.

Recalibration, with a special focus on the abstraction rules and volume-runoff-relations of reservoirs of the project LoInn, led to a more even water balance. Deviations remain at the rivers Mangfall and Rott. At the Mangfall, abstraction rules were obviously changed in the late 1970’s. The water balance of Rott improved compared to the old project, but the water surplus remains, most probably because of overestimations of interpolated precipitation in the headwater area.

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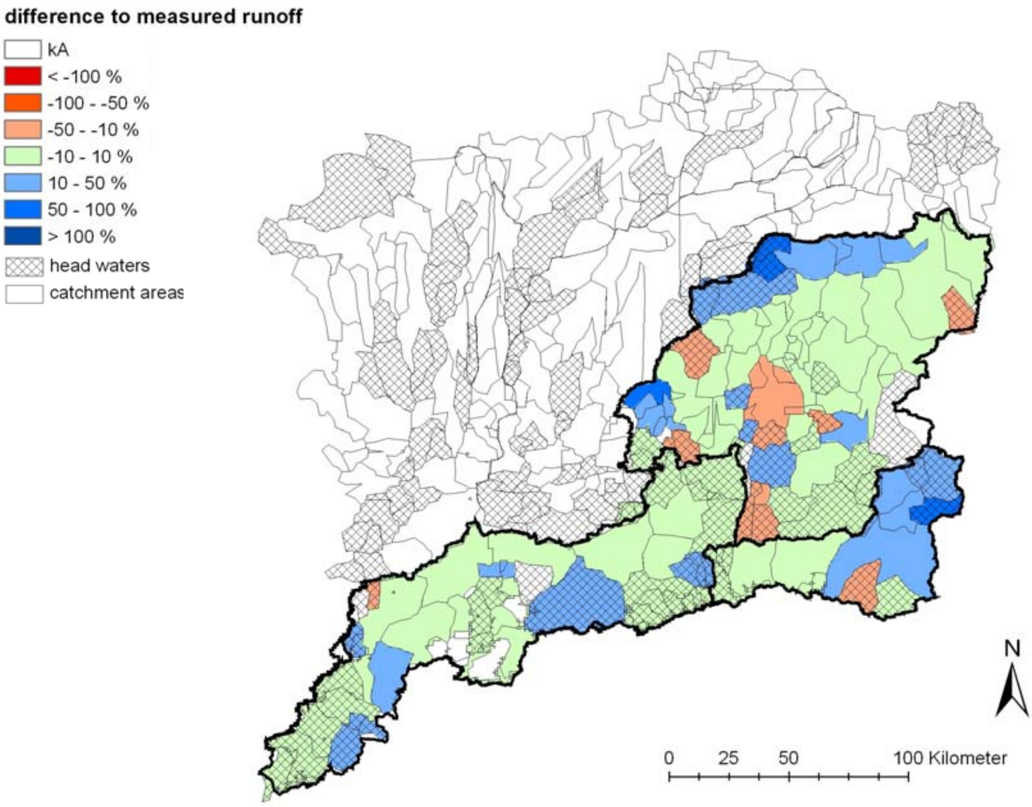

Figure 5: *Calibration of water balance in the projects UInn, Salz and LoInn. Differences between measured and modelled runoff (1971-2000).*

4.1.2.2 Soil model

Through statistical analysis, it was possible to associate every soil type with a dominant land use type. Then typical sites for each soil and land use type were defined. Control sites were chosen with a meteorological station nearby. The soil model in WaSiM-ETH uses the parameterisation method of van Genuchten (1980) to solve the Richards Equation (Richards 1931). Every soil type in the catchment areas of Upper Inn and Upper Salzach was analysed regarding the simulated hydraulic head and water content in different soil layers. They were tested for plausibility and consistency. Parameters were adjusted when inconsistencies or systematic errors were detected. It must be considered that the parameterisation of soils can only be as precise as the soil data in the soil map used for modelling (European Soil Data Base).

Thus, the parameterisation was a first guess derived from information of the soil map. The first test of each soil type indicated very high amounts of residual water and high saturation water contents. As this pattern was implausible, especially on sites with great slopes or on mountain tops, the skeleton fraction of different soil layers was varied. After those modifications, soils were evaluated with respect to seasonal changes and absolute values of hydraulic head in winter. Most of the soils (90 %) turned out to have very plausible seasonal variations in simulated hydraulic head and water content. The same holds for hydraulic head in winter with amounts around 0 – 70 hPa. The other soils were analysed and the parameterisation of the Richards equation was adjusted carefully. Thin soils on mountain tops (mostly Lithosols) were not adjusted because this led to unrealistic numbers for other parts of the water balance at the site, e.g. exceptionally high rates of direct runoff.

4.1.2.3 Run-off

Upper Inn (UInn)

In the model of Upper Inn a model efficiency of 0,46 (R^2 lin) and 0,72 (R^2 log) was achieved (average for all gauging stations, Table 3, annex). The calculated value of R^2 lin is highly dominated by the results for high-water and peak flows, whereas R^2 log is more representative of the quality of simulated discharge regarding the continuum and average runoff. For UInn, the performance criteria R^2 lin and R^2 log clearly indicate that the model simulates lower and middle discharge on a good level but some weaknesses occur when simulating peak discharges. The lower value of R^2 lin reflects the high influence of water management on the catchment area.

For example, the hydroelectric power plant near to gauge Martina/Inn at the border of Switzerland to Austria works with hydro peaking. Due to the daily resolution in the model and the lack of data from the specified power plant, it was not possible to reproduce the exact runoff downstream. As the influence of this power plant declines with increasing catchment area, R^2 lin improves from Martina to Innsbruck continuously (Table 3, Appendix).

In addition to hydropower, several bypasses had to be implemented into the model. For example the drainage basin of river Sanna that delivers water to the river Ill (a tributary of the Rhine) or Gerlosbach, a tributary of the Ziller in the western part of the catchment area UInn, which receives water from the nearby Salzach, or reservoir "Gepatschspeicher", which is in the centre of a complex system of bypasses of all the surrounding catchment areas, especially those of Radurschlbach, Faggenbach and Pitzbach.

Downstream of Innsbruck, further hydropower affects discharge leading to slightly decreasing model efficiency. However, there is satisfying model efficiency (R^2 lin = 0,47, R^2 log = 0,77) at the gauging station Oberaudorf/Inn (Figure 6), where the Inn crosses the border to Germany and which also serves as inflow into the model of the Lower Inn (LoInn).

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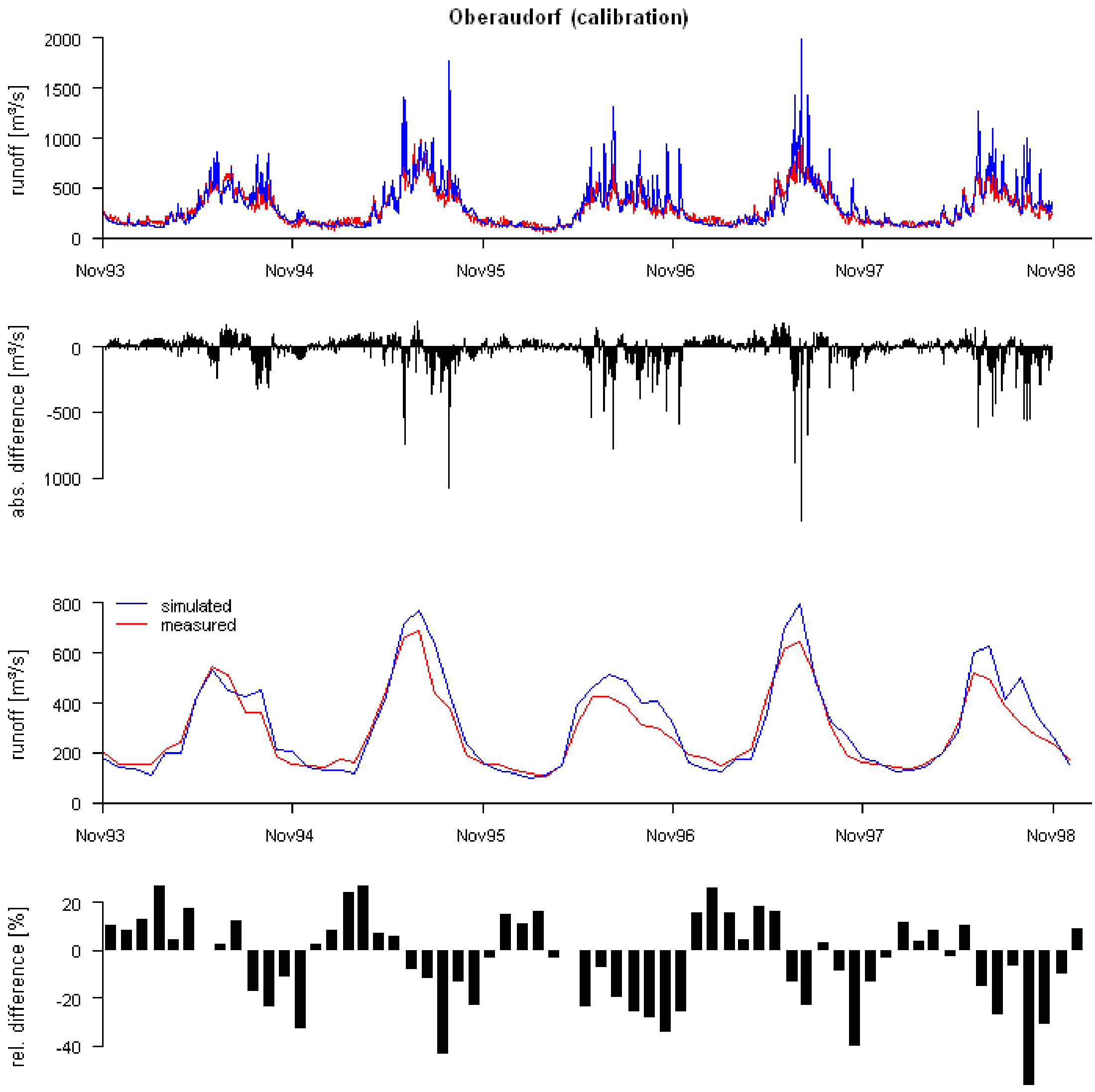

Figure 6: *Calibration of Upper Inn (UInn): gauge Oberaudorf / Inn: simulated (blue) and measured (red) runoff, 1994-1998. From top to bottom: runoff in daily resolution, daily differences (absolute), runoff in monthly resolution, monthly differences (relative to measured runoff).*

In general, the model produced too little runoff in springtime compared to the measurements. It could be concluded that this deficit is due to underestimated snow melt in spring and early summer. A change of the snow model within WaSiM-ETH from the temperature-index-approach to the temperature-wind-index approach resulted in better model efficiencies and a better reproduction of springtime runoff in western parts of the catchment area UInn. Using the temperature-index-approach yielded clearly better model efficiencies for most of the tributaries to the Upper Inn. Thus, the snow model was not changed in the catchment area of the Upper Inn in contrast to the catchment area of the Salzach, where the approach after Anderson (1973) led to the best results for Salzach and its tributaries.

Salzach (Salz)

For the model of the Upper Salzach a model efficiency of 0,61 (R^2 lin) and 0,75 (R^2 log) was achieved (average for all gauging stations except Kreuzbergmaut, Table 4, Appendix). Similar to the modelling region UInn, the model simulates lower and middle discharge for Salz much better than peak discharge. As the Salzach-catchment is highly influenced by water management, this is not a surprising outcome. Abstractions at the headwater area of the Salzach into the catchment area of Gerlosbach (modelling region UInn), inflows from catchment area of Drau and a great number of reservoirs upstream of gauges Bruck and St. Johann and some hydropower plants in the Salzach River itself were included in the model.

It was not possible to reproduce measured runoff at gauge Kreuzbergmaut / Fritzbach. As mentioned in the context of the disappointing results for the simulated water balance at this gauge, the reasons may lie in the measured data or in the very small number of rain gauges in that region (compare chapter 4.1.2.1). Though the Salzach River is strongly affected by water resource management and hydropower, a good model efficiency (R^2 lin = 0,59, R^2 log = 0,78, Figure 7) for the gauging station Golling/Salzach could be obtained. Golling serves as inflow into the model of the Lower Inn (LoInn).

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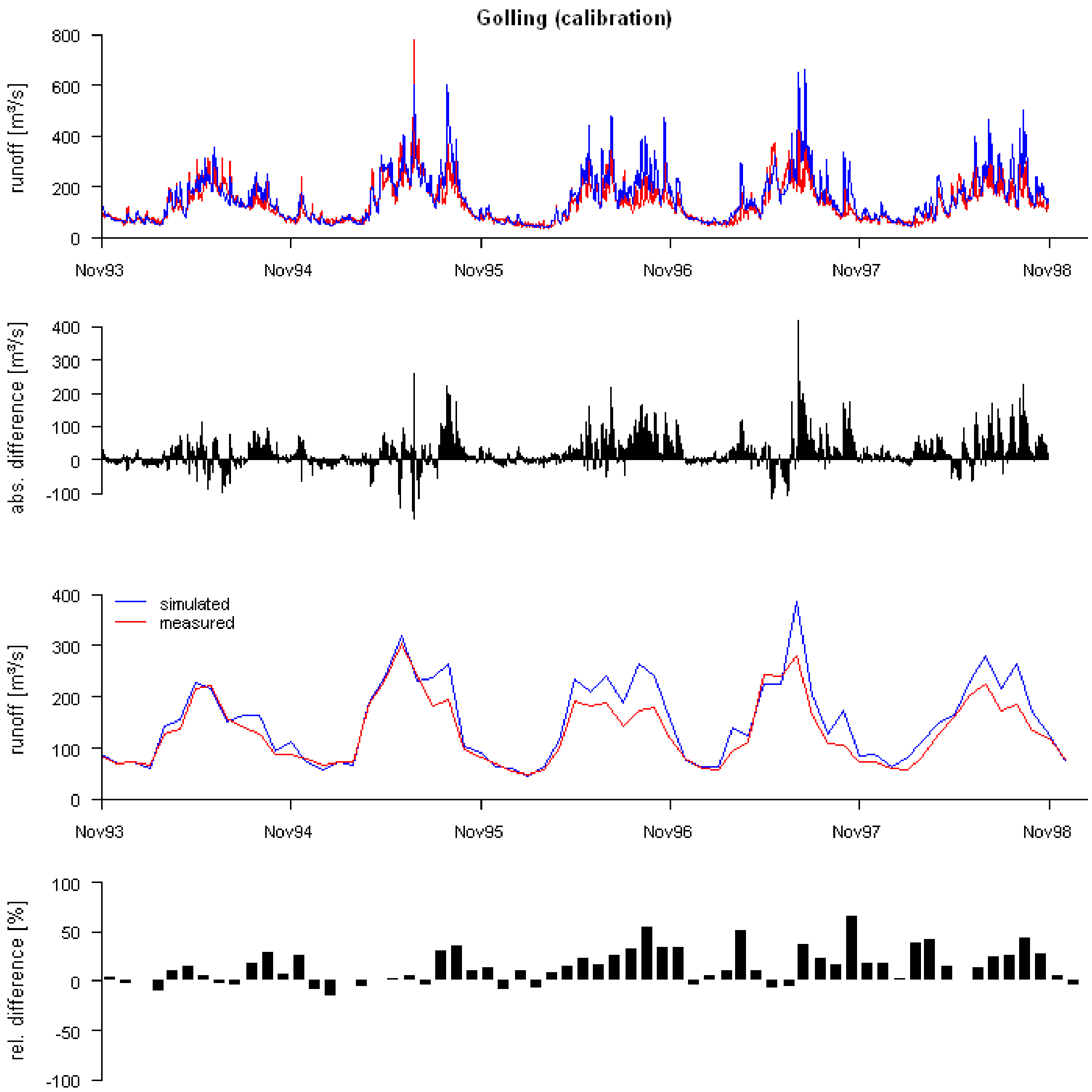

Figure 7: Calibration of Upper Salzach (Salz): gauge Golling / Salzach. From top to bottom: runoff in daily resolution, daily differences (absolute), runoff in monthly resolution, monthly differences (relative to measured runoff).

Lower Inn (LoInn)

In the eastern parts of the catchment of the Lower Inn (e.g. headwaters of Alz, Saalach) the new precipitation input led to better model efficiencies even without re-calibration of the runoff parameters (Table 5, Appendix). However, model efficiencies decreased significantly in the western part. This is most probably due to the new precipitation input resulting in the need to recalibrate abstraction rules and volume-runoff-relations of reservoirs. After the necessary recalibration for the catchment areas of Mangfall, Sims and Rott, model efficiencies improved remarkably. Besides, the areas with a high proportion of agriculture such as the catchment area of the Rott displayed a major change in simulated runoff as parameters in the Penman-Monteith-equation were adjusted. Consequently evapotranspiration was reproduced better than in the previous version of the WaSiM-ETH model that only covered the Lower Inn catchment (Table 5, Appendix).

Through recalibration it was possible to improve the overall model efficiency from 0,49/0,41 (R^2 lin/log) to 0,45/0,50. At gauge Passau-Ingling, the last station before the Inn flows into the Danube, the new model efficiencies are 0,59 (R^2 lin) and 0,76 (R^2 log, Figure 8). These are very good results considering the spatial and temporal resolution of the model (spatial resolution 1 km² and time step one day) and the fact that the whole river basin of the Inn is highly influenced by water management.

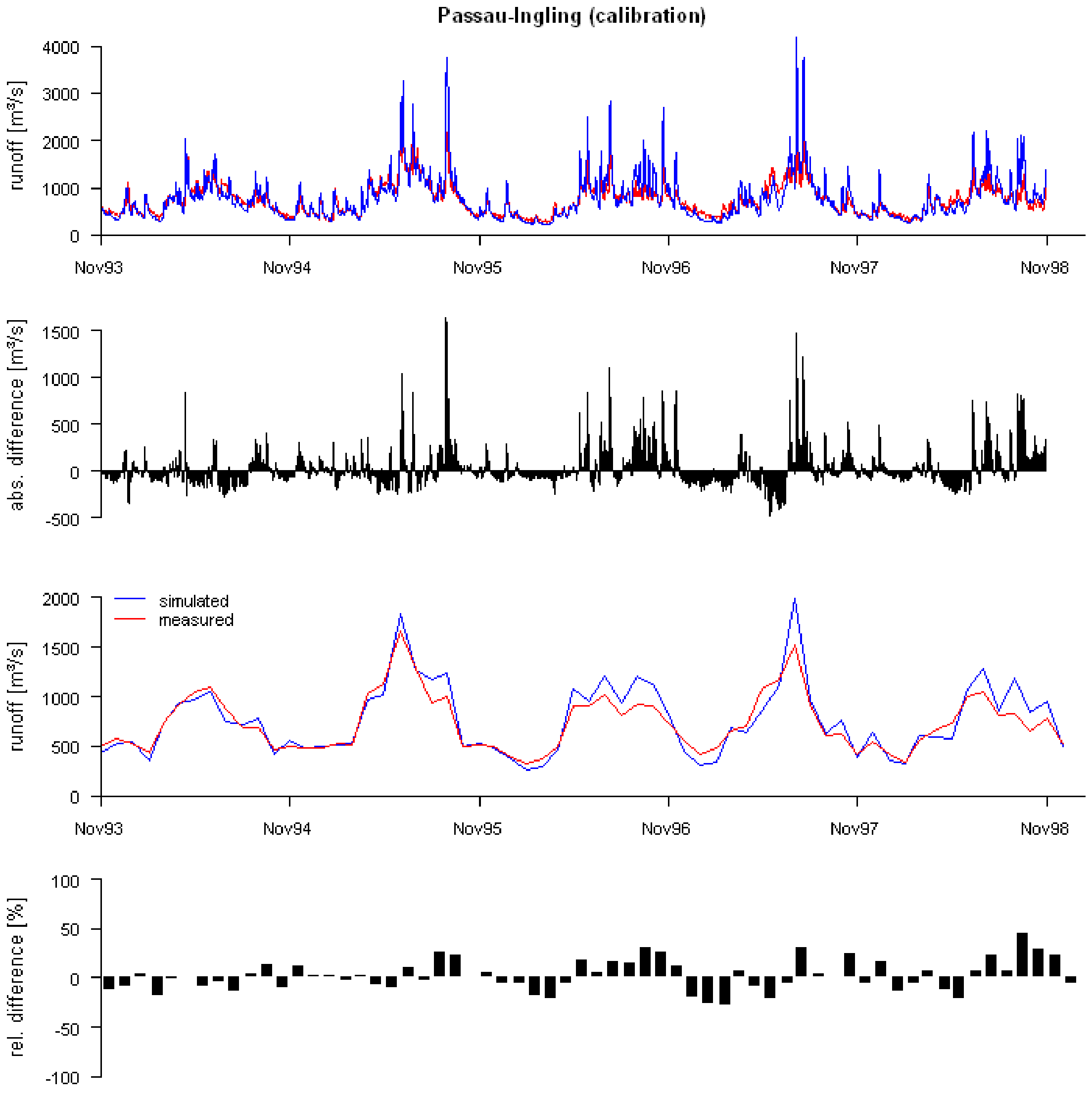

Figure 8: *Calibration of Lower Inn (LoInn): gauge Passau-Ingling / Inn: simulated (blue) and measured (red) runoff, 1994-1998. From top to bottom: runoff in daily resolution, daily differences (absolute), runoff in monthly resolution, monthly differences (relative to measured runoff).*

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4.1.2.4 Validation

Average model efficiencies in the validation period (1999-2003) are very similar to the calibration period: UInn: R^2 lin = 0,38, R^2 log = 0,70; Salz: R^2 lin = 0,61, R^2 log = 0,72; LoInn: R^2 lin = 0,50, R^2 log = 0,52. This is an indication that the calibrated parameters are robust and can be applied also for the long model run.

4.2 Long-time run (1971-2000)

Model efficiencies for the long-time run remained as stable as they were in the calibration and validation period, R^2 lin even slightly increases. The efficiencies for the period 1971-2000 are 0,51/0,71 for the Upper Inn, 0,67/0,76 for the Upper Salzach and 0,52/0,50 for the Lower Inn (always R^2 lin/R^2 log respectively). At the gauging station Passau-Ingling, the logarithmic model efficiency is 0,81, indicating a good quality of simulated discharge regarding the continuum. The linear model efficiency of 0,68 at this station suggests that single events are simulated fairly well. In the long time run, not only the simulated runoff was evaluated, but also the water balance components precipitation and evapotranspiration. Mean annual precipitation (1971-2000) in Salz (1751 mm/a) is higher than in UInn (1480 mm/a) and LoInn (1295 mm/a) (figure 9, Appendix).

Regarding the whole of the Inn River basin, precipitation is highest within the Berchtesgadener Alps in the north-western part and in the so-called Tennengebirge in the north-eastern part of Upper Salzach. As discussed before, these precipitation interpolation results may be due to unevenly distributed rain gauges that possibly produce implausible discharge (compare chapter 4.1.2.1). Lowest precipitation interpolation results (1971-2000) can be found in lower parts of modelling region LoInn, more precisely in the catchment area of the river Rott and for the river Inn close to where it flows into the Danube.

The quantitative distribution of evapotranspiration depends largely on latitude and on land use type. The highest rates of potential evapotranspiration can be found within the valleys of the lower Inn, the lowest rates as expected on mountain tops (Figure 10, Appendix). As expected, groundwater recharge depends on average rainfall and average actual evapotranspiration on each site (not shown). Thus, there are relatively high rates of groundwater recharge in the valleys of important tributaries to Upper Inn and Upper Salzach as rainfall there is quite high but evapotranspiration is relatively low due to mostly sparse vegetation and low temperatures. In the catchment area of the Lower Inn, groundwater recharge is highest in the southern parts of the region. However, parameterisation has a noticeable effect on groundwater recharge, evident in those parts of the models where the parameters Q_0 and k_b differ greatly in neighbouring sub catchments.

5 Summary and Conclusions

Precipitation is considered the most important input parameter for runoff-models, but precipitation interpolation, especially in Alpine regions, is still a matter of discussion. Since a change in precipitation patterns due to climate change is projected, interest in consequences for water management is evident. Hence, runoff-models with a physical basis that manage to simulate actual and future hydrological processes are needed. Within the projects KLIWA („Klimawandel und Wasserwirtschaft“: Climate change and consequences for water management) and the Interreg IVb project AdaptAlp (Adaption to Climate Change in the Alps) a water balance model for the Inn River basin (spatial resolution: 1 km²) was established, calibrated and validated with the physically based model WaSiM-ETH. A long model run (1971-2000) was performed to analyse different components of the water cycle. Embedded in the project was the challenge of precipitation interpolation in the mountainous investigation area. Different precipitation interpolation methods were tested for an area covering the catchments of the southern Bavarian tributaries to the Danube using water balances and different reference datasets.

Water balance simulations showed that in this study area precipitation was interpolated best with uncorrected data and a method based on the residuals of altitude dependent regression. Water balances and model efficiencies suggested that runoff was simulated well, especially considering the pronounced water management.

However, different matters induced problems: Discrepancies in the precipitation interpolation due to an uneven distribution of rain gauges results in a clear water surplus at Gauge Kreuzbergmaut/Fritzbach. Some gauges (e.g. gauges at river Rott, gauge Engfurth/Isen) suffer from an overestimated or underestimated precipitation, respectively in the headwater area. Water management across the river basin borders impedes good simulation of peak flows and discharge regarding the continuum (e.g. gauge Hart i.Z./Ziller, Stauden/Leitzach). Changing water management during the last decades caused relatively bad results especially in the long-time run for some stations (e.g. Fritz a.S., Erb/Leitzach, St. Johann/Kitzbüheler Ache). Another point is that the snow module was adjusted for the projects Upper Inn and Salzach separately, which could result in boundary effects concerning the snow depths. Furthermore, single events like heavy rains and spatial peculiarities such as narrow alpine valleys can not be represented in the model, owing to the relatively low spatial (1 km²) and temporal (daily) resolution.

As discharge regarding the continuum and average runoff was reproduced better than single events, the authors recommend focusing on average runoff rather than extremes for future applications of the model. Moreover, the effect of changing water management is pronounced in the modelling period. When evaluating future scenarios, the strong influence of water management should be discussed.

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7 Appendix

7.1 Precipitation interpolation methods

Table 2: List of the methods used to interpolate precipitation

code	method	Modellversion	precipitation input	comment
3	one region, IDW+EDREXT	WaSiM-ETH 8.0.10	corrected after Richter (1995), old	control run, project areas Do1, Do2, Do3, Isar, Inn
5	one region, IDW+EDREXT	WaSiM-ETH 8.0.10	corrected after Richter (1995), new	control run, project areas Do1, Do2, Do3, Isar, Inn
6	one region, IDW+EDREXT	WaSiM-ETH 8.5.06	corrected after Richter (1995), new	control run, all project areas
7	„alt.“	WaSiM-ETH 8.5.06	corrected after Richter (1995), new	all project areas
8	„IDW/REGNIE“	WaSiM-ETH 8.5.06	corrected after Richter (1995), new	all project areas
9	„IDW/combi“	WaSiM-ETH 8.5.06	corrected after Richter (1995), new	all project areas
10	„cont.“	WaSiM-ETH 8.5.06	corrected after Richter (1995), new	all project areas
11	„expos.“	WaSiM-ETH 8.5.06	corrected after Richter (1995), new	all project areas
12	„Residuals“	WaSiM-ETH 8.5.06	corrected after Richter (1995), new	all project areas
6u	one region, IDW+EDREXT	WaSiM-ETH 8.5.06	uncorrected	all project areas
9u	„IDW/combi“	WaSiM-ETH 8.5.06	uncorrected	all project areas
12u	„Residuals“	WaSiM-ETH 8.5.06	uncorrected	all project areas

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7.2 Calibration: model efficiencies

Table 3: Calibration result for model Upper Inn (UInn)

Gauge	River	Gauge code	Catchement area (WaSiM-ETH) (km²)	Influenced by water management	Calibration R^2 lin	Calibration R^2 log.
Cinuos	Inn	1	742	-	0,68	0,82
Tarasp	Inn	2	1561	+	0,24	0,80
Martina	Inn	3	1920	+	0,09	0,36
Prutz	Inn	4	2433	+	0,22	0,38
Magerbach	Inn	5	5058	+	0,63	0,74
Innsbruck o.S.	Inn	6	5717	+	0,63	0,77
Jenbach-Rotholz	Inn	7	7248	+	0,60	0,77
Kirchbichl-Bichlwang	Inn	8	9355	+	0,55	0,77
Oberaudorf	Inn	9	9776	+	0,47	0,77
Punt dal Gall	Spöl	10	288	+	0,91	0,93
Tumpen	Ötztaler Ache	13	772	-	0,85	0,90
Landeck-Bruggen	Sanna	11	712	+	0,66	0,87
Innsbruck-Reichenau	Sill	14	865	-	0,31	0,82
Hart	Ziller	15	1092	+	-0,14	0,32
Mariathal	Brandenberger Ache	16	267	-	0,44	0,69
Bruckhäusl	Brixentaler Ache	17	337	-	0,16	0,75

* not calculated because of large gaps in measured data

Table 4: Calibration result of model Upper Salzach (Salz)

Gauge	River	Gauge code	Catchment area (WaSiM-ETH) (km²)	Influenced by water management	Calibration R^2 lin.	Calibration R^2 log.
Wald i.P.	Salzach	31	203	-	0,76	0,89
Mittersill	Salzach	32	589	+	0,74	0,89
Bruck	Salzach	33	1165	+	0,66	0,72
St. Johann i.P	Salzach	34	2610	+	0,45	0,65
Golling	Salzach	35	3571	+	0,59	0,77
Rauris	Rauriser Ache	36	243	-	0,72	0,84
Bad Hofgastein	Gasteiner Ache	37	236	-	0,70	0,72
Kreuzbergmaut	Fritzbach	38	169	-	-3,43	-0,51
Obergäu	Lammer	39	375	-	0,38	0,60

Table 5: Recalibration of model Lower Inn (LoInn): comparison of model efficiency between old results in Pöhler et al. (2009), the effect of the new precipitation and new model version on the modelling and the results after recalibrating the new model. In the old model, inflow from Upper Inn and Upper Salzach were measured data, now it is simulated data. CA: Catchment area.

Gauge	River	Gauge code	Cat. area (WaSiM-ETH)	Influenced by water management	Former project		New precipitation and model version, old parameters		Recalibration	
			km²		R^2 lin	R^2 log	R^2 lin	R^2 log	R^2 lin	R^2 log
Seebruck	Alz	403	1477	+	0,83	0,78	0,84	0,85	0,84	0,85
Altenmarkt o. d. T.	Alz	402	1523	+	0,79	0,73	0,80	0,79	0,80	0,79
Trostberg	Alz	401	1958	+	0,36	0,68	0,36	0,66	0,46	0,66
Trostberg and canal	Alz	405	1991	+	0,76	0,74	0,73	0,77	0,78	0,79
Burgkirchen	Alz	400	2159	+	0,56	0,51	0,52	0,49	0,53	0,49
Burgkirchen and canal	Alz	400	2164	+	0,72	0,71	0,70	0,74	0,76	0,77
Haging	Antiesen	600	179	-	0,44	0,31	0,41	0,23	0,51	0,39
Sperten	Aschauer Ache	740	137	-	0,67	0,78	0,69	0,80	0,70	0,80
Anger	Attel	117	241	-	0,41	0,60	0,44	0,59	0,57	0,61
Berchtesgaden	Berchtesgadener Ache	116	369	-	0,46	0,64	0,01	0,58	0,44	0,69
Panzing	Bina	310	117	-	-0,17	0,07	-2,12	-0,40	-0,95	-0,53
Almdorf	Fieberbrunner Ache	760	205	-	0,63	0,75	0,62	0,79	0,62	0,79
Unverzug	Götzinger Achen	440	117	-	0,47	0,73	0,02	0,66	0,73	0,77
Kössen-Hütte	Großache	750	842	-	0,34	0,61	0,28	0,68	0,26	0,67
Rosenheim / Inn u.d.M.	Inn	108	11284	+	0,96	0,96	0,40	0,70	0,43	0,75
Wasserburg	Inn	107	11998	+	0,97	0,97	0,44	0,74	0,47	0,75
Kraiburg	Inn	106	12249	+	0,87	0,58	0,07	0,43	0,61	0,66
Mühldorf	Inn	105	12396	+	0,89	0,62	0,06	0,48	0,63	0,70
Eschelbach	Inn	104	13344	+	0,94	0,93	0,48	0,70	0,51	0,72
Passau-Ingling	Inn	101	26235	+	0,83	0,74	0,53	0,74	0,56	0,76
Engfurth	Isen	500	591	-	0,43	-0,08	0,30	0,12	0,41	0,48
Kitzbühel	Kitzbüheler Ache	731	160	-	0,69	0,78	0,75	0,85	0,74	0,85
St.Johann	Kitzbüheler Ache	730	340	-	0,69	0,80	0,74	0,85	0,73	0,85
Stauden	Leitzach	210	114	-	0,49	-0,10	0,11	-0,93	0,54	-0,03
Erb	Leitzach	211	179	+	0,28	0,10	-0,25	0,07	0,51	0,34
Schmerold	Mangfall	203	229	+	0,70	0,62	0,65	0,63	0,67	0,64
Valley	Mangfall	202	439	+	-0,24	0,01	-0,30	0,01	0,61	0,40
Feldolling	Mangfall	201	756	+	-0,40	-0,14	-0,89	-0,15	0,52	0,24
Bad Aibling	Mangfall	204	773	+	0,45	0,60	0,12	0,57	0,34	0,61
Hohenaschau	Prien	413	52	-	0,55	0,48	0,57	0,42	0,57	0,41
Prien mit Kanal	Prien	410	73	+	0,56	0,25	0,57	0,22	0,58	0,17
Wernleiten	Rote Traun	710	80	-	0,61	0,43	0,61	0,46	0,61	0,58
Kinning	Rott	304	112	-	-0,11	-0,74	-1,19	-0,31	-1,13	-0,30

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Gauge	River	Gauge code	Cat. area (WaSiM-ETH)	Influenced by water management	Former project		New precipitation and model version, old parameters		Recalibration	
			km²		R^2 lin	R^2 log	R^2 lin	R^2 log	R^2 lin	R^2 log
Linden	Rott	303	538	+	0,10	-0,84	-0,84	< -3	-0,01	-0,17
Postmünster	Rott	302	597	+	-0,03	-0,47	-1,17	-1,82	-0,07	0,06
Birnbach	Rott	301	855	+	0,06	-0,85	-0,78	-0,66	-0,02	0,17
Ruhstorf	Rott	300	1024	+	0,28	-0,68	-0,46	-0,73	0,30	0,25
Weißbach	Saalach	452	602	-	0,02	0,68	0,06	0,77	0,39	0,79
Unterjettenberg	Saalach	451	885	-	0,37	0,68	0,20	0,79	0,47	0,82
Laufen (S. K.)	Salzach	431	6211	+	0,83	0,86	0,65	0,82	0,66	0,82
Burghausen	Salzach	430	6834	+	0,83	0,82	0,71	0,79	0,71	0,80
Stephanskirchen	Sims	150	94	+	0,50	0,53	-7,04	-2,52	0,19	0,29
Staudach	Tiroler Ache	420	957	-	0,58	0,61	0,54	0,68	0,53	0,67
Stein	Traun	700	388	-	0,58	0,61	0,49	0,53	0,62	0,69
Oberach	Weißach	230	95	-	0,54	0,43	0,41	0,35	0,63	0,61
Fritz a. S.	Weiße Traun	721	94	-	0,39	0,14	-0,07	-1,43	0,31	-0,91
Siegsdorf	Weiße Traun	720	194	+	0,52	0,45	0,27	-0,33	0,56	0,45

1) measured data since Nov. 1973, 2) measured data since Nov. 1972, 3) measured data since Jan. 1993

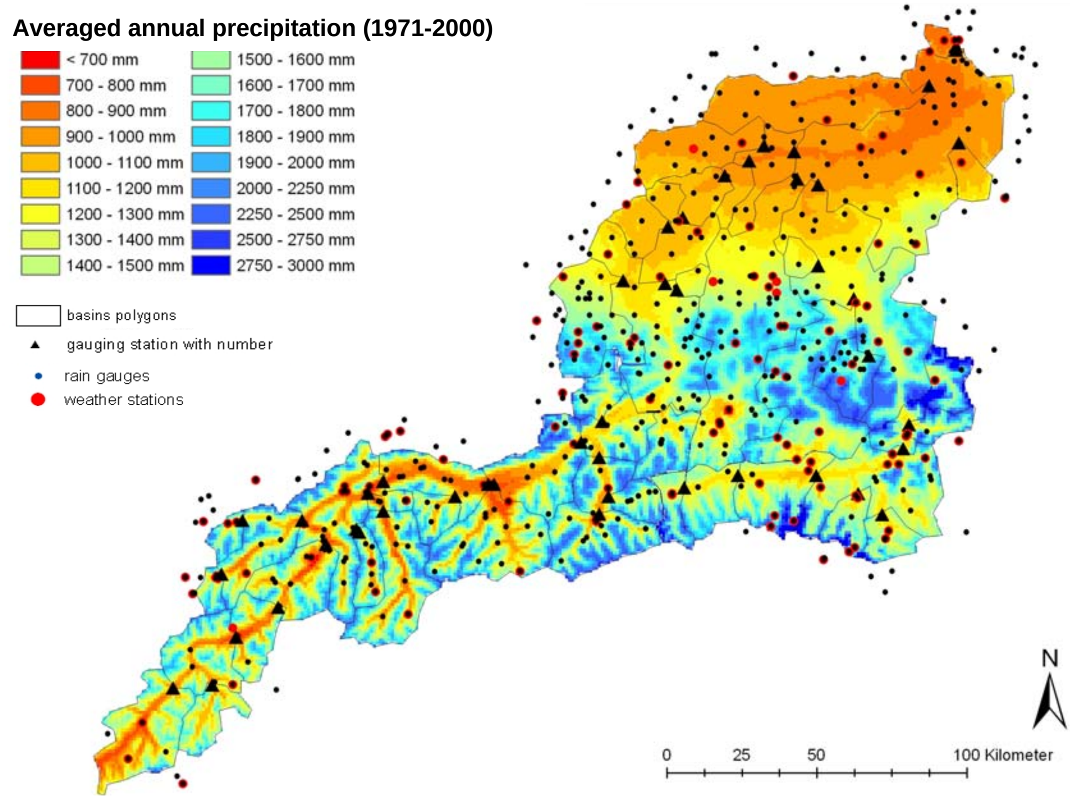

Figure 9: *Annual mean precipitation for the Inn River basin (1971-2000).*

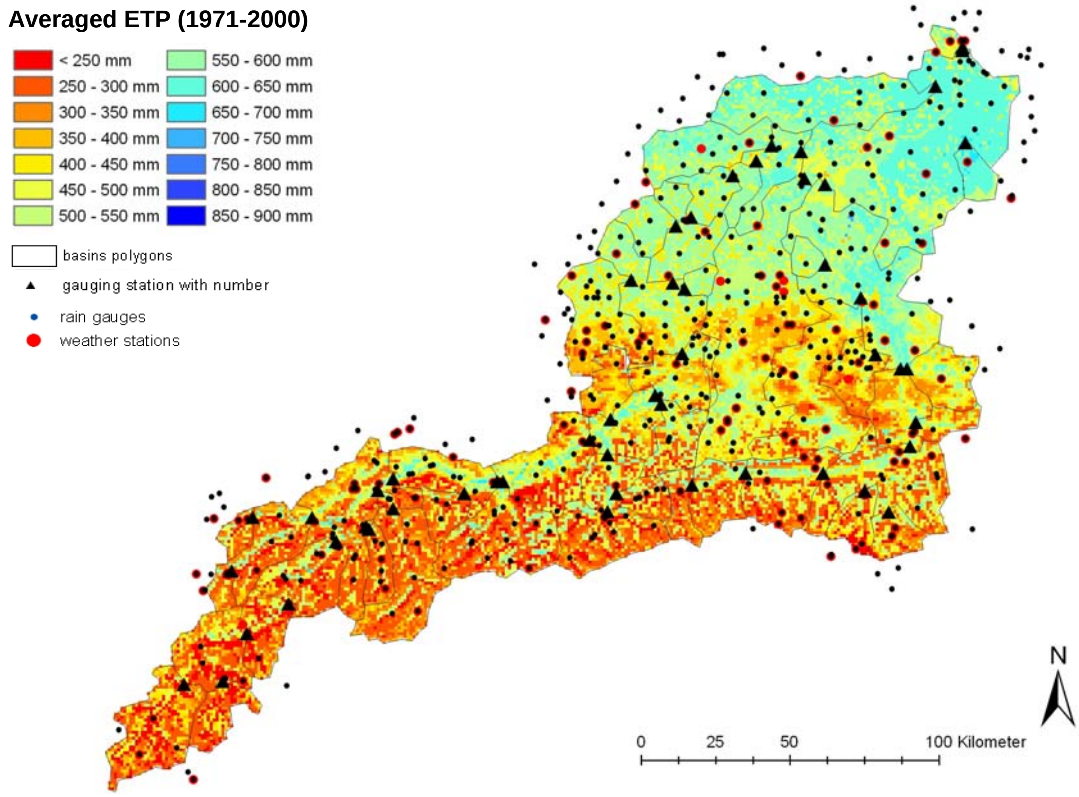

Figure 10: *Annual mean potential evapotranspiration for the Inn River basin (1971-2000).*

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