Environ Monit Assess (2017) 189:128
DOI 10.1007/s10661-017-5846-1

Integrated groundwater resource management in Indus Basin using satellite gravimetry and physical modeling tools

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Received: 9 November 2015 / Accepted: 13 February 2017

Abstract Reliable and frequent information on groundwater behavior and dynamics is very important for effective groundwater resource management at appropriate spatial scales. This information is rarely available in developing countries and thus poses a challenge for groundwater managers. The in situ data and groundwater modeling tools are limited in their ability to cover large domains. Remote sensing technology can now be used to continuously collect information on hydrological cycle in a cost-effective way. This study evaluates the effectiveness of a remote sensing integrated physical modeling approach for groundwater management in Indus Basin. The Gravity Recovery and Climate Experiment Satellite (GRACE)-based gravity anomalies from 2003 to 2010 were processed to generate monthly groundwater storage changes using the Variable Infiltration Capacity (VIC) hydrologic model. The groundwater storage is the key parameter of interest for groundwater resource management. The spatial and temporal patterns in groundwater storage (GWS) are useful for devising the appropriate groundwater management strategies. GRACE-estimated GWS information with large-scale coverage is valuable for basin-scale monitoring and decision making. This frequently available information is found useful for the identification of groundwater recharge areas, groundwater storage depletion, and pinpointing of the areas where groundwater sustainability is at risk. The GWS anomalies were found to favorably agree with groundwater model simulations from Visual MODFLOW and in situ data. Mostly, a moderate to severe GWS depletion is observed causing a vulnerable situation to the sustainability of this groundwater resource. For the sustainable groundwater management, the region needs to implement groundwater policies and adopt water conservation techniques.

Keywords GRACE · Remote sensing · Pakistan · Indus Basin · Groundwater management

Submitted to: *Environmental Monitoring and Assessment Journal*

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Introduction

The role of groundwater is very important to maintain the agricultural productivity and economic development in a water-scarce country like Pakistan. The irregular surface water supply has encouraged farmers to exploit groundwater for irrigation (Alam and Olsthoorn Theo 2014). The increasing demand for food and fiber has further aggravated the situation, and farmers are pumping extensive groundwater to meet the food security challenges. The agricultural sector is the largest user of groundwater for agricultural production in Pakistan (Qureshi et al. 2008). The overexploitation of groundwater has caused several groundwater management problems. Water table depletion, increased salinity, groundwater quality deterioration, and groundwater mining are some of the challenges for the groundwater managers in Pakistan (Qureshi et al. 2010; Chandio and Larock 1984; Khan et al. 2008; Saeed and Ashraf 2005; Sufi et al. 1998). The assessment of groundwater abstraction and changes in recharge are the major parameters for sustainable groundwater management (Cheema et al. 2014). Due to overexploitation, Pakistan is ranked among the top five countries in the world where groundwater abstraction rate has reached 80 km^3 per year from 1961 to 2010 (Wada et al. 2014). Groundwater resource management has become more crucial due to climate change, population growth, and changing patterns of groundwater availability on spatial and temporal scales (Elliott et al. 2014; Schewe et al. 2013). Groundwater regulation is an important aspect of effective groundwater resource management.

The availability of frequent and reliable data, application of suitable groundwater models, and implementation of groundwater management strategies are very critical for sustainable groundwater resource management. The accuracy of models is very much dependent on the reliability of input datasets. Thus, the effectiveness of groundwater models is hampered by unreliable and insufficient data causing uncertainties in groundwater management strategies (Singh 2014; Wu et al. 2003). The situation is more serious in developing countries due to an inadequate distributed data measurement network, data paucity, and accessibility issues (Moore and Fisher 2012; Brunner et al. 2007).

In Pakistan, the in situ measurements of water table changes are only limited to seasonal scales (bi-annual) and are more likely to be influenced by local drivers of change. The groundwater models have their own limitations of requiring extensive spatially distributed input data (Wondzell et al. 2009). The geophysical data (i.e., resistivity surveys, electromagnetic and physical well drilling) and isotopic methods are accurate but are very costly and laborious and involve field surveys. Remote sensing has now emerged as a progressive and cost-effective tool for spatial input data collection (Dar et al. 2010; Stisen et al. 2011; Sood and Smakhtin 2015) and analysis of hydrological cycle. Although remote sensing technology provides large-scale spatial and temporal coverage, its accuracy can be limited due to an indirect measurement method. All these concerns have hampered effective groundwater management by posing a big challenge for the groundwater managers. The sustainability of groundwater is indirectly related to food security in agrarian countries like Pakistan (Basharat and Tariq 2013). The groundwater managers are always demanded for a very cost-effective and continuous monitoring application. The integration of remote sensing with traditional groundwater management tools is potentially useful for the improvement of groundwater modeling (Brunner et al. 2007). The remotely sensed frequently available spatial information on groundwater storage variations is a direct measure of changes in groundwater dynamics referring to the variations in abstraction and recharge. It is also potentially helpful for accurate prediction of management strategies.

The satellite gravimetric observation from Gravity Recovery and Climate Experiment (GRACE) has shown its potential to bridge data paucity (Rodell et al. 2009; Tiwari et al. 2009; Famiglietti et al. 2011). The groundwater storage information can be inferred from GRACE data. Since its launch in 2002, GRACE is continuously providing time-varying gravity fields which are linked with the changes in mass over earth surface (Rodell et al. 2007). GRACE has shown its potential for the estimation of groundwater depletion rates over many basins globally (Rodell et al. 2009; Tiwari et al. 2009; Famiglietti et al. 2011; Tiwari et al. 2009; Strassberg et al. 2007; Strassberg et al. 2009; Feng et al. 2013; Scanlon et al. 2012). The groundwater storage is a key parameter of interest for groundwater resource management (Jin and Feng 2013), and GRACE is found very skillful for the estimation of groundwater storage changes (GWS) at monthly scales (Rodell et al. 2009; Famiglietti et al. 2011).

GRACE satellite provides monthly gravity anomalies at global scale. The large-scale coverage, high temporal frequency, water measurement capability of various hydrological parameters, and free data availability are the main characteristics of the GRACE satellite. GRACE has been extensively applied by the research community to improve the understanding of the hydrological cycle by monitoring groundwater storage variations in many big basins (Wouters et al. 2014) and better tuning of hydrological models globally (Lo et al. 2010; Werth and Güntner 2010).

This study assesses the impact of GRACE-based application as a tool for groundwater resource management in the Indus Basin. It demonstrates the use of

GRACE in groundwater management strategies for the sustainability of groundwater resources. The study also evaluates the potential to use GRACE in groundwater resource management in the Indus Basin by forecasting the groundwater storage changes up to 180 days. The study examines the impact of satellite gravimetric groundwater storage (GWS) estimation and monitoring methodology to enable decision making along with traditional modeling approaches. This study is structured as follows. The "Description of study area" section describes the study region. The detailed methodology is explained in the "Data and methods" section. The "GRACE groundwater storage" section is focused on the derivation of GRACE-based groundwater storage (GWS) estimation. The discussion on results is summarized in the "Results and discussion" section. The "Integrated groundwater management" section refers to the integration of gravimetry with traditional physical modeling tools and in situ measurements. Finally, the "Conclusions and recommendations" section summarizes the general findings and future directions for further improvements in GRACE-based integrated groundwater resource management in the Indus Basin.

Description of study area

The study area consists of four riverine floodplains locally known as doabs spreading over the fertile agricultural land of Punjab Province in Pakistan (Fig. 1). These four doabs (Thal, Chaj, Rechna, and Bari) are bounded by the Indus River and its four major tributaries (Jhelum, Chenab, Ravi, and Sutlej). The extensive irrigation network as a part of the Indus Basin Irrigation System (IBIS) has turned the doabs into a food basket of Pakistan which were once under desert conditions (Alam and Olsthoorn Theo 2014). The major characteristics of the four doabs are summarized in Table 1. All four doabs are part of the unconfined Indus Basin aquifer with unconsolidated sedimentation of the Indus River and its tributaries (Alam and Olsthoorn Theo 2014). The doabs are of alluvial deposits with lithological variations predominantly from fine to medium sand with clay and silt unfolds (Alam and Olsthoorn Theo 2014). The climate of the area is generally semi-humid to arid with significant seasonal variations in precipitation and temperature. The study area is densely populated and under intensive irrigation for agricultural productivity.

The Indus aquifer is mainly recharged through precipitation, seepage from canals, and irrigation return flow (Asghar et al. 2002), whereas the areas along the rivers are dominantly recharged by rivers. The groundwater quality varies spatially both laterally and vertically. A layer of freshwater with varying thickness overlays saline water in doab areas. It is due to the fact that the saline groundwater in the Indus Basin is of marine origin (Ashraf et al. 2011). The excessive water from three western rivers (Indus, Jhelum, and Chenab) is diverted to Ravi and Sutlej through linked canals that maintain a regular surface water supply. The excessive pumping, inadequate precipitation, and little flows in two eastern rivers (Ravi and Sutlej) regulated by India have caused water table depletion in the Bari doab. Based on the physiographic and lithological variations, each doab is a unique hydrological unit with complex groundwater dynamics.

The various studies were conducted in the Indus Basin addressing the different water resource management issues focusing on the conjunctive use of surface water and groundwater (Kazmi et al. 2012), mitigating water logging and salinity (Qureshi et al. 2008; Alam and Olsthoorn Theo 2014; Chandio et al. 2012; Basharat and Tariq 2013), and groundwater resource management using different models at individual doab level (Ashraf and Ahmad 2008; Khan et al. 2008). Remote sensing and GIS techniques were also applied as input data sources for precipitation, evapotranspiration, soil properties, topography, and land use/land cover for hydrological modeling in the Indus Basin (Cheema et al. 2014; Ahmad et al. 2009; Ahmad et al. 2011).

About one third of the Thal doab is under Thal desert covered with sand dunes in the upper part and is mainly dependent on rain-fed agriculture, whereas the middle and lower parts are under major irrigated agriculture through conjunctive use of surface water and groundwater. In the lower part of the Thal doab, the inter-flow from two rivers Indus and Chenab is the major source of groundwater recharge due to narrow distance. The Chaj doab is the smallest area in the Upper Indus Plain bounded by the Jhelum and Chenab rivers. The groundwater is mainly recharged through various hydraulic structures and extensive irrigation networks along with precipitation in the Chaj doab. The Rechna doab is the most populated area with highest tube wells of about 0.33 million (Government of Punjab 2012). The lithological analysis shows that the subsurface clay layers in the Rechna doab causes hindrance in groundwater

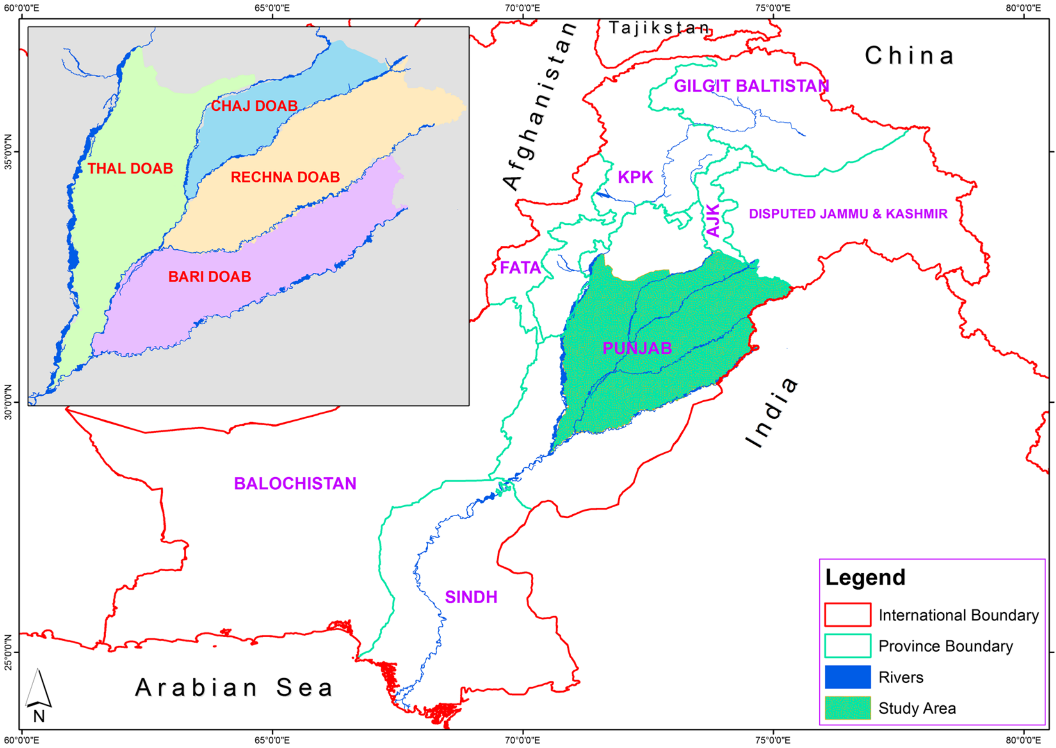

Fig. 1 Location map of the study area

recharge. The high vertical heterogeneity due to the alluvial nature of deposition (Bennett et al. 1967) poses variations in the groundwater dynamics of each doab.

Data and methods

The groundwater storage anomalies were inferred by subtracting soil moisture and runoff information from GRACE terrestrial water storage. The monthly terrestrial water storage (TWS) is the measure of changes in gravity field observed by GRACE satellite. Data smoothing and decorrelation techniques were applied to process data product (RL05) provided by the Centre for Space Research (CSR) from 2003 to 2010. These techniques are required to improve accuracy by removing noises (Shum et al. 2011; Kusche 2007; Duan et al. 2009). The TWS represents the variations in the hydrological cycle comprising from snow to groundwater (Rodell et al. 2009). By considering the major contribution of soil moisture (SM), either field measurements or model-generated SM data is required to extract groundwater storage (GWS) information (Rodell et al. 2009). The Variable Infiltration Capacity (VIC) hydrological

Table 1 Summary of the main characteristics of four doabs

Characteristics	Bari doab	Rechna doab	Chaj doab	Thal doab
Bounded by rivers	Sutlej and Ravi	Ravi and Chenab	Chenab and Jhelum	Chenab and Indus
Area	2.96 mha	3.12 mha	1.36 mha	3.35 mha
Lithology	Medium to coarse sand, silt with clay lenses	Clay to sandy loam	Fine to medium sand with silt	Fine to coarse sand with clay lenses
Total tube wells	0.12 million	0.33 million	0.13 million	0.17 million
Precipitation (mm)	Varies from 100 to 500	Varies from 300 to 1000	778 average annual	500 average annual maximum

model-simulated soil moisture and surface runoff (SR) data is used in this study. The globally accepted semi-distributed VIC model (Siddique-E-Akbor et al. 2014; Liang et al. 1994; Iqbal et al. 2016) was applied in study area at a 0.1° × 0.1° grid scale from 2003 to 2010. The major input datasets for the VIC model include DEM, land use/land cover, soil data, and climatic information (Kummerow et al. 1998) for the simulation of soil moisture and surface runoff fluxes at grid scale. The model is set up for daily scale simulations by considering two soil layers of 1 m thickness (first layer = 0.3 m and the second layer = 0.7 m). The model showed favorable agreement with annual observed reservoir inflow data at various locations in the Indus Basin.

As the study area is extensively exploited for agricultural consumption, it is assumed that variations in TWS are attributed to the major contribution from GWS, SM, and SR. The monthly GWS were inferred by subtracting VIC model-generated soil moisture (SM) and surface runoff (SR) from GRACE-TWS at the 1° × 1° grid scale from 2003 to 2010. In the context of operational groundwater management, the GRACE-GWS anomalies were numerically downscaled to the grid scale of 0.1° × 0.1° using the VIC model. Basically, the VIC-generated SM and SR information at 0.1° × 0.1° is used as guide to downscale the GRACE-TWS information having actual resolution of 1° × 1°. The GRACE-based GWS was compared with in situ piezometric measurements recorded by the Scarp Monitoring Organization (SMO). The seasonal (pre-monsoon and post-monsoon) groundwater level changes were converted into groundwater storage anomalies by multiplying with specific yield (Strassberg et al. 2007). The GWS anomalies were then calculated by subtracting the seasonal changes from the long-term average (2003–2010).

The groundwater managers and policymakers required intensive information on groundwater system behavior and understanding of groundwater dynamics for effective groundwater management. The numerical groundwater modeling is a scientific tool for defining appropriate groundwater management strategies and plays an important role in groundwater development and management (Zhou and Li 2011). MODFLOW is a widely used finite difference numerical groundwater model providing a user-friendly simulation environment (Kashaigili et al. 2003). It is commonly used for the simulation of groundwater flow and contaminant transport analysis. With the objective of regional-scale modeling and data availability, the conceptual model was constructed for individual doabs at the cell size of 2.5 × 2.5 km. Vertically, the aquifer was divided into three layers. The top layer was taken from surface to 50 m depth. Almost the entire pumping in the doab area is from this layer; therefore, this layer needed great consideration. The second layer extended up to 200 m depth based on the assumption that in the near future, the maximum pumping could possibly happen from this part of the aquifer. The third layer extends down to the bed rock, and its thickness varies from place to place due to the variation in topography followed by bedrock. For each doab, the physical and hydraulic boundaries are based on the surface (topography, land form, streams) and subsurface features (geological conditions, pumping depths). The rivers are considered as horizontal hydraulic boundaries whereas the vertical hydraulic boundaries are defined on the basis of different pumping depths. The cells falling in between the bounding rivers were marked active whereas the rest of the area is considered as a no-flow boundary. For the river boundaries, the data of river stage and width is used for the flow calculation in the rivers. The surface recharge is calculated as the sum of percolation from precipitation, seepage from irrigation network, and return flow through pumping. The data of about 140 pumping tests conducted by USGS in the Indus Basin is used to define the aquifer parameters (Bennett et al. 1967). Each doab was then divided into a number of hydraulic conductivity zones based on the variations in the hydraulic conductivity values against each pumping test. The evapotranspiration varies over doabs whereas the other factors are assumed to be constant during the simulation period in the irrigated areas. After characterization of field conditions using various inputs, the model was run for steady-state simulation of hydraulic heads. The year 1984 was considered as steady-state conditions, assuming no change in groundwater storage in the absence of groundwater pumping as the major groundwater development started after 1984. For transient conditions, the output was simulated for flow fluxes as 1991, 1996, 2004, and 2009 at each doab scale averagely (Fig. 1). The model performed favorably well while comparing measure and simulated hydraulic heads. The simulation output of Visual MODFLOW for the years 2004 and 2009 covering the study period (2003 to 2010) is used for the validation of GRACE-GWS results and understanding of groundwater system dynamics at individual doab scales.

Table 2 Comparison of GRACE numerical downscaling results

Grid scale	Year	Bari doab (correlation)	Rechna doab (correlation)	Chaj doab (correlation)	Thal doab (correlation)
1° × 1°	2003–2010	0.92	0.56	0.09	−0.13
0.1° × 0.1°	2003–2010	0.93	0.65	0.15	−0.10

GRACE groundwater storage

The comparison between numerically downscaled GRACE-GWS anomalies at 0.1° × 0.1° (approx. 10 × 10 km) with actual GRACE-GWS (1° × 1°) is given in Table 2. The results of correlation with in situ data indicate that numerical downscaling of GRACE-derived GWS is more useful for operational groundwater management (Table 2). The yearly average groundwater storage variations over four riverine flood plains (Bari, Rechna, Chaj, and Thal doabs) were mapped from 2003 to 2010 (Figs. 2 and 3). The yearly variations in GWS are representative of changes in groundwater abstraction and recharge impacted by anthropogenic and climatic variations. A significant change in the groundwater storage is observed in two southern doabs (Bari and Rechna) from 2003 to 2009 (Fig. 4). The negative groundwater storage anomalies are caused by the overexploitation of groundwater. The spatial patterns of groundwater storage have indicated that the Bari doab is under severe groundwater depletion, whereas in the Rechna

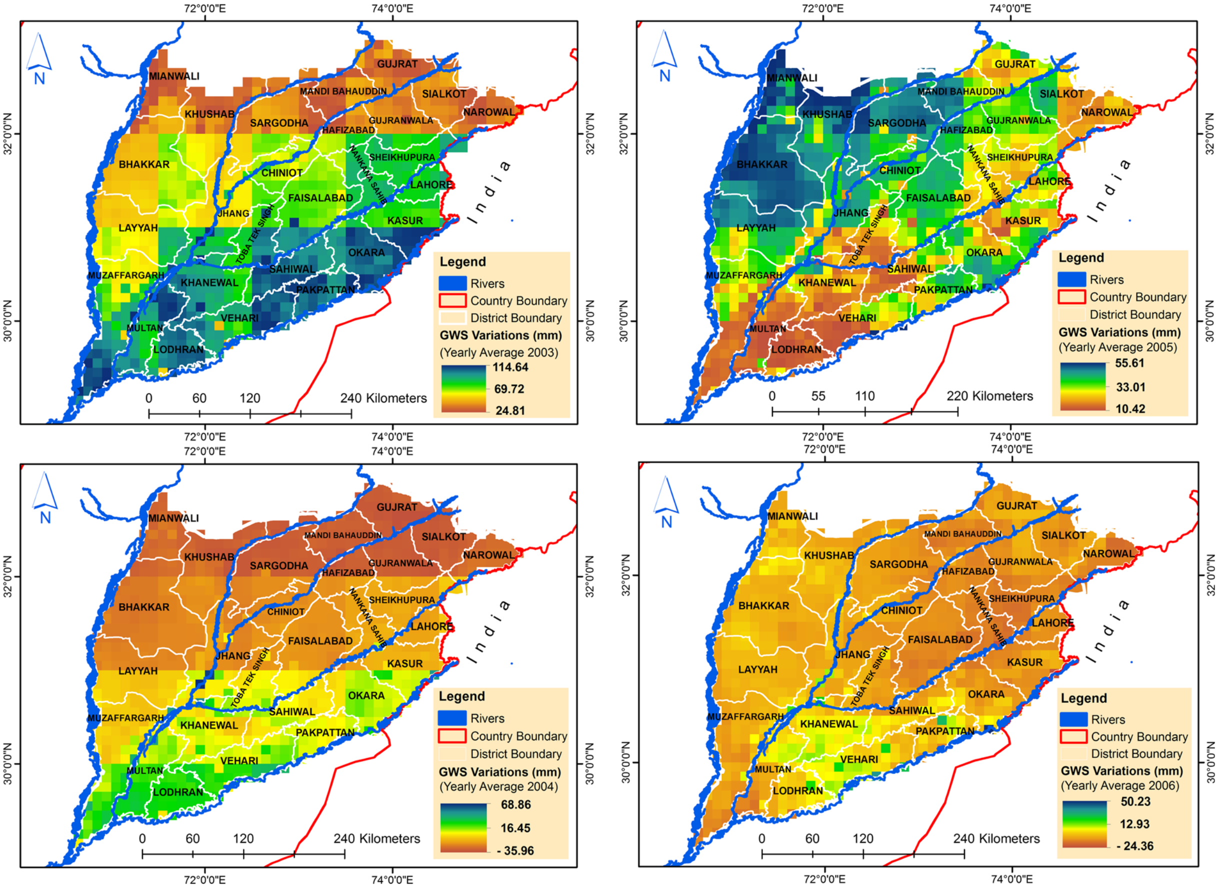

Fig. 2 Yearly average groundwater storage variations over four riverine flood plains from 2003 to 2006

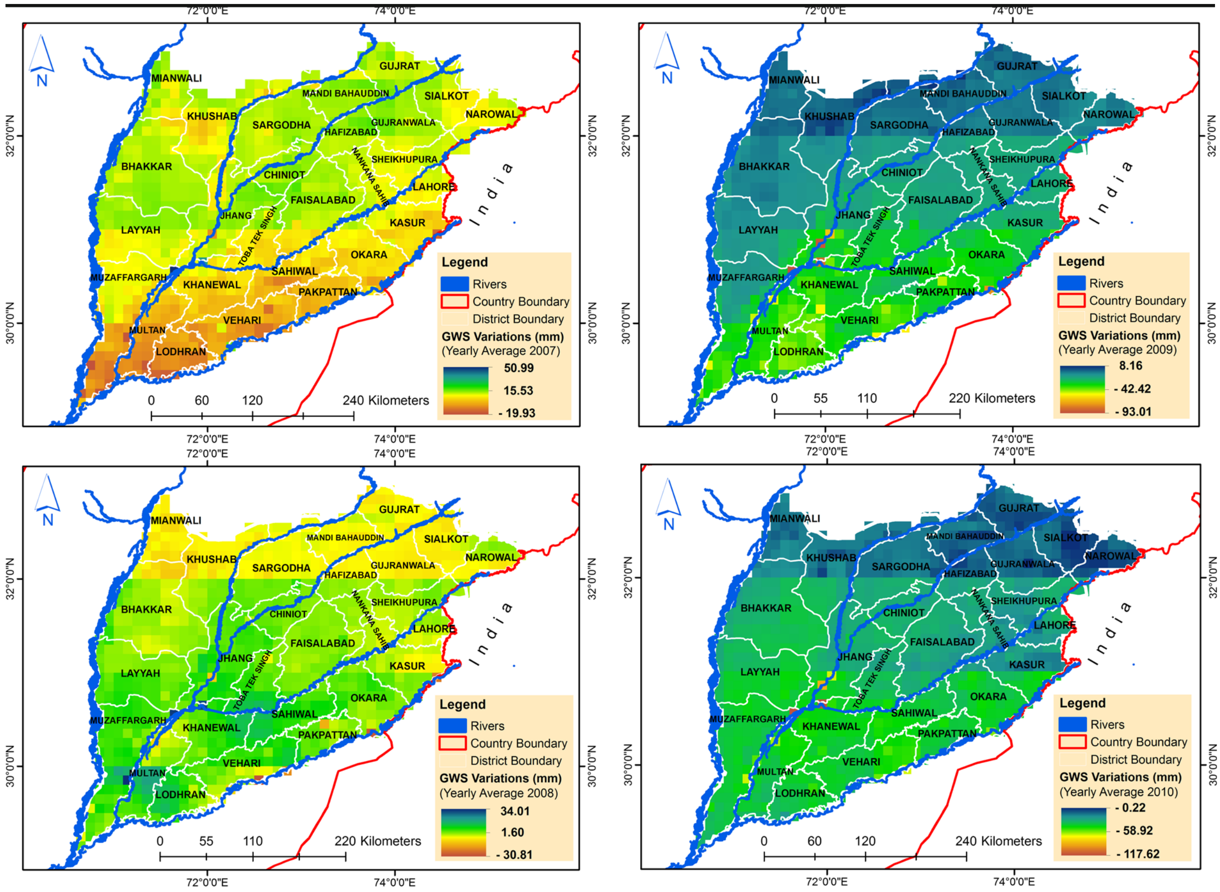

Fig. 3 Yearly average groundwater storage variations over four riverine flood plains from 2007 to 2010

doab, the groundwater depletion varies from moderate to severe. The districts of Toba Tek Singh, parts of Jhang and Faisalabad districts, are under severe groundwater depletion.

At the end of July 2010, the heavy rainfall caused massive flash flooding in Pakistan and many districts of Khyber Pakhtunkhwa, Punjab, and Sindh provinces were extensively flooded. The increasing trend in groundwater storage between July and August 2010 represents the groundwater recharge through the flooding event (Fig. 5). This flooding phenomenon impacted Chaj, Rechna, and some parts of the Bari and Thal doabs by replenishing the groundwater storage. Figure 6 indicates the changes in groundwater storage over the period 2003 to 2010. It is analyzed that most of the Rechna doab areas are under moderate groundwater depletion except Toba Tek Singh and some parts of the Jhang districts. A significant decreasing trend in groundwater depletion is observed in Lahore and some parts of Kasur districts whereas the Bari doab is undergoing severe groundwater depletion. The Chaj doab is found comparatively safe except in Sargodha and parts of the Jhang district. The Thal doab is also comparatively analyzed to be safe except a few districts. GRACE-GWS shows that the lower areas (Layyah and Muzaffargarh districts) of the Thal doab are also undergoing groundwater depletion. The spatial variations in changes of groundwater storage are used to identify the areas with excessive groundwater depletion for devising the groundwater management strategies.

Results and discussion

It is estimated from GRACE that groundwater storage is depleted at an average rate of about 0.38 km^3/year in Bari and about 0.21 km^3/year in the Rechna doab from 2003 to 2010, whereas an average GWS depletion is calculated to be about 0.54 km^3/year in Bari and 0.16 km^3/year in the Rechna doab based on piezometric data. Specifically

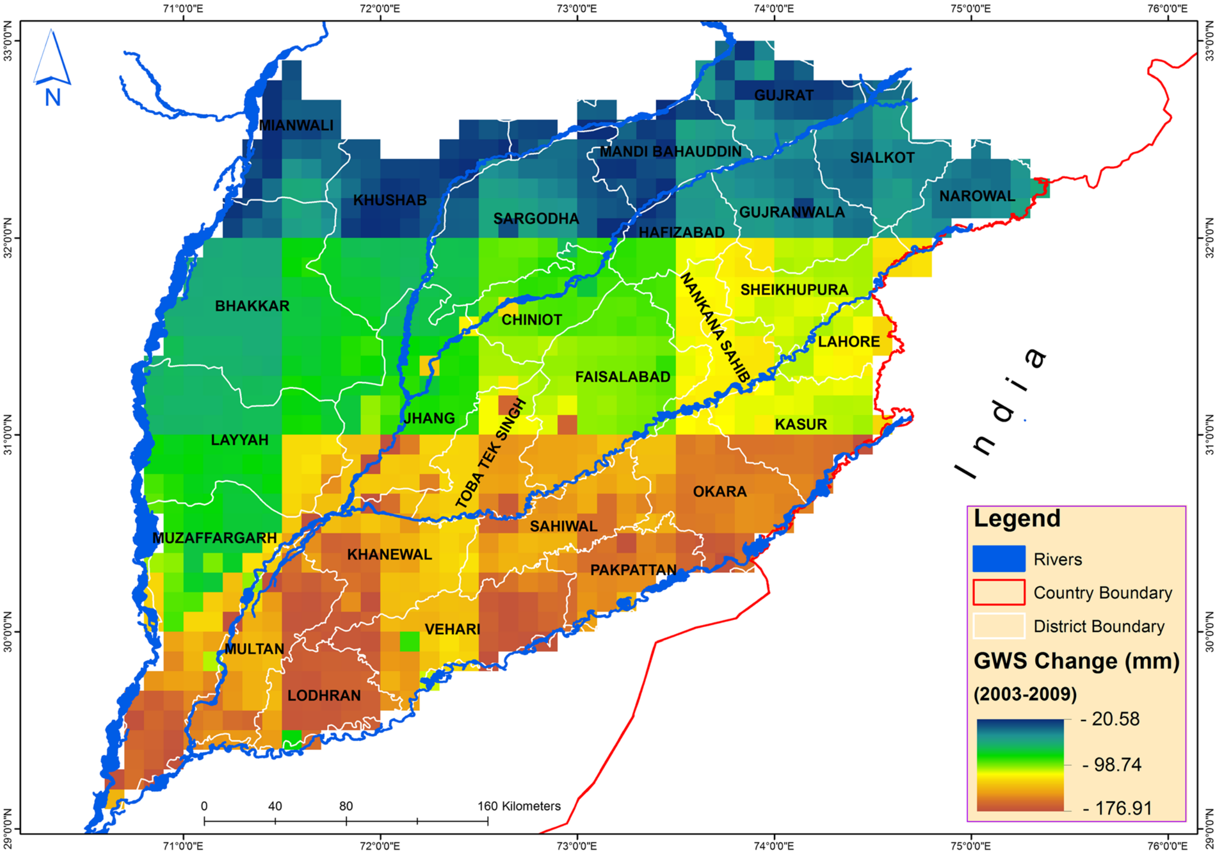

Fig. 4 Overall changes in groundwater storage over four riverine flood plains from 2003 to 2009

in terms of groundwater trends, the satellite-estimated groundwater storage anomalies are found to favorably agree with Visual MODFLOW (VMOD) and in situ data of 31 piezometers in Bari and 56 in the Rechna doab. The analysis of these three techniques (GRACE, VMOD, and piezometers) has shown an average depletion trend irrespective of their working methodology which is quite different from each other. The statistical analysis shows that GRACE has skillfully captured both magnitude and phase in the Bari (correlation = 0.93, RMSE = 24.76 mm) and Rechna doabs (correlation = 0.65, RMSE = 25.43 mm). In the Chaj and Thal doabs, the average depletion rates are found to be about 0.06 km^3/year and 0.25 km^3/year, respectively. The GRACE groundwater storage estimation results are validated by VMOD output showing an overall decreasing trend in the Chaj and Thal doabs. In comparison with in situ data of 35 (Chaj) and 45 (Thal) piezometric data, a disagreement is observed showing an intermixed increasing and decreasing trend. The one important factor of this disagreement is the limitation of insufficient in situ data. The piezometric records of the upper Chaj doab area (Gujrat and Mandi Bahauddin districts) were sporadic with low frequency during the study period from 2003 to 2010. The possible reason of disagreement in the lower parts (Muzaffargarh district) of the Thal doab is its elongated shape with a narrow strip where GRACE is not successful enough to capture actual GWS variations due to the limitations of its spatial resolution. The major disagreement in trends is observed from June 2007 to June 2009 where point data has shown a considerable increase in groundwater storage in contrast with GRACE-GWS.

The low tube well density (Table 1) and high groundwater storage depletion rate (Fig. 4) indicate less recharge than pumping specifically in Bari and Rechna and in Chaj and Thal doabs generally. The variability in climatic conditions is another influential factor for decreasing trends in groundwater storage variations (Table 1). Based on the lithologic changes and surface

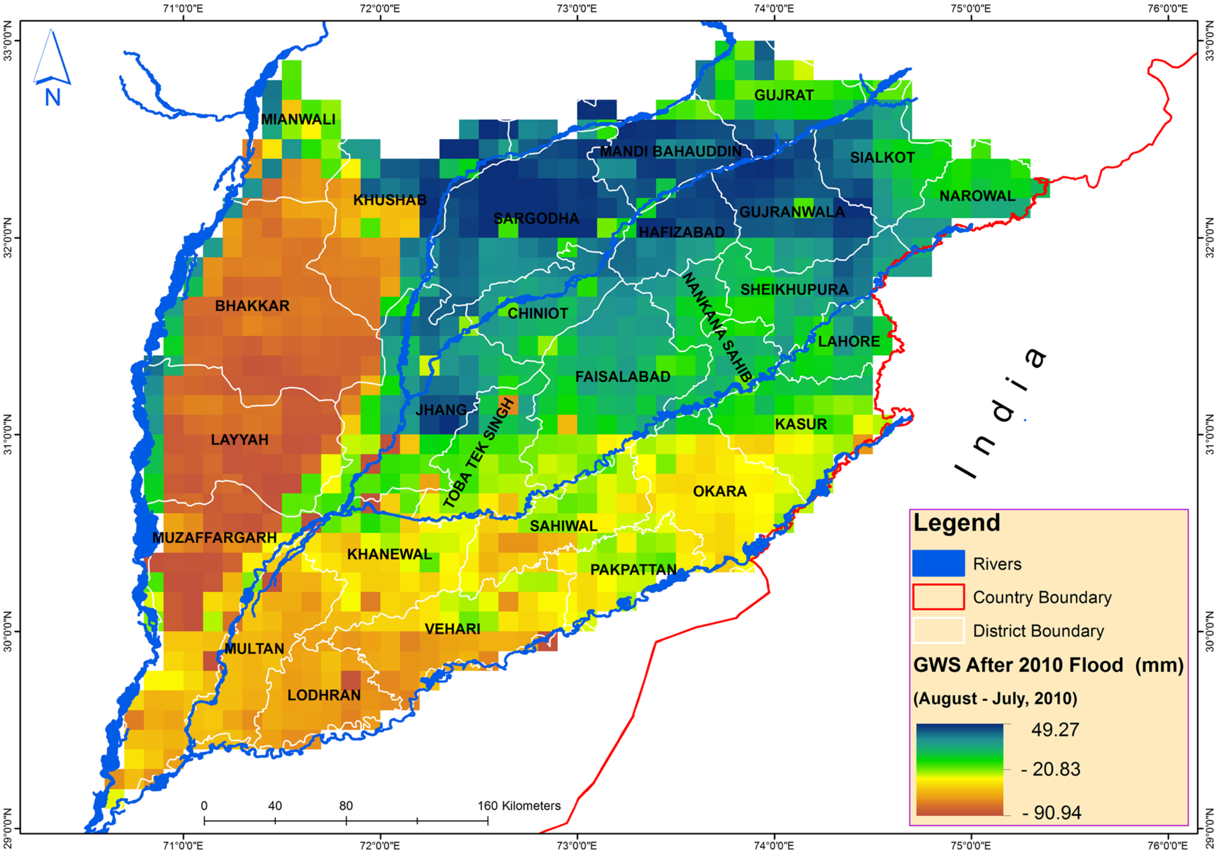

Fig. 5 Overall changes in groundwater storage over four riverine flood plains from 2003 to 2010

water-groundwater interactions, the sub-doab scale variations in GWS over the Chaj and Thal doabs are more frequent as compared to the Rechna and Bari doabs. A persistent depletion trend is observed in Bari (Fig. 7) and Rechna (Fig. 8) doabs, whereas the intermixed recharging and depletion trends are found prominent in Chaj (Fig. 9) and Thal (Fig. 10) doabs. The imbalance between recharge and groundwater abstraction has resulted in a mining situation in the lower parts of the Rechna doab (Khan et al. 2008). The high water table depletion is projected from 2002 to 2025 ranging from 10 to 20 m in the lower parts of the Rechna doab (Khan et al. 2008) which has caused a serious concern for the sustainability of groundwater. The situation is even worse in the Bari and Thal doabs where groundwater storage is depleted at a much higher rate of about 0.38 and 0.25 km^3/year from 2003 to 2010, respectively. On the other hand, most of the areas in the Chaj doab are under normal groundwater storage depletion due to excessive recharge from irrigation networks, nearby rivers and its small area (Fig. 5). Figure 6 shows a significant decrease in groundwater storage reported by GRACE in the lower part of the Thal doab (Muzaffargarh district) over the period 2003 to 2010.

In the perspective of operational management, the GRACE groundwater storage estimation was divided into two phases. Considering the period 2003–2007 as calibration with piezometric point data, the regression approach is applied to validate the GWS changes from 2008 to 2010 (Figs. 7 and 8). The average standard errors (SE) are calculated as per the following equation.

$$S_E = S_D/\sqrt{N}$$

where

S_E = standard error

S_D = standard deviation (between validation period regression GWS with piezometric data)

N = No. of data readings

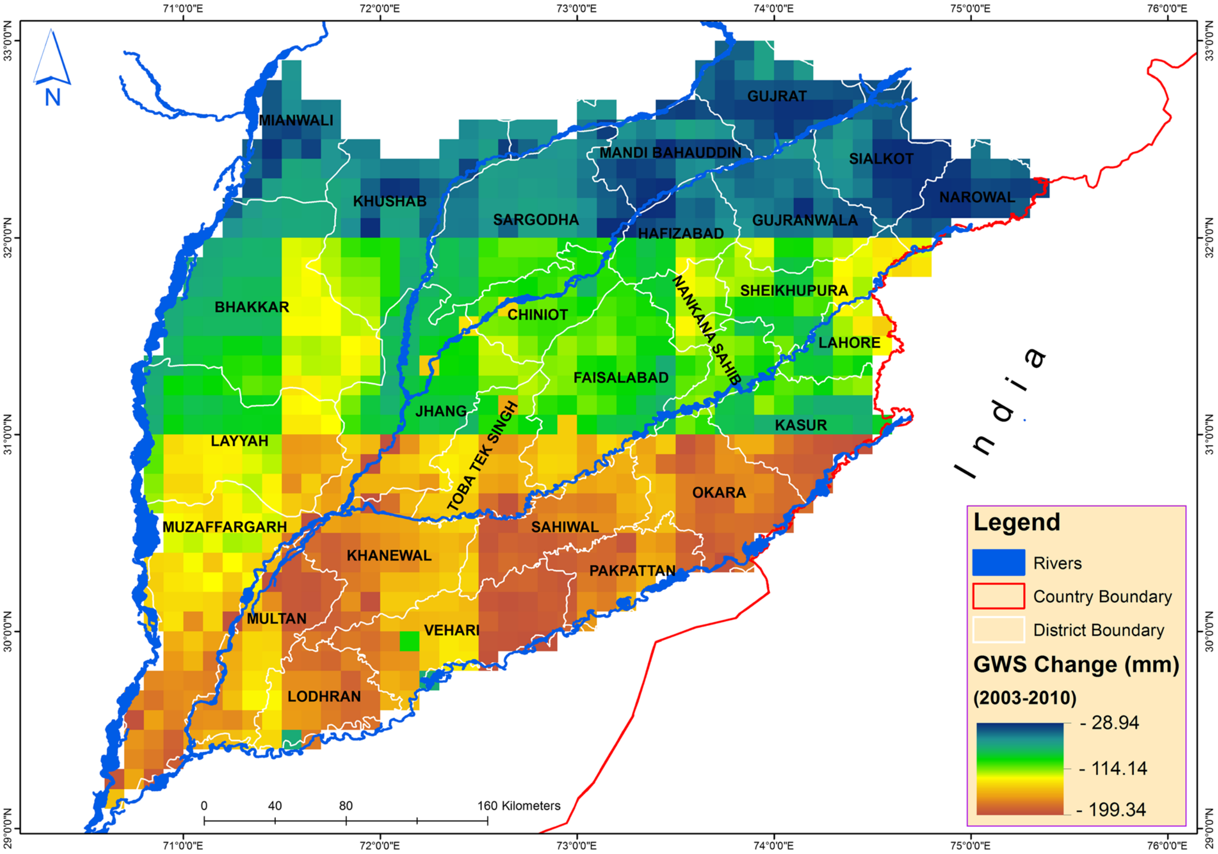

Fig. 6 Changes in groundwater storage due to the 2010 flooding event over four riverine flood plains

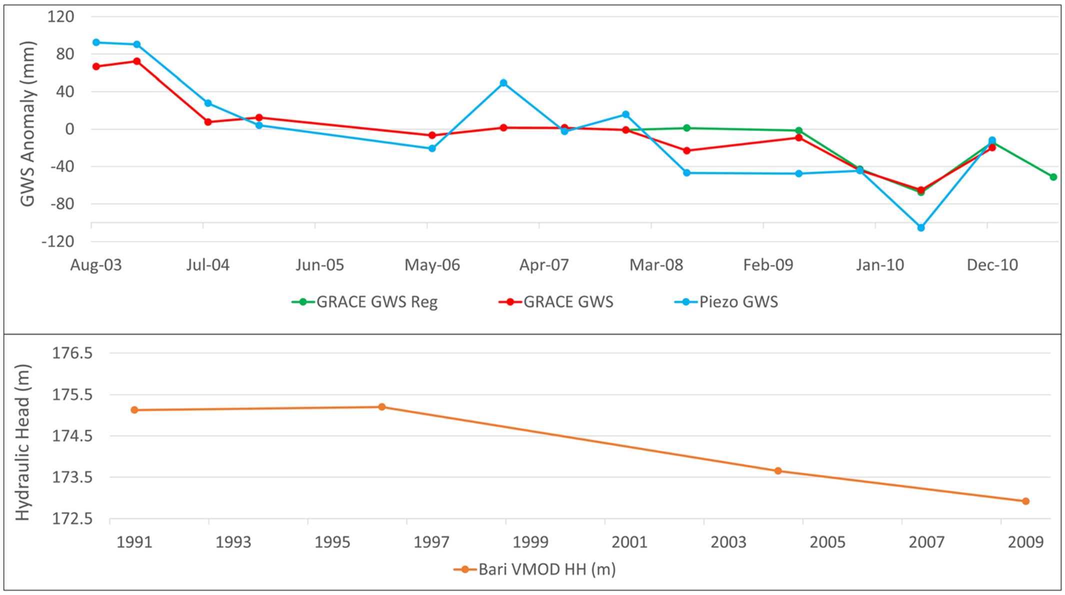

Fig. 7 *Upper panel*: Comparison of GRACE-derived seasonal groundwater storage anomalies with piezometric in situ data from 2003 to 2010 over the Bari doab area. The *green line* represents the regression-based GWS variations for the validation period (2008–2010) along with 180-day future predictions. *Lower panel*: Simulation results of Visual MODFLOW-based groundwater modeling for comparison of trends from 2004 to 2009. The groundwater storage variations are represented in hydraulic head (m)

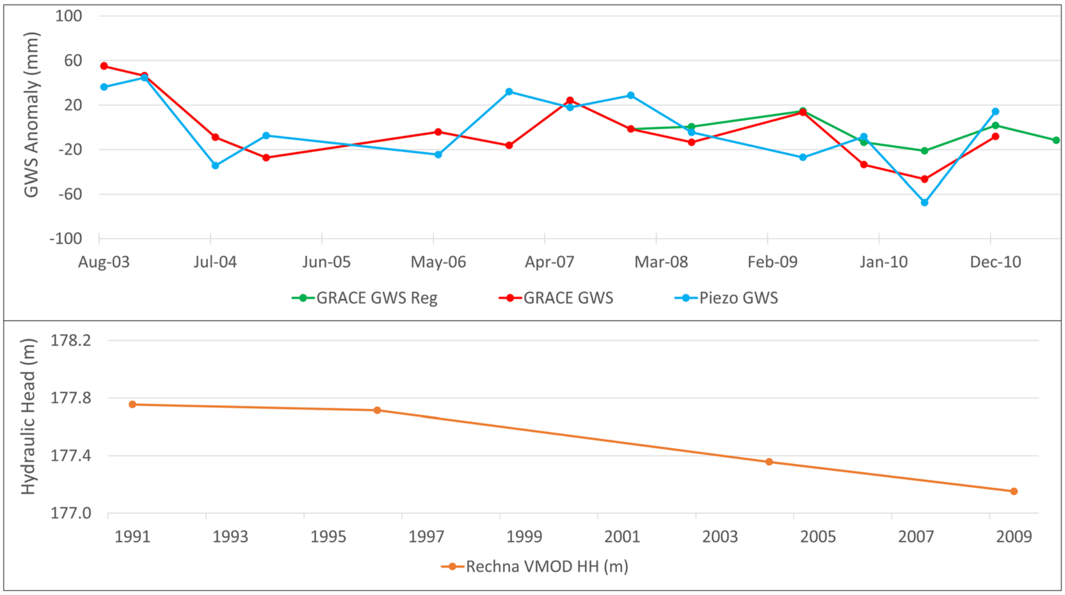

Fig. 8 *Upper panel*: Comparison of GRACE-derived seasonal groundwater storage anomalies with piezometric in situ data from 2003 to 2010 over Rechna doab area. The *green line* represents the regression-based GWS variations for the validation period (2008–2010) along with 180-day future predictions. *Lower panel*: Simulation results of Visual MODFLOW-based groundwater modeling for comparison of trends from 2004 to 2009. The groundwater storage variations are represented in hydraulic head (m)

The results are found favorable for seasonal future predictions in the Bari (SE = 9 mm, Fig. 11) and Rechna doabs (SE = 7 mm, Fig. 12) with a correlation of 0.70 and 0.48 for the validation periods, respectively. The predicted scenarios for 6 months ahead (180 days) have indicated a decreasing trend in

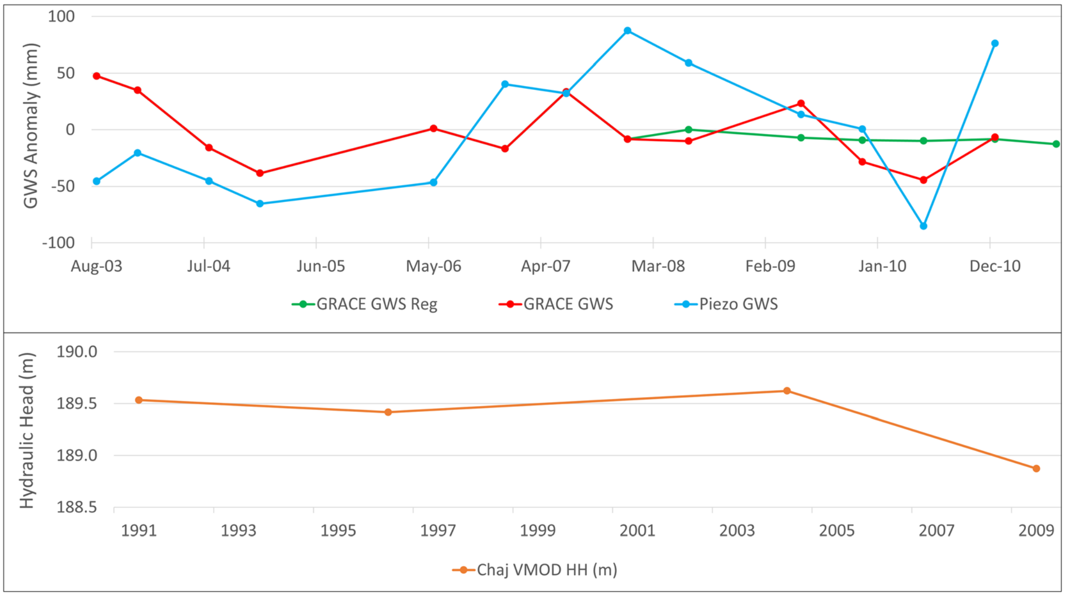

Fig. 9 *Upper panel*: Comparison of GRACE-derived seasonal groundwater storage anomalies with piezometric in situ data from 2003 to 2010 over Chaj doab area. *Lower panel*: Simulation results of Visual MODFLOW-based groundwater modeling for comparison of trends from 2004 to 2009. The groundwater storage variations are represented in hydraulic head (m)

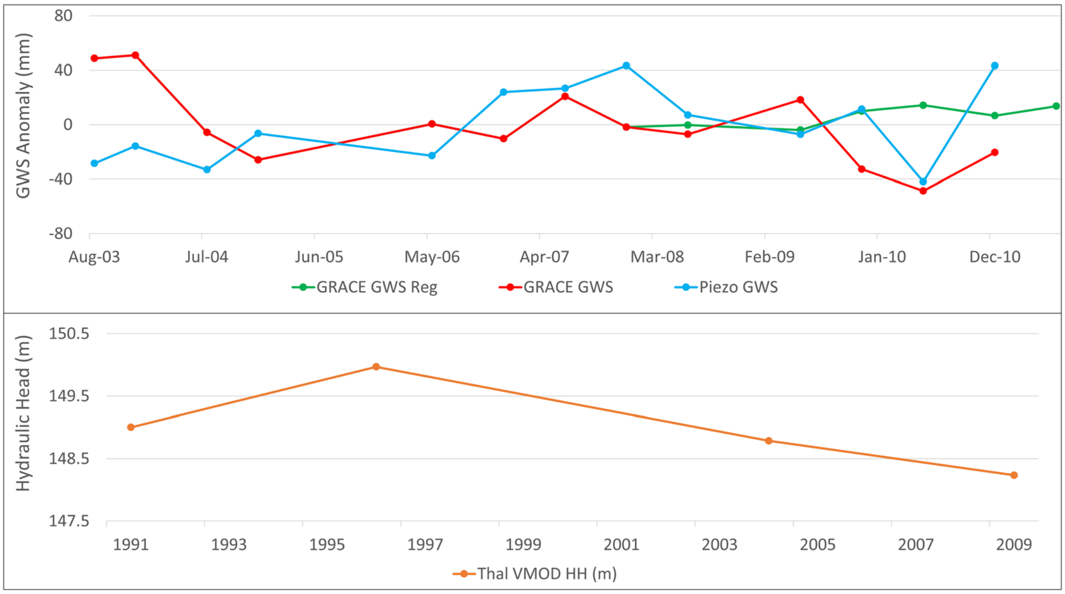

Fig. 10 *Upper panel*: Comparison of GRACE-derived seasonal groundwater storage anomalies with piezometric in situ data from 2003 to 2010 over Thal doab area. *Lower panel*: Simulation results of Visual MODFLOW-based groundwater modeling for comparison of trends from 2004 to 2009. The groundwater storage variations are represented in hydraulic head (m)

groundwater storage which is useful information for groundwater managers in the perspective of groundwater regulation.

Integrated groundwater management

The monthly to annual scale changes in spatial patterns of groundwater storage are useful indicators for defining appropriate groundwater management strategies. The continuous information on groundwater storage depletion in combination with groundwater abstraction data is a viable approach for groundwater regulation and policy recommendations. It is learned from the spatial and temporal analysis of groundwater storage dynamics that different management strategies are required at individual doabs.

Due to persistent high depletion rates and low recharge, the sustainability of the groundwater reserve is at risk in the Bari doab and needs immediate attention. As a first measure, it is required to control the groundwater abstraction and start continuous monthly scale monitoring in the Bari doab. The GRACE-based monthly monitoring of groundwater storage changes is useful for this purpose. The detailed groundwater modeling using VMOD is also required to be applied annually for the identification of flow patterns and understanding of the interaction between surface water and groundwater. Alternatively, water conservation techniques and rainwater harvesting should be required instead of flood irrigation for sustainable groundwater management.

The situation of groundwater storage depletion in Rechna is analyzed to be comparably better than the Bari doab due to significant recharge from the irrigation system as well as rainfall. The flooding event has also contributed to recharge groundwater system in the upper Rechna doab. The lower Rechna doab needs more consideration as compared to the upper parts. It is required to control abstraction and protect the groundwater recharge areas for further urbanization. The situation necessitates the continuous monitoring at monthly scale and a more comprehensive understanding of groundwater system behavior using GRACE in combination with VMOD.

Due to the small area and considerable recharge from irrigation and rivers during floods, the upper Chaj doab area is comparatively safe from groundwater depletion than the lower Chaj doab. However, careful monitoring is required especially in the lower Chaj doab for the sustainability of groundwater reserve through continuous monitoring using GRACE and VMOD. It is also important to protect the recharge areas from further expansion of urbanization.

The central part of the Thal doab is under Thal desert, and the major groundwater development is in lower areas. It is envisaged that groundwater conservation strategies are required to be adopted along with groundwater regulation for the effective groundwater management in the Thal doab.

Conclusions and recommendations

This study highlighted the effectiveness of GRACE to derive groundwater storage for the operational groundwater management in the Indus Basin. GRACE-estimated spatial and temporal changes in groundwater storage are found useful for defining the groundwater management strategies. The GRACE-GWS anomalies are found more sensitive to significant changes in groundwater storage either caused by recharge or abstraction. The accuracy of GRACE decreases with increasing complexity representing an intermixed phenomenon (recharge and depletion) over small scales. GRACE is found skillful for the estimation of groundwater storage variations only in Bari and Rechna doabs showing significant depletion trends. But for Chaj and Thal, GRACE is not found potentially suitable enough to adopt as a monitoring tool for operational management due to its coarse spatial resolution. For future study, to overcome such type of challenges, it may be possible to downscale GRACE-derived GWS using other remote sensing data such as synthetic aperture radar (SAR) images in order to enhance the existing spatial resolution (Lee et al. 2016).

It is analyzed that the flood event of 2010 has contributed significantly in the Chaj and Rechna doabs for the replenishment of the groundwater system. The continuous expansion in urbanization is foreseen as a big challenge for the protection of recharge areas. It is envisaged that the Bari and some parts of the Rechna doab areas may be under severe risk to their sustainable groundwater resources. This situation demands controlled abstraction rates through groundwater regulation policies and exploitation of alternate groundwater conservation techniques. The Chaj and Thal doabs are comparatively less stressful or safe, but a careful management and monitoring of groundwater abstraction is required in some parts of Chaj and Thal doabs.

This study establishes that GRACE is a cost-effective skillful groundwater management tool to monitor the monthly groundwater storage changes at the appropriate scale. The monthly groundwater storage changes are effective for frequent monitoring and decision making for operational managers. This information is also useful for groundwater modeling to bridge data gaps by minimizing the in situ data requirements where the measuring network is either weak or not available. An integrated approach consisting of GRACE, physical modeling, and in situ piezometric data can be more effective for operational groundwater management.

The sub-doab-level study of groundwater recharge and depletion is very critical from the perspective of sustainable groundwater management at such effective scales. Therefore, the authors suggest the need for the further use of spatial downscaling of GRACE signal with Synthetic Aperture Radar data. Future studies should evaluate the potential of satellite soil moisture data for the extraction of groundwater storage anomalies from GRACE-TWS signal. The GRACE-derived groundwater storage information may also be of interest to groundwater policymakers to see the holistic picture of the basin-scale hydrology for groundwater regulation and policy recommendations at national level. The potential limitation of this study is the coarse spatial resolution of the GRACE satellite which is a future research area.

Acknowledgements The authors acknowledge the NASA SERVIR program (NNX12AM85AG) and NASA WATER (NNX15AC63G) for supporting this work. Authors also express gratitude to Dr. C. K. Shum of Ohio State University for providing the GRACE data processing program. The Pakistan Council of Research in Water Resources (PCRWR), which is the home of the first author, and Quaid-i-Azam University are gratefully acknowledged. This study was made possible because of the generous support provided by the Ivanhoe Foundation (to first author), University of Washington Global Affairs, and VISIT program that provided the training to the first author on GRACE data.

Appendix 1

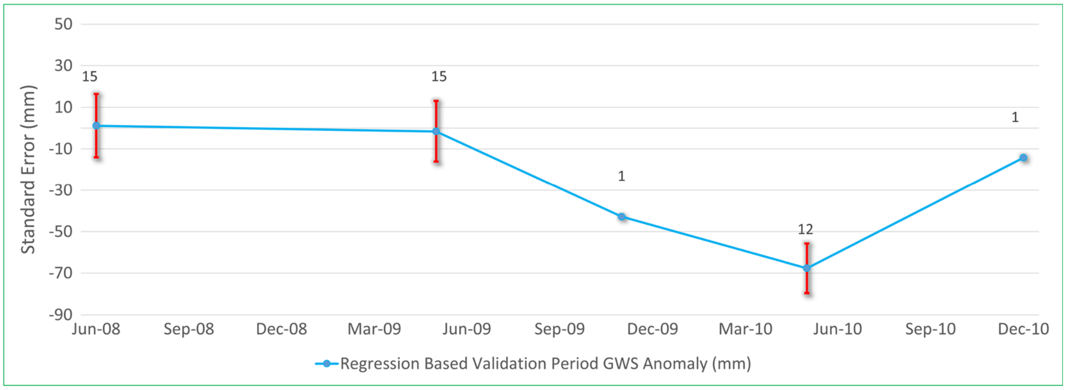

Fig. 11 Results of standard error calculations for the validation period (2008–2010) over the Bari doab

Appendix 2

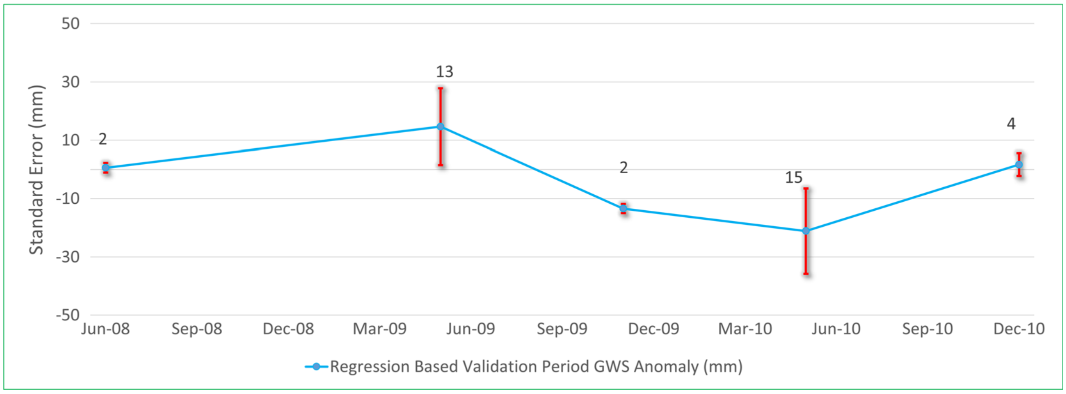

Fig. 12 Results of standard error calculations for the validation period (2008–2010) over the Rechna doab

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