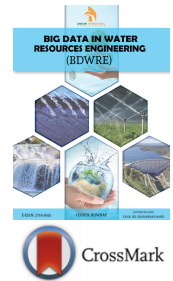




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RESEARCH ARTICLE

GROUNDWATER STORAGE CHANGE ESTIMATION USING GRACE SATELLITE DATA IN INDUS BASIN

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ABSTRACT

Over exploitation of Ground Water (GW) has resulted in lowering of water table in the Indus Basin. While waterlogging, salinity and seawater intrusion has resulted in rising of water table in Indus Basin. The sparse piezometer network cannot provide sufficient data to map groundwater changes spatially. To estimate groundwater change in this region, data from Gravity Recovery and Climate Experiment (GRACE) satellite was used. GRACE measures (Total Water Storage) TWS and used to estimate groundwater storage change. Net change in storage of groundwater was estimated from the change in TWS by including the additional components such as Soil Moisture (SM), Surface water storage (Qs) and snowpack equivalent water (SWE). For the estimation of these components Global Land Data Assimilation system (GLDAS) Land Surface Models (LSMs) was used. Both GRACE and GLDAS produce results for the Indus Basin for the period of April 2010 to January 2017. The monitoring well water-level records from the Scarp Monitoring Organization (SMO) and the Punjab Irrigation and Drainage Authority (PIDA) from April 2009 to December 2016 were used. The groundwater results from different combinations of GRACE products GFZ (GeoforschungsZentrum Potsdam) CSR (Center for Space Research at University of Texas, Austin) JPL (Jet Propulsion Laboratory) and GLDAS LSMs (CLM, Noah and VIC) are calibrated (April 2009-2014) and validated (April 2015-April 2016) with in-situ measurements. For yearly scale, their correlation coefficient reaches 0.71 with Nash-Sutcliffe Efficiency (NSE) 0.82. It was estimated that net loss in groundwater storage is at mean rate of 85.01 mm per year and 118,668.16 Km³ in the 7 year of study period (April 2010-Jan 2017). GRACE TWS data were also able to pick up the signals from the large-scale flooding events observed in 2010 and 2014. These flooding events played a significant role in the replenishment of the groundwater system in the Indus Basin. Our study indicates that the GRACE based estimation of groundwater storage changes is skillful enough to provide monthly updates on the trend of the groundwater storage changes for resource managers and policy makers of Indus Basin.

KEYWORDS

GRACE, GLDAS, Indus Basin, groundwater.

1. INTRODUCTION

All forms of water play a vital role in human sustainability on earth but due to unique nature groundwater got special importance. It is assumed that GW is safest among all forms of water because many soil layers filtered and cleaned the GW from many contaminations. World's freshwater resources have threatened by the rapid increase in global population and unmanaged water utilization. Around the world, common concerns are the management of the water demand, minimum daily consumption of water, planning for the water resources, and depletion of the groundwater. In developing countries these challenges are very higher

to mitigate the common prime problems. GW storage has been observed more expensive in Indus Basin; almost 35 years ago, improvement of this storage began (Sarwar, 2000).

The main reason for the usage of the groundwater is the deficiency and fluctuation of the surface water. On the other hand, groundwater accessibility is simple as compared to surface water that make the irrigation system more valuable (Iqbal et al., 2016). Currently, about 50% of groundwater has been used for irrigation practices in Indus Basin (Shah, 2007). In Indus Basin, evidence that irrigation with surface water mixed with groundwater or with only groundwater have 50-100% more yields in comparison to only surface water. Depletion in groundwater resources

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and worsening of groundwater quality has an adverse effect on crop yield and land productivity. Good policies are required to control the decreasing depth of aquifer in Indus Basin (Shamsudduha et al., 2012).

In Pakistan, there is complex and largest infrastructure of irrigation system containing of twenty-five million hectare of irrigated agriculture, 56,000 km of canals, 600,000 tube wells and hundred million people dependent on 107,000 water-courses discharged by the forty-four canal system (Sarwar, 2000). Since 1960s, Indus Basin GW is becoming primary source for irrigation in Pakistan. Firstly, environmental and economic benefits were by the groundwater, but now unmanaged withdraw of water has reduced the quality and level of fresh groundwater in Indus Basin (Briscoe et al., 2006). Annual GW extraction increased by 10 Billion Cubic Meters (BCM) from 1965 to 68 BCM in 2002. Unplanned abstraction of groundwater has caused excessive decline in groundwater level in some areas, utilization of deeper saline solution groundwater and higher pumping costs. More than 80% farmers in the private sector are extracting groundwater. About 17% of Punjab area and 75% of the Sindh areas are under saline groundwater. For irrigation, about 70% of tube wells are pumping saltwater (Bhutta et al., 2006). Aquifer management is considered as the most effective away of establishing a balance between discharge and recharge components. In this respect most of the developed countries like USA, Germany, Netherland and Sweden has positive efforts regarding recharging of groundwater but limit to 15-20%. In Indus Basin only India has used lot of funds for recharging the groundwater and got positive results at large scale (Miro et al., 2018; Rodell et al., 2001).

GW is the major supplier of domestic, Industrial and agriculture sectors due to over abstraction of clean water. These resources are under constrain, causing the consequences such as saltwater instruction, sea water intrusion and coastal erosion. To measure the GWS variation hydrological scientists especially rely on observation well (Kuss et al., 2012; Li et al., 2001). However, in the areas of mountains and arid region, it is very difficult to install observation well that cause the serious issue regarding GWS information. Changes in groundwater storage are difficult to estimate, given the spatial and temporal limitations required to achieve complete and accurate groundwater measurements for large geographic regions (Li et al., 2001; Nazir, 1995; Sun et al., 2010). GRACE aimed at comparing temporal variations in the Earth's gravitational field with respect to the evaluation of the water storage for all types of terrestrial conditions. Through the spatial-temporal resolution (not in excess of 160,000 km² per week or monthly) is very low in comparison with other satellite missions. The primary favorable position of GRACE is, it can "sense" the stored water at all levels, as well as GW. Effortlessness, dissimilar to different innovations, for example, radar and radiometers, GRACE can sense water variations as well as groundwater with precision in excess of 1cm of comparable water heights (Rodell et al., 2004; Yeh et al., 2006). In the most recent decade, GRACE has been utilized to evaluate changes in local water storage e.g., United States, Amazonia, Yangtze River,

monitor the mass balance in Antarctica and Greenland. For instance, changes in the surface water storage of the global earth from GLDAS, and minus from the TWS. GRACE provides a new prospect to assess the changes in groundwater reservoirs (Yeh et al., 2006).

Changes in monthly land storage in a region, GRACE data is an estimate of changes in bulk storage capacity, and the data cannot be differentiated. Different components of water quality are stored. Therefore, GRACE data must be interpreted using a hydrological model. Even this GRACE data is still a very valuable data set as an independent measurement large-scale, large-capacity water storage changes (Bonsor et al., 2010).

In this study, annual terrestrial water storage changes derived from GRACE gravity measurements were compared with in situ measurements groundwater levels. An extensive groundwater level measurement was used to derive in situ estimates of terrestrial water storage. This comparison is important to evaluate the reliability of GRACE derived GWSC. In many areas of the world monitoring of groundwater is limited, and in such cases the combination of GRACE-derived GW and in-situ groundwater data could be used to estimate regional groundwater storage changes. A unique aspect of this study is the comparison of GRACE-derived GWS in a semiarid region over a large aquifer with a deep groundwater table, where variability in groundwater storage is dominated by irrigation. The nature of the region, together with the large amount of available soil moisture and groundwater data, provides an ideal test bed to assess the applicability of GRACE data for monitoring groundwater storage changes.

2. MATERIALS AND METHODS

2.1 Study Area

The transboundary river Basin of the Indus lies between latitude 24° 38' to 37° 03' N and longitude 66° 18' to 82° 28' E covers a total area of 1120000 km² of Pakistan, India, China and Afghanistan. The Indus Basin starts from the North Mountains of Himalaya to Arid alluvial Plains of the province Sindh in Pakistan and finally end into Arabian Sea in the South. Elevations range from 0 to 8600 m above mean sea level. The Indus Basin covers most of area in Pakistan, providing the benefits to four provinces of Pakistan, whole area of Khyber-Pakhtunkhwa and Punjab province, Most area of Baluchistan and Sindh. The drainage of Indus Basin is in India, in the Jammu Kashmir, province of Punjab, Rajasthan state, Haryana, states of Himachal Pradesh and Chandigarh, and the remaining area is in China and Afghanistan

Indus Basin did not include the whole area of the Pakistan. But in this research we are also focusing the remaining areas of the Pakistan etc. Balochistan and Sindh. So, research is focused on the Indus Basin and whole area of the Pakistan. In Balochistan irrigated land is very small and 25% area of the Balochistan is productive else are out of crops.

Table 1: Showing Indus Basin Share of Allied Countries

Basin	Area		Countries Included	Area of country in basin (Km ²)	As % of total area of the basin	As % of total area of the country
	Km ²	% of Southeast Asia				
Indus	1120000	54	Pakistan	520000	47	65
			India	444000	39	14
			China	88000	8	1
			Afghanistan	72000	6	11



Figure 1: Location of the Study Area

2.2 Data and Method

TWS is an integrated measurement high water storage changes, groundwater, soil moisture, surface water, ice and snow. The previously study showed that soil moisture and the GW are the major contributor of TWSC, and minor contribution is by the biomass, surface runoff, ice and snow (Khaki et al., 2018; Yeh et al., 2006; Zaitchik et al., 2008). The contribution of snow water to terrestrial water storage variability in the Indus Basin approaches 1 cm in some cases but is small as compared to soil moisture. Generally,

$$\Delta TWS = \Delta GW + \Delta SM + \Delta SW + \Delta SWE + \Delta BIO \quad (1)$$

For terrestrial water storage soil moisture, groundwater, snow water equivalent, surface water storage and variations in biosphere are the

contributors. Where Δ is change (e.g., monthly, seasonal, or annual changes) in this study annual change, GWS is groundwater storage, SM is surface water runoff and SWE is snow water equivalent water. SM in this context refers to volumetric soil moisture content, which is the volume of water stored within the soil column. BIO represents the variations in the biosphere. Based on the assumption that biosphere is negligible. For GWSC equation 1 was used by (Qureshi et al., 2010; Sun et al., 2010; Yeh et al., 2006; Zaitchik et al., 2008).

$$\Delta GW = \Delta TWS - (\Delta SM + \Delta SW + \Delta SWE) \quad (2)$$

In this study, GRACE derived groundwater storage change was compared with the in-situ well data. Flow chart of the study is mentioned in figure 2.

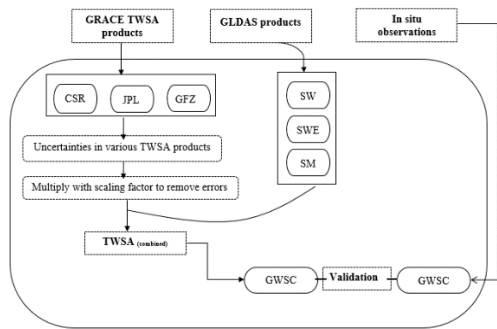


Figure 2: Flow chart of the study

2.3 TWS from the GRACE (Data Acquisition and Processing)

The Centre for Space Research (CSR) at University of Texas, Austin GRACE data product release-5 (RL05) Level-3 was used to process gravity anomalies for extraction of TWS from April 2010 to April 2017. Monthly GRACE derived TWS data are freely downloadable. (Available at ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land_mass/RL05/). In this study, GRACE version (Level 3, Release-05) used to derive the TWS. GRACE RL05 product is more accurate than previously versions (Chen et al., 2016; Iqbal et al., 2016). Because de-stripping procedure applied requires less spatial smoothing as compared with the earlier versions of GRACE. For filling of missing data, linear interpolation was used because TWS results have some missing data due to battery management issue (January and June 2011). This time span is selected because in-situ data overlaps the GRACE data (Xiao et al., 2015).

To acquire large-scale and spatial-temporal comprehensive data is the main advantage of GRACE data. For higher accuracy at larger spatial scales annual and seasonal estimates of TWS can be derived easily, despite having relatively low spatial and temporal resolution, it has the advantage of sensing the changes in total water storage in all TWS levels or components (Rodell et al., 2004; Sanval et al., 2016). Monthly, $1^{\circ} \times 1^{\circ}$ CSR GRACE time-series dataset masked over the whole of Indus Basin where energy of GRACE TWS signal amplitude was compensated multiplying by a scaling factor. All anomalies in downloaded data are relative to average data over the period from January of 2004 to December of 2009 (Yeh et al., 2006).

2.4 Qs, SWE and SM from the GLDAS

As Qs, SWE and SM are the essential components for groundwater storage, and these can be measured accurately by the in-situ method. But for the large-scale basin it is not possible to attain data, so for large scale global hydrological changes GLDAS perform better than other stations. (GLDAS) of NASA aims to utilize advanced surface modeling and data assimilation methods to capture satellite and terrestrial observation data products to produce flow fields and optimal land surface status (Rodell et al., 2009).

GLDAS implements multiple terrestrial models (off-line) through LIS integrates large amounts of data based on observation and achieves a high resolution (2.5°-1km) (<http://disc.sci.gsfc.nasa.gov/hydrology/dataholdings>). Currently, GLDAS consists of four lands surface models namely, Noah, Community Land Model (CLM), Mosaic, and Variable Infiltration Capacity (VIC). So, GLDAS driven models are used to observe the SWE, Qs and SM at different time interval (daily, 3days and monthly). For the TWS estimation, GWS, surface

runoff (Qs), Snow water equivalent (SWE) and soil moisture (SM) are the major contributor. While the precisely spatially observation of the soil moisture is not presently available matched the observation from the four hydrological model with the modeled groundwater observation and concluded that estimation from these models would not affect the groundwater storage estimation (Xiao et al., 2015). So, GLDAS (Noah model) is used in this study to measure the SWE, Qs and SM on temporal resolution (monthly) at the spatial resolution 0.25°, total depth of 4 layers in Noah, the four land surface models (LSMs) do not include GW storage and soil moisture changes in deep unsaturated soil (Strassberg et al., 2009; Sun et al., 2010).

2.5 Analyzing Groundwater Storage from Monitoring Wells

SM, SWE and Qs are the contributors of TWS and GWSC can be measured by the subtracting all these contributors from TWS based on the assumption that biomass change is negligible. To verify the GRACE based GWSC in-situ wells data is obtained from the SCARPs (Scarps monitoring organization) SMO a sub department of Pakistan Water and Power Development Authority (WAPDA) and Punjab Irrigation and Drainage Authority (PIDA). SMO and PIDA have their own separately piezometric wells for measuring water level. In this research, piezometric data is combined taken from both Organization (SMO and PIDA), so that averaged data was used for better precision. These organizations are responsible for the measurement of water table depth and hydraulic head twice in a year, Pre-monsoon (April-May) and Post-monsoon (September-December). However, each piezometer within the network is recorded its reading without temporal uniformity across all wells. For example, neighboring wells will rarely experience record keeping the same month and would be a few months apart due to man-power issues. Although piezometric wells provide accurate information regarding water level but it is not directly comparable with the GRACE based GWSC, it was transferred in term of groundwater storage for April 2010 to April 2016 by (Tariq et al., 2012; Yeh et al., 2006; Zaitchik et al., 2008).

$$\Delta GWS = \sum_j^N S_j C_j \Delta h_j / \sum_j^N C_j \quad (3)$$

Where N refers to the number of sub areas or zones divided in the study region; S_j represent the specific yield values of the unconfined aquifers; C_j are the sizes of sub areas; and Δh_j refer to the mean values of the well water-level variations in each sub area. Specific yield is the difficult process to measure for regional scale, it is no longer a simple geologic parameter and can hardly be determined by the pumping test. In this study we use only Pre-monsoon (April-April) data for two consecutive years and same for the GRACE based GWSC for calibrating and validating results. we select only one Cell of $1^{\circ} \times 1^{\circ}$ and pixel averaging method as it was converting into $0.25^{\circ} \times 0.25^{\circ}$ in the Rachna doab and take the mean value of GWS for 16 sub cells and multiplies with specific yield 0.14 which was reported as average value for the Rachna doab (Bennet et al., 1967; NASA, 2002; Sanval et al., 2016).

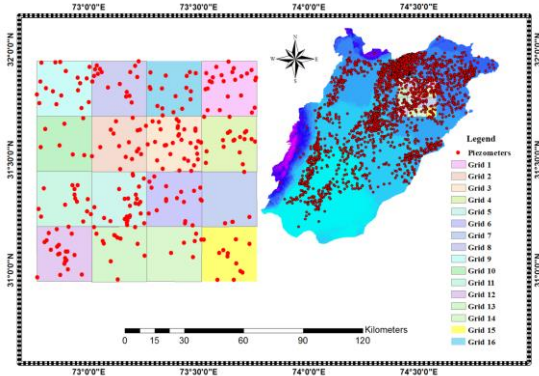


Figure 3: a) Right side shows the Piezometric wells in the Punjab b) Left side shows the Piezometric in the 25 x 25 km (16 grids) for Calibration and Validation)

In 2010, 2449 piezometers, in 2011, 2214 piezometers, in 2012, 1845 piezometers, in 2013, 3701 piezometers, in 2014, 2570 piezometers, in 2015, 1715 piezometers and in 2016, 856 piezometers in Punjab were

available. From which those wells data were used for validation, which were fall in 16 cells of 0.25° x 0.25° scales. In this study, we have adopted technique to calibrate GRACE based GWSC is Regression Analysis (RA). For this technique, April 2010 to April 2014 (five years data) were exposed for calibration procedure between GRACE and Piezometric groundwater storage change. The remaining April 2015 to April 2016 (two years data) was used for validation purpose only. GRACE derived GWSC estimates have proven relationship with in-situ GWSC before many researchers (Bhanja et al., 2016; Chen et al., 2008; Feng et al., 2013). An empirical relationships is derived between GRACE derived GWSC and in-situ GWSC. A second order polynomial equation was obtained from the regression analysis with R² of 0.68 shown in figure 07

$$\text{GRACE GWSC}_{i(\text{cal})} = -0.00004(\Delta P_i)^2 + 1(\Delta P_i) - 17.262 \quad (4)$$

Where cal is the resultant calibrated GRACE GWSC, ΔP represent the Piezometric GWSC and *i* denotes year.

3. RESULTS AND DISCUSSION

GRACE TWS represents the total water storage including snow, surface runoff water, groundwater and soil moisture. In this study, assume that biosphere has negligible effect on the groundwater storage so that GW is calculated by subtracting the all parameters (SWE, soil moisture and surface runoff) from the TWS obtained by the GRACE (Hassan et al., 2016; Xiao et al., 2015; Yeh et al., 2006; Zaitchik et al., 2008).

Average soil moisture, storm surface runoff and the accumulated snow variation was calculated between April 2010- Jan 2017 with 0.25° from the GLDAS-Noah model on the monthly basis. SWE, Qs and average soil moisture upper layer up to 2m are the main contributor of the GWS (Shown in Figure-4).

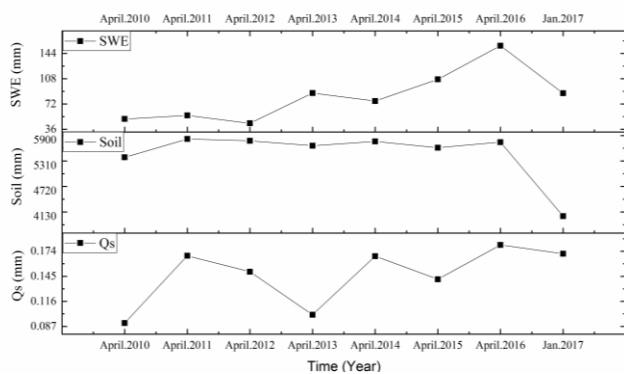


Figure 4: Mean trend of Qs, soil moisture and SWE anomalies from 2010–2017 over Indus Basin of Pakistan

The comparisons of TWS derived from GRACE with that from LSMs are shown in Figure 5. The water storage variations are computed via time-variable gravity field model provided by CSR, GFZ and JPL difference is existed in few months, but the total results are constant. The GRACE which is known as (Tom and Jerry) satellite measures the monthly gravity field changes by a series of complicated inversion of relative ranging observations (Sun et al., 2010; Yin et al., 2017). For processing different institutions adopted various solution strategies, such as the precise orbit determination from on-board GPS and the corrections for spacecraft platform accelerations. So, there are differences in products from different institutions. The correlation coefficients between the GRACE TWS results of CSR, GFZ and JPL is 0.92 with a 95% confidence. GRACE TWS was in the 1° x 1° scale and further downscaled up to 0.25 x 0.25 degree scale. Average TWS (mm) (annual mean of three models i.e. CSR, CFZ, JPL) ranges from -380mm to 17mm for the April 2010 to Jan 2017 figure 6.

Figure 5 showed the huge amount of depletion from April 2010-Jan 2017 except for the 2011 and 2015 because of the massive flood hit the Pakistan and heavy rainfall in the 2010. Flood of 2010 was the worst ever in the history of the Pakistan, 160,000km² total area was affected due to the flood and province Sindh was badly affected to the unprecedented rains and poor drainage system during monsoon 2011 (Khaki et al., 2018; Tiwari et al., 2009).

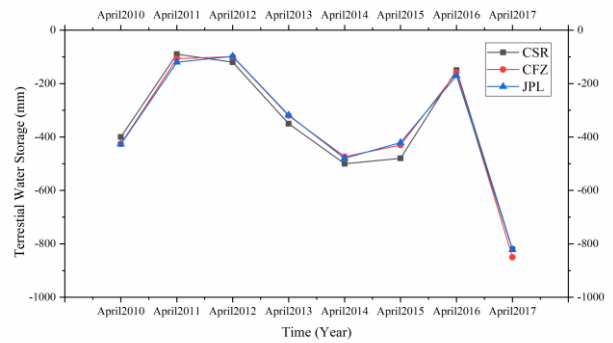


Figure 5: Terrestrial Water Storage from three institutions (LSM, CFZ and JPL)

Water table decreased due to the discharge from the aquifer and level of the groundwater increased due to the recharge from the river and canal system framework.

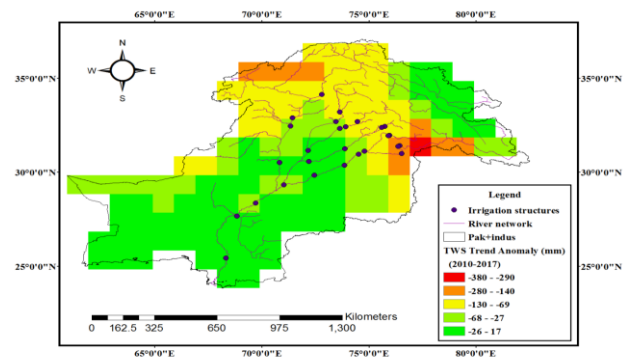


Figure 6: Mean trend of TWS anomalies from 2010–2017 over Indus Basin of Pakistan

The soil moisture, surface runoff and accumulated snow variation is featured by a prominent seasonal character, with the annual amplitude of around 5560 ±0.276 mm. Groundwater is also characterized by evident seasonal variations. The phase difference between the two series is null, and generally, in-situ observations match the phase of simulated SM and SWE. The changes of soil moisture, surface runoff and accumulated snow may take the largest part of TWS variations. This implies these two components (i.e., SM and SWE, Qs) are the dominant contributors to TWS changes in this region annual measurement is shown in the figure 4.

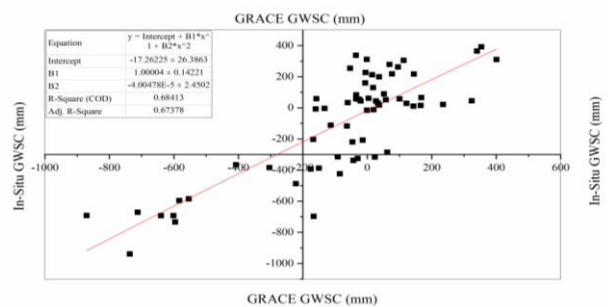


Figure 7: Calibration of GRACE-derived groundwater storage change with the in-situ groundwater storage change over April 2010-April 2014

After calibration, to validate the results of GRACE GWSC with in-situ level data regression equation was applied for estimated GRACE GWSC for the two years (April 2015-April 2016). Fig.8. showed the time series of GRACE GWSC in the 25km x 25km of 16 grids. Each grid GRACE GWSC was validated with the In-situ GWSC data and correlation 0.86 was estimated with RMSE of 0.07, R² =0.74 and Nash-Sutcliffe Efficiency (NSE) 0.86, 1:1 line shown in figure 9. Annual estimated spatial pattern of GWSC in millimeters each grid with 0.25° x 0.25° is shown for 2010-2012 in the fig 11(a), for 2013-2015 in fig 11(b) and for 2016- 2017 in the fig 11(c).

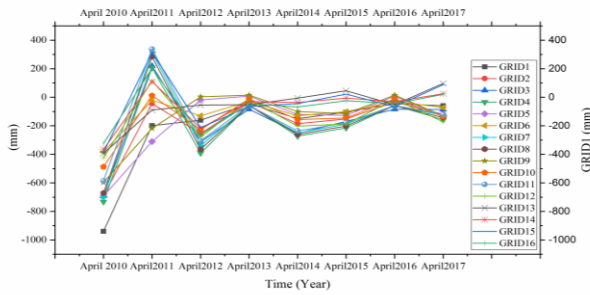


Figure 8: GRACE-derived GWSC anomalies in 16 grids of 25 x25 km

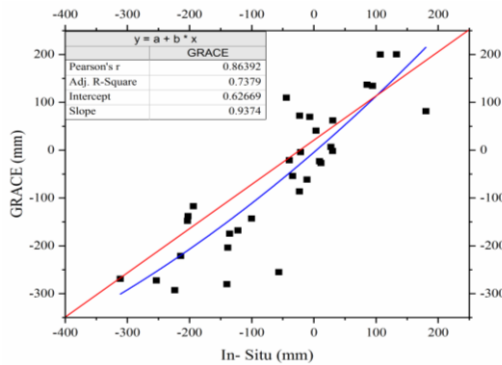


Figure 9: Validation of GRACE-derived GWSC and 1:1 line between GRACE-derived and in-situ well data

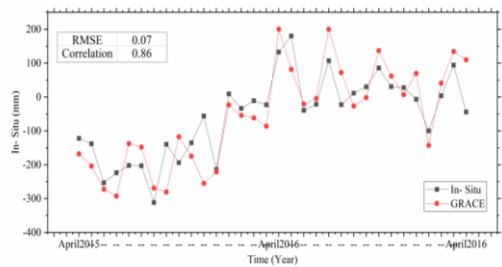


Figure 10: Line graph of GRACE-derived GWSC with In-situ GWSC

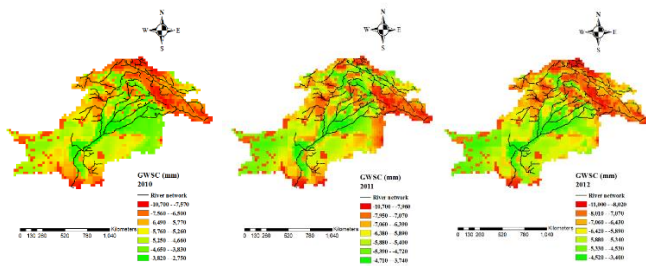


Figure 11: (a,b,c) Shows annual spatial pattern of GWSC (mm) anomalies 2010-2012 with 0.25° x 0.25° grids in the Indus Basin.

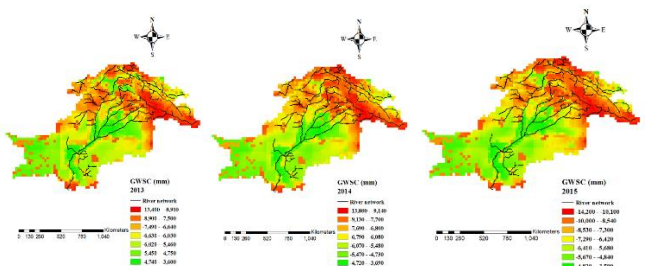


Figure 12: (a,b,c). Shows annual spatial pattern of GWSC (mm) anomalies 2013-2015 with 0.25° x 0.25° grids in the Indus Basin.

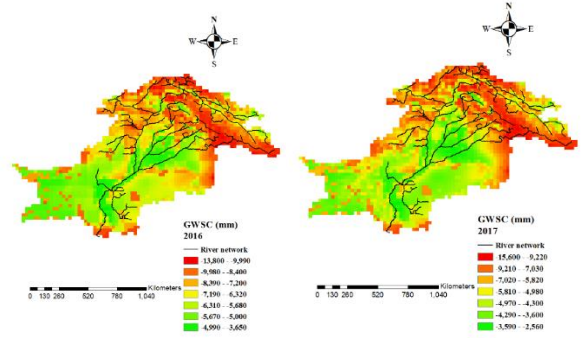


Figure 13: (a, b). Shows annual spatial pattern of GWSC (mm) from 2016 and 2017 with 0.25° x 0.25° grids in the Indus Basin

4. CONCLUSION

In this study terrestrial water storage (TWS) anomalies from the GRACE was used to calculate the groundwater storage change. In this research we used average of TWS from three institutions (CSR, CFZ and JPL). For this water storage anomalies (SWE, Soil moisture and Qs) was subtracted from the GRACE TWS anomalies. All the Water storage anomalies were calculated from the GLDAS with the 0.25° x 0.25° resolution. For the total groundwater storage changes of the study period April 2010- Jan 2017 a linear trend of yearly groundwater storage anomalies was used. To achieve the Second goal of the study Groundwater storage change calculated from the GRACE TWS 1°x1° was downscaled to 0.25°x0.25°, downscale was done by the pixel averaging and calibrated with the piezometric data at 0.25°x0.25°, a suitable relation was made between the estimated and the in-Situ data for the study period of April 2010-April 2014. The estimated GRACE groundwater storage changes were validated with the in-Situ data for the study period of April 2015-April 2016, with R²=0.74 and NSE=0.86 and not for the 2017 because of no availability of the Piezometric data for 2017.

The study showed dynamic behavior of the groundwater variation along with the groundwater recharge change at regional scale. Moderate groundwater depletion rate was found, but in few doabs higher rate of groundwater change was found. It was estimated from the TWS anomalies figure 6 and the well data that Rachna and the Bari doab are the more stressed area of groundwater because of the stoppage of the water in the Sutlej and the Ravi River. The Second reason of the depletion of the groundwater in the Pakistan and in India border is low rainfall and the huge pumping of the groundwater. This study addressed that groundwater storage change is decreased in UIP more rapidly than the Lower Indus plain. The study showed that groundwater storage change has been depleting except in the year of 2011 and the 2015, because of the massive floods hit the Pakistan in the 2010 in the history of Pakistan and known as the super flood so 39.97mm. Water was recharged instead of the depleting second the recharge was observed in 2015 due to the flood in 2014 and the 7.39 mm recharge was observed, next continuously water is depleting drastically after the 2014 figure 11 (a,b,c), 12 (a,b,c) and 13 (a,b). It was estimated that net loss in groundwater storage is at a mean rate of 85.01 mm per year (for study area 1396096 km²) and 118,682.12 Km³ in the 7 year of study period (April 2010-Jan 2017). In UIP GWSC was 8.5mm/year in 109418 km². This study showed that GRACE-derived GWSC are comparable with the In-situ data and can be used for the large scaled basin and the sub basin.

REFERENCES

Bennett, G.D., Sheikh I.A., Alr S. 1967. Analysis of aquifer tests in the Punjab region of West Pakistan. USGPO.

Bhanja, S.N., Mukherjee, A., Saha, D., Velicogna, I., Famiglietti, J.S. 2016. Validation of GRACE based groundwater storage anomaly using in-situ groundwater level measurements in India. Journal of Hydrology. 543:729-738.

Bhutta, M.N., Alam, M.M. 2006. Prospectives and limits of groundwater use in Pakistan. Groundwater Research and Management: Integrating Science into Management Decisions.105.

- Bonsor, H., Mansour, M., Macdonald, A., Hughes, A., Hipkin, R., Bedada, T. 2010. Interpretation of GRACE data of the Nile Basin using a groundwater recharge model. *Hydrology and Earth System Sciences Discussions*. 7:4501-4533.
- Briscoe, J., Qamar, U., Contijoch, M., Amir, P., Blackmore, D. 2006. *Pakistan's water economy: running dry*, Oxford University Press Karachi.
- Chen, J., Wilson, C., Tapley, B., Scanlon, B., Güntner, A. 2016. Long-term groundwater storage change in Victoria, Australia from satellite gravity and in situ observations. *Global and Planetary change*. 139:56-65.
- Chen, J., Wilson, C., Tapley, B., Blankenship, D., Young, D. 2008. Antarctic regional ice loss rates from GRACE. *Earth and Planetary Science Letters*. 266:140-148.
- Feng, W., Zhong, M., Lemoine, J.M., Biancale, R., Hsu, H.T., Xia, J. 2013. Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. *Water Resources Research*. 49:2110-2118.
- Hassan, A., Jin, S. 2016. Water storage changes and balances in Africa observed by GRACE and hydrologic models. *Geodesy and Geodynamics*. 7:39-49.
- Hu, L., Jiao, J.J. 2016. An innovative method to estimate regional-scale hydraulic diffusivity using GRACE data. *Hydrological Sciences Journal*. 61:2694-2703.
- Iqbal, N., Hossain, F., Lee, H., Akhter, G. 2016. Satellite gravimetric estimation of groundwater storage variations over Indus Basin in Pakistan. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. 9:3524-3534.
- Khaki, M., Awange, J., Forootan, E., Kuhn, M. 2018. Understanding the association between climate variability and the Nile's water level fluctuations and water storage changes during 1992–2016. *Science of the Total Environment*. 645:1509-1521
- Kuss, A., Brandt, W.T., Randall, J., Floyd, B., Bourai, A., Newcomer, M., Schmidt, C. 2012. Comparison of changes in groundwater storage using GRACE data and a hydrological model in California's Central Valley. *ASPRS Ann. Conf.*
- Li, Y. 2001. Groundwater recharge. Unpublished. Nanjing Institute of Hydrology and Water Resources, China.
- Miro, M., Famiglietti, J. 2018. Downscaling GRACE remote sensing datasets to high-resolution groundwater storage change maps of California's Central Valley. *Remote Sensing*. 10:143.
- NASA. 2002. Studying the earth's gravity from space: The Gravity Recovery and Climate Experiment (GRACE), National Aeronautics and Space Administration, Greenbelt, MD.
- Nazir. 1995. *Groundwater resources of Pakistan*. Shehzad nazir publisher. Lahore, Pakistan.
- Ouma, Y.O., Aballa, D., Marinda, D., Tateishi, R., Hahn, M. 2015. Use of GRACE time-variable data and GLDAS-LSM for estimating groundwater storage variability at small basin scales: a case study of the Nzoia River Basin. *International Journal of Remote Sensing*. 36:5707-5736.
- Qureshi, A.S., Mccornick, P.G., Sarwar, A., Sharma, B.R. 2010. Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. *Water resources management*. 24:1551-1569.
- Rodell, M., Famiglietti, J. 2001. An analysis of terrestrial water storage variations in Illinois with implications for the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*. 37:1327-1339.
- Rodell, M., Velicogna I., Famiglietti, J.S. 2009. Satellite-based estimates of groundwater depletion in India. *Nature*. 460:999.
- Rodell, M., Houser, P., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M. 2004. The global land data assimilation system. *Bulletin of the American Meteorological Society*. 85:381-394.
- Sanval, N., Helfand, S. 2016. Optimal groundwater management in Pakistan's Indus Water Basin, *Intl Food Policy Res Inst.*
- Sarwar, A. 2000. A transient model approach to improve on-farm irrigation and drainage in semi-arid zones, sn.
- Sarwar, A., Eggers, H. 2006. Development of a conjunctive use model to evaluate alternative management options for surface and groundwater resources. *Hydrogeology Journal*. 14:1676-1687.
- Shah, T. 2007. The groundwater economy of South Asia: an assessment of size, significance and socio-ecological impacts. *The agricultural groundwater revolution: Opportunities and threats to development*. 7-36.
- Shamsudduha, M., Taylor, R., Longuevergne, L. 2012. Monitoring groundwater storage changes in the highly seasonal humid tropics: Validation of GRACE measurements in the Bengal Basin. *Water Resources Research*. 48.
- Strassberg, G., Scanlon, B.R., Chambers, D. 2009. Evaluation of groundwater storage monitoring with the GRACE satellite: Case study of the High Plains aquifer, central United States. *Water Resources Research*. 45.
- Sun, A.Y., Green, R. Rodell M. Swenson, S. 2010. Inferring aquifer storage parameters using satellite and in situ measurements: Estimation under uncertainty. *Geophysical Research Letters*. 37.
- Tariq, M.A.U.R., Van De Giesen, N. 2012. Floods and flood management in Pakistan. *Physics and Chemistry of the Earth, Parts A/B/C*. 47:11-20.
- Tiwari, V., Wahr, J., Swenson, S. 2009. Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophysical Research Letters*. 36.
- Xiao, R., He, X., Zhang, Y., Ferreira, V.G., Chang, L. 2015. Monitoring groundwater variations from satellite gravimetry and hydrological models: a comparison with in-situ measurements in the Mid-Atlantic region of the United States. *Remote Sensing*. 7:686-703.
- Yeh, P.J.F., Swenson, S., Famiglietti, J., Rodell, M. 2006. Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*. 42.
- Yin, W., Hu, L., Jiao, J.J. 2017. Evaluation of Groundwater Storage Variations in Northern China Using GRACE Data. *Geofluids*. 2017.
- Zaitchik, B.F., Rodell, M., Reichle, R.H. 2008. Assimilation of GRACE terrestrial water storage data into a land surface model: Results for the Mississippi River basin. *Journal of Hydrometeorology*. 9:535-548

