Response Letter concerning the manuscript:

Dynamics of water fluxes and storages in an Alpine karst catchment under current and potential future climate conditions (hess-2017-216)

Zhao Chen, Andreas Hartmann, Thorsten Wagener, Nico Goldscheider

We thank Editor for his effort and valuable comments! Now, we have considered all his comments. Editor's comments are in black. Our answers in the response list are highlighted in blue.

Editor' comments:

Comment 1: Potential overlap with the paper by Chen and Goldscheider (JHyd, 2014). We are trying to discourage the practice of publishing similar material several times.

Answer: There is no overlap with the paper by Chen & Goldscheider (2014). The current study presents entirely new research questions, new data, new results and new conclusions. The model tested and evaluated in this manuscript is a further development of the model introduced in the study by Chen & Goldscheider (2017). The major novel aspects include:

1) The new research questions (presented in the introduction) focus on variable flow and storage over the entire hydrologic year, including the period of snow accumulation and snowmelt, and on potential impacts of climate change on the dynamic water balance. Accordingly, extensive new data series (including winter and spring) were considered.
2) The updated model adopts the HBV-snow routine and is able to simulate snow storage and snowmelt and their influence on groundwater recharge processes.
3) The earlier model considers baseflow / slow flow as a constant value, which is insufficient for long-term climate-change impact predictions. In the updated model, we applied the linear reservoir approach by Hartmann et al. 2011 to simulate transient slow-flow components, depending on groundwater recharge and recession coefficients.
4) The laterally adjacent and hydrogeologically connected non-karst area is included in the current model domain. The updated model is able to simulate variable infiltration of surface runoff from the non-karst area into the underground karst drainage network.
5) In the updated model, the spatial discretization of the catchment area is much finer by using the elevation bands approach, which allows for a better representation of the spatial variability of meteorological variables.

Comment 2: The huge fraction of rainfall that recharges has been politely pointed as unusual. I find it inappropriate to reply that "We will discuss the possible overestimation of recharge percentage of precipitation". You must either argue why such percentage (95%) is right or why your model is wrong. Certainly, constraining the model with an overestimated recharge does not sound appropriate, because calibration will twist all model parameters to yield numerically consistent, but conceptually erroneous, results.

Answer: We agree that a recharge of 95% appears unusual. However, very high recharge rates in mountainous karst areas, ranging between 60% and 90%, are also reported in the literature (e.g. Malard et al 2016). In alpine regions, low temperatures and high precipitation (P) favor low evapotranspiration (ETP). In our test site, and other alpine karst areas, soil and vegetation are almost entirely missing in the elevated parts, and the limestone is extremely karstified, so that water infiltrates directly into open fractures, as can be seen on the photo (the lower parts of the area are covered by shallow soil and forest, causing higher ETP and lower recharge):

We are convinced that our conceptual model is appropriate, as it is based on detailed hydrogeological field investigations, including 18 tracer tests (Goldscheider 2005, Göppert & Goldscheider 2008, Sinreich et al. 2002). The overall size of the karst system, the catchment areas of the individual springs and the general configuration of the underground drainage network are exceptionally well known, which is a major advantage of this test site.

However, the quantification of recharge is associated with uncertainties and the value of 95% is probably an overestimation. Possible reasons include:

1) The interpolation of precipitation is uncertain. Most weather stations used for interpolation are located outside the study area, at lower elevations. Uncertainty depends on the density of observation points and the interpolation method (e.g. Ohmer et al 2017).
2) Discharge quantities during very high flow conditions are also uncertain. We measured continuously water stages at all gauging stations, and we performed numerous flow measurements (salt-dilution method) to establish rating curves, which were used to obtain continuous hydrographs for all system outlets. However, most flow measurements were done during low to moderately high flow conditions, and the rating curves had to be extrapolated for very high flows. Therefore, substantial uncertainties have to be expected for very high flow conditions (e.g. Baldassarre & Montanari 2009, Coxon et al 2015).

3) Another source of uncertainty is that evaporation from snow was not taken into account in the current model. However, some studies suggest that snow evaporation can be significant in some high elevated catchments (e.g. Leydecker & Melack 2000).

In conclusion, we are convinced that our hydrogeological understanding and conceptual model are appropriate (very low uncertainties). The measurement and interpolation of precipitation, ETP, discharge and, as a consequence, recharge are associated with inherent uncertainties, related to the remoteness and complexity of this alpine karst catchment. The resulting recharge of 95% is probably an overestimation, but it is the best estimation that we can obtain, and it is not far above the reported range of recharge values for high alpine karst catchments.

We will discuss these uncertainties in the revised manuscript.

Comment 3: You have left unanswered the question by reviewer 2 about the scientific merit of this study.

Answer: We believe that the main scientific merit of this study is to better understand the highly variable groundwater dynamic in mountainous karst catchments, which can be highly vulnerable under future changing climate conditions. Our paper presents the first study to investigate potential impacts of climate change on mountainous karst systems by using a combined lumped and distributed parameter modeling approach with consideration of subsurface karst drainage structures. Additionally, this work presents a novel holistic modeling approach, which can be transferred to similar karst systems for studying the impact of climate change on local karst water resources with consideration of their individual hydrogeological complexity and hydraulic heterogeneity. This novelty will be better explained in the revised paper, both in the introduction and in the conclusions.

Comment 4: In response to comments by reviewer 1 about the specifics of your model, you reply "We will add a brief discussion"

Answer: Our model is construced by using a hybrid-struture: a combined lumped-parameter and distributed-parameter approach. Basically, the lumped-parameter model represents water storage and drainage in the soil and epikarst. The distributed paramter model represents the underground karst drainage network in the karst area, and the network of surface streams in the non-karst area; these linear structues drain the flow generated from the lumped paramter model. Due to the new developements (see our anwser to comment 1), the current model is able to simulate simultaneously all system outlets for a complete hydrological year, including priods of snow acculumuation, snowmelt and rainfall; additionally, the current model is able to reproduce system discharge behavior during drought periods, as the system baseflow was implemented as a function of groundwater recharge and recession coeffient. In this study, the simulation started in late autumn (November 2013), during very low flow conditon. The discharge of QS during this time consists of slow flow components from the karst area. This hydrologic state was used to define the initial model condition.

Comment 5: In response to the comment of also reviewer 1 about the unclear relevance of your findings for the general hydrogeological knowledge, you again reply "we will".

Answer: Reviewer 1 wrote "The conclusions are valid but they do not seem to be relevant for the general hydrogeological knowledge. The authors should try to generalize them".

We are thankful for this comment, and we will include new and more generalized conclusions, which also demonstrate the broader relevance and transferability of our modeling approach and scientific findings. The general conclusions can be summarized as follows:

Because of their unique hydraulic characteristics, karst aquifers respond faster and stronger on hydrological events and seasonal variations, including snow accumulation and melting, than other types of aquifers. The frequency and intensity of extreme events and the seasonal patterns of precipitation and snow regimes are projected to change in a changing climate. Karst systems are especially vulnerable to these changing hydro-meteorological conditions. However, because of their hydrogeological complexity and hydraulic heterogeneity, every karst system has its individual characteristics, and different karst springs respond differently on changing climatic conditions. Therefore, site-specific investigations are required. The holistic modeling approach presented in our study can be adapted to other types of karst systems and can be used for studying impacts of climate change on alpine karst water resources.

References cited in this response letter:

Baldassarre, G., Montanari, A., 2009. Uncertainty in river discharge observations: a quantitative analysis. Hydrol. Earth Syst. Sci. 13, 913–921.

Chen, Z., Goldscheider, N., 2014. Modeling spatially and temporally varied hydraulic behavior of a folded karst system with dominant conduit drainage at catchment scale, Hochifen–Gottesacker, Alps. J. Hydrol. 514, 41–52. 10.1016/j.jhydrol.2014.04.005.

Coxon, G., Freer, J., Westerberg, I., Wagener, T., Woods, R., Smith, P., 2015. A novel framework for discharge uncertainty quantification applied to 500 UK gauging stations. Water Resour. Res., 51, 5531–5546. 10.1002/2014WR016532.

Goldscheider, N., 2005. Fold structure and underground drainage pattern in the alpine karst system Hochifen-Gottesacker. Eclogae geol. Helv 98 (1), 1–17. 10.1007/s00015-005-1143-z.

Göppert, N., Goldscheider, N., 2008. Solute and Colloid Transport in Karst Conduits under Low- and High-Flow Conditions. Ground Water 46 (1), 61–68. 10.1111/j.1745-6584.2007.00373.x.

Hartmann, A., Kralik, M., Humer, F., Lange, J., Weiler, M., 2011. Identification of a karst system's intrinsic hydrodynamic parameters: upscaling from single springs to the whole aquifer. Environ. Earth. Sci. 65, 2377–2389. 10.1007/s12665-011-1033-9.

Leydecker, A., Melack, J., 2000. Estimating evaporation in seasonally snow-covered catchments in the Sierra Nevada, California. J. Hydrol. 236 (1-2), 121–138. 10.1016/S0022-1694(00)00290-0.

Malard, A., Sinreich, M., Jeannin, P.-Y., 2016. A novel approach for estimating karst groundwater recharge in mountainous regions and its application in Switzerland. Hydrol. Process. 30 (13), 2153–2166. 10.1002/hyp.10765.

Ohmer, M., Liesch, T., Goeppert, N., Goldscheider, N., 2017. On the optimal selection of interpolation methods for groundwater contouring: An example of propagation of uncertainty regarding inter-aquifer exchange. Advances in Water Resources 109, 121–132.

Sinreich, M., Goldscheider, N., Hötzl, H., 2002. Hydrogeologie einer alpinen Bergsturzmasse (Schwarzwassertal, Vorarlberg). Beit. z. Hydrogeologie 53, 5–20.