*"**Estimating long-term groundwater storage and its controlling factors in Alberta, Canada**", by Soumendra N. Bhanja, Xiaokun Zhang, Junye Wang*

Reviewer #1:

General comments: The study presents an interesting use of gravity based remote sensing data (GRACE) for monitoring of groundwater resources in Alberta region and comparing it to available in situ monitoring well data. It is mostly nicely structured and written that the study is easy to follow for the reader. However, there are issues especially concerning the use of the data and the methods that should be revised thoroughly to enhance the quality of the manuscript.

Reply: We would like to thank the reviewer for his/her interest in our work and also for careful consideration of the manuscript. We have addressed all of his/her concerns in the revised manuscript.

Rev 1. Comment 1: First main issue is how the in situ data is used. Authors mention in the abstract and in the text that the unconfined and unconfined aquifer monitoring wells are separated from the in situ data and different approach for groundwater storage change has been used (equation 1 & 2). This is good as the well reading from confined aquifer compared to unconfined aquifer tell a different information on the aquifer storage. However, this separation of the data does not show in results or in discussion. In addition, this connects to the second issue of the manuscript. You have not given any information where on the studied catchments the wells are situated. As there is no spatial data for the wells or the information how the confined and unconfined aquifers are presented in each catchment, it is rather hard to say how representative the in situ data is for a specific catchment where you have the satellite data calculated and compared.

For example: the basin 7 in situ data and GRACE data do not seem to correlate. You have 15 wells in this catchment, but are these e.g. situated in one aquifer? Are they all unconfined aquifers? The average well data in figure 3 might indicate a strong annual snowmelt impact to the groundwater level in basin 7 average groundwater levels. This would happen in unconfined aquifers in snow dominated region (see comment on snow melt below). With the information given in the manuscript this cannot be confirmed or discussed in detail.

Reply: We would like to thank the reviewer for raising this concern. We fully agreed with him. We have added Figs 1 d-e and Table S2 to show the spatial distributions of both confined and unconfined wells in each catchment. We have added two paragraphs within Section 3.1 to discuss effects of snowmelt and aquifer types and provided a figure in supplementary information.

Table S2: Basin-wide distribution of wells screened in different types of aquifers

Basin	**Unconfined**	**Semi-confined**	**Confined**	**Unclassified**	**Total**

ID					
1				3	**3**
2	6		7	2	**15**
3	2		6		**8**
4	5	2	14		**21**
5	3	6	19		**28**
6	1	3	16	1	**21**
7	3	1	4	7	**15**
8	2	1	6	1	**10**
9		1	4	1	**6**
10	1	1	7		**9**
11	1	2	17	1	**21**
Total	**24**	**17**	**100**	**16**	**157**

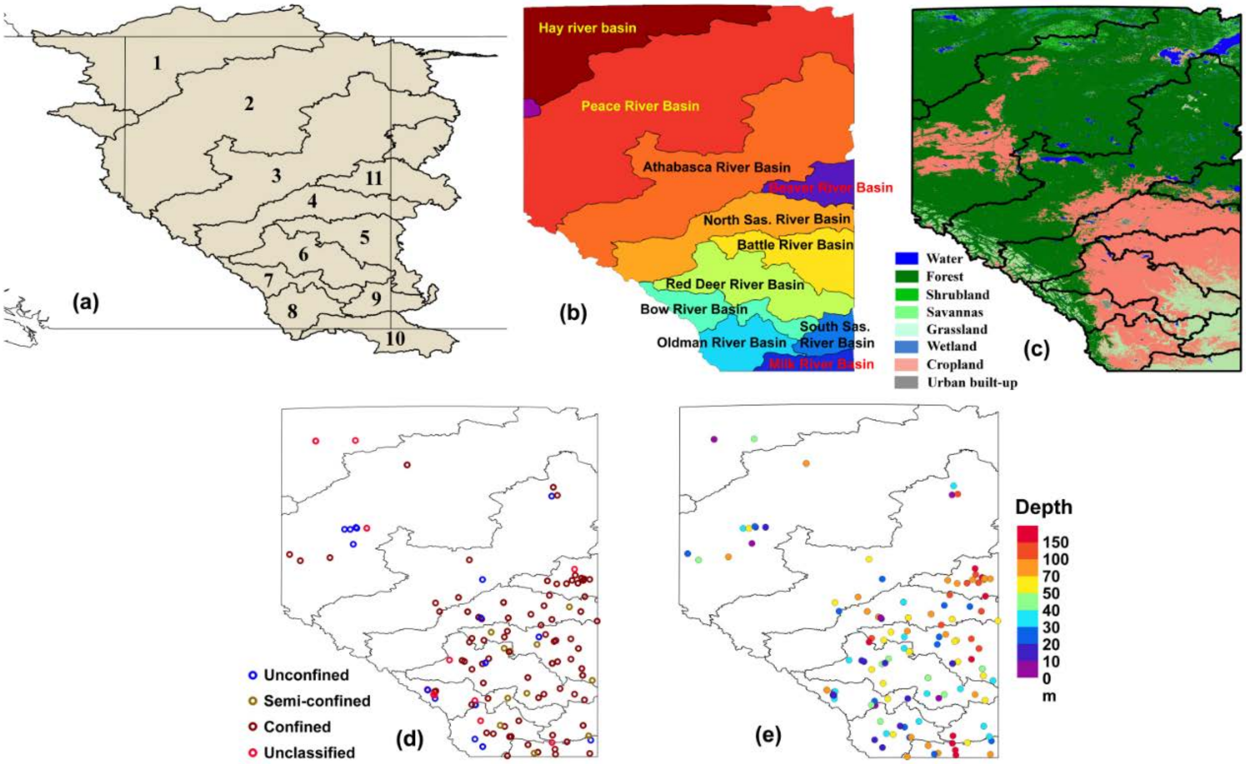


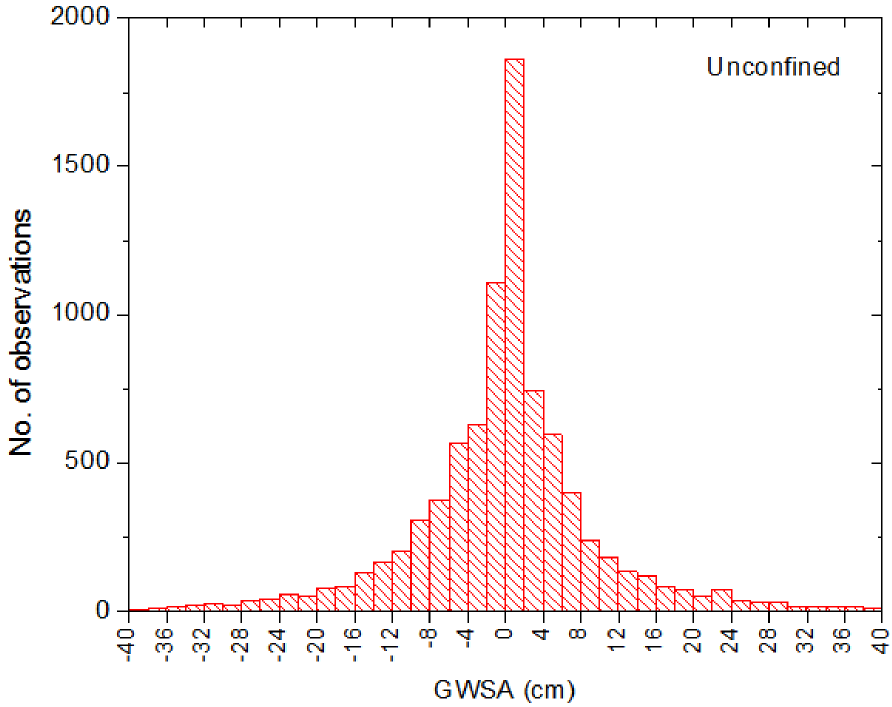
Figure 1: Major river basins in Alberta, (a) full basin extent; (b) Alberta only; (c) dominant land cover types; (d) aquifer types represented through the studied wells; (e) depth of wells screened in Alberta, overlaid by basin boundaries

"*Out of the 157 measurement locations used in the study, 24 are located in unconfined aquifers, 17 are located within semi-confined aquifers, 100 are located within confined aquifers and 16 are unclassified (Figure 1d). The screen depth of the wells varies from 6 m to 220 m (Figure 1e).*" [**Page: 4; Lines:** 7-10]

We added two paragraphs to discuss snowmelt impact and different types of aquifers.

"*Another important factor influencing groundwater recharge as well as the groundwater storage, is the snowmelt processes prevailing in cold regions during the onset of spring-summer. The river basins have been receiving substantial amount of snowfall during winter months (Figure 3). This leads to snow accumulation in the region. At the end of winter season, snowmelt processes are majorly accounting for our observation of increasing GWSA in April onwards (Figure 3). The observation is in line with the observations from the earlier studies conducted within the study region (Hayashi and Farrow, 2014; Hood and Hayashi, 2015). Comparatively higher rates of precipitation during summer months and the snowmelt during the start of the summer season, are the major processes responsible for the observation of higher GWSA during summertime at the entire study region (Figure 3).*" [**Page: 8; Lines:** 4-11]

"$GWSA_{obs}$ values from the unconfined aquifers reflect higher magnitude than that in the confined aquifers (Figure S1). This is because of the intrinsic property of the different types of aquifers. For instance, dewatering from the saturated zone during a pumping event, is mainly responsible for the release of water in unconfined aquifer (Alley et al., 1999). On the other hand, a net decrease in groundwater potential and associated reduction in water pressure have been occurred during a pumping event in a confined aquifer. The indigenous water expands slightly due to the decrease in water pressure, leading to slight compression in the aquifer material (Alley et al., 1999). This can explain why the groundwater storage change in the confined aquifers are comparatively lower than that in the unconfined aquifers." [**Page: 8; Lines:** 12-19]



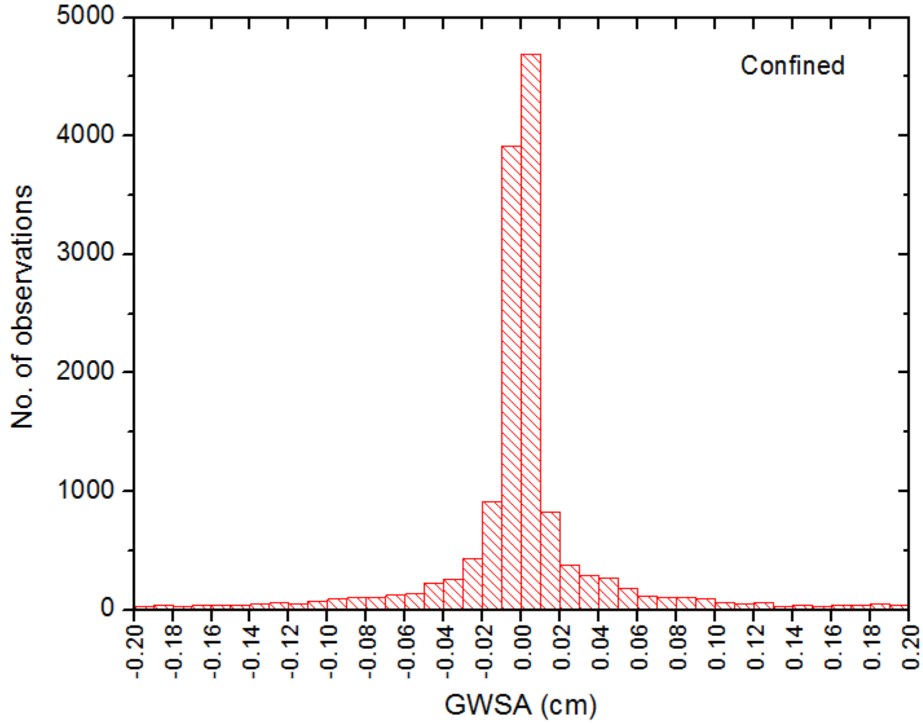


Figure S1: Histogram of GWSA estimates from unconfined and confined aquifers

Rev 1. Comment 2: How deep aquifers the wells are monitoring? If the screening zone is for a deeper, confined aquifer, how much a yearly recharge impacts this aquifer? All in all, it would be beneficial to present more in detail how the monitoring wells are presenting the prevailing aquifer conditions in different catchments.

Reply: We would like to thank the reviewer for his/her suggestion. We have provided more details on well depth and types of aquifers encountered in the revised version of the manuscript. Please see our answer to **Rev 1. Comment 1**. Recharge impact on groundwater storage in confined aquifer is a complex issue to deal with, this is beyond the scope of this manuscript at present. Here, we are not dealing with the absolute storage but estimating the storage anomaly (that is the deviation of storage from a mean value). If the confined aquifer recharge is constant over the years, it will be cancelled out by computing storage anomaly.

Rev 1. Comment 3: And concerning the methods used: the smallest catchment size (or part of the catchment studied) in this manuscript is Milk basin with 11834 km2. In total, the size in three of the catchments is smaller than 20000 km2. Is the size of the catchments a problem for the GRACE data methods used or does it cause uncertainty? This issue is previously discussed e.g. in Wishvakarma et al. 2017 for different GRACE approach.

Reply: We thank the reviewer for his/her suggestion. We agree that the use of GRACE data is not always appropriate for smaller basins. We have discussed these issues in Section 2.7 Assumptions and limitations.

"*We have shown the satellite-based estimates for all of the basins, however, users should be cautious to use GRACE data in the smallest basins. This is because GRACE's native resolution could not allow users to directly use the data for smaller basins. Other processes, such as, the use of GRACE and integrated land surface model's operation could make the data available to use for smaller basins (Landerer and Swenson, 2012; Watkins et al., 2015). Data processing methods Proposed by Dutt Vishwakarma et al. (2016) could be used to make the data available for smaller basins with GRACE-SH products.*" [**Page: 7; Lines:** 15-20]

Rev 1. Comment 4: Authors have studied how the precipitation is connected to the GWSA (chaper 3.5). However, role of snow is not discussed in detail. In many northern areas the snow melt can be the driving factor for the groundwater storage recharge. Same goes to large areas in Alberta. As during the winter months the precipitation accumulates in snowpack and then usually melts in a short period, it would be more beneficial to compare warm period precipitation and winter time conditions (<0 degree C) separately, or take the snow water equivalent from GLDAS and add this to your analyses. With the straight comparison between monthly precipitation and GWSA a large portion of the yearly hydrological dynamics is missing. Authors have tested different approach in chapter 3.6., but this approach does not takes into account in detail the snow accumulation and snow melt.

Reply: We would like to thank the reviewer for his/her concern. We have now included the analyses of snowmelt and its influence on GWSA. We have modified the Figure 8 and include the combined data of rainfall and snowmelt along with the precipitation and GWSA. We have modified the Section 3.3 as:

"*In general, precipitation is the major controlling factor for variations in water storage (Scanlon et al., 2012). In this study, we have observed that GWSA values are not directly influenced by the precipitation pattern in some of the basins (Figure 8). The HP trend analysis shows a good match of $GWSA_{obs}$ with precipitation in basins 1 and 10 only (Figure 8, Table S5). $GWSA_{obs}$ trends are not following precipitation pattern in other basins (Figure 8, Table S5). The cross-correlation analysis between HP trends provide similar inferences (Table S5). In order to investigate the relationship with more detail, the Granger causality analyses (Granger, 1988) were performed with order 1 (insignificant results were found when other orders were used). Results show precipitation significantly (p value <0.01) causes $GWSA_{obs}$ in 4 of the 11 studied basins, basin 1, 5, 7 and 11. The results were found to be insignificant or even negatively correlated in other basins (Table S5).*

A part of the precipitation, in particular, snowfall has little influence in modulating the groundwater storage, unless it is converted to snowmelt water. Therefore, we have studied the combined influence of rainfall and snowmelt water on $GWSA_{obs}$. Here, the rainfall and the snowmelt water data are retrieved from the three LSMs (CLM, VIC and Noah) in GLDAS archive and used in combination. Good match between rainfall and snowmelt water, and $GWSA_{obs}$ have been obtained in basins 1 and 11. Cross-correlation analyses indicate similar *inference (Table S6). Granger causality analyses (order 1) show the combined effect of rainfall and snowmelt water significantly causes GWSA$_{obs}$ in 6 basins: 1, 2, 5, 7, 9 and 11 respectively. This implies that other factors, such as domestic and industrial water withdrawal etc., play major roles in influencing the GWSA in other basins.*" [**Pages: 9-10; Lines:** 19-2]

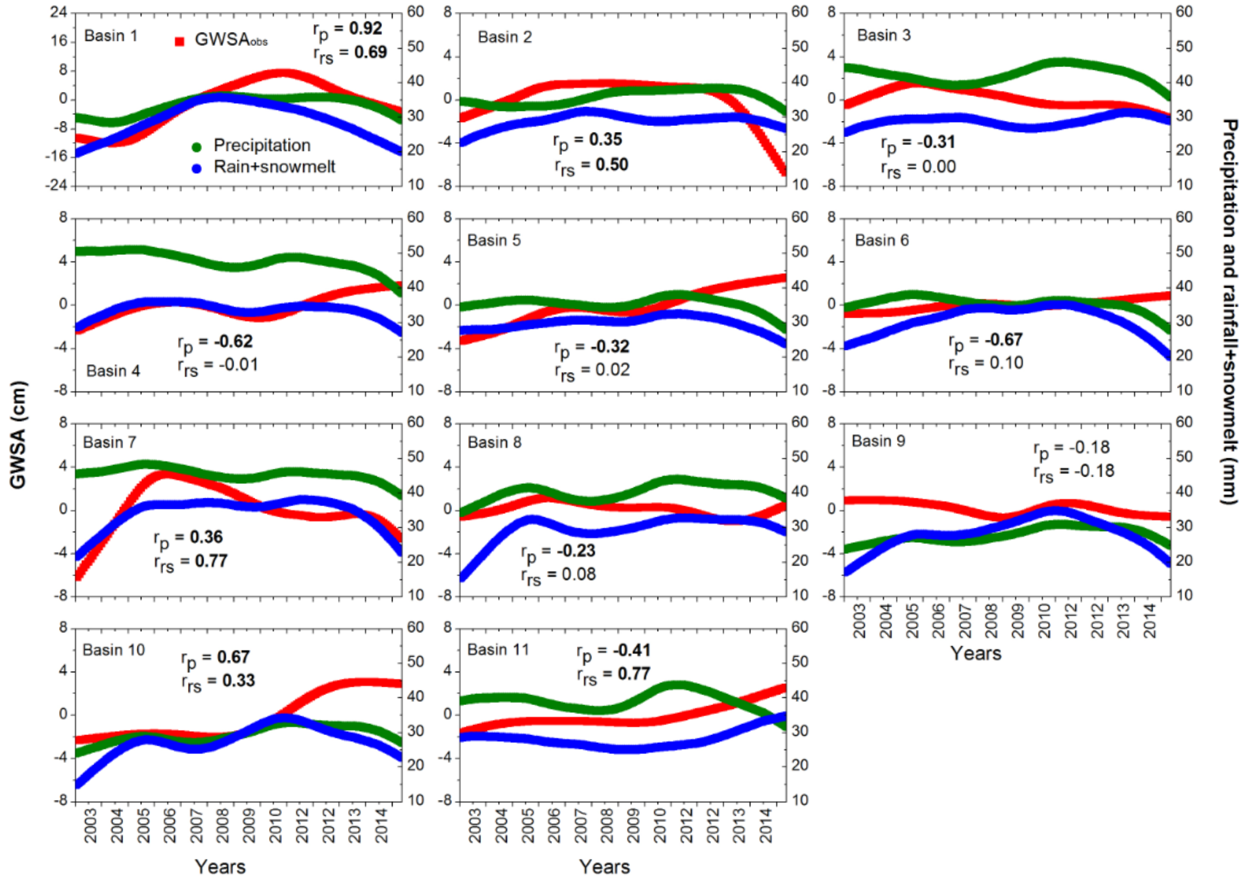


Figure 8: Basin-wide time-series of HP filter data for in situ GWSA (OBS, red squares), precipitation data (green circles) and rainfall+snowmelt data (blue circles). Pearson's correlation coefficient (r) values are provided in in-set and statistically significant (*p value* < 0.01) values are shown in bold font. r_p and r_{rs} indicate correlation between GWSA, and precipitation and rainfall+snowmelt, respectively

Also included these in abstract and conclusions.

"*A combination of rainfall and snowmelt positively influence the GWSA$_{obs}$ in 6 basins.*"[**Page: 1; Lines:** 19-20]

"*A combination of rainfall and snowmelt water causes significant GWSA variations in 6 basins, indicating prevalence of other factors for influencing GWSA in the remaining basins.*" [**Page: 11; Lines:** 2-4]

We have also added cross-correlation analyses details in Table S6 between rainfall+snowmelt and the $GWSA_{obs}$.

Table S6: Correlation analysis between Hodrick-Prescott trend of rainfall+snowmelt and $GWSA_{obs}$ (no lag, 1 month lag and 2 months lag)

Basin id	**R** **No lag**	**R** **1 month lag**	**R** **2 months lag**
1	0.69	0.72	0.75
2	0.50	0.47	0.43
3	0.00	-0.02	-0.03
4	-0.01	0.02	0.05
5	0.02	0.06	0.10
6	0.10	0.13	0.16
7	0.77	0.76	0.74
8	0.08	0.06	0.05
9	-0.18	-0.19	-0.20
10	0.33	0.37	0.40
11	0.77	0.77	0.76

In the revised version of the manuscript, we have also discussed the snowmelt issues in the Result and Discussions Section 3.1.

"*Another important factor influencing groundwater recharge as well as the groundwater storage, is the snowmelt processes prevailing in cold regions during the onset of spring-summer. The river basins have been receiving substantial amount of snowfall during winter months (Figure 3). This leads to snow accumulation in the region. At the end of winter season, snowmelt processes are majorly accounting for our observation of increasing GWSA in April onwards (Figure 3). The observation is in line with the observations from the earlier studies conducted within the study region (Hayashi and Farrow, 2014; Hood and Hayashi, 2015). Comparatively higher rates of precipitation during summer months and the snowmelt during the start of the summer season, are the major processes responsible for the observation of higher GWSA during summertime at the entire study region (Figure 3).*" [**Page: 8; Lines:** 4-11]

Detailed comments:

Rev 1. Comment 5: Use of abbreviations: the text does not follow good order of abbreviations. E.g. in abstract in line 17 you present GWSAobs first time without explanation. And in line 19 has GWsat two times which mixes reader of the abstract. Same continues in text. E.g. in page 2 line 34 GWS is presented first time without explanation.

Reply: We would like to thank the reviewer for his/her careful observation. We have modified the sentences as suggested by the reviewer.

"*Storage coefficients for the individual wells were incorporated to compute the monthly in situ groundwater storage (GWSA$_{obs}$).*" [**Page: 1; Lines:** 13-14]

"*They used ground water levels at 36 wells, mostly confined to the southern Alberta region, and were correlated with both the GRACE total water storage (TWS) and groundwater storage (GWS) variations.*" [**Page: 2; Lines:** 14-16]

Rev 1. Comment 6: Page 2, line 20: extra comma

Reply: Thanks for the observation. The comma has been deleted.

Rev 1. Comment 7: Page 2, line 9, space after point

Reply: Thanks for the observation. A space is given after the point in the revised version.

Rev 1. Comment 8: Page 3, lines 17-18: sentence structure

Reply: Following the reviewer's suggestion, we have modified the sentences in the revised version.

"*To find the role of natural hydrological components (e.g. precipitation, snowmelt, evapotranspiration) for influencing groundwater storage variations. We have also studied long-term groundwater recharge trends from a global-scale hydrological model for inferring long-term variabilities in groundwater recharge rates.*" [**Page: 3; Lines:** 4-6]

Rev 1. Comment 9: Page 7: the two equations have a wrong number

Reply: We would like to thank the reviewer for his/her careful consideration. The equation numbers are modified in the revised version.

Rev 1. Comment 10: Page 7, line 20: repetition from previous sentence

Reply: Following the reviewer's suggestion, we have modified the sentence.

"*Basin 3 has been subjected to the highest amount of licensed groundwater withdrawal allocation in Alberta (basin 3 accounts for 39% of the total groundwater usage in Alberta).*" [**Page: 7; Lines:** 28-30]

Rev 1. Comment 11: Page 10, line 6: 470 wells were monitored but 157 were used (page 4, lines 13-15) Is Figure 8 is not presented in the text.

Reply: We would like to thank the reviewer for his/her suggestions. We have modified the sentence in conclusion, reflecting the number of wells use for final analyses.

"*A network of 157 daily groundwater monitoring wells was used to compute groundwater storage anomalies (GWSA) in 11 major river basins in Alberta, Canada between January 2003 and April 2015.*" [**Page: 10; Lines:** 22-23]

We have referred the Figure 8 in text within Section 3.3.

"*In general, precipitation is the major controlling factor for variations in water storage (Scanlon et al., 2012). In this study, we have observed that GWSA values are not directly influenced by the precipitation pattern in some of the basins (Figure 8). The HP trend analysis shows a good match of $GWSA_{obs}$ with precipitation in basins 1 and 10 only (Figure 8, Table S5). $GWSA_{obs}$ trends are not following precipitation pattern in other basins (Figure 8, Table S5). The cross-correlation analysis between HP trends provide similar inferences (Table S5). In order to investigate the relationship with more detail, the Granger causality analyses (Granger, 1988) were performed with order 1 (insignificant results were found when other orders were used). Results show precipitation significantly (p value <0.01) causes $GWSA_{obs}$ in 4 of the 11 studied basins, basin 1, 5, 7 and 11. The results were found to be insignificant or even negatively correlated in other basins (Table S5).*

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