**Answer to Report #1**
*Submitted on 16 Oct 2022*

Note that the **line numbers** are **based** on the **"revised_v3_marked.pdf"** version of the manuscript.

- *Reviewer's comments in italic font*
- Response to reviewers' comments in normal type
- Changes to the manuscript in red

## Anonymous referee #1

*In my opinion, this is an excellent technical report. I confirm my first impression about this work, i.e., the comparison of three GRACE solutions (JPL, CSR, GSFC) is interesting, but the manuscript lacks some innovative content from the methodologicl point of view, in order to be considered for publication on HESS. The specific application, even if it is dedicated to a very important hydrogeological structure, is of minor interest for HESS' readers, whereas it would be more adequate for an hydrogeological journal. This is confirmed also by the abstract, which is almost fully focused on the specific application, i.e., the analysis of the recharge of the Saq-Ram aquifer system.*

*I am sorry, because I realize that I did not explain in a very explicit way my concern about scale issues. However, the authors basically caught the concept. GRACE data have a poor resolution with respect to the typical scale lengths characterizing the heterogeneity of aquifer recharge, which is discussed in a less accurate way. Also, the discussion in section 4.3 refers to a structure that is considered at a scale length which is not consistent with GRACE resolution.*

Admittedly the GRACE approach presented in this study is regional whereas this section (4.3) involves a local recharge value as clearly indicated by its title. Praised by one of the reviewers (Anonymous Referee #1 - May 8, 2022 - Specific comment #4), this section highlights a feature poorly discussed in the literature (only one article to our knowledge): a relative disconnection of the infiltration front with the declining water table induced by intensive pumping. As an opening discussion, we used local data to calculate conservative recharge and piezometric decline velocities showing a temporarily zero recharge. Hence, we believe that this rarely highlighted feature provides an additional source of recharge heterogeneity likely to occur elsewhere (i.e. multiple similar drawdown cones induced by pumping and potentially exhibiting the same behavior at their periphery).

*Moreover, the clarifications given in the authors' response shows that the remarks of section 4.3 are based on literature information characterized by high uncertainty.*

While this article is fairly uncertain is terms of exact location of the studied site, it has been illustrated by multiple maps that the exact location is of little importance for the demonstration since the whole sand dune area studied by Al-Sagaby and Moallim (2001) is under the influence of the 500km-diameter drawdown cone of Al-Qasim region (see our previous response Report #2 - July 25, 2022 - Specific comment #2).

*Therefore, I am sorry, but my overall opinion is that the manuscript cannot be considered for publication on HESS, mostly because I think that the innovative content is not sufficient for the ambitions of the journal.*

*However, if the editor's decision were different, I suggest to take section 4.3 off the manuscript and to fix the following technical details.*

In order to ease the publication process and since this opening discussion is not pivotal for the understanding of the study, we have removed it from the manuscript as recommended by the reviewer and the editor:

(Line 540) ~~4.3 Local recharge velocity and water table decline~~

~~Using the Al-Sagaby and Moallim (2001) study, it is possible to estimate the recharge velocity through a sand dune located in the Al Qasim region (within the Saq-Ram domain). An average natural recharge of 1.8 mm yr$^{-1}$ obtained by chloride mass-balance together with a mean measured water content on the vadose zone of 0.01% yields a local pore velocity equivalent to a 'natural recharge front velocity' of about 0.2 m yr$^{-1}$.~~

~~It is interesting to compare this recharge velocity with the water table decline velocity. By definition, this sand dune area is located away from any agricultural plot (i.e. zero artificial recharge by irrigation return flow) but within one of the largest drawdown areas worldwide (about 500 km diameter; Sharaf and Hussein, 1996) caused by intensive pumping. Considering a conservative 30 m water table decline in 45 years (BRGM and Abunayyan Trading Corp., 2008), a minimum 0.7 m yr$^{-1}$ decline is computed on the outskirts of this piezometric depression. This is significantly faster than the local natural recharge velocity of 0.2 m yr$^{-1}$, suggesting that the unsaturated zone is thickening faster than the percolation flows into it. Note that we estimated (900 ± 450) × 10$^{6}$ m$^{3}$ yr$^{-1}$ of irrigation return flow (2002-2019 average; see Sect. 3.2) corresponding to (167 ± 83) mm yr$^{-1}$ distributed only over the irrigated areas of the aquifer (i.e. about 5 400 km² for the 2002-2019 period; General Authority for statistics, 2019). Such a recharge value, two orders of magnitude larger than its natural counterpart, certainly prevents the disconnection between the recharge front and the free groundwater table in irrigated areas.~~

~~Hence, while irrigation excess is great enough to artificially sustain the recharge of the aquifer within agricultural plots, the effective recharge becomes locally and temporally zero on the outskirts of such crop areas, similar to observations of a semiarid aquifer of the North China Plain by Cao et al. (2016). Some regions behave as preferential recharge areas for the Saq-Ram Aquifer System, but a mechanism of a relative disconnection of the infiltration front with the declining water table likely occurs in intensively exploited regions, most probably in the vicinity of the main irrigated areas (represented by green areas in Figure 1) where there is no artificial recharge but still a piezometric drawdown induced by intensive pumping.~~

Therefore, the abstract, introduction and conclusion should be amended accordingly:

(Line 33) ~~. Within agricultural plots, irrigation excess is great enough to artificially recharge the aquifer (i.e. (167 ± 83) mm yr$^{-1}$ distributed over irrigated areas). However, on the outskirts of these crop areas subjected only to the natural recharge but still influenced by pumping drawdown, there is a risk of relative disconnection from the infiltration front with the declining water table (i.e. the unsaturated zone thickens faster than percolation flows through it), making effective recharge locally zero.~~

is replaced by: : chiefly induced by irrigation excess over irrigated surfaces (about 1% of the domain), artificial recharge corresponds to half of the total recharge of the aquifer.

(Lines 40-44) In order to improve the now shortened abstract, we suggest to add another discussion output regarding a methodological aspect of the GRACE approach, as recommended by the reviewer:

Due to large lag times of the diffuse recharge mechanism, annual analysis using this GRACE-GLDAS approach in arid domains should be limited to areas where focused recharge is the main mechanism, while long-term analysis is valid regardless of the recharge mechanism. Moreover, it appears that about 15 years of GRACE records are required to obtain a relevant long-term recharge estimate.

(Line 150) ~~potential local disconnection between the groundwater recharge and the declining water table, causing a local zero recharge in areas of extensive exploitation, is discussed~~

is replaced by: this artificial recharge corresponds to half of the total aquifer recharge.

(Line 653) ~~Further, due to intensive groundwater withdrawal in the last decades, a mechanism of relative disconnection from the infiltration front with the water table position (i.e. the unsaturated zone thickens faster than percolation flows through it) is suggested to occur at the outskirts of major irrigated areas, presumably making recharge locally null.~~

is replaced by: Further, due to the intensive agricultural practices of the last decades, artificial recharge by irrigation excess (about 1% of the domain area), corresponds to half of the total recharge of the aquifer.

*1) At lines 156 & 157. Add "°C" after "27" and "8".*

Done (Lines 173-174).

*2) Substitute the last sentence of the caption of Figure 2, at lines 237 & 238, as follows: "Most of this previously published data comes from governmental entities, without providing any associated uncertainty."*

Done (Lines 253-254).