RC3 - Anonymous Referee #3 – May 18, 2022

Review Report: egusphere-2022-22

The paper "Influence of intensive agriculture and geological heterogeneity on the recharge of an arid aquifer system (Saq-Ram, Arabian Peninsula)" presents a water budget estimation of regional groundwater recharge flux for an arid aquifer system.
The approach is well driven and the paper is really well written. I do have three remarks.

1) The authors claim that there is a strong spatial heterogeneity of groundwater recharge over the domain. However, such heterogeneity is barely discussed and not illustrated. A representation of the variation of the estimated recharge flux over the studied region would be a great asset. It would be interesting to have such a map and to discuss about the heterogeneity of the estimated recharge in the results. Moreover, it is not clear for now how the water budget has been computed and how the other component of the water budget has been assimilated and combined with the satellite-based products. Are the authors computed the water budget on a regular grid over the whole region? The method section (2.4) is more a theory section and is missing information about how the water budget was practically computed.

Indeed, we have not been able to provide a mapping of the recharge. This is because the GRACE-derived approach is highly integrative, in addition to the coarse resolution of the raw data (i.e. 3° x 3°, giving only 10 meshes partially in the domain with zero totally included). So, such mapping could not be relevant with this approach, and would be even very complicated with other approaches since most of the data is not spatialized if it exists. Thus, we stated explicitly that we investigate the regional-scale water mass-balance (e.g. Line 277 in the method section) using only domain averages of each contribution.
However, heterogeneities are addressed through the discussion in section 4.2 (i.e. a natural recharge fifteen times more effective on fractured basaltic deposits than on sedimentary formations) and in section 4.3 (i.e. a recharge temporally null at the outskirt of the large irrigated areas due to a recharge front velocity much lower than the thickening of the unsaturated zone resulting from the nearby pumping).

2) The authors present an estimation of the regional groundwater recharge about 2.4 mm.y-1 (with an uncertainty of 1.4 mm.y-1). Beside that, it is unclear if all the uncertainties presented in the paper are for 1 or 2 σ. Knowing that each component of the water budget contained large errors, it is not clear to me how the authors can have such a precise estimate of groundwater recharge. I would rather think that estimation of such a small recharge flux would be very challenging as the cumulative effects of the errors in each water budget components are also large. It would be great to have a discussion about what is really quantified in the "uncertainties" and what are the major limits of such estimation of recharge flux with a large-scale water balance approach. Also, what are the effects of boundary conditions (lines 187, 188) in the calculation of natural discharge?

Also required by Rewiever #2, we propose to add some information about uncertainties at the beginning of the discussion (section 4):
"This study provides an estimate of the 2002-2019 domain-average natural recharge with associated uncertainty (one sigma) accounting for temporal variations in natural discharge,

groundwater pumping and irrigation return flow. The uncertainties associated with the calculation of the ΔGWS long-term trends with the GRACE and GLDAS products have also been considered. Errors associated with GRACE measurements could not be accounted for as they are not provided with the raw Mascons data (i.e. before the application of unwanted scaling factors). However, Blazquez et al. (2018) investigated the uncertainty of GRACE data by solving a global water budget using trends in ocean mass, ice loss from Antarctica, Greenland, arctic islands and trends in water storage over land and glaciers. The authors estimated a 0.27 mm yr-1 uncertainty for the GRACE data, a figure significantly lower than the uncertainties of the ΔGWS trends used in this study (Table 1)."

- A Blazquez, B Meyssignac, JM Lemoine, E Berthier, A Ribes, A Cazenave, Exploring the uncertainty in GRACE estimates of the mass redistributions at the Earth surface: implications for the global water and sea level budgets, Geophysical Journal International, Volume 215, Issue 1, October 2018, Pages 415–430, https://doi.org/10.1093/gji/ggy293

However, the probability associated to the uncertainties was indeed missing. Thus, we added "one sigma" to the beginning of the suggested paragraph above, as well as in the Table 1 and its caption.

The effects of boundary conditions have been also addressed by Reviewer #2 so we invite you to refer to our answers to the second and third General comments of Reviewer #2 which, we hope, will respond to these legitimate questions. Thereby, we suggested to add this sentence at the end of section 2.2.2 (Line 195):
"Finally, with regard to historical piezometric maps of the Saq aquifer (Sharaf and Hussein, 1996; Lloyd and Pim, 1990), it can be assumed that the southeastern limit with the Khuff aquifer is likely inactive given the large drawdown cone created by the intensive pumping of the Al Qasim area."

- Sharaf, M. A. and Hussein, M. T.: Groundwater quality in the Saq aquifer, Saudi Arabia, Hydrol. Sci. J., 41, 683–696, https://doi.org/10.1080/02626669609491539, 1996.
- Lloyd, J. W. and Pim, R. H.: The hydrogeology and groundwater resources development of the Cambro-Ordovician sandstone aquifer in Saudi Arabia and Jordan, J. Hydrol., 121, 1–20, https://doi.org/10.1016/0022-1694(90)90221-I, 1990.

3) In section 4.4, the authors are discussing the focused groundwater recharge. I do miss a complement discussion about the effects/importance of the ephemeral stream (so-called wadi systems) in groundwater recharge processes at this scale. Are these systems quantified in the approach or ignored. In both cases, it is not clear.

This was also addressed by Reviewer #2 in its third general comment. We propose to add the following paragraph at the beginning of the discussion section:
"Even if the Saq-Ram domain is devoid of any permanent surface water bodies, ephemeral streams are known to be important for (eco)hydrology and local groundwater recharge in arid regions (Shanafield et al., 2021; Dogramaci et al., 2015; Schilling et al., 2021). However, runoff coefficients were estimated at about 1% in the region (Al-Hasan and Mattar, 2013) while more than 90% of this runoff is lost by evaporation in the low lands. Thus, accounting for recharge redistribution through ephemeral streams in the water budget of the large Saq-Ram aquifer system would be quantitatively insignificant."

- Al-Hasan, Abdul Aziz Saleh and Yousry El-Sayed Mattar. “Mean runoff coefficient estimation for ungauged streams in the Kingdom of Saudi Arabia.” Arabian Journal of Geosciences 7 (2013): 2019-2029.

Minor comments

 # In the abstract, I think the JPL, CSR, GSFC, VIC, etc. might be removed to facilitate the comprehension.

We can modify this part of the abstract as follows:
“The three existing GRACE solutions were tested for their local compatibility to compute groundwater storage variations in combination with the three soil moisture datasets available from the Global Land Data Assimilation System (GLDAS) land surface models.”

 # The authors use the word “global” (e.g. line 31, 75 etc.) several times in the text. Is the word “large-scale” or “regional” would better fit? This study is not at a global scale.

This can be indeed misleading.
“Regional-scale” can be used Line 31.
“considering the regional water table decline initiated in the mid-1980s” Line 75.
“regional-scale mass-balance equations” Line 95.
“Leading to domain-averaged values for the groundwater fluxes, the integrative approach proposed here” Line 124-125.

To sum-up, the present paper is an interesting study lacking of some clarity in the approach and discussion about the reliability of the proposed estimates of groundwater recharge. The scientific quality is good but the scientific significance is not as well because the authors are using a well-established method and I do not see the real contribution to scientific progress for such a study. Maybe the authors can be better explicit about the real significance of such a study. The figures are good quality overall.
This manuscript can be accepted with some minor revisions in my opinion.