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

<u>Prof. B. Klöve's comments:</u>

<u>SC #1</u> General comments: The work by Bhanja et al. presents a study where GRACE observational products are compared with monitored and estimated groundwater storage changes in Alberta, Canada. The study shows that GRACE data can be used to understand groundwater storage changes and responses. As such, the results are important and the study of broad international interest. However, the manuscript is poorly organized and several sections are poorly written.

Reply: We sincerely thank Prof. Klöve for his interest in our work. We have thoroughly revised the manuscript to take into consideration your concerns and comments. We have re-organized and rewritten several sections, insert new figures, tables and discussions, which we believe, have improved the manuscript to a great respect.

SC1 Comment 1: The title promises too much. A more specific title with the focus on Alberta as case study would be more appropriate considering the content of the work. Also, is Alberta really a cold region or temperate region?

Reply: Following Prof. Klöve's suggestion, we have modified the title to "*Estimating long-term groundwater storage and its controlling factors in Alberta, Canada*". In general, most parts of Alberta falls within cold climate region based on Koppen-Geiger classification. Please refer to Figure 6 in Peel et al. (2007).

SC1 Comment 2: Generally, the role of snow accumulation and melt is not well discussed or included in the work. Certainly, this must be a main reason for seasonal changes in water storage in regions with winter and snow (4 seasons). Improve e.g. section 3.1. on this issue. Also on line 29, page 8, the statement on precipitation is a bit odd for cold climate (correct to snow).

Reply: We would like to thank Prof. Klöve for raising this concern. We agree with him that snowmelt is a main factor in groundwater storage in cold region. We have now included the analyses of snowmelt and its influence on GWSA. We have modified the Figure 8 and included the combined data of rainfall and snowmelt along with the precipitation and GWSA. We have modified the subsection 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]

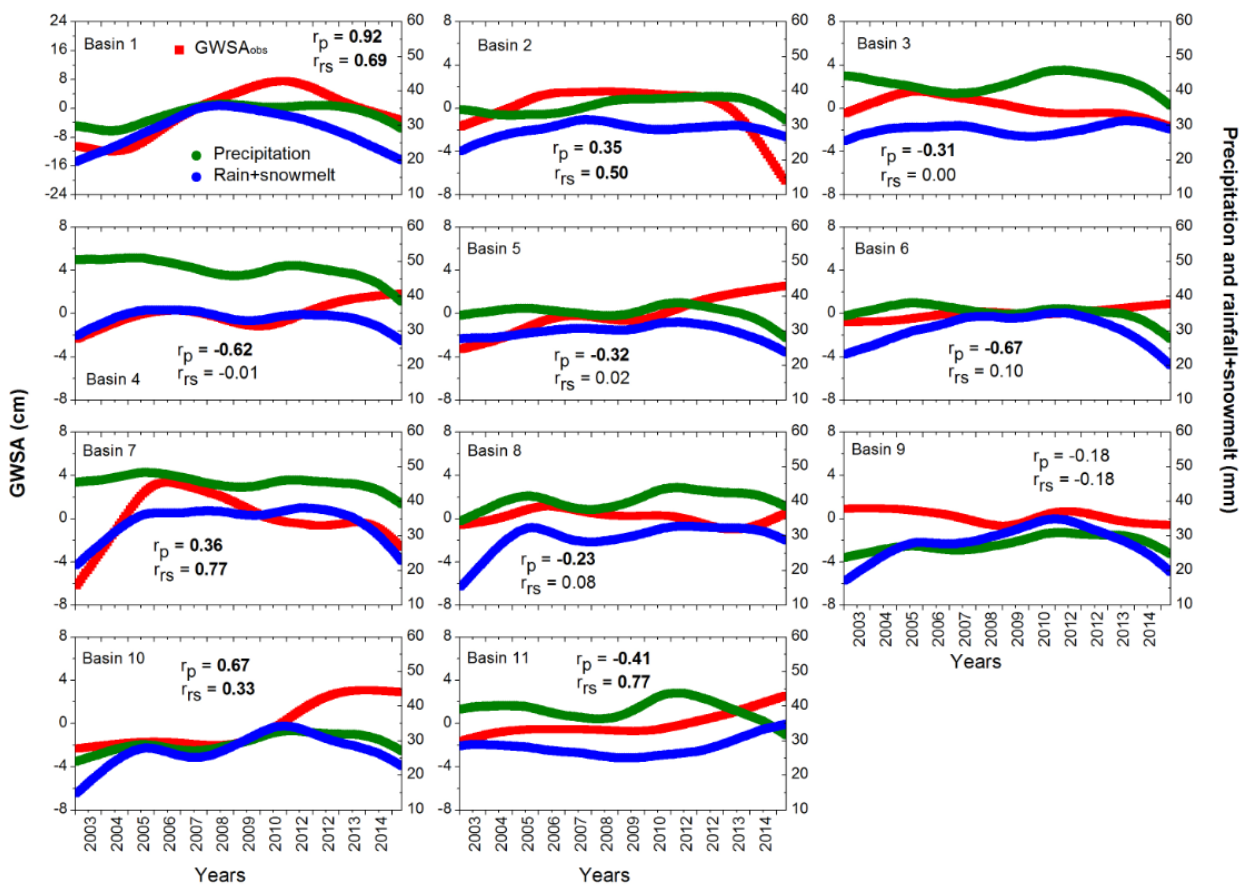

Figure 8: Basin-wide time-series of HP filter data for in situ GWSA (OBS, red squares), precipitation data (green circles) and rainfall+snowmelt data (blue circles). Pearson's

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]

SC1 Comment 3: I find it surprising that the global scale hydrological modelling used to estimate recharge has not explained in the methods at all (only shortly in section 3.5). A sub-section is needed on this under section 2 including aspects of uncertainty. Revise section 3.6 to focus on results of the modelling.

Reply: Following Prof. Klöve's suggestion, we have included subsection 2.6 for description of the model generated groundwater recharge output including uncertainties. Section 3.4 (earlier 3.6) has now included only the results and discussions related to the modelled recharge.

We used global scale hydrological modelling output to discuss about the patterns and trends of the groundwater prevailing over the region. There are no direct measurement for groundwater recharge is available.

"*We have studied the long-term (1960-2009) groundwater recharge occurrence from the global-scale model output because of unavailability of direct groundwater recharge measurement in the region.*" [**Page: 10; Lines:** 14-15]

"***2.6 Groundwater recharge from global-scale hydrological model***

In order to find the historical groundwater recharge pattern, we used a global-scale hydrological model, WaterGAP (version 2.2) (Doll et al., 2014) to estimate long-term groundwater recharge data (1960-2009). The WaterGAP simulates global-scale water storage and transport including human water use and groundwater recharge from surface water bodies at $0.5^0 \times 0.5^0$ *resolution (Doll et al., 2014). Water withdrawal from both groundwater and surface water have also been considered. We used a combination of diffuse groundwater recharge and recharge from the surface water bodies, which we termed as "total groundwater recharge". As the WaterGAP simulation consider simple water balance approach for groundwater recharge estimation, uncertainties may arise as a function of groundwater table gradient (Doll et al., 2014). Furthermore, increasing groundwater recharge from surface water* *bodies as a function of groundwater withdrawal, has not been considered here (Doll et al., 2014). More information on model processes, data used and other details can be found in Doll et al. (2014).*" [**Page: 6; Lines:** 16-24]

Detailed comments:

SC1 Comment 4: Several sections are poorly organized such as: â˘A ´c abstract: the 4 fist lines are too general. Provide 1 line as intro. â˘A ´c introduction: delete the first 2 paragraphs which are really poor in content (lines 1-18), and split the 3nd paragraph into 2-4 sub section on lines e.g. 23, 28 â˘A ´c the third objective is not presented as a number (bullet point) similar to the other sub-objectives. Why not?

Reply: We thank Prof. Klöve for his suggestion. We have modified the sections in the revised version of the manuscript. We have deleted two introductory sentences from Abstract.

Following your suggestion, we have deleted the initial paragraphs of Introduction section and divided the third paragraph into three paragraphs.

We would like to thank Prof. Klöve for his careful observation. The third objective is now numbered as 3.

Abstract:

"*Groundwater is one of the most important natural resources for economic development and environmental sustainability. In this study, we estimated groundwater storage in 11 major river basins across Alberta, Canada using a combination of remote sensing (Gravity Recovery and Climate Experiment-GRACE), in situ surface water data, and land surface modelling estimates ($GWSA_{sat}$). We applied separate calculations for unconfined and confined aquifers, for the first time, to represent their hydrogeological differences. Storage coefficients for the individual wells were incorporated to compute the monthly in situ groundwater storage ($GWSA_{obs}$). The $GWSA_{sat}$ from the two satellite-based products were compared with $GWSA_{obs}$ estimates. The estimates of $GWSA_{sat}$ were in good agreement with the $GWSA_{obs}$ in terms of pattern and magnitude (e.g., RMSE ranged from 2 to 14 cm). While comparing $GWSA_{sat}$ with $GWSA_{obs}$, most of the statistical analyses provide mixed responses, however the Hodrick-Presscott trend analysis clearly showed a better performance of the GRACE-mascon estimate. The results showed trends of $GWSA_{obs}$ depletion in 5 of the 11 basins. Our results indicate that the precipitation played an important role in influencing the $GWSA_{obs}$ variation in 4 of the 11 basins studied. A combination of rainfall and snowmelt positively influence the $GWSA_{obs}$ in 6 basins. Water budget analysis showed an availability of comparatively lower terrestrial water in 9 of the 11 basins in the study period. Historical groundwater recharge estimates indicate a reduction of groundwater recharge in 8 basins during 1960-2009. The output of this study could be used to develop sustainable water withdrawal strategies in Alberta, Canada*." [**Page: 1; Lines:** 9-23]

Introduction:

"*Fresh water is an important resource for economic development and social sustainability around the world. Approximately, 1.2 billion people live in water scarce areas across the globe (UN-Water/FAO, 2007). More than a billion people lack access to safe drinking water and this number is increasing due to an increasing population (Connor, 2015). However, the effects of climate change on glaciers and snowpack, and human activities, such as over-use and over-extraction of resources, can result in lowering water tables and groundwater depletion (Scanlon et al., 2016; Bhanja et al., 2017b). In situ monitoring of wells is the traditional approach for estimating groundwater storage. However, well monitoring is spatially not continuous and has a high cost at a large region. There are only scant observation stations in some areas, especially in semi-arid and arid environments, or cold climate regions covered by glacier and snowpack, due to difficulties of access and monitoring. As a result, proper groundwater management and decision-making are hampered considerably by the scarcity of data.*

Remote sensing data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission could be used to estimate groundwater storage at a continuous and large scale across the globe, and offers a new opportunity for groundwater storage assessment (Rodell et al., 2007). Although the GRACE satellite mission currently provides global-scale data for the detection of temporal gravity changes (Tapley et al., 2004), these temporal gravity changes are not a direct measurement of groundwater storage. A relationship would have to be established between temporal gravity changes and groundwater storage variations through the continuously evolving algorithms (Watkins et al., 2015). Estimates of groundwater storage using the remote sensing have been performed around the globe (Swenson et al., 2006; Rodell et al., 2007; Strassberg et al., 2007; Rodell et al., 2009; Tiwari et al., 2009; Scanlon et al., 2012; Shamsudduha et al., 2012; Voss et al., 2013; Bhanja et al., 2014; Richey et al., 2015; Panda and Wahr, 2016; Bhanja et al., 2016; Chen et al., 2016; Long et al., 2016; Bhanja et al., 2017b; Bhanja et al., 2018). Huang et al. (2016) used remote sensing data for computing the groundwater storage anomalies (GWSA) in order to estimate groundwater storage in Alberta. 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. Then they compared the TWS with groundwater levels instead of the groundwater storage and without considering surface water data due to the lack of available high resolution data.

Recent studies (e.g. Huang et al., 2015; Nanteza et al., 2017) have considered both confined and unconfined aquifers for in situ GWSA computation but they have not separated the data from the two types. The two types of aquifers have different recharge and storage patterns. Confined aquifers are overlain by relatively impermeable rock or clay, which limits vertical water infiltration, while in unconfined aquifers, vertical water infiltration can occur from precipitation, snowmelt, surface water etc. The two types of aquifers are also responding differently with effect from pumping (Alley et al., 1999). Therefore, these should be studied separately for estimating *groundwater storage at a region. Further, Rodell et al. (2007) indicated the importance of surface water factors in the GWSA estimation and sought for inclusion of surface water storage variations in GWSA disaggregation. They also pointed out the importance of separating contributions to temporal mass variability using auxiliary observations and numerical models when estimating groundwater storage changes in large scale regions. In cold climate regions, such as in Alberta, the surface water could make a significant contribution to groundwater storage variations due to the effects of climate change on snowpack, glaciers, permafrost, and wetlands. Therefore, more efforts are required to properly evaluate groundwater storage for aquifer storage coefficients in transforming groundwater level information to groundwater storage in cold climate regions (Feng et al., 2013). The main objectives of this study are:*

1. *To investigate the long term groundwater storage conditions in cold climate regions, such as the 11 river basins in Alberta, Canada, by combining all of the processing steps, such as the surface water storage estimates.*
2. *To validate the remote sensing estimates from two different remote sensing products using the maximum available in situ observation well data. The in situ groundwater storage has been estimated by combining the storage coefficients and aquifer thickness (for confined aquifers) with the water table fluctuation.*
3. *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.*" [**Pages: 1-3; Lines:** 25-6]

SC1 Comment 5: In section 2, on lines 12-20, some information is provided about the aquifers. A map of the aquifers of Alberta could be useful. More importantly, how are the aquifers split into confined, semiconfined and unconfined?

Reply: We would like to thank Prof. Klöve for his concern. We have added two new figures within Figure 1, indicating the types of aquifer encountered and the screen depth of the wells. We have also discussed this issue in text and provided a figure and a table in supplementary information. Aquifer map development is out of the scope of this study, however, it can be found in Lemay and Guha (2009).

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

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

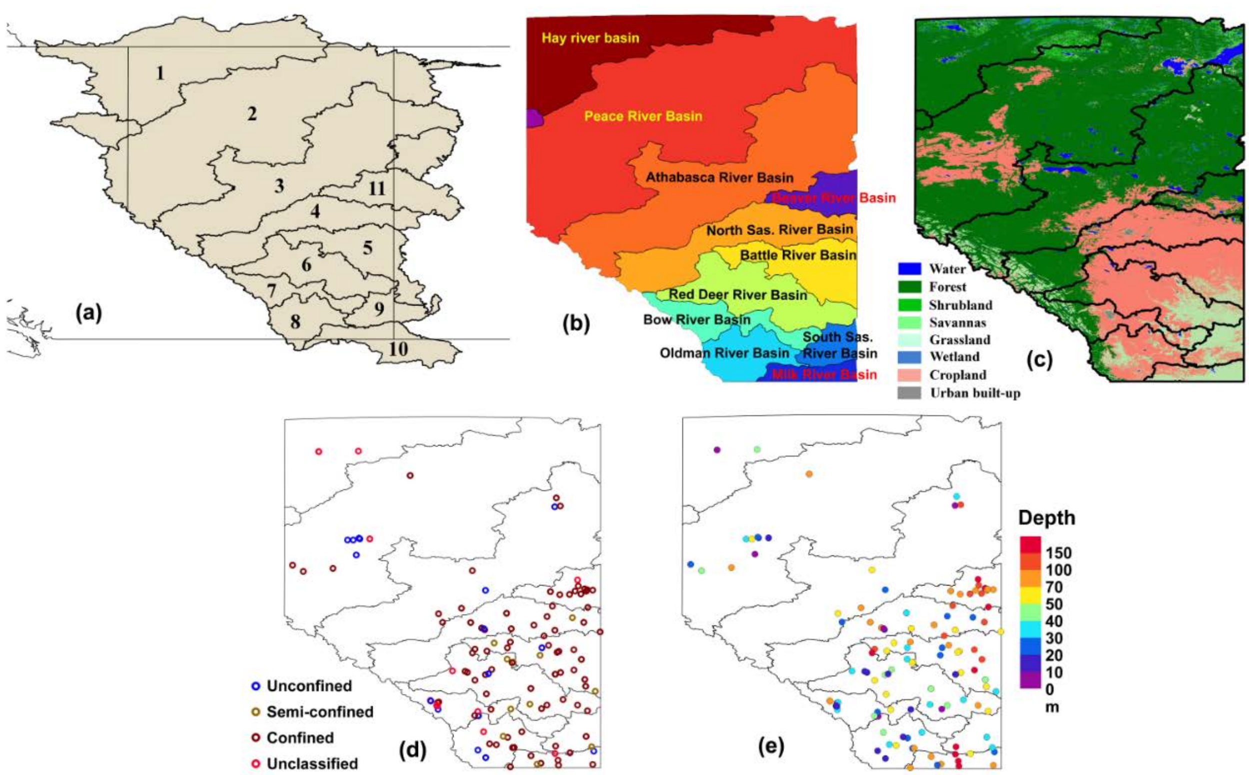

Figure 1: Major river basins in Alberta, (a) full basin extent; (b) Alberta only; (c) dominant land cover types; (d) aquifer types represented through the studied wells; (e) depth of wells screened in Alberta, overlaid by basin boundaries

"*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]

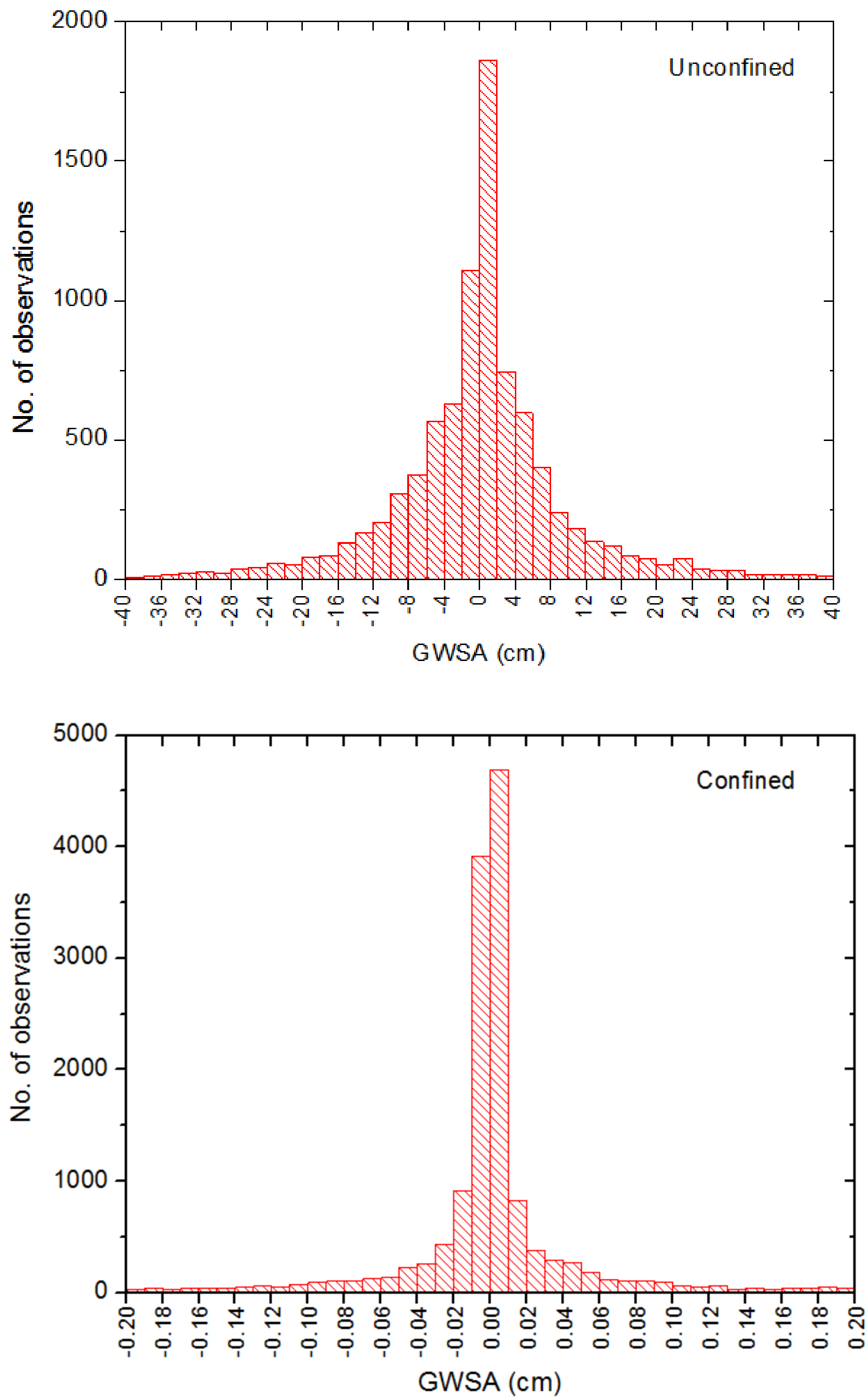

Figure S1: Histogram of GWSA estimates from unconfined and confined aquifers

SC1 Comment 6: In section 2.6, the equations 4-8 are general knowledge and should be deleted.

Reply: Following the suggestion, we have moved the Equations 4-8 to Supplementary information in the revised manuscript.

SC1 Comment 7: I feel that more information is needed on the comparison of GRACE MS and SH is needed in section 3.1.

Reply: Based on Figure 3 only, it is found that the GRACE MS and SH estimates match each other. Detailed information on comparison of GRACE MS and SH products are provided in section 3.2. We indicated this at the end of section 3.1.

"*In general, the magnitude of the $GWSA_{sat}$ compares well with that of the $GWSA_{obs}$ (Figure 3).*" [**Page: 8; Line:** 21]

"*Overall, the two satellite based estimates are found to be closely matching with one another, detailed comparisons are provided in section 3.2.*" [**Page: 8; Lines:** 24-25]

SC1 Comment 8: Combine section 3.3-3.4. Also provide a meaningful title! RMSE etc. is not a good choice of title. Provide the result or outcome in the title.

Reply: We would like to thank Prof. Klöve for raising this concern. We have merged the three section 3.2-3.4 to make a single Section 3.2 "*Comparison between observed and satellite-based GWSA*". We have also modified the title of the section.

SC1 Comment 9: The section 3.6. on assumptions is quite odd. Focus perhaps on uncertainty or delete the section, or put it into section 2.

Reply: Following your suggestion, we have moved the Section 3.6 from a "*Results and Discussions*" section to "*Materials and Methods*" section. The new section number is 2.8.

SC1 Comment 10: The "conclusions" section 4 is well written.

Reply: We would like to thank Prof. Klöve for his appreciation.

References:

Peel, M.C., Finlayson, B.L. and McMahon, T.A.: Updated world map of the Köppen-Geiger climate classification, Hydrology and earth system sciences, 11, 1633-1644, 2007.

Lemay, T. G. and Guha, S.: Compilation of Alberta groundwater information from existing maps and data sources ERCB/AGS Open File Report 2009-02, ISBN 978-0-7785-6969-5 (http://ags.aer.ca/document/OFR/OFR_2009_02.PDF accessed on November 21, 2017), 2009.