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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Monitoring Groundwater Storage Depletion Using Gravity Recovery and Climate Experiment (GRACE) Data in the Semi-Arid Catchments" *by* Nizar Abou Zaki et al.

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We very much appreciate the review of our anonymous referee. The insightful and comprehensive comments helped us to make numerous changes in the way how our data and methodology are interpreted, presented and discussed. After making these changes, we will appreciate if the referee would suggest publishing of the article.

The aim of this study is to assess the efficiency of the (GRACE) derived data in catchments smaller than the recommended limitation of 200,000 km2 suggested by (Longuevergne et al., 2010). This approach was stated clearly in the abstract (Page 1: Line 16-17), and discussed later in the discussion section (Page 17: Line 7- 18). When

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approached on smaller scale, GRACE data tend to show more uncertainty. For a better understanding, Bekhtegan catchment is chosen as a study site, as detailed data is available from 448 groundwater observation wells, and 22 climatic monitoring station. The water mass balance of the catchment is calculated from this, which includes the daily precipitation, evapotranspiration and soil moisture. This water mass is compared with GRACE derived data (Figure 4B and 4C). Also the two constants (KA) and (KB) (Page 7: equations 6 and 7) (Figure 5D) show the uncertainty when comparing the (GRACE) data with both the water mass and the groundwater volume variation. The study also suggests that the uncertainty can also be related to the catchment's aquifers type, as the aquifers in the study area are considered to be shallow (Page 14: Line 5-10) and (Page 14 Line 20-25). All the previous (GRACE) studies have in common the large scale study area. In our study, smaller scale helps noticing the direct effects of local hydrologic phenomena like droughts (Page 8: line 6-24) on the groundwater level and its occurrence in (GRACE) derived data. The study discusses the efficiency of (GRACE) data as a tool that can be used for water management on local level (Page 17 Line 19 till Page 18 Line 2). From what mentioned, we believe this study gives innovation against already published studies. Below are our point by point answers for the referee comments:

* Title: This is really a study of one basin not a study of semi-arid basins in general and the title should be revised to reflect this:

We agree on this comment, and the title can be changed to (Monitoring Groundwater Storage Depletion Using Gravity Recovery and Climate Experiment (GRACE) Data in Bakhtegan Catchment).

* Introduction: There is some reference to previous GRACE work in the introduction, but additional discussion is needed to better explain how this specific location adds information to the comparisons that have already been done:

The introduction mentions quickly some previous studies, and more studies are men-

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tioned in the discussion section. In the revised version, a paragraph is added to compare our finding with previous studies finding. This can lead to general conclusions about the effects of the specific location on the results.

* Methods: There are many points in the methodology that are inaccurate or are not clear. I have listed some examples below: - In equation 3 how is porosity accounted for:

In equation 3, (ΔS) is expressed in (mm) and shows the actual variation of the groundwater levels. Here the porosity doesn't affect the calculation, as the groundwater level here is based on actual site measurements. (ΔS) is the difference in measurements between two consecutive readings. Actually porosity rate in used in equation (2), (WBI), which is the net precipitation volume. According the Atlas report, the precocity volume fraction is considered 0.1 (Reference will be added in revised version)

* There is no detail on how the well data was combined to get the groundwater storage estimates and what hydrogeologic properties were used:

Section (2.3) (Page 6) describes how the groundwater level variation in the catchment was calculated. Equation (3) shows the conversion of the monthly reading of the observation wells (in meters) to a variation in (mm), on the sub-catchment level. In Equation (4) the variation in the whole catchment is calculated. Expanding the explanation of the methodology in the revised version will give a better understanding of the last two comments.

* It is also unclear how the ET rates were calculated. What time period were the 'average ET rates' averaged over? And how was land use data used to adjust these values for agricultural land and forests? A figure showing the ET with some uncertainty bounds on ET would be helpful:

(Line 7 Page 4 till Line 1 Pages 5) states that the land use data and the evapotranspiration data was estimated from images and data available on (USGS Modis) and

(Climengine.appspot.com). The evapotranspiration data is hourly data referred to different land use zones in the catchment. The data covers the same study period from April 2002 till December 2011. We agree with the review that an equation must be added, before equation (1), regarding the calculation of the average evapotranspiration in the catchment (mm). The average evapotranspiration rate is shown in (figure 3C).

* In equation 5 why do the GW and total Water components have the MI subscript but not the other two:

(MI) is added in this equation to separate (WMI) as the total water mass, from (WBI) as the net monthly effective precipitation volume mentioned in equation (2). (SW) and (SM) and monthly volume on surface water and soil moisture variation, and were mentioned in this equation only. (MI) is used to differentiate two similar constants.

* Equation 5 talks about total storage but to be consistent with GRACE these should be changes in storage correct? I don't see anywhere here where the total groundwater storage is calculated:

Please refer to (Page 7 – Line 8): The GRACE data shows the total water mass variation in the catchment. According to (Rodell and Famiglietti, 2002) to get the groundwater volume variation from GRACE, other water components masses must be eliminated. Here we eliminate the surface water volume, based on calculation of the Bakhtegan and Tashk lakes volume variation, and the soil moisture volume, which was computed from GLDAS datasets as mentioned.

* More details on the surface storage calculations as well as soil moisture would also be helpful. For example, where are the stream gauges located? How exactly were storage changes calculated taking into account the Water Atlas report:

We agree that this calculations must be shown in more details in the methodology section. Lake Bakhtegan and Tashk are the only sources of surface water in the catchement. The stream gauge are located in the lakes inlet. The calculation in the surface

water volume is calculated from the flow data recorded, subtracting the lake evapotranspiration. The soil moisture data is the average of the soil moisture in the three measured soil layers. This data as mentioned is computed from GLADS database. This will be mentioned in the revised version.

* It looks like Equation 2 assumes that all of the net precipitation goes to recharging groundwater. What about runoff? How is this accounted for:

As mentioned before, the porosity volume factor considered for this calculation is 0.1 as recommended. This will be added with reference to the manuscript.

* Page 8 Line 1: Please specify exactly what 'the GRACE data' you are referring to here:

In page 7, equation (5) states that the GRACE data intends to mean the groundwater volume variation derived from GRACE data. This will be mentioned in the revised version

* Page 8 Line3: Contrary to the text, It looks like KB is actually the relationship between groundwater volume changes and precipitation not GRACE? Is this correct:

True, (KB) shows the relationship between the groundwater volume changes and the precipitation. This will be corrected in the revised version

* Page 8 Line 11: How was monthly net precipitation calculated from GRACE? This does not make sense to me:

This sentence (Page 8 line 11) must be corrected from (Monthly net precipitation calculated from GRACE) to (Monthly groundwater volume variation derived from GRACE)

* Terminology: The terms groundwater storage, and groundwater levels are used interchangeably in the manuscript. I think the authors should be more careful in the definition and use of these terms. This especially needs clarification because the storage changes are expressed in length units which can give the impression that they

reflect groundwater depth changes, when they do not:

Equation (3) and (4) (Page 6 Line 6 and 10) defines the groundwater storage variation derived from the in-situ data, while equation (5) (Page 7 Line 11) defines the groundwater storage derived from GRACE data. Groundwater level are mentioned a variable used for calculating equation (3 and 4) in (Page 6 Line 7). It will be clarified that the groundwater depth in (mm) is a unit of measuring the storage changes and not the depth changes.

* Page 10 Lines 13-16: The authors note it is difficult to calculate volumetric losses from the groundwater measurements. However, this is one of the key goals of the study and is necessary for a meaningful comparison to GRACE. As noted above, I would like additional details on how groundwater storage was calculated and what the uncertainties in this calculation are:

As answered before the methods of calculating groundwater storage from in-situ and GRACE data have been clarified. Here we intend to show that the difference in the volume variation from the two data sources, can be referred to aquifer geology and transboundary flow from surrounding catchments.

* Page 11 Line 12: What constitutes a 'good fit'? Can you be more precise in how this was quantified:

"Good Fit" was related to the results of (Figures 4B and 4C). In (Figure 4C) it can be noticed that (ΔS) and (WB) have almost identical results. In the (Figure 4B), the both (ΔS) and (WMI) show negative trend and decrease in the storage volume.

* Page 14 Lines 15-17: This sentence doesn't make sense to me, please revise:

This will be revised in the meaning of: The lower confined aquifers have higher volume compared to the upper alluvial aquifer. Any depth changes in these aquifers, will have a direct change on the water volume storage change.

* Page 14 paragraph starting on lines 18: This discussion is a bit hard to follow. I think

it would fit better in the methods section where the details on how groundwater storage changes are calculated should be included. It's not clear from this discussion how the confined and unconfined units were treated in the delta S calculation:

(Figure 4D) shows that post the drought period of the year 2007, there was an increase in the groundwater exploitation volume. This can be due to the increase in the groundwater usage to adjust the low precipitation volume. Also the drop in the groundwater level, as the paragraph starting on line 18 states, might also be related to pressure stabilization due to the increase of the well depth. This means that the level drop can be related to two factors, rather than just over exploitation rates. Confined and unconfined units are involved in the (ΔS) calculation.

* Discussion Page 15 Lines 3-5: it is unclear how the combination of these datasets provides unique information on water use. Mainly what has been presented here is a comparison between methods and it's not clear that the difference between these two reflects anything other than uncertainty in all of the water balance components. Please clarify what you mean by this:

I think you meant (PAGE 16, Line 3-5). In the same paragraph (Line 7-8) we mentioned that GRACE data can help draw general conclusions about aquifer conditions. Here referring to (Figure 5C), GRACE showed a negative trend in the groundwater storage volume. Also later in the discussion, we mentioned that the area of the catchments directly can be related to uncertainty of the GRACE results, but still referring to the word (general), some conclusions can be drawn. This, and what stated in the first page of the authors response, is what mainly presented.

* Page 16 lines 14-15: I disagree that 7.6 mm is a 'severe water loss' even for a semiarid area. Can you provide some justification for this classification:

7.6 mm is the annual volume depth lost on the catchment level, which is equivalent to 2.4 km3 in the period of 10 years. Referring to (Figure 6 Page 15) that loss reached 30 meters in groundwater table level in some aquifers. This decrease, increased the wells

depth in many aquifers

* Page 16 line 18: The analysis presented here does not do anything to prove that 'confined fossil aquifers' were reached so this should not be included in the discussion:

As part of our discussion we used the word (have) to indicate that this might be a case. Moreover previously we mentioned that drop in the groundwater level might be due to pressure stabilization when reaching confined aquifers. Also as mentioned before we know from the study area that the well depth has increased

* The authors talk about water level drops of 10 -30 m over the 10 year study period which but then have annual trends of 7.6mm. In order to rectify these measurements we need a better understanding of the physical properties of the aquifer. Without knowing this it is difficult to understand how reasonable the trends in volume are:

The 7.6 mm annual volume depth lose is calculated considering the catchment as one aquifer. The more detailed sub-aquifer lose is presented in (Figure 6 page 15), where the properties of the aquifer play an important role in this level loss. Also and assumption discussed in the discussion section when describing the areas aquifers as shallow aquifers

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