INTEGRATED GROUNDWATER RESOURCE MANAGEMENT IN INDUS BASIN USING SATELLITE GRAVIMETRY AND PHYSICAL MODELING TOOLS

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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 remote sensing integrated physical modeling approach for groundwater management in Indus Basin. The Gravity Recovery and Climate Experiment Satellite (GRACE) based gravity anomalies from 2003-2010 were processed to generate monthly groundwater storage changes using 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 pin pointing 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

1. 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 et al, 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 et al. 1984; Khan et al. 2008; Saeed et al. 2005; Sufi et al. 1998). 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. 2013; Schewe et al. 2013). Groundwater regulation is an important aspect of effective groundwater resource management.

Adequate and frequent information is required to formulate groundwater management strategies and provide decision making for operational managers. The variations in groundwater storage are caused by the imbalance between groundwater abstraction and recharge. The assessment of groundwater abstraction and changes in recharge are the major parameters for sustainable groundwater management (Cheema et al. 2014). The groundwater resource management has become more critical in the absence of any groundwater regulation policy in Punjab Province. Due to overexploitation, Pakistan is ranked among the top four countries in the World where groundwater abstraction rate has reached 80 km^3 per year from 1961 to 2010 (Wada et al. 2014). The availability of frequent groundwater storage information is desired by operational managers for the implementation of groundwater policies.

Availability of reliable and frequent data, application of suitable groundwater models and the implementation of groundwater management strategies are equally important for sustainable groundwater resource management. The data and models are interlinked with each other. The models are used for the simplified understanding of complex groundwater system dynamics and defining management strategies based on existing input information on various parameters. 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 et al. 2014). The situation is more serious in developing countries due to an inadequate distributed data measurement network, data paucity and accessibility issues (Moore et al. 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, laborious and involve field surveys. Remote sensing has now emerged as a progressive tool for spatial input data collection (Dar et al. 2010; Stisen et al. 2011) and analysis of hydrological cycle. It is a cost effective and viable scientific tool that can reduce the uncertainties linked with data collection (Sood et al. 2015). Although remote sensing technology provides large scale spatial and temporal coverage, its accuracy can be limited due to 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 et al. 2013). The piezometric water table monitoring is the most commonly applied method for continuous analysis of groundwater behavior in the Indus aquifer. Different groundwater models were also applied in Indus Basin to devise different management options for the groundwater management. But, the groundwater managers are always demanded for a very cost effective and continuous monitoring application.

The groundwater models provide a continuous and accurate prediction of groundwater system dynamics but are more data intensive. Thus, remote Sensing can help to bridge this data gap with improved water management by integrating with physical modeling tools. 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. The integration of remote sensing derived groundwater storage information with groundwater models is potentially useful for detailed and 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. 2004). 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 et al. 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 GRACE satellite. Due to these features, GRACE has gained the interests of hydrologists. 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 et al. 2010). It has made possible for the hydrologist to estimate the terrestrial water storage changes (TWS) at earth's surface from regional to global scales with high temporal frequency (Wouters et al. 2014).

This study assesses the effectiveness 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 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. Section 2, describes the study region. The detailed methodology is explained in section 3. Section 4, is focused on the derivation of GRACE based groundwater storage (GWS) estimation. The discussion on results is summarized in section 5. Section 6, is referred to the integration of gravimetry with traditional physical modeling tools and in-situ measurements. Finally, section 7, summarizes the general findings and future directions for further improvements in GRACE based integrated groundwater resource management in the Indus Basin.

2. 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 Indus Basin Irrigation System (IBIS) has turned the doabs into a food basket of Pakistan which were once under desert conditions (Alam et al. 2014). The major characteristics of four doabs are summarized in Table 1. All four doabs are part of the unconfined Indus Basin aquifer with unconsolidated sedimentation of Indus River and its tributaries (Alam et al. 2014). The doabs are of alluvial deposits with lithological variations predominantly from fine to medium sand with clay and silt unfolds (Alam et al. 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. 2012). 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 has caused water table depletion in 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. 2003; Alam et al. 2014; Chandio et al. 2012; Basharat et al. 2013), groundwater resource management using different models at individual doab level (Ashraf et al. 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 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 and groundwater. In the lower part of Thal doab, the inter-flow from two rivers Indus and Chenab is the major sources of groundwater recharge due to narrow distance. Chaj doab is the smallest area in 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 show that the subsurface clay layers in Rechna doab causes hindrance in groundwater recharge. The high vertical heterogeneity due to the alluvial nature of deposition (Bennet et al. 1967) poses variations in the groundwater dynamics of each doab.

3. 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 Centre for Space Research (CSR) from 2003-2010. These techniques are required to improve accuracy by removing noises (Shum et al. 2011; Kusche et al. 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 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 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) was applied in study area at 0.1˚x0.1˚ grid scale from 2003-2010. The model showed favorable agreement with annual observed reservoir inflows 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 1˚x1˚ grid scale from 2003-2010. In the context of operational groundwater management, the GRACE-GWS anomalies were numerically downscaled to the grid scale of 0.1˚ x 0.1˚ using VIC model. The GRACE based GWS were compared with in-situ piezometric measurements recorded by Scarp Monitoring Organization (SMO). The seasonal (Pre-Monsoon and Post-Monsoon) groundwater level changes were converted in to 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 policy makers 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 play an important role in groundwater development and management (Zhou Y. and Li W. 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. The conceptual model was constructed for individual doabs at the cell size of 2.5˚x2.5˚. For each doab, the rivers were considered as horizontal hydraulic boundaries. 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. The model performed favorably well while comparison between measure and simulated hydraulic heads. The simulation output of MODFLOW for the year 2004 and 2009 covering study period (2003 to 2010) is used for the validation of GRACE-GWS results and understanding of groundwater system dynamics at individual doab scales.

4. GRACE Groundwater Storage

The comparison between numerically downscaled GRACE-GWS anomalies at 0.1˚ x 0.1˚ (approx. 10x10 km) with actual GRACE-GWS (1˚ x 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 2003-2010 (Fig. 2, 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 (Bai 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 has indicated that the Bari doab is under severe groundwater depletion. Whereas in Rechna doab, the groundwater depletion varies from moderate to severe. The districts of Toba Tek Singh, Nankana Sahib and parts of Faisalabad, Jhang and Sheikhupura 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 represent 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. Fig. 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 the Sargodha and parts of the Jhang district. The lower areas (Bhakkar, Layyah, and Muzaffargarh districts) of the Thal doab are also undergoing moderate to severe 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.

5. 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 Rechna doabs from 2003-2010. Whereas, an average GWS depletion is calculated about 0.54 km^3/year in Bari and 0.16 km^3/year in Rechna doabs based on piezometric data. The satellite estimated groundwater storage anomalies are found to favorably agree with VMOD and in-situ data of 31 piezometers in Bari and 56 in Rechna doabs. The statistical analysis shows that GRACE has skillfully captured both magnitude and phase in 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 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 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 in-sufficient 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 2003-2010. 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 wells density (Table 1) and high groundwater storage depletion rate (Fig. 4) indicates less recharge than pumping in Bari and Thal doabs as compared to Chaj and Rechna doabs. 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 water-groundwater interactions, the sub-doab scale variations in GWS over the Chaj and Thal doabs are more frequent as compared to 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 Rechna doab (Khan et al, 2008). The high water table depletion is projected from 2002-2025 ranging from 10-20 m in lower parts of Rechna doab (Khan et al. 2008) 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 km^3/year and 0.25 km^3/year from 2003-2010, 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). Fig. 6, shows a significant groundwater storage depletion 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 were 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 2008-2010 (Fig. 7, 8). The average standard errors (SE) are found favorable for seasonal future predictions in the Bari (SE = 9 mm) and Rechna doabs (SE = 7 mm) with a correlation of 0.70 and 0.48 for validation periods, respectively. The predicted scenarios for 6 months ahead (180 days) has indicated a decreasing trend in groundwater storage which is useful information for groundwater managers in the perspective of groundwater regulation.

6. 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 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 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 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 fur 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 less at risk from groundwater depletion than the lower Chaj doab. However, careful monitoring is required 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 Thal doab.

7. 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 intermixed phenomenon (recharge and depletion) over small scales. GRACE is found skillful for the estimation of groundwater storage variations in Bari and Rechna doabs showing significant depletion trends. A favorable agreement is observed between GRACE and in-situ measurements.

It is estimated that groundwater storage has depleted at an average rate of about 0.38 km^3/year in Bari and about 0.21 km^3/year in Rechna doabs from 2003-2010. The results reveal that the flood event has contributed significantly in Chaj and Rechna doabs for the replenishment of groundwater system. The recharge areas needs to be protected from the further expansion of the urbanization. It is envisaged that the Bari, lower Thal and 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 doab is comparatively less at risk with an average depletion rate of about 0.06 km^3/year. In Thal doab, an overall depletion in groundwater storage is estimated as an average rate of about 0.25 km^3/year. A careful management and monitoring of groundwater abstraction is required in the lower parts of Chaj and Thal doabs. Due to the flood irrigation method, the groundwater exploitation is increasing day by day against the constantly growing needs of food and fiber.

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 policy makers to see the holistic picture of basin scale hydrology for groundwater regulation and policy recommendations at national level.

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8. References

Alam N, Olsthoorn Theo N (2014) Punjab scavenger wells for sustainable additional groundwater irrigation. Agricultural Water Management 138:55-67

Ahmad MD, Turral H, Nazeer A (2009) Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan. Agricultural Water Management 96(4):551-564

Ahmad Z, Ashraf A, Fryar A, Akhter G (2011) Composite use of numerical groundwater flow modeling and geoinformatics techniques for monitoring Indus Basin aquifer, Pakistan. Environmental Monitoring And Assessment 173(1-4):447-457

Ashraf M, Bhatti ZA, Zaka-Ullah (2011) Diagnostic analysis and fine tuning of skimming well design and operational strategies for sustain-able groundwater management-Indus basin of Pakistan. Irrig Drain http://dx.doi.org/10.1002/ird.636

Asghar MN, Prathapar SA, Shafique MS (2002) Extracting relatively-fresh groundwater from aquifers underlain by salty groundwater. Agric Water Man-age 52:*119-137*

Bennett GD, Rehman A, Sheikh IA, Ali S (1967) Analysis of aquifer tests in the Punjab region of West Pakistan. USGS Water Supply Paper 1608-G, Washington, DC.

Brunner P, Hendricks Franssen H-J, Kgotlhang L, Bauer-Gottwein P, Kinzelbach W (2007) How can remote sensing contribute in groundwater modeling? Hydrogeology Journal 15(1):5-18

Cheema MJM, Immerzeel WW, Bastiaanssen WGM (2014) Spatial quantification of groundwater abstraction in the irrigated Indus Basin. Ground Water 52(1):25–36

Dar IA, Sankar K, Dar MA (2010) Remote sensing technology and geographic information system modeling: an integrated approach towards the mapping of groundwater potential zones in Hardrock terrain, Mamundiyar basin. J Hydrol 394:*285–95*

Duan XJ, Guo JY, Shum CK, Wal W (2009) On the postprocessing removal of correlated errors in GRACE temporal gravity field solutions. J Geodesy 83(11):1095-1106. doi: 10.1007/s00190-009-0327-0

Elliott J, Deryng D, Müller C, Frieler K, Konzmann M, Gerten D et al (2014) Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences of the United States of America 111(9):3239-3244

Famiglietti JS, Lo M, Ho SL, Bethune J, Anderson KJ, Syed TH, Swenson SC, De Linage CR, Rodell M (2011) Satellites measure recent rates of groundwater depletion in California’s central valley. Geophys Res Lett 38. doi: 10.1029/2010GL046442

Feng W, Zhong M, Lemoine JM, Biancale R, Hsu HT, Xia J (2013) Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. Water Resour Res 49(4):2110–2118. doi: 10.1002/wrcr.20192

Government of Punjab (2012) Pakistan Development Statistics, Lahore. Bureau of Statistics 48

Kusche J (2007) Approximate decorrelation and non-isotropic smoothing of time variable GRACE-type gravity field models. J Geodesy 81(11):733–749. doi: org/10.1007/s00190-007-01

Kashaigili JJ, Mashauri DA, Abdo G (2003) Groundwater management by using mathematical modeling: case of the Makutupora groundwater basin in dodoma Tanzania. Botsw J Technol 12(1):19–24

Kummerow C, William B, Toshiaki K, James S, Simpson J (1998) The tropical rainfall measuring mission (TRMM) sensor package. J Atmos Oceanic Tech 15(3):809–8017. http://dx.doi.org/10.1175/1520- 0426(1998)015<0809:TTRMMT>2.0.CO;2

Liang X, Lettenmaier DP, Wood EF, Burges SJ (1994) A simple hydrologically based model of land surface water and energy fluxes for GSMs. J Geophys Res 99:14415-14428. doi: 10.1029/94JD00483

Lo M-H, Famiglietti JS, Yeh P J-F, Syed TH (2010) Improving parameter estimation and water table depth simulation in a land surface model using GRACE water storage and estimated base flow data. Water Resources Res 46:5517

Rodell M, Velicogna I, and Famiglietti JS (2009) Satellite-based estimate of groundwater depletion in India. Nature 460. doi: 10.1038/nature08238

Rodell M, Chen J, Kato H, Famiglietti JS, Nigro J, Wilson CR, (2007) Estimating groundwater storage changes in the Missippi River Basin (USA) using GRACE. Hydrogeol J 15(1):159-166

Schewe J, et al (2013) Multimodel assessment of water scarcity under climate change. Proc Natl Acad Sci USA. doi: 10.1073/pnas.1222460110

Scanlon BR, Longuevergne L, Long D (2012) Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA. Water Resour Res. 48. doi: 10.1029/2011WR011312

Shum CK, Guo JY, Hossain F, Duan J, Alsdorf DE, Duan X-J, Kuo C–Y, Lee H, Schmidt M, Wang L (2011) Inter-annual Water Storage Changes in Asia from GRACE Data. In: Lal R et al (ed) Climate Change and Food Security in South Asia, Springer. doi: 10.1007/978-90-481-9516-9_6

Singh A (2014) Groundwater resources management through the applications of simulation modeling: A review. Science of the Total Environment 499:414-423

Siddique-E-Akbor AHM, Hossain F, Sikder S, Shum CK, Tseng S, Yi Y, Turk FJ, Limaye A (2014) Satellite Precipitation Data Driven Hydrologic Modeling For Water Resources Management, In the Ganges, Brahmaputra And Meghna Basins. Earth Interactions 18(17) doi: 10.1175/EI-D-14-0017.1

Stisen S, McCabe MF, Refsgaard JC, Lerer S, Butts MB (2011) Model parameter analysis using remotely sensed pattern information in a multi-constraint framework. J Hydrol 409:337-49

Strassberg G, Scanlon BR, Rodell M (2007) Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA). Geophys Res Lett 34(14). doi: 10.1029/2007GL030139

Strassberg G, Scanlon BR, Chambers D, (2009) Evaluation of groundwater storage monitoring with the GRACE satellite: Case study of the High Plains aquifer, central United States. Water Resour Res 45. doi: 10.1029/2008WR006892

Tiwari VM Wahr J, Swenson S (2009) Dwindling groundwater resources in northern India, from satellite gravity observations. Geophys Res Lett 36. doi: 10.1029/2009GL039401

Wondzell SM, La Nier J, Haggerty R (2009) Evaluation of alternative groundwater flow models for simulating hyporheic exchange in a small mountain stream. J Hydrol 364(1):142–151

Wada Y, Beek LPH, Bierkens Marc FP (2012) Non sustainable groundwater sustaining irrigation: A global assessment. Water Resour Res 48. doi: 10.1029/2011WR010562

Werth S, G¨untner A (2010) Calibration analysis for water storage variability of the global hydrological model WGHM. Hydrol Earth Syst Sci 14:59–78

Wouters B, Bonin JA, Chambers DP, Riva REM, Sasgen I, Wahr J (2014) GRACE, time-varying gravity, Earth system dynamics and climate change. Rep Prog Phys 77(11). doi: 10.1088/0034-4885/77/11/116801

Wu J, Hu BX, Zhang D, Shirley C (2003) A three-dimensional numerical method of moments for groundwater flow and solute transport in a nonstationary conductivity field. Adv Water Resour 26(11):1149–69

Zhou Y, Li W (2011) A review of regional groundwater flow modeling. Geoscience Frontiers 2(2):205-214

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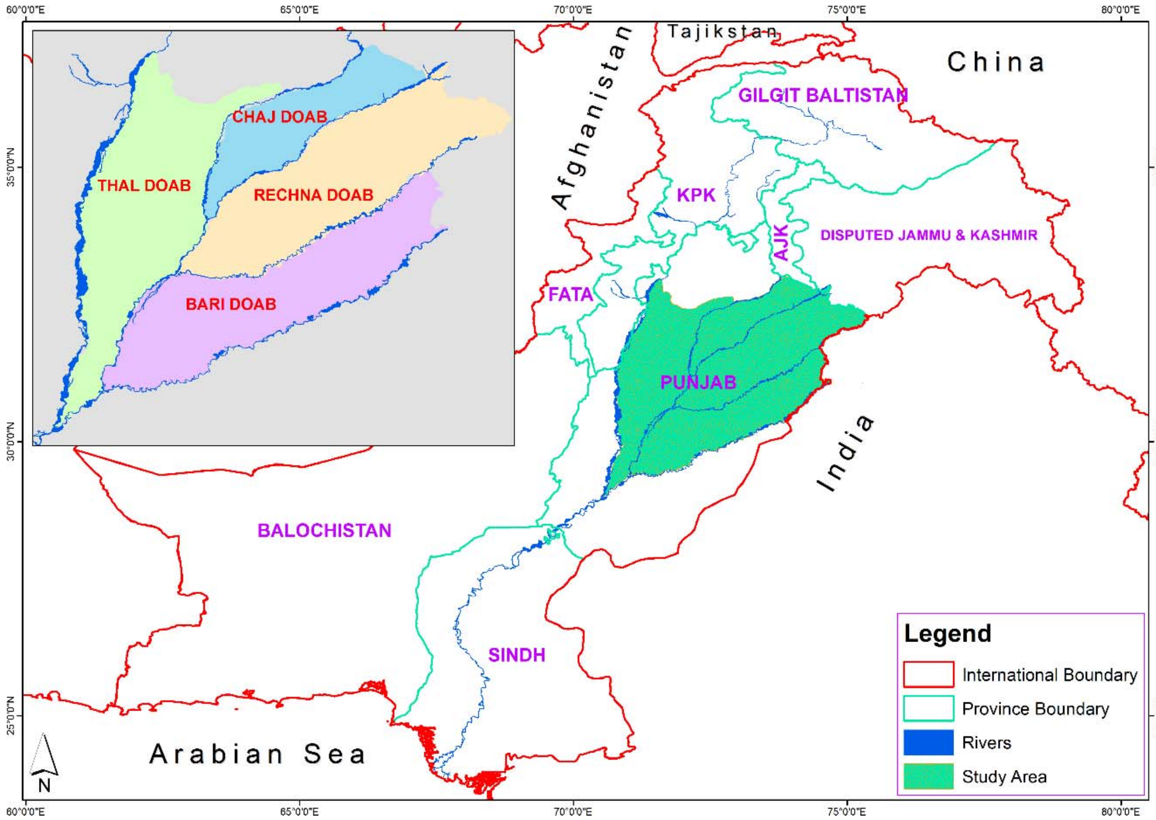

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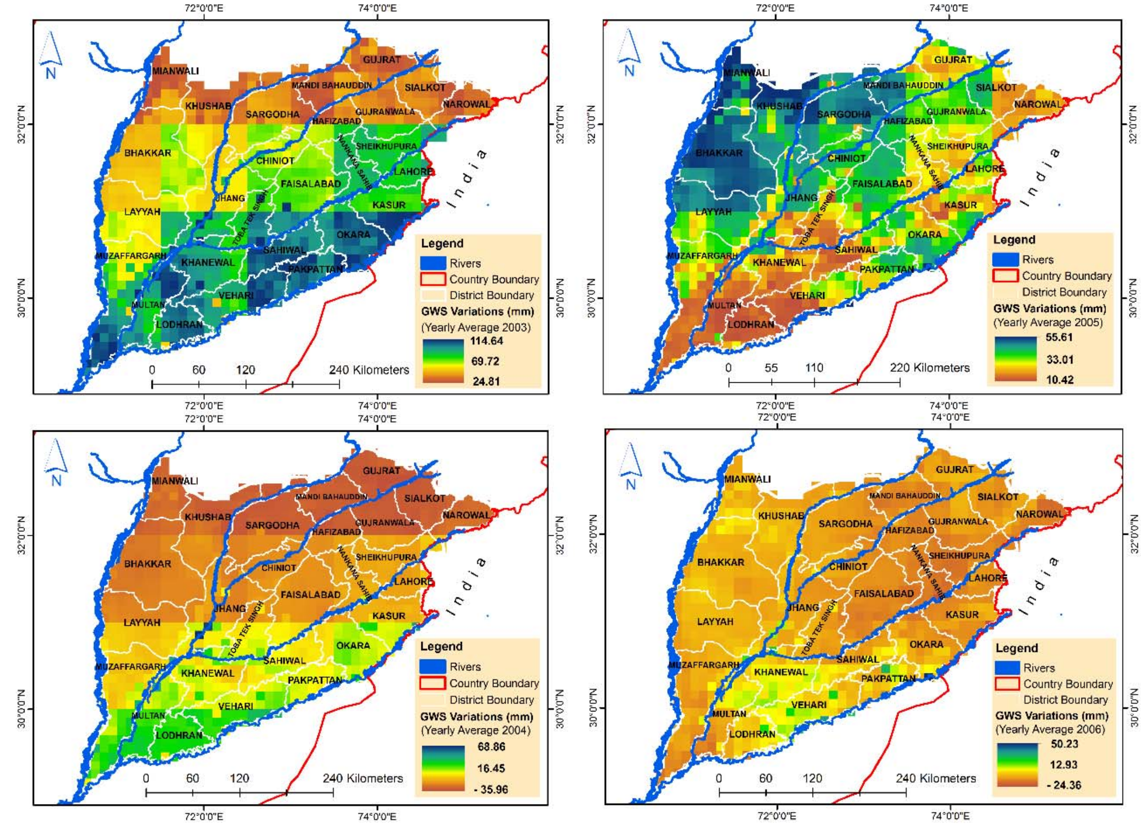

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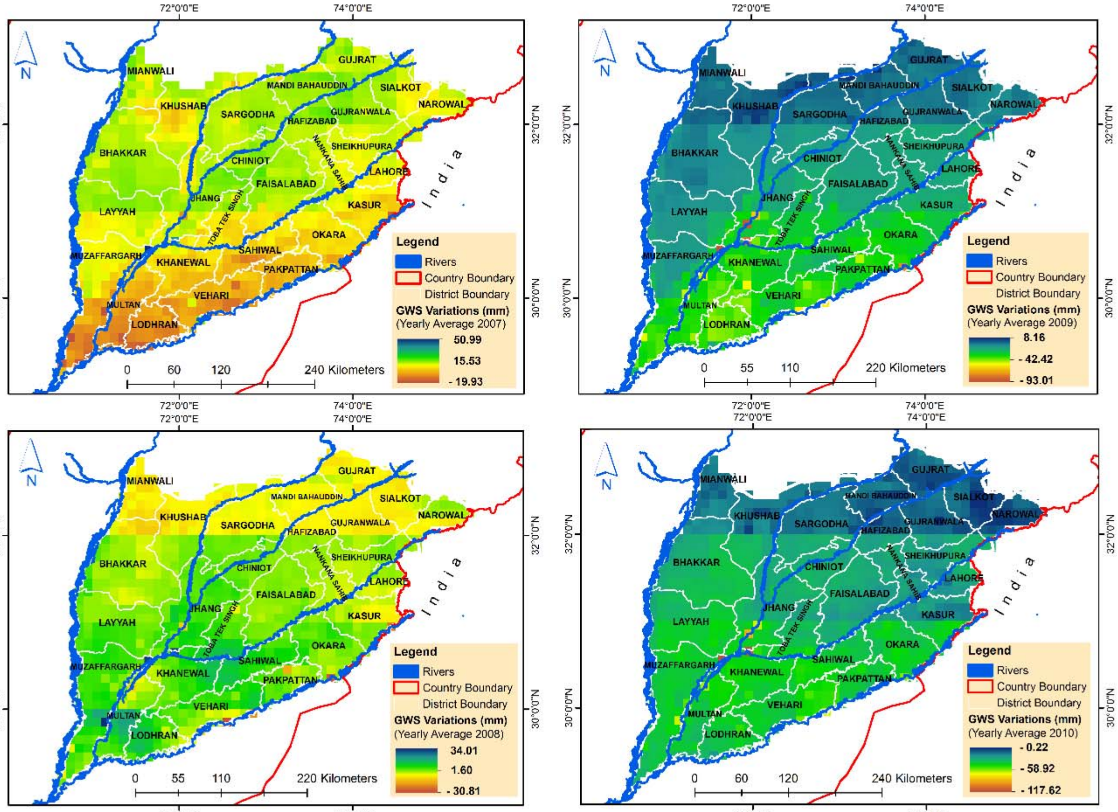

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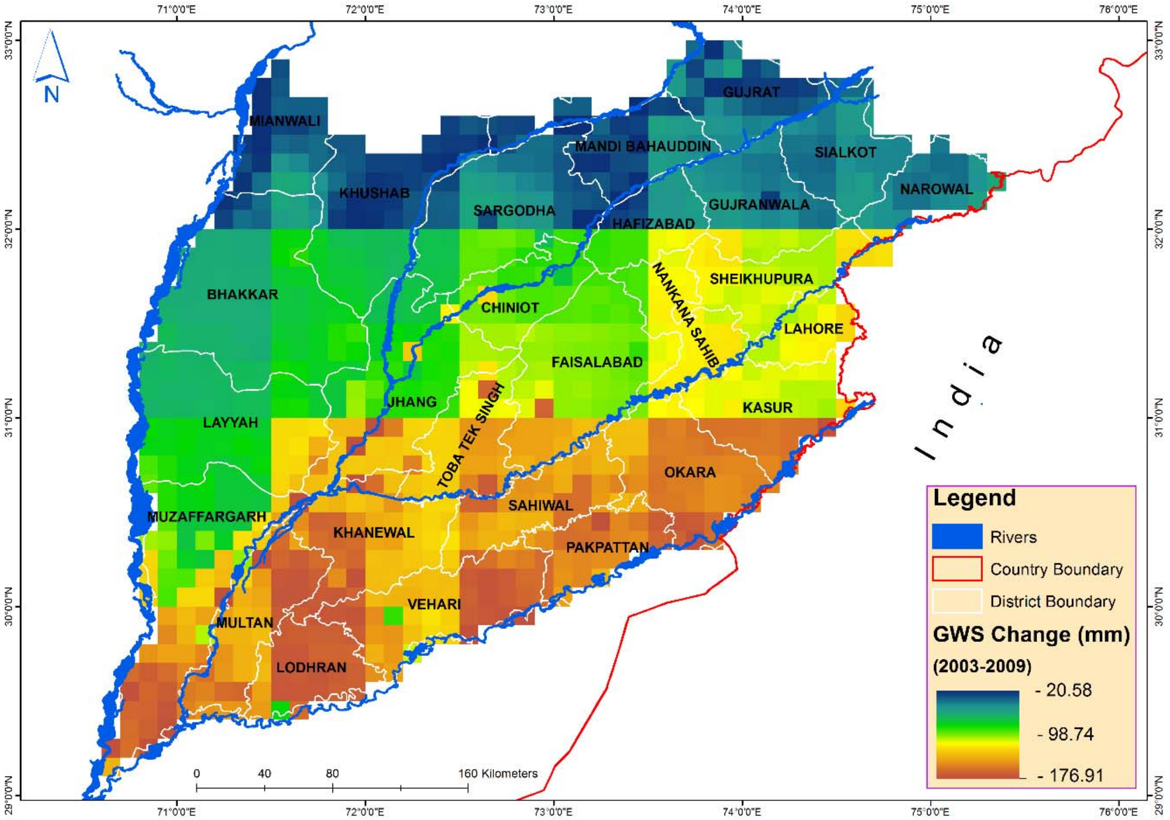

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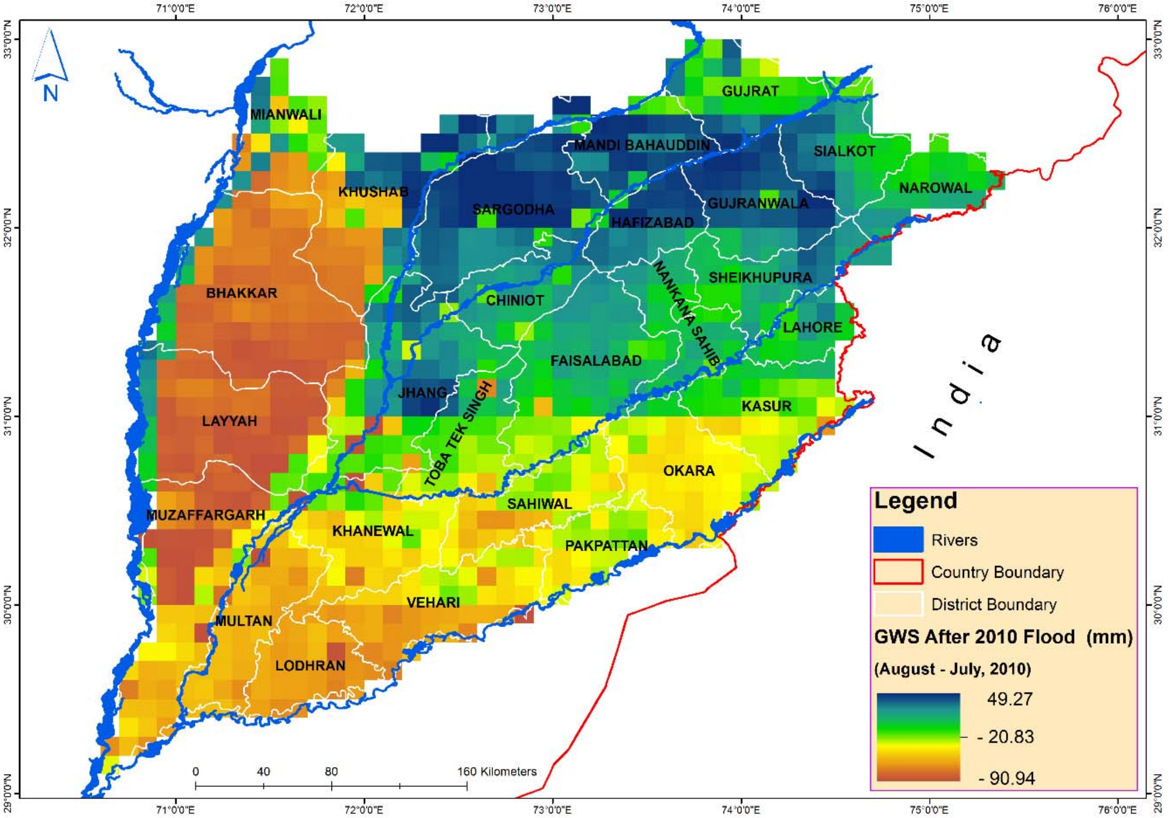

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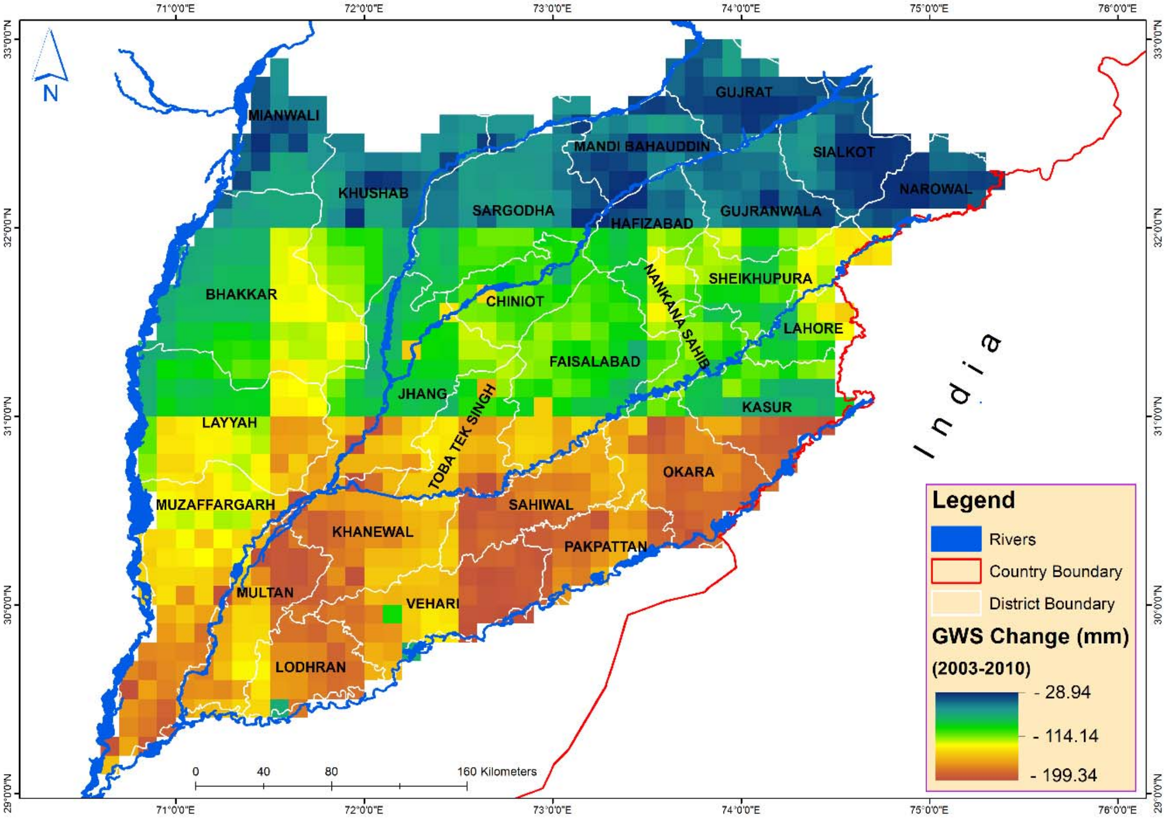

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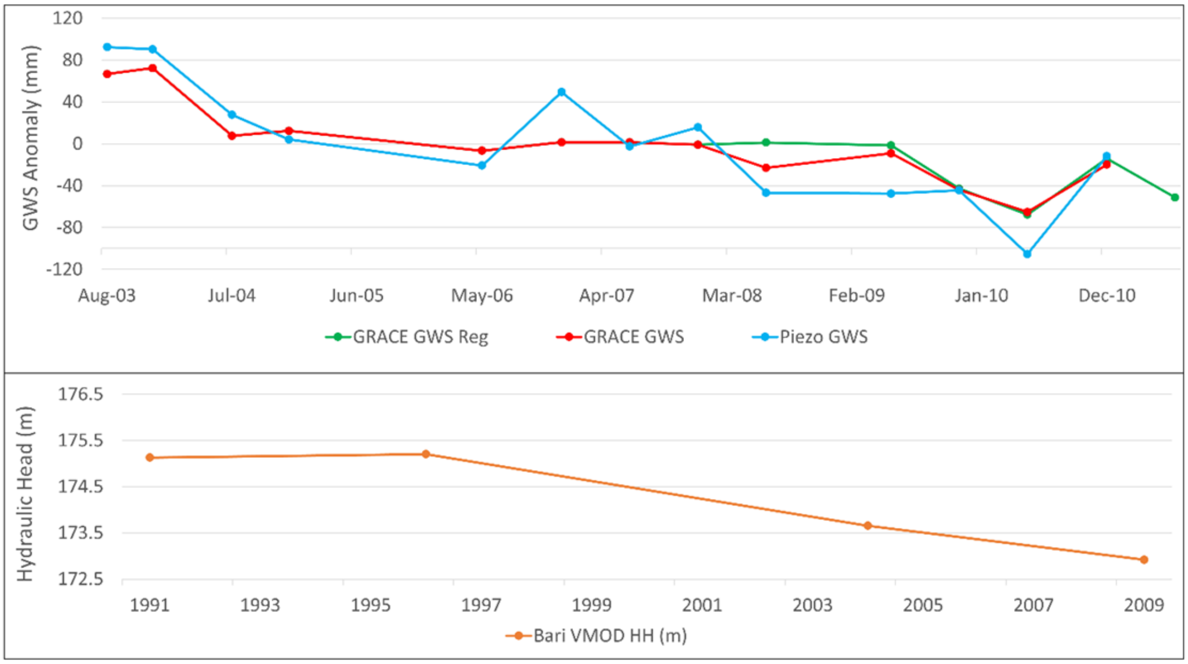

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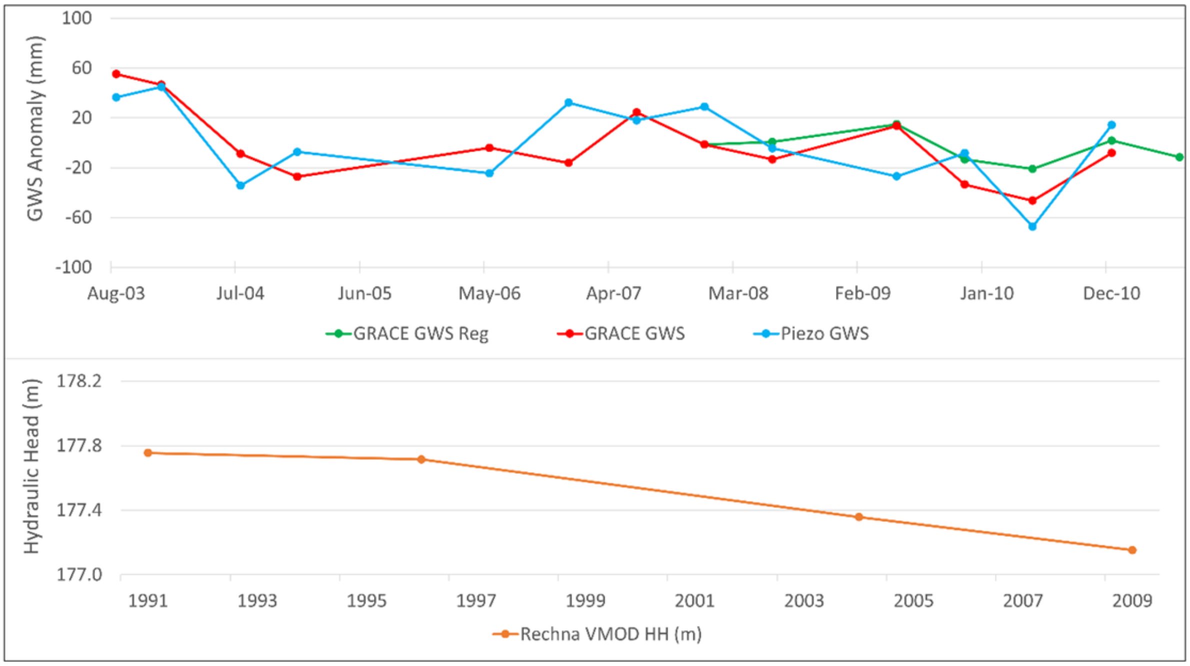

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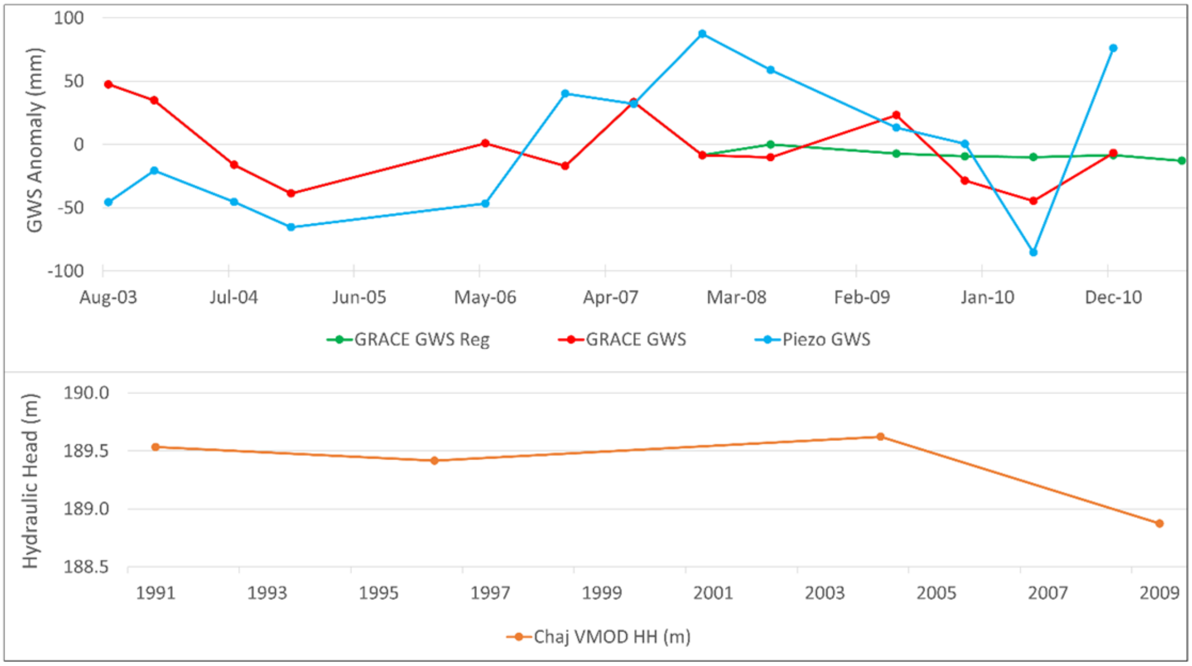

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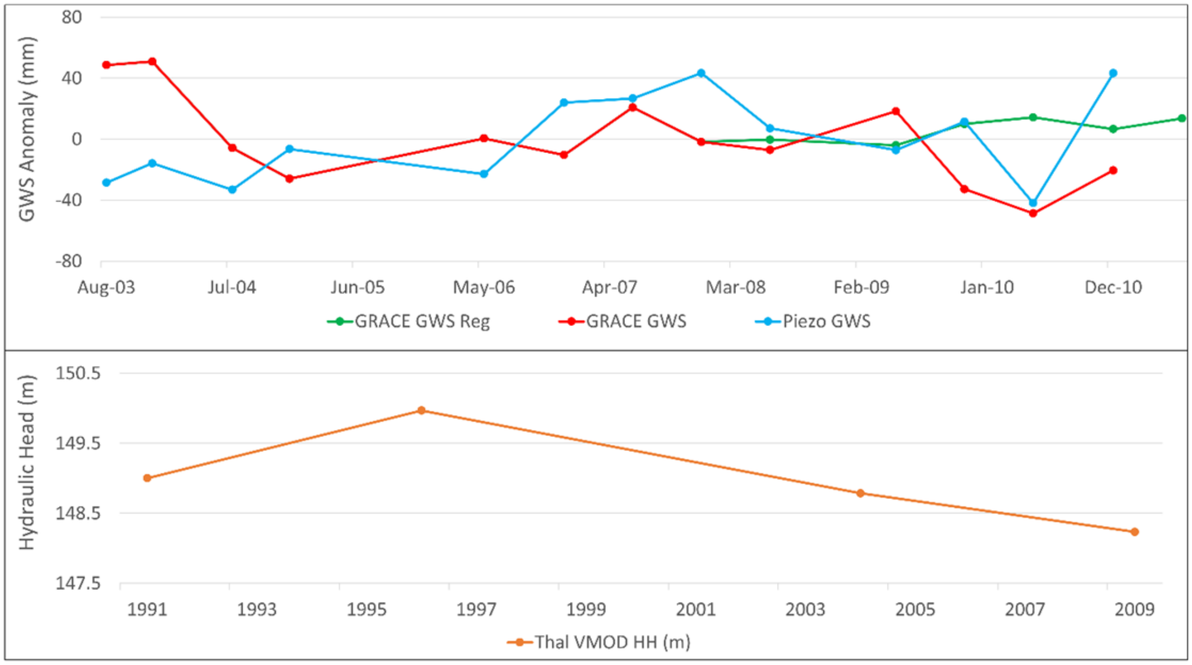

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Table 1: Summary of the main characteristics of four doabs (Source: Government of Pakistan, 2012)

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 100-500	Varies from 300-1000	778 average annual	500 Average annual maximum

Table 2: Comparison of GRACE numerical downscaling results

Grid Scale	Year	Bari Doab (Correlation)	Rechna Doab (Correlation)	Chaj Doab (Correlation)	Thal Doab (Correlation)
1˚ x 1˚	2003-2010	0.92	0.56	0.09	-0.13
0.1˚ x 0.1˚	2003-2010	0.93	0.65	0.15	-0.10

Appendix

Stand Errors Calculation:

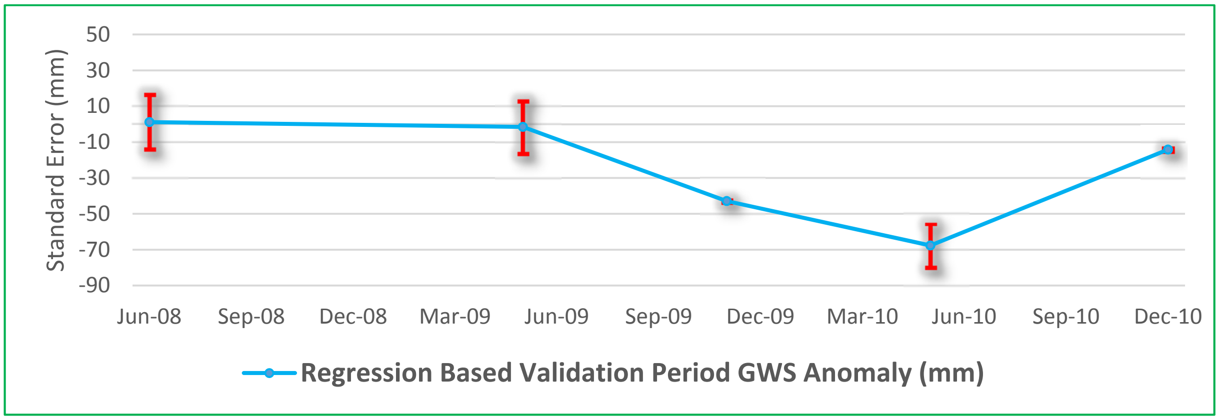
$$S_E = S_D/\sqrt{N}$$

Where;

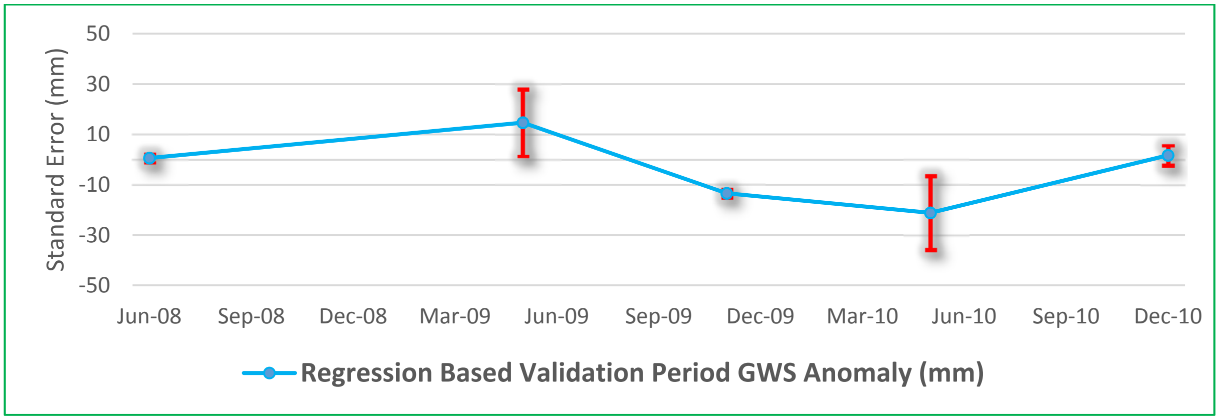
S_E = Standard Error

S_D = Standard Deviation (between validation period regression GWS with piezometric data)

N = No. of Data Readings



Appendix A. Results of standard error calculations for validation period (2008-2010) over Bari doab



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