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Hydrology and Earth System Sciences Discussions

Interactive comment on "Water balance estimation in high Alpine terrain by combining distributed modeling and a neural network approach (Berchtesgaden Alps, Germany)" *by* G. Kraller et al.

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First of all the authors want to thank the Referee for his detailed and thoughtful comments which are contributing to the improvement of our manuscript. In the following we address the comments. Please note that Referee comments are bolded and our responses are in regular font format.

It was, in my opinion, not sufficiently tried to exclude effects of interpolation and precipitation correction. At least for the Königssee-subbasin, the missing runoff could have been easily created by increasing precipitation by either a larger precipitation correction (especially for snow) and/or using other interpolation methods (like a combination of Thiessen polygons with a fix "lapse rate" or gradient, as is available in the used model WaSiM-ETH since May 2010 (version 8.07). In essence, this means, that the proposed correction of subsurface storages by ANN results could simply be a correction of missing precipitation – only more sophisticated and transferred to a later stage in the model chain. I would strongly suggest to do some model runs with larger precipitation correction in order to show if and under which circumstances the runoff balance could be modeled without considering external inflows. If this correction would be unrealistic huge, then this would support the theory of the authors.

We agree with the referee, that precipitation correction in sub basin Königsseetal would lead to an improvement of the summer balance. Of course, we tested precipitation correction in several model runs but we did not mention results in the manuscript. Precipitation correction led to two effects: Albeit runoff performance slightly increased in subbasin Wimbachtal, it decreased in the neighboring subbasins Königsseetal, Klausbachtal and also in the northern subbasin Bischofswiesener Ache, Berchtesgadener Ache and St.Leonhard. Precipitation correction leads to an overestimation of runoff in those catchments. The neighboring subbasins Klausbachtal, Wimbachtal and Königsseetal appear to be hydrologically very different, and measured runoff cannot be reproduced with or without precipitation correction in all sub-basins at the same time. Based on the analysis of interpolation methods (comparison of the results with station data), station data, the precipitation quantities and the fact the effect of model mismatch would be vice versa with included precipitation correction in the high alpine terrain, we decided to model the water balance with the presented approach (REG+IDW, no precipitation correction). Furthermore, this approach showed best results in all subbasins. We are aware of highly dynamic meteorological processes in high Alpine terrain and we cannot exclude these effects to be a part of the cause of model mismatch. However, as the study area is in profound karst terrain, we also conclude unknown storage processes to be a main cause for the model mismatch.We included a figure showing the effect of precipitation correction on the annual sums of modeled runoff in subbasin Klausbachtal, Wimbachtal and Königsseetal and show NSE-values for the model runs in a new table. The results are presented in chapter 3.2. For this paper, WaSiM model version 8.8.0 was applied in the study area. We were not aware of the proposed interpolation Thiessen polygons with a fix "lapse rate", as this was to our knowledge officially released with version 8.10.0 or at least no option in the control file of 8.8.0.

To be sure about the reason for the mismatch in observed vs. modeled storage balance and runoff, the water balances of the surrounding catchments to the south and south-east must be taken into account in order to estimate the potential inflow from these sources. Is it realistic that the required amounts of water can originate from the relative small areas of sufficient elevation (to ensure a sufficient gradient) outside the Königssee catchment? This becomes even more critical when looking at the Wimbach catchment: The two neighboring catchments, the Klausbachtal and the Königssee catchment, are contained in the model domain already, so subsurface water exchanges between these subbasins wouldn't show up in the balance of the entire basin. The Königssee catchment may lose some water to the Wimbachtal, but this effect should partly cancel out the mismatch between modeled and observed runoff in that catchment (i.e. Königssee) as well. The required additional water for the Wimbachtal catchment equals approx. 63% of the modeled runoff (table 3, last row), which is around 800mm/a. So where does this water come from?

We are aware that there may be potential flows in between subbasins because there were several tracer experiments that showed subsurface runoff direction to spring locations throughout sub-basin borders. However, Kraller (2011) synthesized that the main underground flow direction within the area tends to be north. Therefore, we conclude that preferentially water fluxes in northern direction take place, that means fluxes from outside the study area into the assumed subbasin. Of course, it could also be the case that huge water amounts are stored in the karst rock matrix and activated by certain precipitation intensities. The underlying real effects remain a black box, and the question "where does this water come from" arised to the authors as well. Analyzing the measured runoff the authors found, that the water balance is quite different in the three neighboring high Alpine valleys. The distributed model is not able to reproduce the water balance which is the basis for the development of the Artificial Neural Network. As we did not mention the exclusion of internal boundary fluxes in this manuscript, we updated the manuscript in chapter 5.

The effect of the ANN application seems to be quite limited. Although there is an improvement in the modelled storages for the months May to September 2007 (fig. 12), there are no or only minor improvements or even worse results in other years (April 2007, May/June 2008, April and July 2009, May, July, August 2010) not to speak about the large deviations in November 2007. Consequently, the discussion and the results shown in figs. 14 and 16 are focusing on 2007, the only year for which the approach works really nice.

We want to thank the referee for this statement. Based on this helpful comment, we completely revised the codes and routines of the ANN and the influx to improve ANN results. We trained and tested ANNs with four Inputs for different time increments (5-day, 10-day, 15-day, 20-day, 25-day, and 30-day) to learn about ANN performance for this application and to find the best setup to correct the monthly water balance. Furthermore, we wanted to investigate the effects of the time increments in the distributed model correction. The new ANN setups and results are presented in chapter 4.1., results of the influx performance of each ANN in chapter 4.2.

I'm missing a comparison of the observed hydrograph against the modeled hydrographs with and without ANN-corrections (similar to fig. 5, but for several years, not only one year). This could demonstrate the effectiveness of the approach much better than the total balance, since it will show the changes in the dynamic of the hydrograph.

This approach was developed to correct underestimated water balance by the distributed model at a monthly time basis. Due to the additional work with different time increments, we also investigated the effect of those on runoff dynamics during model correction. We found that the 20-day time increment led to best improvement of the distributed model. We updated the manuscript in chapter 5 and included a hydrograph for the subbasin Königsseetal after model correction.

One thought about the method: Applying constant fluxes to the boundary cells (by the way: which cells where selected by which criteria?) will work for underestimated storages only (so the storage change applied by the ANN is positive), because then the applied flux is positive and the additional groundwater will flow through the subsurface system to the rivers. But what if the storage change is negative? A negative boundary condition (negative constant flux) at the higher elevation rim of the catchment will have almost no effect (except on the cells the boundary condition was applied to). Wouldn't it be better to apply negative boundary fluxes to all cells of a catchment or at least to cells at the lower end of the aquifer? Since the ANN results may well give positive and negative corrections, this must be implemented somehow in the model in

order to apply the model+ANN corrections in karst environments where larger fractions of the groundwater flow out of the basin.

The author is right. In the first approach we implemented the influx on specified cells in the subbasin Königsseetal (spring locations). We agree, that an influx in a given area in the subbasin would be better to improve distributed model results. We implemented an influx in subbasin Königssee at the border of the aquifer.

Detailed comments/technical issues:

The schema in figure 2 and the description of the method do not clarify, if the ANN is applied to each grid cell or to the sub catchments only (I assume the latter).

We added the information to the figure description (page 3).

If monthly mean values for T, QS and RH are used as input for the ANN, and the result (Storage) is valid for the same month: how were the monthly mean values of interpolated inputs calculated? In another model run in advance to the "real" run? Or are the results valid for the month following the month, the mean input values are valid for?

The sums were all calculated with results of a complete model run without distributed model correction (model run in advance to the "real" run). We revised the section in the manuscript and added the information in chapter 4.

How are the lakes modeled? Using the fully integrated lake model (with connection to unsaturated and saturated zone etc.) or with the conceptual lake model

included in channel routing? There is no mention of this module in the model description

The lakes are modeled with the fully integrated lake model. We provide this information now in the model setup (chapter 3.1.)

The Wimbachtal catchment with its large groundwater storage (4 years mean retention time) indicates that the model initialization could require evenly long or even more time to make sure the internal groundwater dynamic is in an equilibrium state. There is no mention on how long the initialization period was.

The initialization period was from 2001-2002. Numerous model runs showed that model equilibrium was each time reached before the end of this hydrological year. We added this information in the model description (chapter 3.1).

Also, the average aquifer depth (and soil depth) is not specified. I have no idea if it is tens of meters or hundreds of meters (except the legend of figure 15, suggesting a maximum aquifer thickness of 30 m). An aquifer of a few hundred meters thickness would be appropriate, according the description of the study area (p. 221, lines 1-10)

The aquifer depth is 15 m, and soil depth ranges from 15 to 56 meters. We tried several aquifer thicknesses during model calibration, however lower aquifer assumption led to better model results. We updated the model description with this information (chapter 3.1).

Since the ANN corrects the groundwater fluxes, the affected runoff components are rather the slower ones. Consequently, the model efficiency should be shown not only by using the (linear) NSE or r2 (which emphasizes the peak flows) but also by using the logarithmic results (r2 and NSE of the logarithms of the modeled runoff).

We agree with the referee, that the model efficiency should be shown with logarithmic results. We added this statistic in the result section of the ANNs and the distributed model correction (Table 6 and Table 8).

What is the reason for using monthly time steps for the ANN? Since karst systems often react much faster, I would think of time steps of 10 days or even shorter...

The reason for using monthly time steps are that after analyzing the annual sums we looked at the monthly balance as a next step and set up the ANN. We agree with the author, that implementation of the ANN at different time aggregations is of course noteworthy to examine. We trained ANNs for different time increments (5-day, 10-day, 15-day, 20-day, 25-day and 30-day) and adjusted the resulting boundary fluxes. Results are presented in chapter 4.1., 4.2. and 5.

We revised the manuscript according to the ***detailed comments and technical issues*** *mentioned in page 3 and 4 of the review comment document. We agree with the referee′s comments and* ***updated the manuscript*** *in the according chapters/pages. Furthermore, we* ***revised all figures and tables****.*

Thank you very much for your investment of time and effort! We hope to have addressed your comments adequately and would like to thank you again for your valuable suggestions! Your endeavors are highly appreciated!