Satellite Gravimetric Estimation of Groundwater Storage Variations Over Indus Basin in Pakistan

Naveed Iqbal, Faisal Hossain, Hyongki Lee, and Gulraiz Akhter

***Abstract*—Like other agrarian countries, Pakistan is now heavily dependent on its groundwater resources to meet the irrigated agricultural water demand. Groundwater has emerged as a major source with more than 60% contribution in total water supplies. In the absence of groundwater regulation, the uneven and over-exploitation of groundwater resource in Indus Basin has caused several problems of water table decline, groundwater mining, and deterioration of groundwater quality. This study evaluates the potential of Gravity Recovery and Climate Experiment Satellite (GRACE)-based estimation of changes in groundwater storage (GWS) as a cost-effective approach for groundwater monitoring and policy recommendations for sustainable water management in the Indus basin. The GRACE monthly gravity anomalies from 2003 to 2010 were analyzed as total water storage (TWS) variations. The variable infiltration capacity hydrological model-generated soil moisture and surface runoff were used for the separation of TWS into GWS anomalies. The GRACE-based GWS anomalies are found to favorably agree with trends inferred from *in situ* piezometric data. A general depletion trend is observed in Upper Indus Plain (UIP) where groundwater is found to be declining at a mean rate of about 13.5 mm per year in equivalent height of water during 2003–2010. A total loss of about 11.82 km^3 per year fresh groundwater stock is inferred for UIP. Based on TWS variations and ground knowledge, the two southern river plains, Bari and Rechna are found to be under threat of extensive groundwater depletion. GRACE TWS data were also able to pick up 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 Indus Basin. Our study indicates that the GRACE-based estimation of GWS changes is skillful enough to provide monthly updates on the trend of the GWS changes for resource managers and policy makers of Indus basin.**

***Index Terms*—Gravity Recovery and Climate Experiment Satellite (GRACE), groundwater, Indus basin, Pakistan, remote sensing.**

I. INTRODUCTION

THE socio-economic development of an agrarian country like Pakistan is dependent on its water resources. Indus basin is the major source of groundwater which contributes more than 60% in the total water supplies. More than 80% of the groundwater originates from Upper Indus Plain (UIP) consisting of four riverine plains (known locally as "doabs"). The term doab is specifically defined as the floodplain located between two rivers and is a fertile ground for irrigated agricultural production. The irrigated agricultural requirements mainly depend on the groundwater supplies for more than 90% of agricultural production in Pakistan [1]. The Indus Basin Irrigation System (IBIS) is the world's largest well-connected irrigation system which was constructed after Indus Water Treaty in 1960 [2]. The seepage from contiguous IBIS has played its major role to naturally replenish the groundwater system.

After 2000, major groundwater development was initiated where the total number of tube wells installed in Punjab Province crossed 0.94 million in just one decade (2000–2010) [3]. The indiscriminate pumping of groundwater using these wells has caused several management problems. Water table depletion, salt water up-coning, water quality deterioration, and groundwater mining have become problematic issues in the doab areas [4]–[9]. In fresh groundwater areas of Punjab, the imbalance between abstraction and recharge has caused water table depletion [4]. In Central Punjab, a thin layer of fresh groundwater exists over the saline water due to recharge. As a result of overexploitation, the downward gradient has caused salt water intrusion in fresh groundwater layer [4]. The percentage of area with shallow water table (< 6 m) has considerably decreased due to groundwater mining. On the other hand, the percentage of the area with ground water table at depths below 6 m has rapidly increased. The water table depletion of about 2–3 m per year has resulted groundwater mining in different fresh groundwater areas of Punjab Province [4]. The groundwater is mainly pumped to meet the agricultural, domestic, and industrial needs for over 80 million population [3] in the Punjab Province. The farmers use groundwater as a main source of continuous supply for the production of wheat, rice, sugarcane, potatoes, other cash, and fodder crops. In Pakistan, the rice crop is irrigated by a traditional flood irrigation method which requires a lot of water to meet the standing water demand in the fields. During summer period in the rice growing areas, almost 90% demand of irrigation is met from groundwater supply. In future, the groundwater will become more expensive and could adversely impact food security [4].

Sustainable groundwater resource management requires the routinely updated (high frequency) knowledge about character, dynamics, and behavior of the groundwater system at appropriate spatial scales [10]. Many physical groundwater models such as Visual Mod Flow [11] and FeFlow [12] have been applied to study the groundwater system in Indus basin. But these studies

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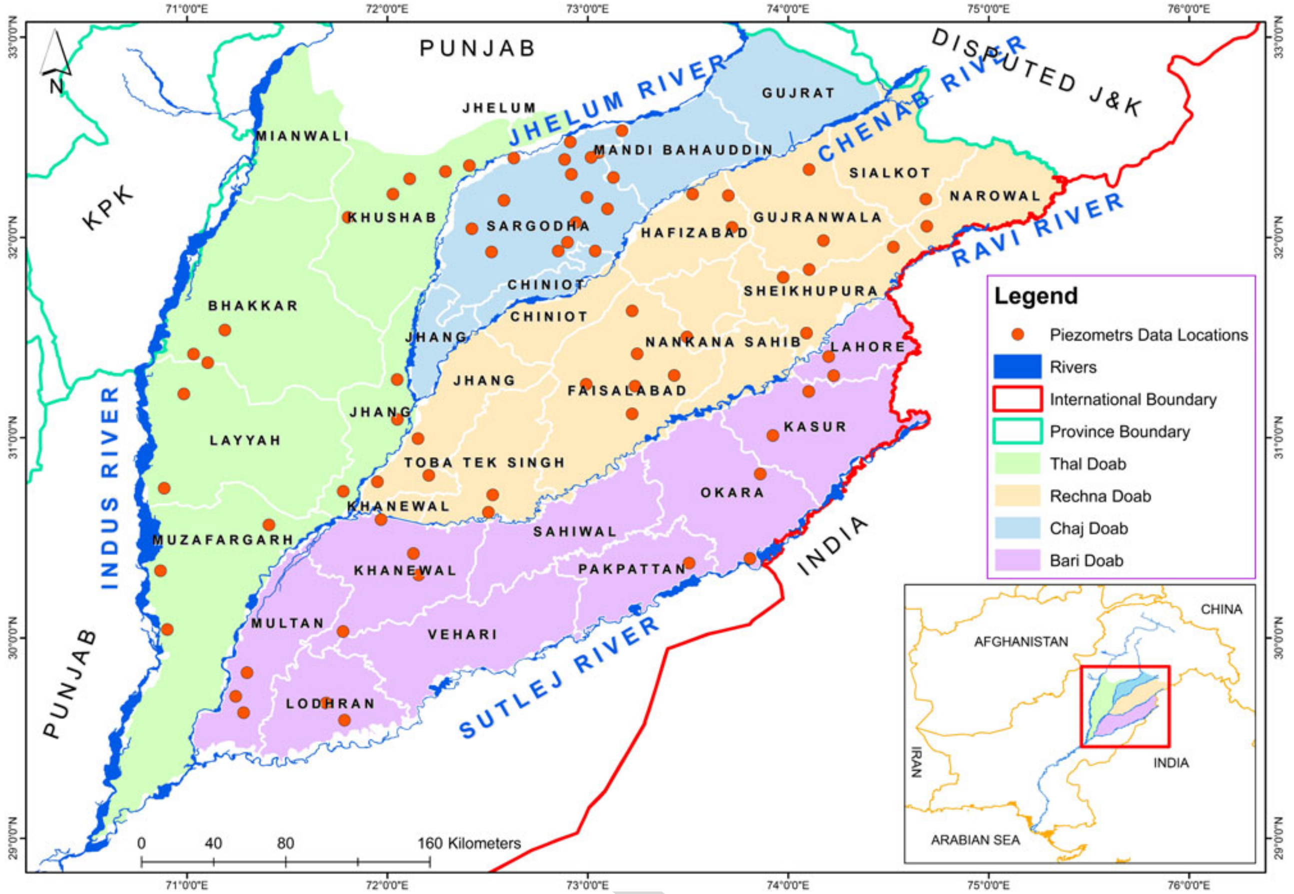

Fig. 1. Location map of UIP in Pakistan.

were only limited in their spatial domain due to the scarcity of i*n situ* measurements for model calibration. An integrated approach based on geophysical surveys and groundwater modeling recently took one decade to complete as a groundwater study of UIP (Punjab Province). Although as a baseline detailed study such an approach is acceptable, the long time required is not conducive to high-frequency water management decisions through frequent updating of policy and planning measures. A sustainable groundwater system monitoring and management requires a robust and cost-effective system that allows the study of the groundwater system at seasonal to annual scales.

The twin satellite system Gravity Recovery and Climate Experiment (GRACE) [13] can be one such "robust and cost-effective" approach to monitor the dynamics of groundwater storage (GWS) variations. GRACE is very unique in its features as a remote sensing platform. It provides large-scale coverage, good temporal resolution (monthly) for groundwater management and is suited for sensing the complete vertical profile of water cycle storage as snow, glacier, surface water, soil moisture (SM), biomass, and groundwater [14]. The GRACE data can provide 10 daily to monthly scale water storage anomalies which are the estimates of the changes in total water storage (TWS) over a specific region. GRACE has already demonstrated its potential to monitor GWS changes and estimate groundwater depletion in countries such as India [15]–[17], USA (High Plain Aquifer [18], [19], Central Valley [20], [21], Mississippi River Basin [22], Illinois [14]), China (North China [23], Congo Basin [40], Western Jilin [24]), and Ethiopia [24]. GRACE data have also been used to estimate GWS changes in the poorly monitored regions from seasonal to annual scales [26].

In this study, we evaluate the potential of GRACE satellite for studying the GWS variation at various spatial scales for the Indus basin. The study assesses the effectiveness of GRACE gravity data as an alternate research-grade tool for the groundwater resource management in Indus Basin. It also evaluates the impact of satellite gravimetric GWS estimation and monitoring methodology to enable decision making over conventional approaches. This study is organized as follows. Section II describes the study region. The details of data and methodology used are discussed in Section III. Section IV outlines the analysis of GWS derived from GRACE-TWS anomalies. Finally, Section V summarizes the general findings and future directions for GRACE-based research on groundwater resource management in Indus basin. The detailed calculations are explained in appendix.

II. UPPER INDUS PLAIN

The UIP is the main agricultural part of Indus basin consisting of four doabs named as Thal, Chaj, Rechna, and Bari, all located in the Punjab Province (see Fig. 1). The unconfined Indus basin aquifer is mainly composed of alluvial formation.

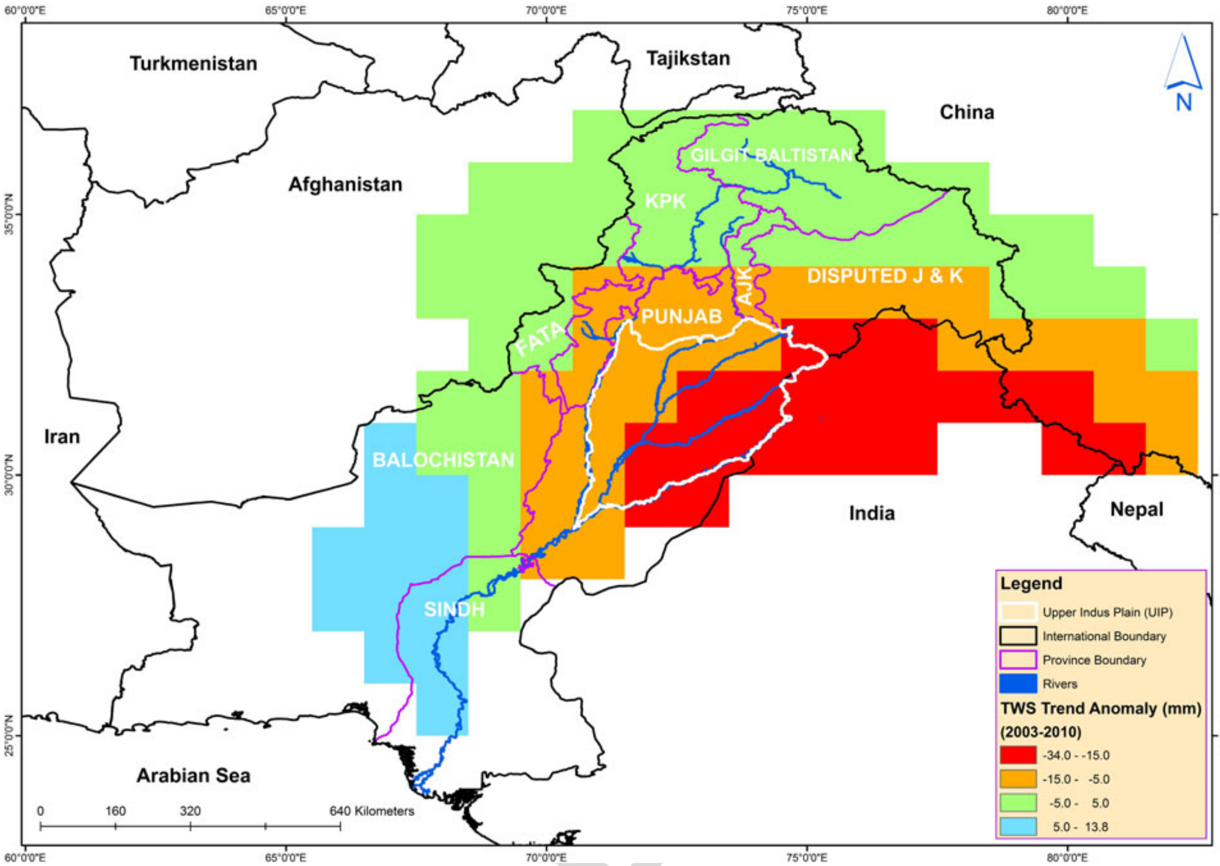

Fig. 2. Mean trend of TWS anomalies from 2003–2010 over Indus Basin of Pakistan.

The lithology mainly varies from fine to coarse sand with clay lenses. The study area is very fertile and is rich in groundwater. The groundwater is currently exploited extensively for domestic to agricultural productivity. In the absence of any groundwater regulation in Punjab Province, farmers pump huge amounts of groundwater for anthropogenic use causing stress on groundwater resources. Consequently, water table has been depleting and groundwater mining is taking place at many places of the aquifer. The contiguous IBIS plays a major role in the recharge of groundwater system. Since 1960, the IBIS irrigation system has expanded through a network of canals such as link, main, and distributaries. The role of link canals is to transfer surplus water from Western Rivers (Indus, Jhelum and Chenab) to Eastern Rivers (Ravi and Sutlej). The main purpose was to maintain the regular supply of surface water for irrigation throughout the year. Through seepage from channels and irrigation of the field, significant recharge takes place of the aquifer system. The total area of UIP (four doabs) is approximately 109 418 km^2.

III. DATA AND METHODS

The Centre for Space Research (CSR) at University of Texas, Austin GRACE data product (http://www.csr.utexas.edu/grace/RL05.html) release-5 (RL05) Level-2 was used to process gravity anomalies for extraction of TWS from 2003 to 2010 (available at ftp://podaac.jpl.nasa.gov/allData/grace/L2/CSR/RL05/) [39]. The GRACE monthly gravity field datasets were processed to extract spherical harmonic coefficients (SHCs). The smoothing and decorrelation techniques are applied to reduce the signal noise due to short wavelength component of the gravity field. The function of the decorrelation technique is to filter out the correlated errors among the spherical coefficients of geopotential changes with the same order and degree [26]. The SHCs with higher degree and order are more affected by correlated noises [27], [28]. A decorrelation filter is applied where the SHCs of lower degree and order are kept unchanged and remaining are filtered based on a moving polynomial window fit [29]. The smoothing is still required to remove the high-frequency noises, and an isotropic filter with 300-km radius is applied to smooth the data in this study [49]. In order to restore the signal dampened due to the smoothing, we used the average (1.132) of the so-called scaling factors for the Indus basin derived from six global hydrological models (GHM) including Noah 2.7, VIC, Mosaic, CLM 2.0, CLM 4.0, and WGHM 2.2, listed in [43, Table III]. However, a scaling factor derived using a GHM such as PCR-GLOBWB might result in more accurate signal restoration in basins, such as the Indus basin, with intensive human activities because it simulates surface water storage changes, natural and human-induced GWS changes, and the interactions between surface water and subsurface water [48]. The resultant TWS anomalies were mapped at 1° × 1° grids to analyze the time series variations over Indus basin.

The TWS mean trend anomaly map (see Fig. 2) shows that total water storage has changed more rapidly over UIP with a decrease of 18.54 mm per year (2.03 km^3/year) as compared to whole Indus basin (6.52 mm/year) from 2003 to 2010. It indicates that UIP is playing an important role in the overall hydrology of Indus basin. The major reason of this significant change in the variation of TWS over UIP is the extensive use of groundwater for anthropogenic activities. The maximum variations in TWS anomalies ranging from -34 to -15 mm are observed in the Southern part of UIP as compared to Northern part (-15 to -5 mm). This indicates that the total water storage has decreased more in two Northern doabs (Bari and Rechna) over the period 2003–2010 (see Fig. 2). The changes in TWS are basically the sum of variations in all hydrological components of water cycle [14]

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

where GW refers to the change (Δ) in groundwater, SM is the SM contribution, SW and SWE are the surface water and snow water equivalent or glacier variations, and BIO represents the variations in the biosphere, respectively.

The topography of the study region is plain with warm climate and snow is uncommon. Therefore, SM may have a major impact on TWS variation in the semiarid regions. Global Land Data Assimilation System (GLDAS) model-simulated SM information has been used in past studies to remove SM effect [31]. In the present study, variable infiltration capacity (VIC version 4.0.6) model-derived SM and surface runoff information over Indus basin is used for the separation of GWS anomalies. In comparison with GLDAS, the VIC model output is Indus basin specific (0.1° × 0.1°) with greater accuracy. VIC is a macroscale semidistributed hydrological model [31]. It is extensively used to study hydrology, water and energy budgets, and climate change impact assessment [33]–[38]. As a basic feature, it simulates water balance at daily to subdaily time steps at each grid cell scale [32]. Recently, the VIC model was applied on Ganges–Brahmaputra–Meghna river basins for the simulation of daily runoff and stream flow fluxes [33]. The study revealed that VIC is capable of capturing daily fluxes of runoff and stream flow dynamics. In our study, the VIC model was setup at the grid size of 0.1° for daily time steps considering two soil layers with total 1-m thickness (first layer = 0.3 m and second layer = 0.7 m). The digital elevation model (90 m) derived from the Shuttle Radar Topographic Mission was used for topography. The global land cover classification (version-1, 400 m) data sets are used in the model for land cover details of Indus basin (https://Ita.cr.urgs.gov/GLCC). For soil information, we used harmonized world soil database (version-1.2, approx. 1 km) developed by World Food and Agriculture Organization (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/).

The climatological information was derived from Tropical Rainfall Measurement Mission (TRMM) and Global Surface Summary of the Day of National Climatic Data Center maintained through the global network of the World Meteorological Organization. The TRMM daily data product 32B4RT (0.25° resolution) (http://pmm.nasa.gov/data-access/downloads/trmm) was used for precipitation data. The setup was run for daily simulation of SM and surface runoff from 2002 to 2010 and the first year (2002) output was excluded as spin-up time. For consistency with monthly TWS, the VIC-generated monthly (instead of daily) SM and runoff fluxes are used for the extraction of GWS anomalies. The VIC model was calibrated using the observed "total annual inflow" for the period 2003–2010 at different rim stations (*in situ* observation points) located at different tributaries of Indus River. These rim stations include: Nowshera, Tarbela, Mangla, Marala, Kalabagh, Balloki, and Suleimanki. The calibration locations are shown in Fig. 3 and results are shown in Table I. We found that Balloki and Sulemanki were challenging cases for modeling the observed inflow due to upstream regulation structures (barrages in Indian Territory). Otherwise, it can also be seen that VIC is able to simulate annual streamflow (which is mostly driven by snow and glacier melt during Spring and rainfall during Summer and Fall) with a Nash–Sutcliffe efficiency of greater than 0.7 and % RMSE ranging from 12% to 50%. Although there is always room for improvement in snow-dominated regions [45]–[47], we consider this acceptable for studying the GWS change in the Indus plains that is considerably far removed from the high-elevation snow region. We revisit this issue of simulation accuracy of streamflow of hydrological models in snow-dominated regions later in Section V.

The VIC-generated output of SM and runoff from 2003 to 2010 at 0.1° × 0.1° was up-scaled to TWS resolution (1° × 1°) for the extraction of GWS. The monthly anomalies were calculated by subtracting the long-term monthly average from SM and runoff data sets. Fig. 4 shows the VIC model-generated long-term average of monthly SM and runoff over Indus Basin. Based on the variations in the precipitation, topography, and lithology, the maximum average SM and runoff are observed in the UIP consisting of Punjab Province both in Pakistan and India. A comparison between GLDAS and VIC for SM and runoff shows a good agreement (Correlation = 0.71, RMSE = 9.6 mm per month) leading to statistically indistinguishable difference in GWS trend differences over the study area (shown later as Fig. 7).

IV. ANALYZING GWS CHANGES

The TWS represents a combined signal including snow, glaciers, surface water, SM, and groundwater. Based on the assumption that snow and biosphere contribution is very negligible, the GW storage information can be derived by subtracting the SM and surface runoff from TWS [34], [30], [15], [14], [23], [21], [31], [24], [35]. It can be seen from Fig. 5 that the excessive groundwater has caused significant depletion in GWS from September 2009 to July 2010. On the other hand, the rising trend after July 2010 is the recharge impact due to the massive flooding in August 2010. Pakistan was hit by a heavy rainfall at the end of July 2010. During summer, there is huge pumping in doabs for the irrigation of rice crop using the traditional method of flood irrigation.

The piezometric point measurements are collected from Scarp Monitoring Organization (SMO); a subdepartment of Pakistan Water and Power Development Authority (WAPDA) is used for calibration. SMO collects groundwater data in

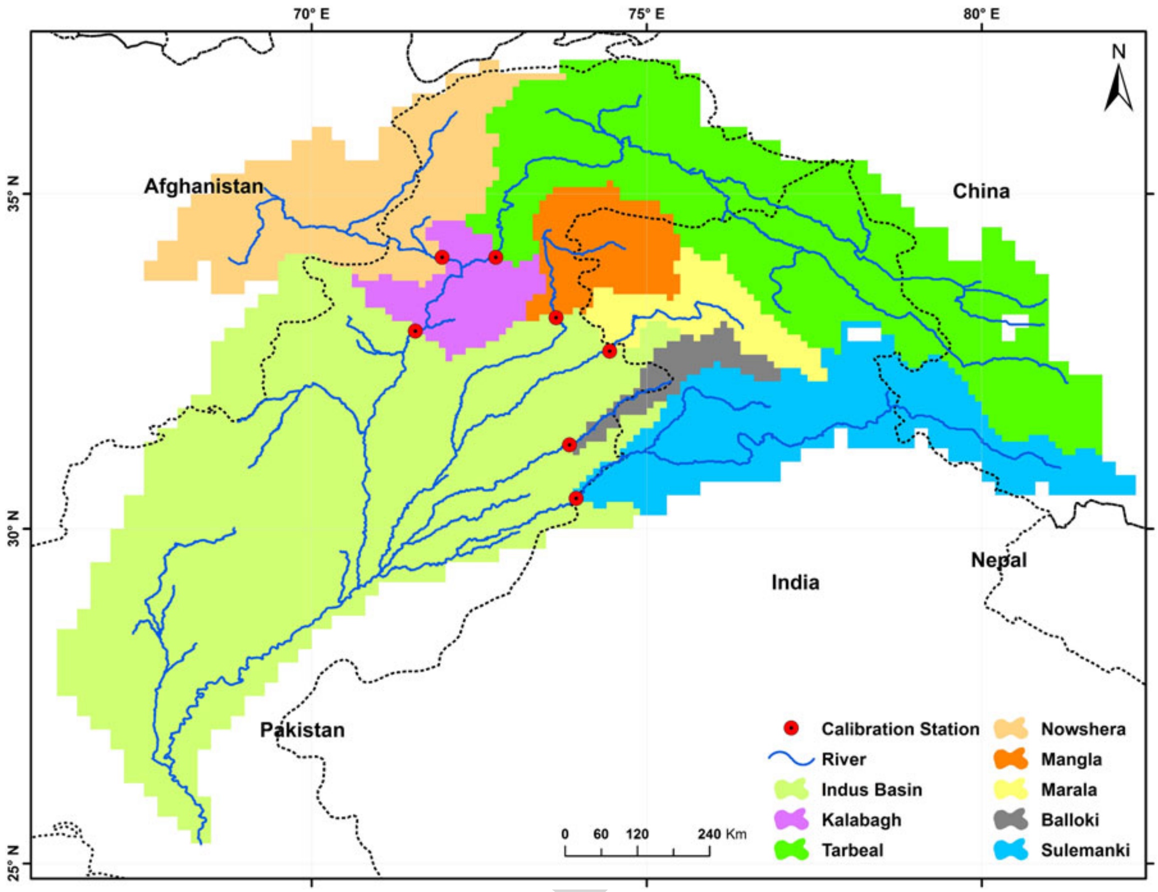

Fig. 3. VIC model calibration locations for stream flows in Indus Basin of Pakistan.

TABLE I
VIC MODEL PERFORMANCE AT VARIOUS GAUGING STATIONS UPSTREAM OF MAJOR RESERVOIRS IN UPPER INDUS BASIN SHOWN IN FIG. 3

River Name	Rim Station	Normalized RMSE (%) 2003–2010)	Nash Sutcliffe Efficiency
Indus	Kalabagh	12.66	0.86
	Tarbela	24.32	0.74
Kabul	Nowshera	51.74	0.97
Jhelum	Mangla	17.4	0.98
Chenab	Marala	25.98	0.82

Performance metrics are based reservoir inflow (observed and VIC-simulated).

terms of depth to water table (DTW) and hydraulic head (HH) on seasonal scales like before monsoon (May–July) and after monsoon (September–December) periods. However, each piezometer within the network is recorded of its reading at varying times of the year leading to the lack of temporal uniformity in reading across all wells. For example, neighboring wells will rarely experience recordkeeping the same month and would be a few months apart due to manpower issues. To circumvent this issue, seasonal averaging of both piezometer readings and GRACE-derived GWS across the entire study region was found necessary. Here, the seasonal average is the average of two piezometer readings over a span of 6–8 months (usually a pre- and postmonsoon reading). For GRACE-derived GWS, the seasonal averaging is the average of all the monthly GWS change values. The seasonal groundwater level anomalies were calculated relative to the seasonal mean of the analysis period (2003–2010). Although the piezometric monitoring provides good measurements about the changes in the groundwater level, it cannot be compared directly with GRACE-derived GWS [41]. Therefore, the water table anomalies were converted into water level changes by subtracting the DTW from average depth to bed rock. The seasonal GWS changes (ΔGWS) were then computed by multiplying water level changes with average safe yield [17]. The *in situ* data of about 67 piezometric locations covering the whole UIP were used for comparison of groundwater trend analysis from 2003 to 2010 (see Fig. 1).

Fig. 6 shows comparison between seasonal GRACE-derived GWS anomaly with seasonal piezometric GWS measurements to study the frequent variations in the behavior of groundwater system. The correlation (0.58) and RMSE (0.03 m) indicate that GRACE derived and observed ΔGWS (i.e., changes) are in good agreement with each other at seasonal timescales. GRACE data follow seasonal groundwater fluctuations in terms of trend and the magnitude of ΔGWS. According to GRACE data, the GWS appears to be depleting at an average rate of about 1.48 km^3 per year over the period 2003–2009, whereas an average GWS depletion rate based on piezometric data is calcu-

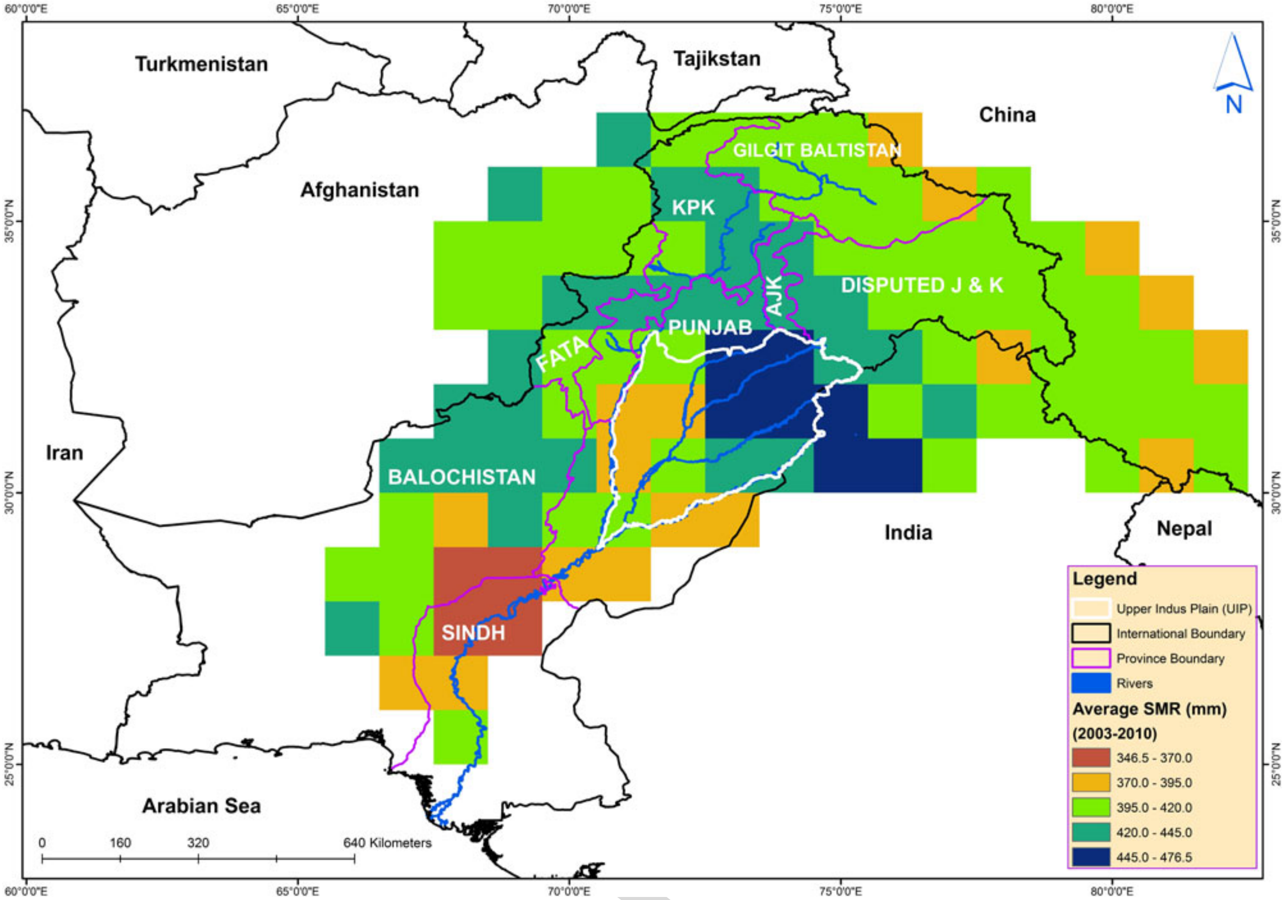

Fig. 4. Variations of VIC-generated monthly long-term average (2003–2010) SM and runoff (SMR) over Indus Basin.

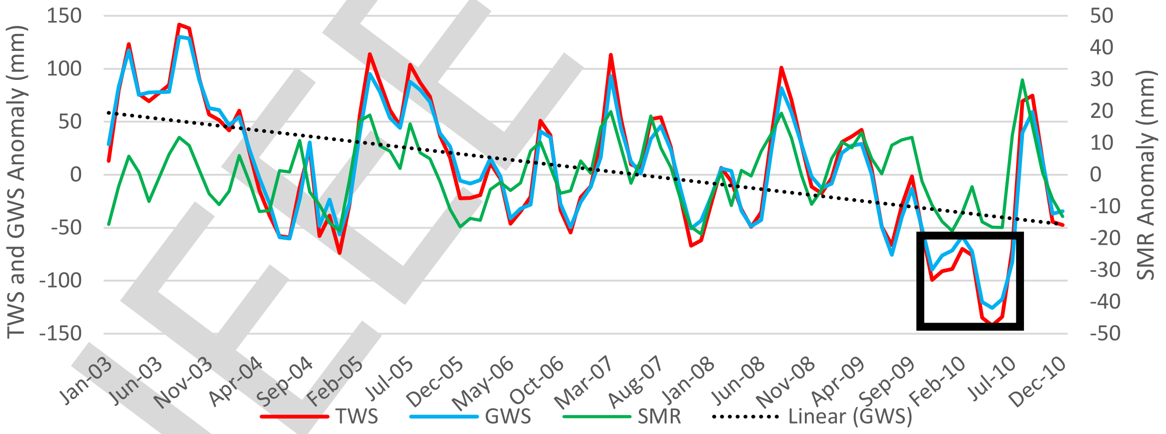

Fig. 5. Monthly variations in TWS, SMR, and GW anomalies over UIP.

lated about 0.39 km^3 per year on the same seasonal scale. The possible reasons of this difference are the limitations in terms of spatially well-distributed network of observed data. It is also noted that the piezometric data are point measurement which is different from large aerial observation of GRACE satellite. The piezometric measurements are more influenced by local effects (recharge and neighborhood pumping). ΔGWS were calculated as a mean of all 67 piezometric data sets within the study area (UIP) to minimize the local variations. The other reason is the limitation of GRACE spatial resolution and the fact that remote sensing is an indirect and spatially a more aggregate measure of a geophysical variable. The accuracy of GRACE-derived GWS is higher at large basin scales (∼200 000 km^2) [30].

It is estimated that the Upper Indus Basin has been losing fresh water stock of about 11.82 km^3 per year (see Table II) in just eight years (2003–2010) due to anthropogenic activities. However, despite the huge groundwater pumping by over 900 000 public tube wells in Punjab Province, the groundwater system

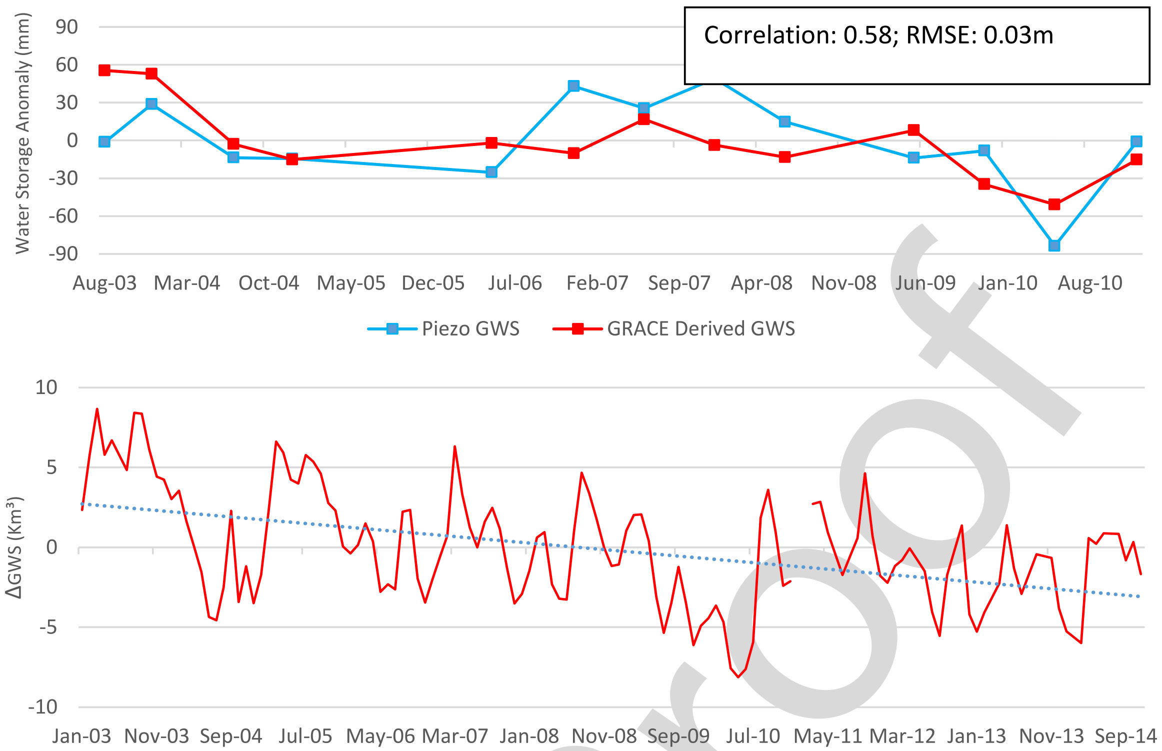

Fig. 6. Upper panel—comparison of seasonal GRACE-derived GWS with seasonal in situ GWS measurement over UIP. The units represent the equivalent thickness of water in millimeter. Lower panel—GRACE-derived monthly GW stock changes over UIP.

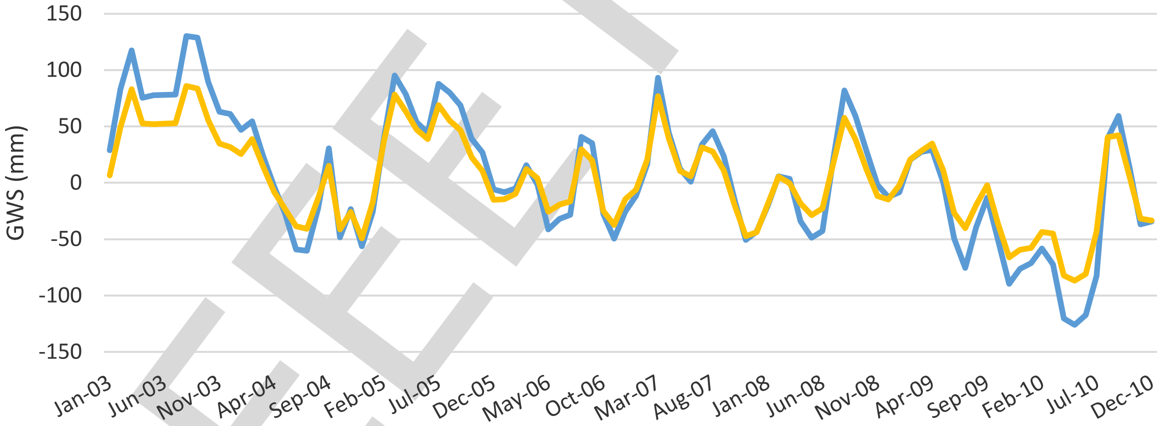

Fig. 7. Comparison of VIC-derived GRACE GWS changes (blue) and GLDAS-1 derived GRACE GWS changes (yellow). The comparison shows that the choice of land surface model appears to make insignificant impact on GWS trends although there is expectedly a modest quantitative difference in GWS changes between the two models.

TABLE II
DETAILS OF THE CALCULATIONS FOR VOLUMETRIC ESTIMATION OF GWS

Description	Year	Mean Depletion Rate (mm/yr)	UIP Area (km^2) UIP Area (km^2)	GWS Depletion Rate (km^3/yr)	Total Loss of GWS (km^3) Dep. Rate $*$ No of Years)
GRACE-GWS	2003–2010	13.50	109418.36	1.48	11.82
Piezo-GWS	2003–2010	3.60	109418.36	0.39	3.15
GRACE-GWS	2011–2014	5.30	109418.36	0.58	2.32
Net GWS Change / Recharge	Between 2010 and 2014	8.20	109418.36	0.90	3.59

seems to be also replenished naturally through frequent flooding events in the Indus Basin along with the seepage contribution from IBIS. Due to heavy rainfall at the end of July 2010, Pakistan was hit by massive flooding and affected 20 million people approximately. Fig. 6 shows a considerable increase in GWS after August 2010 (September–October 2010) and September 2014 which could be attributed to flooding event. As a result of these flooding events, a considerable change in GWS is also observed after July 2010. The predictive scenarios from 2011 to 2014 (based on linear regression between TWS and derived GWS) show that the GWS is depleted with a mean rate of about 0.58 km^3 per year. This depletion has caused a further loss of about 2.32 km^3 per year in the GWS during four years over UIP. Due to the second flooding event in 2014, the groundwater depletion rate appears to have decreased from 1.48 to 0.58 km^3 per year. Assuming that the pumping rate has remained the same during the period 2011–2014, it is estimated that approximately 3.59 km^3 (see Table II) of groundwater has been added in the storage as recharge.

It has been well known that the Northwest India has been experiencing significant GWS depletion over the past decade based on GRACE observations [15]–[17], [50]. Therefore, the GRACE-derived GWS change over UIP in Pakistan is expected to be contaminated by the strong TWS signal from adjacent Northwest India. However, as can be seen from Figs. 5 and 6, we observe strong correlation between GRACE-derived GWS and piezometer-derived GWS changes over UIP, which indicates that the GRACE-observed TWS change over UIP is reliable. In addition, recent study by Long *et al.* [50] reported strong GWS depletion in Pakistan outside of Northwest India revealed from spatial patterns of GWS change from PCR-GLOBWB. Completely separating GRACE TWS signal over UIP from that over Northwest India would be challenging due to GRACE's large footprint (e.g., 200 000 km^2) and is out of scope of this study.

V. CONCLUSION AND RECOMMENDATIONS

The current study presented an overall trend of variations in the dynamic behavior of groundwater along with the changes in groundwater recharge at regional scales. It was based on the premise that the groundwater is the dominant factor for the variations in the TWS. The rate of groundwater depletion over the study region was found to be moderate, whereas in a few doabs, the groundwater appears to be depleting at a much higher rate. The TWS anomalies (see Fig. 2) and the analysis of piezometric *in situ* data indicate that the major depletion is taking place in Bari and Rechna Doabs, near the Pakistan–India border in the South. A few districts of Bari and Rechna doabs were found to be under considerable groundwater mining. The reason of groundwater depletion was attributed to the huge pumping rate and less recharge due to little flows in two eastern rivers Sutlej and Ravi (being controlled by India) and low rainfall. Our study presents the mean changes in the GWS to understand the dynamics of entire Indus aquifer groundwater system as a whole. Such a study is valuable from the perspective of regional hydrology of UIP for long-term analysis and prediction of groundwater system behavior. However, the GRACE has its own limitations in terms of its coarse resolution and physical inertia. Estimation accuracy of GRACE-based TWS variations in the small basins is often a matter of compromise between reducing the noise and spatial resolution [14].

This study demonstrated that there is significant interseasonal (premonsoon and postmonsoon) variability in the total water storage over Indus basin. The total water storage has decreased more rapidly over UIP as compared to overall Indus basin. The changes in TWS are mainly dominated by variations in the GWS in UIP. The GRACE-derived GWS was found agreeing with trends observed *in situ* data. Both the trend and the magnitude of GRACE-GWS are quite comparable with field observations. It was estimated that the groundwater is depleted at a mean rate of 8.5 mm per year and has lost total GWS of about 7.43 km^3 over the period of 2003–2010.

The GRACE-derived GWS changes using the VIC model approach was evaluated in this study. This technique was found potentially skillful for monitoring groundwater behavior and analysis of the long-term seasonal variations in the groundwater system even at subbasin scale (UIP) over Indus basin. This presents GRACE as a cost effective tool that can augment traditional geophysical and physical groundwater modeling approaches in water management applications. As a limitation of this study, the VIC model is only calibrated for reservoir inflows at different locations in Indus basin. Therefore, future studies should consider the need for further calibration of VIC model-generated SM with *in situ* data to evaluate its accuracy especially over the high-altitude and cold region of the Upper Indus basin. Therefore, uncertainties arising from the failures of modeling and products should be thoroughly discussed

A potential limitation of the study is the choice of land surface model and its ability to realistically capture the water fluxes with commensurate fidelity to yield skillful GWS change assessments. It is well known that land surface hydrological models commonly suffer from limitations in estimating hydrological state and flux variables for a variety of settings. In our particular study, the ability of the VIC hydrological model to capture the snow water equivalent and glacier mass can be a potential limitation. Although Fig 7 shows indistinguishable difference between VIC and GLDAS-1 derived GRACE GWS changes, this does not necessarily mean that both models are simulating the cryospheric processes accurately [44]. The uncertainties in simulating the flux in high-altitude region, where cryospheric processes of snowfall and glacier melt dominate, arise due to uncertainties in forcing data and the model complexity. Such uncertainties may also propagate via surface water flux (streamflow) in the GRACE-derive GWS changes. Recent studies indicate a mismatch in total water storage estimation between GLDAS-1 simulations and GRACE observations in the Tibetan Plateau that point to physical limitations of GLDAS [45], [46]. Although VIC can simulate snow processes to a reasonable extent using temperature and radiation algorithms (see Table I), a detailed investigation is beyond the scope of this study. Readers should therefore keep this limitation in mind for future application of GRACE data for groundwater assessments.

The detailed study of GWS variations at each doab level could be more useful for the operational adoption of GRACE technology. For effective groundwater resource management in Indus Basin, the doab level GWS information is more desirous from the groundwater manager's perspective. For this purpose, further doab-level study is required to evaluate the potential and accuracy of GRACE at such small but effective spatial scales. The spatial downscaling of GRACE signal using Synthetic Aperture Radar and satellite radar altimetry should there be pursued [42].

With the wide applicability of GRACE as an effective tool for understanding the basin scale hydrology and estimating groundwater water storage variations, the confidence of end-user community can now be raised. The interest and need for GRACE-based operational water resource management at small basins is poised to be scaled up. It is anticipated that the GRACE follow-on (GRACE-FO) mission will meet the requirement of water resource managers in terms of spatial resolution enhancement and continuous data availability. It will help to promote GRACE as more reliable and successful tool for groundwater resource management.

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APPENDIX

Calculations Procedure for GRACE Derived GWS *Anomalies*

1) Slope Equation

$$b = \frac{\sum \left(T - \tilde{T}\right)\left(\mathrm{GW} - \widetilde{\mathrm{GW}}\right)}{\sum^{\left(T - \tilde{T}\right)^2}}$$

T = Time (days)
$\tilde{T}$ = Mean of time (days)
GW = Groundwater anomalies (days)
$\widetilde{\mathrm{GW}}$ = Mean of groundwater anomalies (days)

2) b. GWS estimation (km^3)

$$\mathrm{GSE}_G = \mathrm{GA}_G * \mathrm{Area(UIP)}$$

where
$\mathrm{GSE_G}$ = GRACE GWS anomalies (Volume in km^3)
$\mathrm{GA_G}$ = GRACE groundwater anomalies (height in m)
Area (UIP) = Area of UIP (109 418.35 km^2)

Calculations Procedure for Piezometric in situ Data Anomalies

1) Groundwater Level Change

$$\mathrm{GLC}_P = \mathrm{DTB} - \mathrm{DTW},$$

where
$\mathrm{GLC_P}$ = Piezometric groundwater level changes (m)
DTW = Depth to water table (m)
DTB = Depth to bedrock (Average DTB for UIP = 400 m)

2) Groundwater Level Anomalies

$$\mathrm{GLA}_P = \mathrm{GLC}_{PM} - \mathrm{GLC}_P,$$

where
$\mathrm{GLA_P}$ = Piezometric groundwater level anomalies (monthly in meters)
$\mathrm{GLC_{PM}}$ = Long-term mean of piezometric monthly groundwater level changes (m)
$\mathrm{GLC_P}$ = Piezometric groundwater level changes (m)

3) GWS anomalies

$$\mathrm{GSA}_P = \mathrm{GLA}_P * S_Y,$$

where
$\mathrm{GSA_P}$ = Piezometric GWS anomalies (m)
$\mathrm{GLA_P}$ = Piezometric groundwater level anomalies (m)
S_Y = Average specific yield (for UIP $S_\mathrm{Y} = 0.12$)[a]

4) GWS estimation (km^3)

$$\mathrm{GSE}_P = \mathrm{GSA}_P * \mathrm{Area(UIP)},$$

where
$\mathrm{GSE_P}$ = Piezometric GWS anomalies (Volume in km^3)
$\mathrm{GSA_P}$ = Piezometric GWS anomalies (m)
Area (UIP) = Area of UIP (109 418.35 km^2)

a—Note: A spatially variable specific yield map is not available. Only specific yield values over different flood plains (point measurements at only few locations) in the UIP are available based on the geological investigations and pumping tests conducted by USGS (United States Geological Survey) in collaboration with WAPDA (Pakistan Water and Power Development Authority) in 1960s [9].

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Satellite Gravimetric Estimation of Groundwater Storage Variations Over Indus Basin in Pakistan

Naveed Iqbal, Faisal Hossain, Hyongki Lee, and Gulraiz Akhter

Abstract*—Like other agrarian countries, Pakistan is now heavily dependent on its groundwater resources to meet the irrigated agricultural water demand. Groundwater has emerged as a major source with more than 60% contribution in total water supplies. In the absence of groundwater regulation, the uneven and overexploitation of groundwater resource in Indus Basin has caused several problems of water table decline, groundwater mining, and deterioration of groundwater quality. This study evaluates the potential of Gravity Recovery and Climate Experiment Satellite (GRACE)-based estimation of changes in groundwater storage (GWS) as a cost-effective approach for groundwater monitoring and policy recommendations for sustainable water management in the Indus basin. The GRACE monthly gravity anomalies from 2003 to 2010 were analyzed as total water storage (TWS) variations. The variable infiltration capacity hydrological model-generated soil moisture and surface runoff were used for the separation of TWS into GWS anomalies. The GRACE-based GWS anomalies are found to favorably agree with trends inferred from *in situ* piezometric data. A general depletion trend is observed in Upper Indus Plain (UIP) where groundwater is found to be declining at a mean rate of about 13.5 mm per year in equivalent height of water during 2003–2010. A total loss of about 11.82 km^3 per year fresh groundwater stock is inferred for UIP. Based on TWS variations and ground knowledge, the two southern river plains, Bari and Rechna are found to be under threat of extensive groundwater depletion. GRACE TWS data were also able to pick up 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 Indus Basin. Our study indicates that the GRACE-based estimation of GWS changes is skillful enough to provide monthly updates on the trend of the GWS changes for resource managers and policy makers of Indus basin.

***Index Terms*—Gravity Recovery and Climate Experiment Satellite (GRACE), groundwater, Indus basin, Pakistan, remote sensing.**

I. Introduction

THE socio-economic development of an agrarian country like Pakistan is dependent on its water resources. Indus basin is the major source of groundwater which contributes more than 60% in the total water supplies. More than 80% of the groundwater originates from Upper Indus Plain (UIP) consisting of four riverine plains (known locally as “doabs”). The term doab is specifically defined as the floodplain located between two rivers and is a fertile ground for irrigated agricultural production. The irrigated agricultural requirements mainly depend on the groundwater supplies for more than 90% of agricultural production in Pakistan [1]. The Indus Basin Irrigation System (IBIS) is the world’s largest well-connected irrigation system which was constructed after Indus Water Treaty in 1960 [2]. The seepage from contiguous IBIS has played its major role to naturally replenish the groundwater system.

After 2000, major groundwater development was initiated where the total number of tube wells installed in Punjab Province crossed 0.94 million in just one decade (2000–2010) [3]. The indiscriminate pumping of groundwater using these wells has caused several management problems. Water table depletion, salt water up-coning, water quality deterioration, and groundwater mining have become problematic issues in the doab areas [4]–[9]. In fresh groundwater areas of Punjab, the imbalance between abstraction and recharge has caused water table depletion [4]. In Central Punjab, a thin layer of fresh groundwater exists over the saline water due to recharge. As a result of overexploitation, the downward gradient has caused salt water intrusion in fresh groundwater layer [4]. The percentage of area with shallow water table (< 6 m) has considerably decreased due to groundwater mining. On the other hand, the percentage of the area with ground water table at depths below 6 m has rapidly increased. The water table depletion of about 2–3 m per year has resulted groundwater mining in different fresh groundwater areas of Punjab Province [4]. The groundwater is mainly pumped to meet the agricultural, domestic, and industrial needs for over 80 million population [3] in the Punjab Province. The farmers use groundwater as a main source of continuous supply for the production of wheat, rice, sugarcane, potatoes, other cash, and fodder crops. In Pakistan, the rice crop is irrigated by a traditional flood irrigation method which requires a lot of water to meet the standing water demand in the fields. During summer period in the rice growing areas, almost 90% demand of irrigation is met from groundwater supply. In future, the groundwater will become more expensive and could adversely impact food security [4].

Sustainable groundwater resource management requires the routinely updated (high frequency) knowledge about character, dynamics, and behavior of the groundwater system at appropriate spatial scales [10]. Many physical groundwater models such as Visual Mod Flow [11] and FeFlow [12] have been applied to study the groundwater system in Indus basin. But these studies

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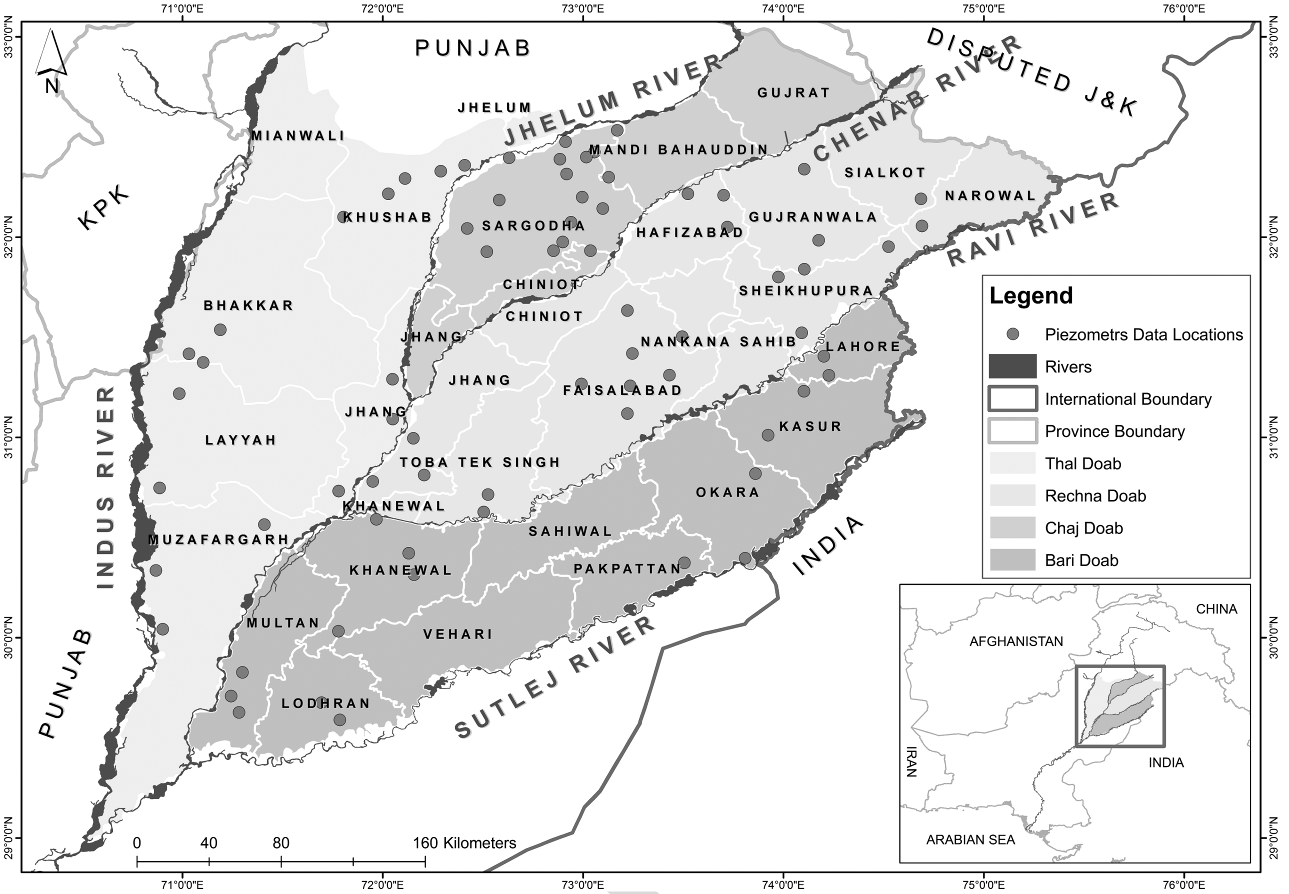

Fig. 1. Location map of UIP in Pakistan.

were only limited in their spatial domain due to the scarcity of i*n situ* measurements for model calibration. An integrated approach based on geophysical surveys and groundwater modeling recently took one decade to complete as a groundwater study of UIP (Punjab Province). Although as a baseline detailed study such an approach is acceptable, the long time required is not conducive to high-frequency water management decisions through frequent updating of policy and planning measures. A sustainable groundwater system monitoring and management requires a robust and cost-effective system that allows the study of the groundwater system at seasonal to annual scales.

The twin satellite system Gravity Recovery and Climate Experiment (GRACE) [13] can be one such "robust and cost-effective" approach to monitor the dynamics of groundwater storage (GWS) variations. GRACE is very unique in its features as a remote sensing platform. It provides large-scale coverage, good temporal resolution (monthly) for groundwater management and is suited for sensing the complete vertical profile of water cycle storage as snow, glacier, surface water, soil moisture (SM), biomass, and groundwater [14]. The GRACE data can provide 10 daily to monthly scale water storage anomalies which are the estimates of the changes in total water storage (TWS) over a specific region. GRACE has already demonstrated its potential to monitor GWS changes and estimate groundwater depletion in countries such as India [15]–[17], USA (High Plain Aquifer [18], [19], Central Valley [20], [21], Mississippi River Basin [22], Illinois [14]), China (North China [23], Congo Basin [40], Western Jilin [24]), and Ethiopia [24]. GRACE data have also been used to estimate GWS changes in the poorly monitored regions from seasonal to annual scales [26].

In this study, we evaluate the potential of GRACE satellite for studying the GWS variation at various spatial scales for the Indus basin. The study assesses the effectiveness of GRACE gravity data as an alternate research-grade tool for the groundwater resource management in Indus Basin. It also evaluates the impact of satellite gravimetric GWS estimation and monitoring methodology to enable decision making over conventional approaches. This study is organized as follows. Section II describes the study region. The details of data and methodology used are discussed in Section III. Section IV outlines the analysis of GWS derived from GRACE-TWS anomalies. Finally, Section V summarizes the general findings and future directions for GRACE-based research on groundwater resource management in Indus basin. The detailed calculations are explained in appendix.

II. UPPER INDUS PLAIN

The UIP is the main agricultural part of Indus basin consisting of four doabs named as Thal, Chaj, Rechna, and Bari, all located in the Punjab Province (see Fig. 1). The unconfined Indus basin aquifer is mainly composed of alluvial formation.

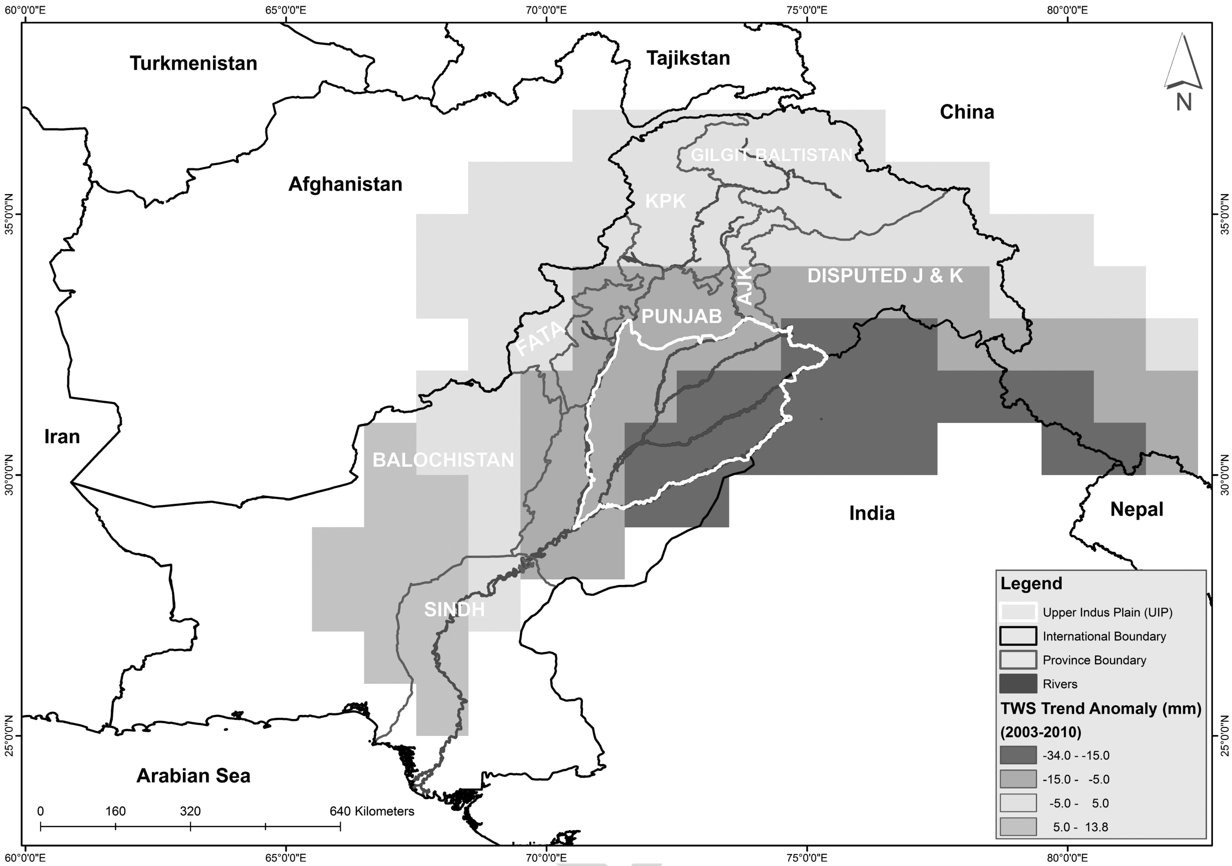

Fig. 2. Mean trend of TWS anomalies from 2003–2010 over Indus Basin of Pakistan.

The lithology mainly varies from fine to coarse sand with clay lenses. The study area is very fertile and is rich in groundwater. The groundwater is currently exploited extensively for domestic to agricultural productivity. In the absence of any groundwater regulation in Punjab Province, farmers pump huge amounts of groundwater for anthropogenic use causing stress on groundwater resources. Consequently, water table has been depleting and groundwater mining is taking place at many places of the aquifer. The contiguous IBIS plays a major role in the recharge of groundwater system. Since 1960, the IBIS irrigation system has expanded through a network of canals such as link, main, and distributaries. The role of link canals is to transfer surplus water from Western Rivers (Indus, Jhelum and Chenab) to Eastern Rivers (Ravi and Sutlej). The main purpose was to maintain the regular supply of surface water for irrigation throughout the year. Through seepage from channels and irrigation of the field, significant recharge takes place of the aquifer system. The total area of UIP (four doabs) is approximately 109 418 km^2.

III. DATA AND METHODS

The Centre for Space Research (CSR) at University of Texas, Austin GRACE data product (http://www.csr.utexas.edu/grace/RL05.html) release-5 (RL05) Level-2 was used to process gravity anomalies for extraction of TWS from 2003 to 2010 (available at ftp://podaac.jpl.nasa.gov/allData/grace/L2/CSR/RL05/) [39]. The GRACE monthly gravity field datasets were processed to extract spherical harmonic coefficients (SHCs). The smoothing and decorrelation techniques are applied to reduce the signal noise due to short wavelength component of the gravity field. The function of the decorrelation technique is to filter out the correlated errors among the spherical coefficients of geopotential changes with the same order and degree [26]. The SHCs with higher degree and order are more affected by correlated noises [27], [28]. A decorrelation filter is applied where the SHCs of lower degree and order are kept unchanged and remaining are filtered based on a moving polynomial window fit [29]. The smoothing is still required to remove the high-frequency noises, and an isotropic filter with 300-km radius is applied to smooth the data in this study [49]. In order to restore the signal dampened due to the smoothing, we used the average (1.132) of the so-called scaling factors for the Indus basin derived from six global hydrological models (GHM) including Noah 2.7, VIC, Mosaic, CLM 2.0, CLM 4.0, and WGHM 2.2, listed in [43, Table III]. However, a scaling factor derived using a GHM such as PCR-GLOBWB might result in more accurate signal restoration in basins, such as the Indus basin, with intensive human activities because it simulates surface water storage changes, natural and human-induced GWS changes, and the interactions between surface water and subsurface water [48]. The resultant TWS anomalies were mapped at 1° × 1° grids to analyze the time series variations over Indus basin.

The TWS mean trend anomaly map (see Fig. 2) shows that total water storage has changed more rapidly over UIP with a decrease of 18.54 mm per year (2.03 km^3/year) as compared to whole Indus basin (6.52 mm/year) from 2003 to 2010. It indicates that UIP is playing an important role in the overall hydrology of Indus basin. The major reason of this significant change in the variation of TWS over UIP is the extensive use of groundwater for anthropogenic activities. The maximum variations in TWS anomalies ranging from -34 to -15 mm are observed in the Southern part of UIP as compared to Northern part (-15 to -5 mm). This indicates that the total water storage has decreased more in two Northern doabs (Bari and Rechna) over the period 2003–2010 (see Fig. 2). The changes in TWS are basically the sum of variations in all hydrological components of water cycle [14]

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

where GW refers to the change (Δ) in groundwater, SM is the SM contribution, SW and SWE are the surface water and snow water equivalent or glacier variations, and BIO represents the variations in the biosphere, respectively.

The topography of the study region is plain with warm climate and snow is uncommon. Therefore, SM may have a major impact on TWS variation in the semiarid regions. Global Land Data Assimilation System (GLDAS) model-simulated SM information has been used in past studies to remove SM effect [31]. In the present study, variable infiltration capacity (VIC version 4.0.6) model-derived SM and surface runoff information over Indus basin is used for the separation of GWS anomalies. In comparison with GLDAS, the VIC model output is Indus basin specific (0.1° × 0.1°) with greater accuracy. VIC is a macroscale semidistributed hydrological model [31]. It is extensively used to study hydrology, water and energy budgets, and climate change impact assessment [33]–[38]. As a basic feature, it simulates water balance at daily to subdaily time steps at each grid cell scale [32]. Recently, the VIC model was applied on Ganges–Brahmaputra–Meghna river basins for the simulation of daily runoff and stream flow fluxes [33]. The study revealed that VIC is capable of capturing daily fluxes of runoff and stream flow dynamics. In our study, the VIC model was setup at the grid size of 0.1° for daily time steps considering two soil layers with total 1-m thickness (first layer = 0.3 m and second layer = 0.7 m). The digital elevation model (90 m) derived from the Shuttle Radar Topographic Mission was used for topography. The global land cover classification (version-1, 400 m) data sets are used in the model for land cover details of Indus basin (https://Ita.cr.urgs.gov/GLCC). For soil information, we used harmonized world soil database (version-1.2, approx. 1 km) developed by World Food and Agriculture Organization (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/).

The climatological information was derived from Tropical Rainfall Measurement Mission (TRMM) and Global Surface Summary of the Day of National Climatic Data Center maintained through the global network of the World Meteorological Organization. The TRMM daily data product 32B4RT (0.25° resolution) (http://pmm.nasa.gov/data-access/downloads/trmm) was used for precipitation data. The setup was run for daily simulation of SM and surface runoff from 2002 to 2010 and the first year (2002) output was excluded as spin-up time. For consistency with monthly TWS, the VIC-generated monthly (instead of daily) SM and runoff fluxes are used for the extraction of GWS anomalies. The VIC model was calibrated using the observed "total annual inflow" for the period 2003–2010 at different rim stations (*in situ* observation points) located at different tributaries of Indus River. These rim stations include: Nowshera, Tarbela, Mangla, Marala, Kalabagh, Balloki, and Suleimanki. The calibration locations are shown in Fig. 3 and results are shown in Table I. We found that Balloki and Sulemanki were challenging cases for modeling the observed inflow due to upstream regulation structures (barrages in Indian Territory). Otherwise, it can also be seen that VIC is able to simulate annual streamflow (which is mostly driven by snow and glacier melt during Spring and rainfall during Summer and Fall) with a Nash–Sutcliffe efficiency of greater than 0.7 and % RMSE ranging from 12% to 50%. Although there is always room for improvement in snow-dominated regions [45]–[47], we consider this acceptable for studying the GWS change in the Indus plains that is considerably far removed from the high-elevation snow region. We revisit this issue of simulation accuracy of streamflow of hydrological models in snow-dominated regions later in Section V.

The VIC-generated output of SM and runoff from 2003 to 2010 at 0.1° × 0.1° was up-scaled to TWS resolution (1° × 1°) for the extraction of GWS. The monthly anomalies were calculated by subtracting the long-term monthly average from SM and runoff data sets. Fig. 4 shows the VIC model-generated long-term average of monthly SM and runoff over Indus Basin. Based on the variations in the precipitation, topography, and lithology, the maximum average SM and runoff are observed in the UIP consisting of Punjab Province both in Pakistan and India. A comparison between GLDAS and VIC for SM and runoff shows a good agreement (Correlation = 0.71, RMSE = 9.6 mm per month) leading to statistically indistinguishable difference in GWS trend differences over the study area (shown later as Fig. 7).

IV. ANALYZING GWS CHANGES

The TWS represents a combined signal including snow, glaciers, surface water, SM, and groundwater. Based on the assumption that snow and biosphere contribution is very negligible, the GW storage information can be derived by subtracting the SM and surface runoff from TWS [34], [30], [15], [14], [23], [21], [31], [24], [35]. It can be seen from Fig. 5 that the excessive groundwater has caused significant depletion in GWS from September 2009 to July 2010. On the other hand, the rising trend after July 2010 is the recharge impact due to the massive flooding in August 2010. Pakistan was hit by a heavy rainfall at the end of July 2010. During summer, there is huge pumping in doabs for the irrigation of rice crop using the traditional method of flood irrigation.

The piezometric point measurements are collected from Scarp Monitoring Organization (SMO); a subdepartment of Pakistan Water and Power Development Authority (WAPDA) is used for calibration. SMO collects groundwater data in

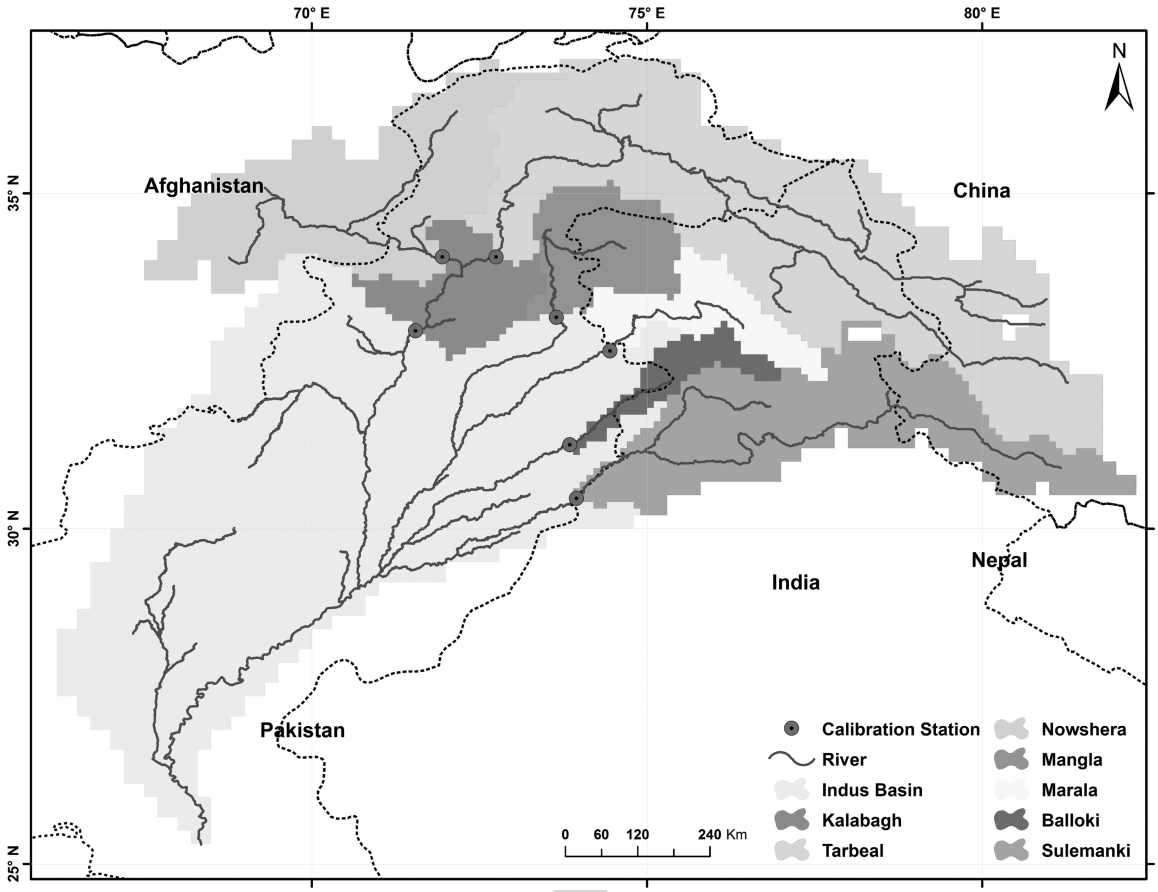

Fig. 3. VIC model calibration locations for stream flows in Indus Basin of Pakistan.

TABLE I
VIC MODEL PERFORMANCE AT VARIOUS GAUGING STATIONS UPSTREAM OF MAJOR RESERVOIRS IN UPPER INDUS BASIN SHOWN IN FIG. 3

River Name	Rim Station	Normalized RMSE (%) 2003–2010)	Nash Sutcliffe Efficiency
Indus	Kalabagh	12.66	0.86
	Tarbela	24.32	0.74
Kabul	Nowshera	51.74	0.97
Jhelum	Mangla	17.4	0.98
Chenab	Marala	25.98	0.82

Performance metrics are based reservoir inflow (observed and VIC-simulated).

terms of depth to water table (DTW) and hydraulic head (HH) on seasonal scales like before monsoon (May–July) and after monsoon (September–December) periods. However, each piezometer within the network is recorded of its reading at varying times of the year leading to the lack of temporal uniformity in reading across all wells. For example, neighboring wells will rarely experience recordkeeping the same month and would be a few months apart due to manpower issues. To circumvent this issue, seasonal averaging of both piezometer readings and GRACE-derived GWS across the entire study region was found necessary. Here, the seasonal average is the average of two piezometer readings over a span of 6–8 months (usually a pre- and postmonsoon reading). For GRACE-derived GWS, the seasonal averaging is the average of all the monthly GWS change values. The seasonal groundwater level anomalies were calculated relative to the seasonal mean of the analysis period (2003–2010). Although the piezometric monitoring provides good measurements about the changes in the groundwater level, it cannot be compared directly with GRACE-derived GWS [41]. Therefore, the water table anomalies were converted into water level changes by subtracting the DTW from average depth to bed rock. The seasonal GWS changes (ΔGWS) were then computed by multiplying water level changes with average safe yield [17]. The *in situ* data of about 67 piezometric locations covering the whole UIP were used for comparison of groundwater trend analysis from 2003 to 2010 (see Fig. 1).

Fig. 6 shows comparison between seasonal GRACE-derived GWS anomaly with seasonal piezometric GWS measurements to study the frequent variations in the behavior of groundwater system. The correlation (0.58) and RMSE (0.03 m) indicate that GRACE derived and observed ΔGWS (i.e., changes) are in good agreement with each other at seasonal timescales. GRACE data follow seasonal groundwater fluctuations in terms of trend and the magnitude of ΔGWS. According to GRACE data, the GWS appears to be depleting at an average rate of about 1.48 km^3 per year over the period 2003–2009, whereas an average GWS depletion rate based on piezometric data is calcu-

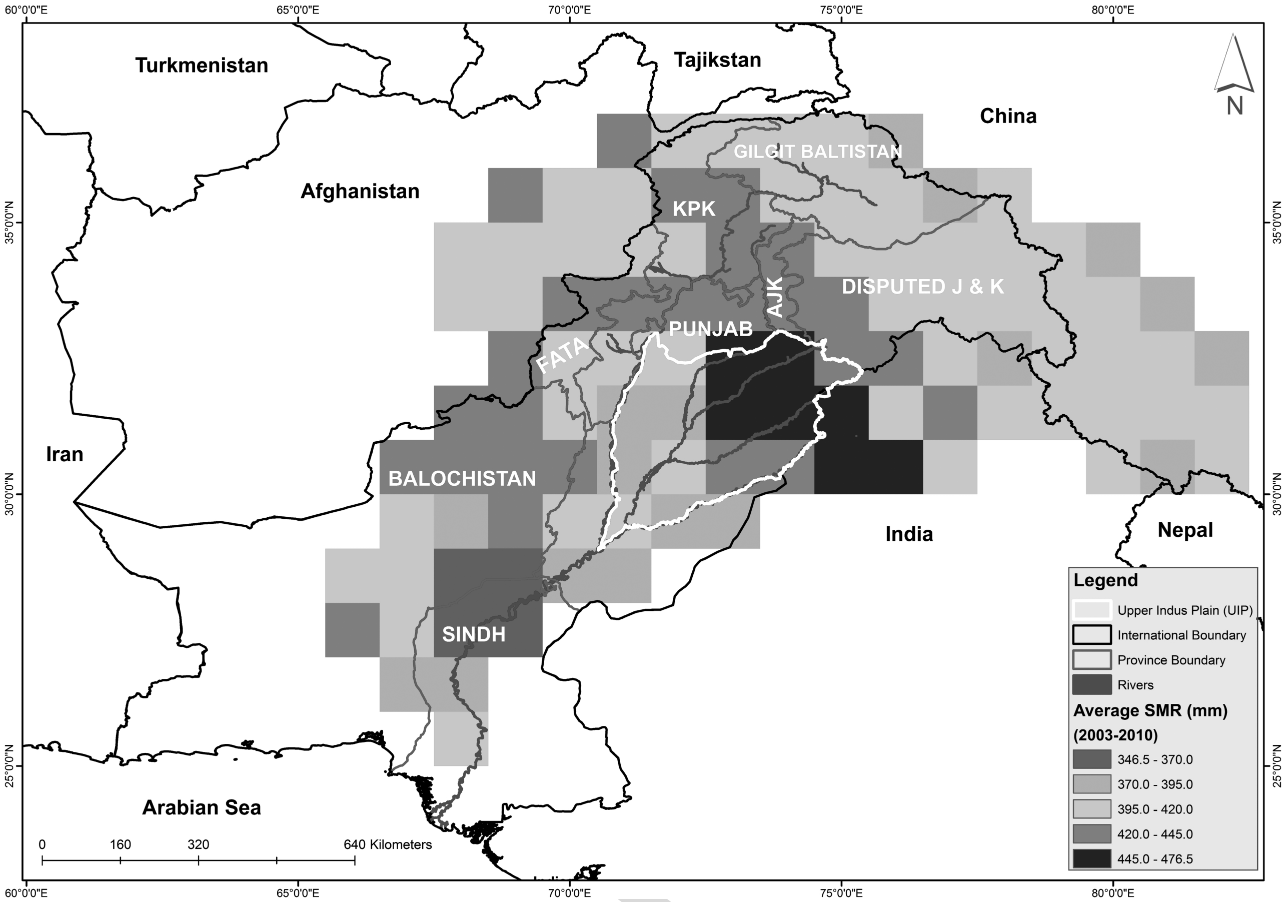

Fig. 4. Variations of VIC-generated monthly long-term average (2003–2010) SM and runoff (SMR) over Indus Basin.

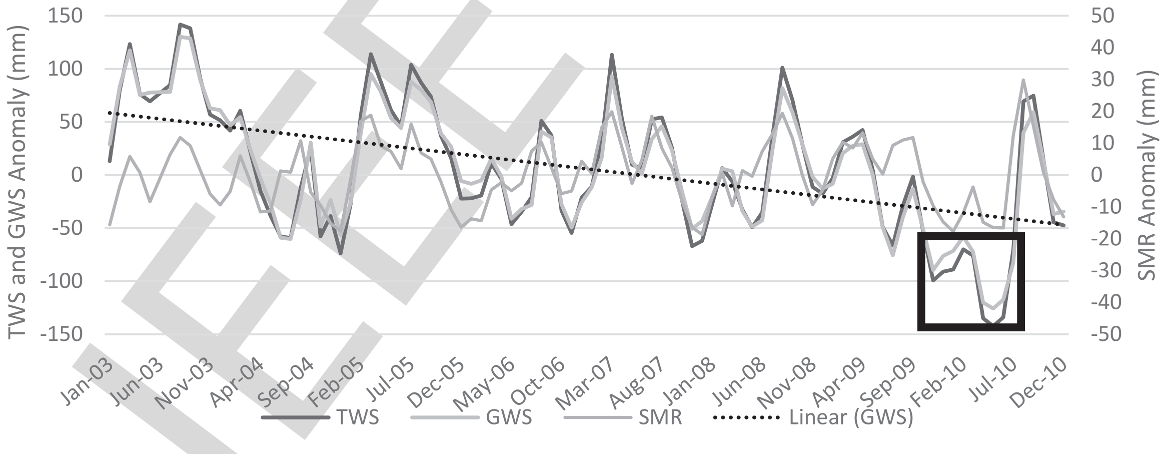

Fig. 5. Monthly variations in TWS, SMR, and GW anomalies over UIP.

lated about 0.39 km^3 per year on the same seasonal scale. The possible reasons of this difference are the limitations in terms of spatially well-distributed network of observed data. It is also noted that the piezometric data are point measurement which is different from large aerial observation of GRACE satellite. The piezometric measurements are more influenced by local effects (recharge and neighborhood pumping). ΔGWS were calculated as a mean of all 67 piezometric data sets within the study area (UIP) to minimize the local variations. The other reason is the limitation of GRACE spatial resolution and the fact that remote sensing is an indirect and spatially a more aggregate measure of a geophysical variable. The accuracy of GRACE-derived GWS is higher at large basin scales ($\sim$200 000 km^2) [30].

It is estimated that the Upper Indus Basin has been losing fresh water stock of about 11.82 km^3 per year (see Table II) in just eight years (2003–2010) due to anthropogenic activities. However, despite the huge groundwater pumping by over 900 000 public tube wells in Punjab Province, the groundwater system

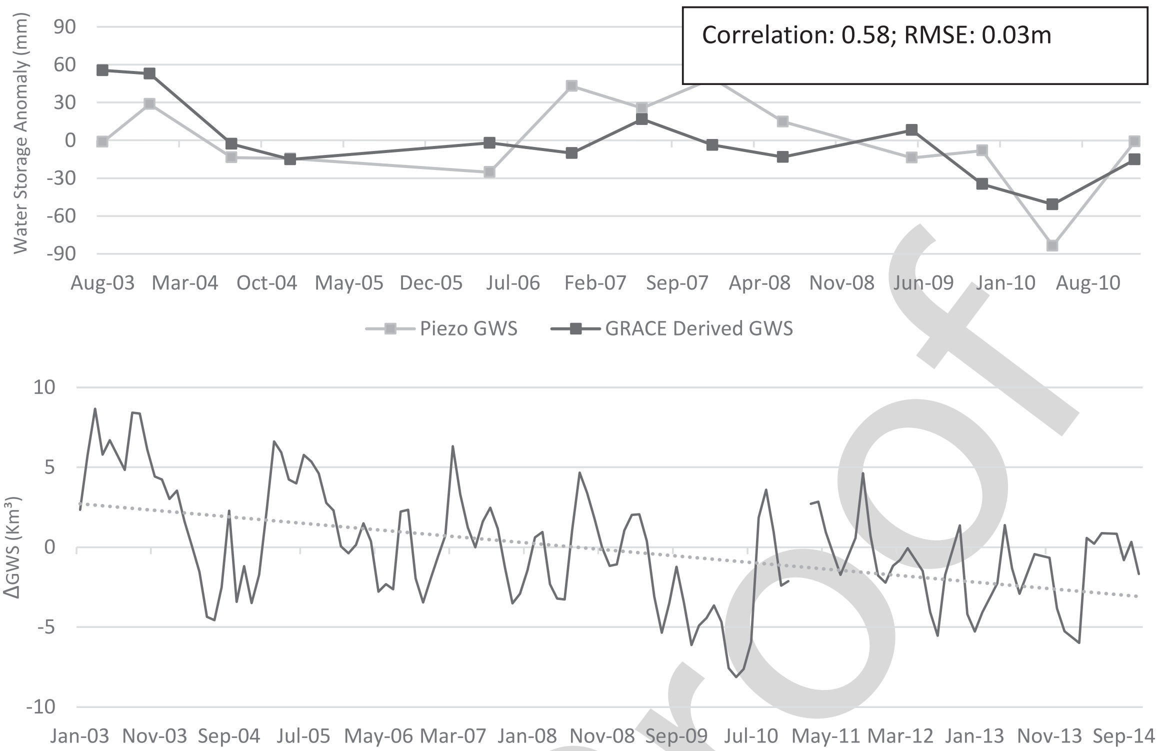

Fig. 6. Upper panel—comparison of seasonal GRACE-derived GWS with seasonal in situ GWS measurement over UIP. The units represent the equivalent thickness of water in millimeter. Lower panel—GRACE-derived monthly GW stock changes over UIP.

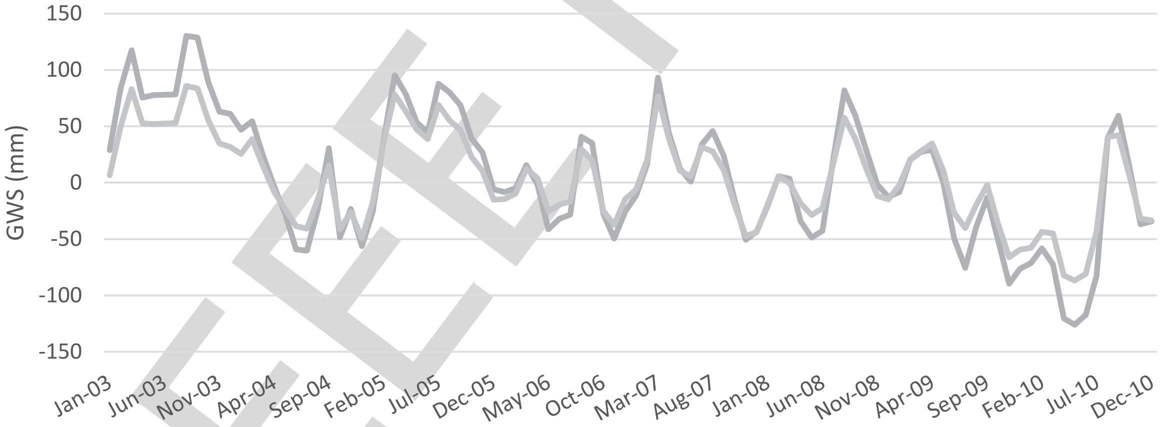

Fig. 7. Comparison of VIC-derived GRACE GWS changes (blue) and GLDAS-1 derived GRACE GWS changes (yellow). The comparison shows that the choice of land surface model appears to make insignificant impact on GWS trends although there is expectedly a modest quantitative difference in GWS changes between the two models.

TABLE II
DETAILS OF THE CALCULATIONS FOR VOLUMETRIC ESTIMATION OF GWS

Description	Year	Mean Depletion Rate (mm/yr)	UIP Area (km^2) UIP Area (km^2)	GWS Depletion Rate (km^3/yr)	Total Loss of GWS (km^3) Dep. Rate $*$ No of Years)
GRACE-GWS	2003–2010	13.50	109418.36	1.48	11.82
Piezo-GWS	2003–2010	3.60	109418.36	0.39	3.15
GRACE-GWS	2011–2014	5.30	109418.36	0.58	2.32
Net GWS Change / Recharge	Between 2010 and 2014	8.20	109418.36	0.90	3.59

seems to be also replenished naturally through frequent flooding events in the Indus Basin along with the seepage contribution from IBIS. Due to heavy rainfall at the end of July 2010, Pakistan was hit by massive flooding and affected 20 million people approximately. Fig. 6 shows a considerable increase in GWS after August 2010 (September–October 2010) and September 2014 which could be attributed to flooding event. As a result of these flooding events, a considerable change in GWS is also observed after July 2010. The predictive scenarios from 2011 to 2014 (based on linear regression between TWS and derived GWS) show that the GWS is depleted with a mean rate of about 0.58 km^3 per year. This depletion has caused a further loss of about 2.32 km^3 per year in the GWS during four years over UIP. Due to the second flooding event in 2014, the groundwater depletion rate appears to have decreased from 1.48 to 0.58 km^3 per year. Assuming that the pumping rate has remained the same during the period 2011–2014, it is estimated that approximately 3.59 km^3 (see Table II) of groundwater has been added in the storage as recharge.

It has been well known that the Northwest India has been experiencing significant GWS depletion over the past decade based on GRACE observations [15]–[17], [50]. Therefore, the GRACE-derived GWS change over UIP in Pakistan is expected to be contaminated by the strong TWS signal from adjacent Northwest India. However, as can be seen from Figs. 5 and 6, we observe strong correlation between GRACE-derived GWS and piezometer-derived GWS changes over UIP, which indicates that the GRACE-observed TWS change over UIP is reliable. In addition, recent study by Long *et al.* [50] reported strong GWS depletion in Pakistan outside of Northwest India revealed from spatial patterns of GWS change from PCR-GLOBWB. Completely separating GRACE TWS signal over UIP from that over Northwest India would be challenging due to GRACE's large footprint (e.g., 200 000 km^2) and is out of scope of this study.

V. Conclusion and Recommendations

The current study presented an overall trend of variations in the dynamic behavior of groundwater along with the changes in groundwater recharge at regional scales. It was based on the premise that the groundwater is the dominant factor for the variations in the TWS. The rate of groundwater depletion over the study region was found to be moderate, whereas in a few doabs, the groundwater appears to be depleting at a much higher rate. The TWS anomalies (see Fig. 2) and the analysis of piezometric *in situ* data indicate that the major depletion is taking place in Bari and Rechna Doabs, near the Pakistan–India border in the South. A few districts of Bari and Rechna doabs were found to be under considerable groundwater mining. The reason of groundwater depletion was attributed to the huge pumping rate and less recharge due to little flows in two eastern rivers Sutlej and Ravi (being controlled by India) and low rainfall. Our study presents the mean changes in the GWS to understand the dynamics of entire Indus aquifer groundwater system as a whole. Such a study is valuable from the perspective of regional hydrology of UIP for long-term analysis and prediction of groundwater system behavior. However, the GRACE has its own limitations in terms of its coarse resolution and physical inertia. Estimation accuracy of GRACE-based TWS variations in the small basins is often a matter of compromise between reducing the noise and spatial resolution [14].

This study demonstrated that there is significant interseasonal (premonsoon and postmonsoon) variability in the total water storage over Indus basin. The total water storage has decreased more rapidly over UIP as compared to overall Indus basin. The changes in TWS are mainly dominated by variations in the GWS in UIP. The GRACE-derived GWS was found agreeing with trends observed *in situ* data. Both the trend and the magnitude of GRACE-GWS are quite comparable with field observations. It was estimated that the groundwater is depleted at a mean rate of 8.5 mm per year and has lost total GWS of about 7.43 km^3 over the period of 2003–2010.

The GRACE-derived GWS changes using the VIC model approach was evaluated in this study. This technique was found potentially skillful for monitoring groundwater behavior and analysis of the long-term seasonal variations in the groundwater system even at subbasin scale (UIP) over Indus basin. This presents GRACE as a cost effective tool that can augment traditional geophysical and physical groundwater modeling approaches in water management applications. As a limitation of this study, the VIC model is only calibrated for reservoir inflows at different locations in Indus basin. Therefore, future studies should consider the need for further calibration of VIC model-generated SM with *in situ* data to evaluate its accuracy especially over the high-altitude and cold region of the Upper Indus basin. Therefore, uncertainties arising from the failures of modeling and products should be thoroughly discussed

A potential limitation of the study is the choice of land surface model and its ability to realistically capture the water fluxes with commensurate fidelity to yield skillful GWS change assessments. It is well known that land surface hydrological models commonly suffer from limitations in estimating hydrological state and flux variables for a variety of settings. In our particular study, the ability of the VIC hydrological model to capture the snow water equivalent and glacier mass can be a potential limitation. Although Fig 7 shows indistinguishable difference between VIC and GLDAS-1 derived GRACE GWS changes, this does not necessarily mean that both models are simulating the cryospheric processes accurately [44]. The uncertainties in simulating the flux in high-altitude region, where cryospheric processes of snowfall and glacier melt dominate, arise due to uncertainties in forcing data and the model complexity. Such uncertainties may also propagate via surface water flux (streamflow) in the GRACE-derive GWS changes. Recent studies indicate a mismatch in total water storage estimation between GLDAS-1 simulations and GRACE observations in the Tibetan Plateau that point to physical limitations of GLDAS [45], [46]. Although VIC can simulate snow processes to a reasonable extent using temperature and radiation algorithms (see Table I), a detailed investigation is beyond the scope of this study. Readers should therefore keep this limitation in mind for future application of GRACE data for groundwater assessments.

The detailed study of GWS variations at each doab level could be more useful for the operational adoption of GRACE technology. For effective groundwater resource management in Indus Basin, the doab level GWS information is more desirous from the groundwater manager's perspective. For this purpose, further doab-level study is required to evaluate the potential and accuracy of GRACE at such small but effective spatial scales. The spatial downscaling of GRACE signal using Synthetic Aperture Radar and satellite radar altimetry should there be pursued [42].

With the wide applicability of GRACE as an effective tool for understanding the basin scale hydrology and estimating groundwater water storage variations, the confidence of end-user community can now be raised. The interest and need for GRACE-based operational water resource management at small basins is poised to be scaled up. It is anticipated that the GRACE follow-on (GRACE-FO) mission will meet the requirement of water resource managers in terms of spatial resolution enhancement and continuous data availability. It will help to promote GRACE as more reliable and successful tool for groundwater resource management.

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APPENDIX

Calculations Procedure for GRACE Derived GWS *Anomalies*

1) Slope Equation

$$b = \frac{\sum\left(T-\tilde{T}\right)\left(\mathrm{GW}-\widetilde{\mathrm{GW}}\right)}{\sum^{\left(T-\tilde{T}\right)^2}}$$

T = Time (days)
$\tilde{T}$ = Mean of time (days)
GW = Groundwater anomalies (days)
$\widetilde{\mathrm{GW}}$ = Mean of groundwater anomalies (days)

2) b. GWS estimation (km^3)

$$\mathrm{GSE}_G = \mathrm{GA}_G * \mathrm{Area(UIP)}$$

where
$\mathrm{GSE_G}$ = GRACE GWS anomalies (Volume in km^3)
$\mathrm{GA_G}$ = GRACE groundwater anomalies (height in m)
Area (UIP) = Area of UIP (109 418.35 km^2)

Calculations Procedure for Piezometric in situ Data Anomalies

1) Groundwater Level Change

$$\mathrm{GLC}_P = \mathrm{DTB} - \mathrm{DTW},$$

where
$\mathrm{GLC_P}$ = Piezometric groundwater level changes (m)
DTW = Depth to water table (m)
DTB = Depth to bedrock (Average DTB for UIP = 400 m)

2) Groundwater Level Anomalies

$$\mathrm{GLA}_P = \mathrm{GLC}_{PM} - \mathrm{GLC}_P,$$

where
$\mathrm{GLA_P}$ = Piezometric groundwater level anomalies (monthly in meters)
$\mathrm{GLC_{PM}}$ = Long-term mean of piezometric monthly groundwater level changes (m)
$\mathrm{GLC_P}$ = Piezometric groundwater level changes (m)

3) GWS anomalies

$$\mathrm{GSA}_P = \mathrm{GLA}_P * S_Y,$$

where
$\mathrm{GSA_P}$ = Piezometric GWS anomalies (m)
$\mathrm{GLA_P}$ = Piezometric groundwater level anomalies (m)
S_{Y} = Average specific yield (for UIP $S_{\mathrm{Y}} = 0.12$)[a]

4) GWS estimation (km^3)

$$\mathrm{GSE}_P = \mathrm{GSA}_P * \mathrm{Area(UIP)},$$

where
$\mathrm{GSE_P}$ = Piezometric GWS anomalies (Volume in km^3)
$\mathrm{GSA_P}$ = Piezometric GWS anomalies (m)
Area (UIP) = Area of UIP (109 418.35 km^2)

a—Note: A spatially variable specific yield map is not available. Only specific yield values over different flood plains (point measurements at only few locations) in the UIP are available based on the geological investigations and pumping tests conducted by USGS (United States Geological Survey) in collaboration with WAPDA (Pakistan Water and Power Development Authority) in 1960s [9].

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