Report #2

Submitted on 25 Jul 2022

Note that the **line numbers** are **based** on the **“revised_v2_marked.pdf”** version of the manuscript (line numbers changed with Microsoft Word’s revision tracking mode).

- *Reviewer comments in italic font*
- Answer to reviewer comments in regular font
- Modifications of manuscript in red

Anonymous referee #1

The manuscript revision has not considered the referees’ comments in a fully satisfactory way.

I think that an appropriate and thorough discussion of scaling issues is still missing and this negatively impacts on the reliability of the remarks about the effects of intensive agriculture and geological heterogeneity on groundwater recharge. In my opinion, the concerns by Referee #3 (“…lacking of some clarity in the approach and discussion about the reliability of the proposed estimates of groundwater recharge… the authors are using a well-established method and I do not see the real contribution to scientific progress for such a study”) have not been overcome.

Therefore, I am sorry, but I think that the manuscript cannot be considered for publication on a high-quality international scientific journal like HESS, unless it is heavily revised.

Below, I provide a couple of specific comments and a couple of technical comments.

Acknowledging this severe appraisal of our study, it is however difficult to fully respond to the criticisms of Referee #1 as they flag general “scaling issues” without specifying which issues. Referee #1 cites Referee #3’s initial review, whose comments are addressed in the manuscript revised version, namely:

- Better characterizing uncertainties
- Clearing the southeastern boundary condition inactivity (also illustrated by Figure 2 of this document)
- Discussing the effects and importance of ephemeral streams

The final conclusion of Referee #3 was: “*This manuscript can be accepted with some minor revisions in my opinion”*, which means that his / her concerns were only secondary and that this study is expected to be published following minor revisions. Minor revisions are addressed in the second version of the manuscript and we believe that this should be taken into account.

Perhaps Referee #1’s comment about “scaling issues” questions the low resolution of GRACE data used to constrain the water budget of a large aquifer system, and specifically its modern recharge. Although GRACE data only allow domain-average estimates, we believe that this approach constitutes a breakthrough in hydrology and remains a worthwhile estimate, as evidenced by the numerous recent publications on this subject in "high-quality international scientific journal"(Scanlon et al., 2016, 2019, 2021; Sun et al., 2020; Fallatah et al., 2019; Bonsor et al., 2018; Mohamed et al., 2017; Fallatah et al., 2017; Rodell et al., 2018; Richey et al., 2015).

SPECIFIC COMMENTS

1) Lines 49 to 51. The scientific literature on "groundwater sustainability" or "water budget" has been unacknowledged. For instance, Bredehoeft et al. (1982) provide a discussion and older references relevant for this work.

We believe that the reference cited in this comment (Bredehoeft et al., 1982), dealing with the maximum pumping capacity of hypothetical small aquifers, is not really directly relevant to the topic of our manuscript, because the authors studied 2 very specific cases: (i) a small island in the middle of a freshwater lake with head boundary conditions allowing its replenishment by lake water beyond a given pumping rate; and (ii) a small homogeneous closed basin (3000 km²) recharged by two rivers with a single pumping location and a single natural discharge location.

In contrast, arid aquifers lack open water surfaces (i.e. lakes, rivers…) that could replenish groundwater and balance pumping beyond local recharge, making the comparison with the above cases inadequate. Thus, groundwater mining is a common feature that must be considered in the management of groundwater resources in arid systems.

Conclusions on such hypothetical, small-scale and simplified cases as those presented in Brefehoeft et al. (1982) are not transposable to the Saq-Ram aquifer, one of the largest aquifer systems in the world (500 000 km²) that includes multiple layers, several inlets and outlets, strong heterogeneities, and complex interactions (e.g. irrigation return flow).

Nevertheless, the reviewer's concern about scientific literature on groundwater sustainability has raised the issue of giving a relevant definition of "groundwater sustainability" in our manuscript. We have therefore included the definition of Gleeson et al. (2020), whose paper is focused precisely on this subject. We suggest modifying the first paragraph of the introduction (Lines 45-56) as follows:

"Freshwater resources in arid regions of the world face growing pressure. Limited reserves, sporadic rainfall, droughts, agricultural production, increasing population and living standards are contributing to environmental and economic pressures. As defined by Gleeson et al. (2020): "groundwater sustainability is maintaining long-term, dynamically stable storage and flows of high-quality groundwater using inclusive, equitable, and long-term governance and management". Groundwater resources in arid zones have been heavily exploited for the past 50 years or so, in order to meet growing demands, which has led to overexploitation and local long-term depletion in many cases (Al-Zyoud et al., 2015; Othman et al., 2018). When aquifer recharge is much lower than withdrawals, this depletion can constitute permanent groundwater mining (Bierkens and Wada, 2019; Wada et al., 2010). In arid and semi-arid regions, this is a frequent phenomenon, in particular where large aquifer replenishment mostly occurred under past climatic conditions (so called "fossil aquifers")."

2) Section 4.3. I downloaded Al-Sagaby and Moallim (2001) from the web site https://www.osti.gov/etdeweb/servlets/purl/20224661. Is this the right paper? In that paper, I was not able to find data, which supports the remarks of section 4.3. Therefore, important information is missing. First, in order to discuss issues related to spatial scales, it is necessary to give data about the extension of the Al-Qasim sand dune and on the thickness of the vadose zone (I could not find support in the scientific literature to the estimate of 70 m; is this a fault of mine?). Furthermore, data about the distance of this sand dune from agricultural plots is missing.

This is indeed the right paper (Al-Sagaby and Moallim, 2001). The poor precision of the data provided in the paper led to making inferences, especially regarding the location of the site. The authors only mentioned that "The field sampling was carried out at the KACST field station located at Qassim (320-km northwest of Riyadh)". Therefore, we deduced that it must be located in the sand dune area East of Buraydah (see attached map, Figure 1).

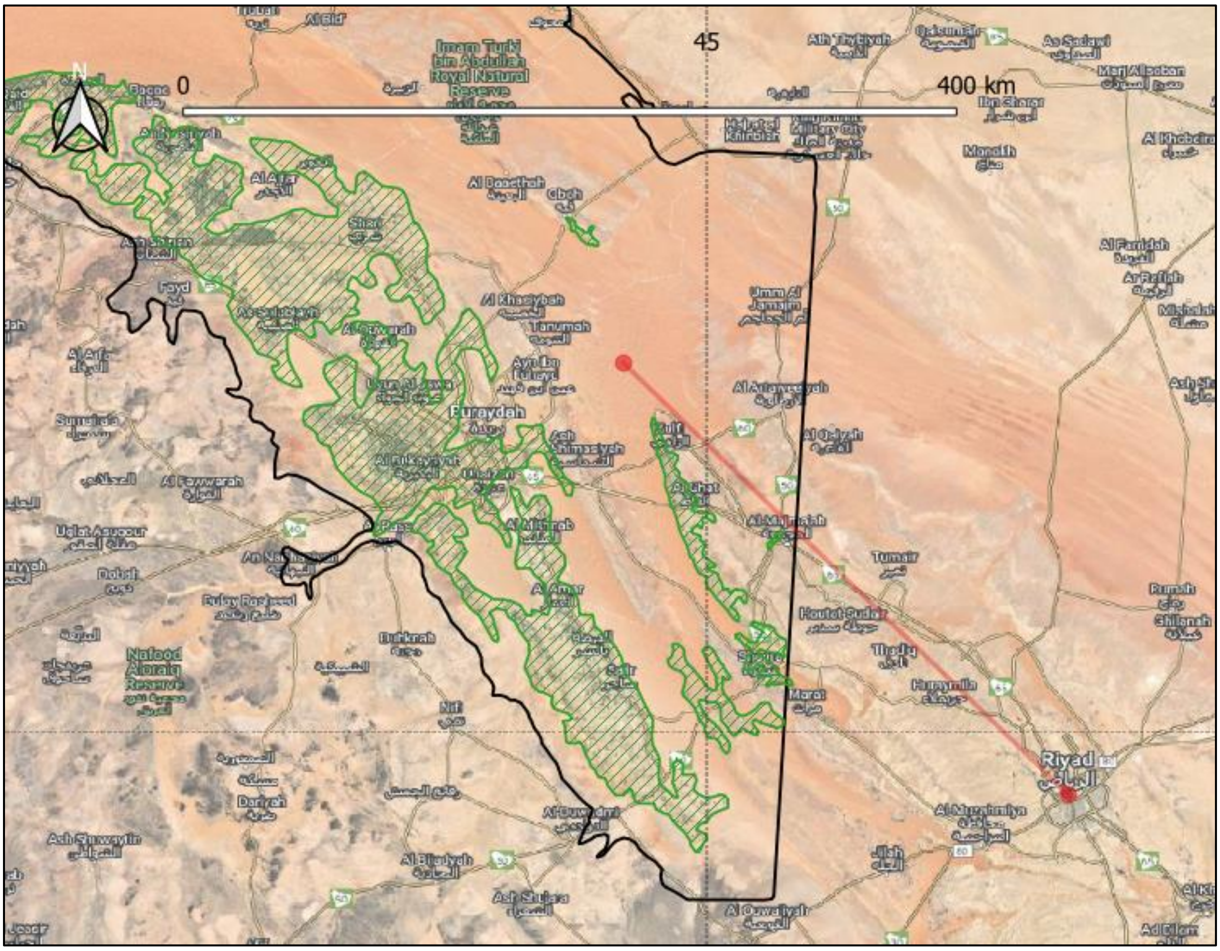

Figure 1: Estimated location of the KACST field station "320-km northwest of Riyadh" (Al-Sagaby and Moallim, 2001) shown by the red line. The black line represents the contour of the Saq-Ram aquifer, and the green hashed areas corresponds to agricultural areas.

Beyond this geographical estimate, the key topic discussed in section 4.3 is the comparison between orders of magnitude of natural recharge and the decline rate of the groundwater table.

As illustrated in the piezometric contour map below (Figure 2), the entire Al-Qasim region is influenced by one of the largest drawdown cones worldwide (about 500 km diameter at its maximum). Thus, the exact location of the site studied by Al-Sagaby and Moallim (2001) has little impact on the demonstration because the sand dune area is, by definition, not an agricultural zone. Hence, only the natural recharge estimated by the authors (i.e. 1.8 mm/yr) is effective on the soil column. Using the average water content of 0.01%, this leads to a 'natural recharge front velocity' of 0.18 m/yr, well below the minimum water decline of 0.7 m/yr reported by BRGM and Abunayyan Trading Corp (2008).

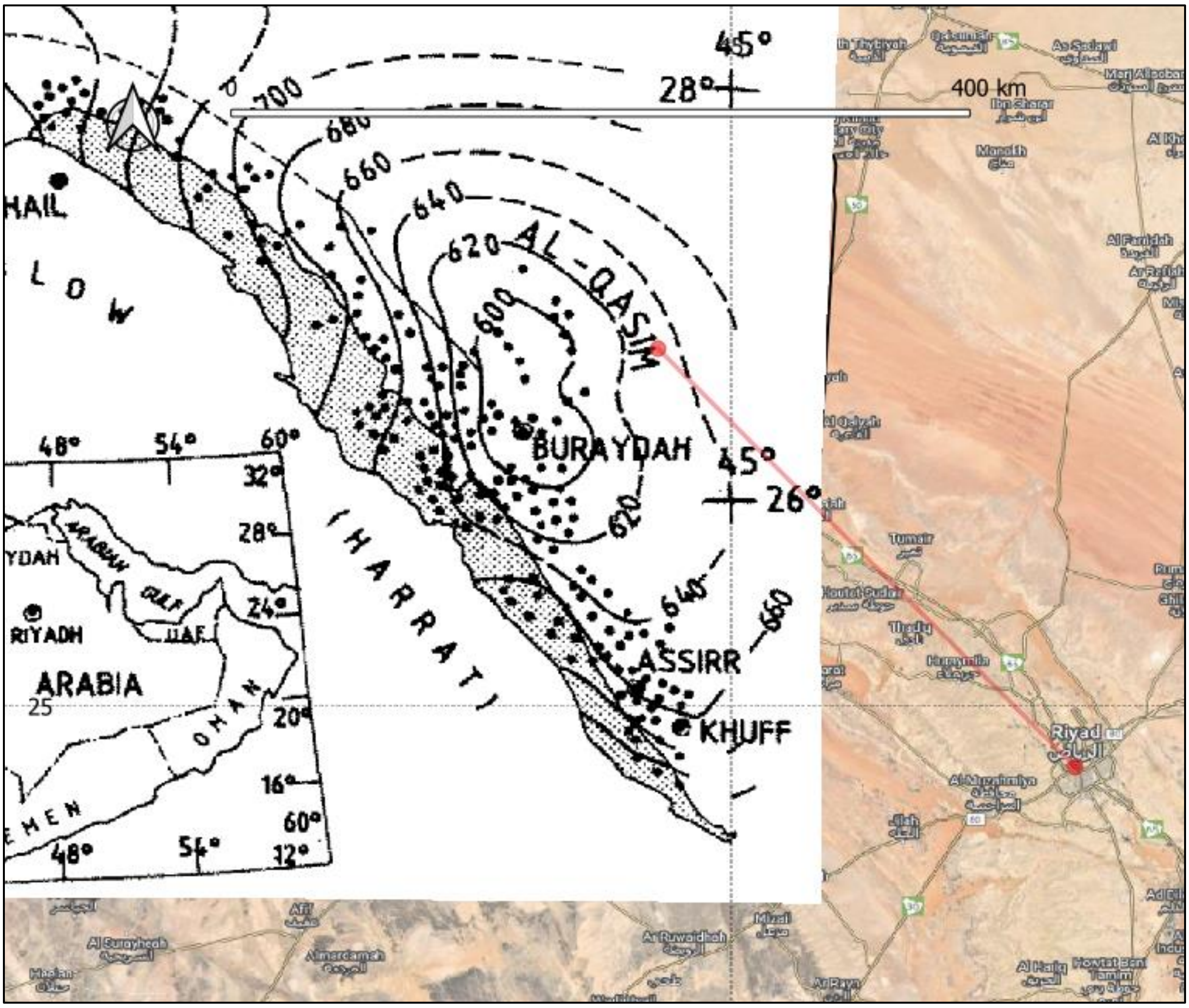

Figure 2: Piezometric contour map of the Al-Qasim region extracted from Sharaf and Hussein (1996).

In order to clarify this in the manuscript, we suggest modifying the first two paragraphs of section 4.3 (Lines 527-539) as follows:

"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."

TECHNICAL COMMENTS

1) Figure 2. The remark that "the data previously published were not given with associated uncertainties since it originally comes from the Ministry of Agriculture" should be added somewhere, either in the text or in the figure caption.

The sentence "Since most of this previously published data comes from governmental entities, no associated uncertainty is provided with it" was added to the caption for Figure 2 (Lines 239-240).

2) Line 420 & Table 1. In table 1 "(1 sigma)" is superfluous after "(standard deviation)". Moreover, at line 420, it should be preferred to mention "standard deviation" as a quantification of uncertainty, rather than the informal expression "1 sigma".

This was required by Anonymous Referee #2 and #3 ("*it is unclear if all the uncertainties presented in the paper are for 1 or 2 σ.*"). In our opinion, this addition (i.e. one sigma) was relevant since the reviewers were surprised by the low uncertainty associated with our recharge estimate. We leave it to the editor to decide whether or not it should be mentioned in Table 1 and associated caption.

However, the wording "standard deviation" is now used instead of "one sigma" (Line 425) since it comes directly after Table 1 in the manuscript.

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