ORIGINAL PAPER

Assessment of Water Storage Changes Using Satellite Gravimetry and GLDAS Observations over a Part of Indus Basin, India

Mohit Arora[1] · Mayank Dixit[2] · Brijendra Pateriya[1]

Abstract

Water storage (including surface and groundwater) changes are difficult to assess due to their complexity and the lack of spatio-temporal observations. This study used Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (FO) Level-3 data from three products (JPL, GFZ, and CSR) to estimate monthly water storage changes (TWS, terrestrial water storage; and GWS, groundwater storage) both spatially and temporally over a part of Indus Basin, India, for the period from April 2002 to December 2021. GRACE satellite missions measure the time-dependent Earth's gravity field which represents water storage variations. Punjab and Haryana states which lie in the Indus Basin situated in the northern part of India are two of the largest producers of agricultural products and are highly dependent on the water resource. Nowadays, Indus Basin is facing a severe water crisis due to the over-exploitation of water resources. The GRACE data have been analyzed in three phases—(i) monthly variations; (ii) seasonal variations (pre-monsoon and post-monsoon); and (iii) annual variations—to see the changes in the water storage changes over a part of the Indus Basin. This research found that the water storage from GRACE satellite missions exhibits decreasing pattern of average TWS from $+17.4$ to -28.8 cm and GWS from $+18.1$ to -30.2 cm over the study area, and found complete negative trends after 2008. The negative trends represent a deficit of both TWS and GWS. The highest peak deficit of TWS (-28.8 cm) and GWS (-30.2 cm) has been observed in June 2021 and May 2021. We correlated GRACE data with rainfall dataset derived from the Global Precipitation Mission (GPM) and water level data obtained from the Water Resources Information System (India-WRIS) to see the trends of rainfall anomaly and water level changes over the study area. The downward trends of water storage may be occurring as a result of complex activities of natural and anthropogenic impacts. The fluctuations of groundwater table, change in soil moisture (SM) storage, and canopy water amount contribute a large portion of the changes over the region. This research specifies that water resource monitoring is essential for water resource managers, and policymakers for sustainable water management and to reduce high-risk impacts in the future.

Keywords Water resource · Groundwater · Soil moisture · Water management

Introduction

Water is one of the essential and primary natural resources for human beings, agricultural production, economic stability, and environmental health throughout the world [1]. Water resources (including surface and groundwater) have been decreasing significantly in many parts of the world, particularly in developing countries, and can lead to a paucity of regional water resources. The severity of the impact of water storage depends on different conditions such as climate change, topography, weather patterns, and management plans over the region [2]. For instance, an increase in temperature/evaporation, variations in soil moisture, and changes in precipitation distribution affect the hydrological cycle [3, 4]. India is the largest consumer of water worldwide with an estimated annual withdrawal exceeding over 230 km^3 [5]. The excessive withdrawal of water resources can lead to the depletion of water resources which poses a significant impact on the ecosystem, economy, food, health, and social developments [2]. Many regions of India are facing severe water deficiency due to increasing

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dependence on water resources. According to the report of the Central Ground Water Board (CGWB) [6], water resource scarcity is a critical issue in northern India and agriculture plays an important role in the livelihood of people. Many researchers reported the depletion of water resources at an alarming rate in Punjab and Haryana states because of natural and anthropogenic activities [7, 8]. The rainfall in both states during the monsoon season (June to September) is highly variable and uncertain. Irrigation, population growth, urbanization, and increasing industries are the major factors causing potential stress on water resources [9]. The insufficient amount of surface water caused people to be overly dependent on groundwater resources through pumping. Excessive use of pumping leads to groundwater depletion and causes land subsidence and water contamination [8, 10].

Water resource conservation is one of the major challenges for mankind. Water resource availability prediction has become problematic for scientific communities and water resource managers. It is partly due to data-related problems such as fewer water monitoring field stations, lack of adequate quantitative data, and low frequency of field data collections. Many researchers investigated water resource changes in different regions using satellites, models, and ancillary data [2, 7, 11–13]. It is difficult to rely on ancillary data measurements for accurate quantification of large or regional water storage changes, especially at long timescales. Water sustainability depends on recharge rate, discharge rate, and abstraction by consumers and it is often problematic to accurately quantify the available water resources on the large scale. Satellite-based remote sensing data helps provide information on water resources [12].

GRACE missions are one of the most powerful tools that can estimate spatio-temporal water storage changes (all forms of water stored above and below the surface of the earth) on a regional and global basis with unprecedented accuracy [14, 15]. Many studies have been done on GRACE-derived time-variable gravity data to evaluate long-term water storage changes and drought index in different regions over the globe where water has been depleted significantly in the last two decades. Many previous studies have evaluated GRACE-based terrestrial water storage (TWS) and groundwater storage (GWS) changes based on the water balance method [16–18]. The water balance method can be used to describe the flow of water in and out of the system. TWS is a key component of the terrestrial and global hydrological cycles, exerting important control over the water, energy, and biogeochemical fluxes. GWS is vital to sustaining agriculture, industrial, and domestic activities. Such unique datasets combined with external information are widely used to quantify water storage change variations in major aquifers over the world.

During the past two decades, intensive natural and anthropogenic activities have led to dramatic declines in water storage in India. TWS has been reduced in the Ganga–Brahmaputra river basins during the period from August 2002 to October 2008 [7, 19]. Rodell et al. [7] observed that TWS and GWS declined steadily from 2003 onwards over north India (including Rajasthan, Punjab, Haryana, and Delhi) and are being depleted at the rate of 4.0 ± 1.0 cm per year. Gautam et al. [13] found that groundwater has been depleted in Uttar Pradesh and reported a depletion rate of -2.76 ± 0.87 cm/year in Meerut and -1.46 ± 0.74 cm/year in Lucknow. Chen et al. [20] reported that groundwater has been depleted at a rate of $\sim 20.4 + 7.1$ Gt/year in North West India. Chinnasamy and Agoramoorthy [21] also reported groundwater depletion at the rate of 21.4 km^3 per year. Good knowledge of TWS and GWS changes plays a significant role to understand the hydrological cycle and its relations with climate change. GRACE-derived TWS data comprises vertically integrated water storages of all columns of a region, which represents the sum of soil moisture, surface water, groundwater, snow, and ice. Their results indicated that hydrological changes such as soil moisture, snowpack, precipitation, evapotranspiration, snowmelt, and groundwater caused the largest water storage variations. Such hydrological datasets are estimated from the Global Land Data Assimilation (GLDAS) hydrological model.

The objective of the study is to assess the long-term variability of water storage changes (TWS and GWS) using GRACE missions and GLDAS model data to prevent water resources over a part of the Indus Basin, India. The emphasis of this study has been focused on three phases: (i) monthly variations; (ii) seasonal variations; and (iii) annual variations which reflect trends of TWS and GWS over a period from April 2002 to December 2021 in the entire study region. Additionally, the study also examines TWS and GWS variations with GPM-derived rainfall data and groundwater level data obtained from Water Resources Information System (India-WRIS). A long-term assessment of water storage is essential for maintaining sustainable economic development. The study may help water resource managers, researchers, and policymakers to have an understanding of the long-term impact of TWS and GWS.

Study Area

The Indus Basin is one of the largest basins in Asia recognized as the ideal and practical unit of water resource management. It allows the holistic understanding of upstream–downstream hydrological interactions and solutions for management for all completing sectors of water demand. The Indus Basin extends over China (Tibet), India, Afghanistan, and Pakistan

draining an area of 11, 65, 500 km^2. The Indus Basin is bounded by the Himalayans on the east, the Karakoram and Haramosh range on the north, the Sulaiman and Kirthar ranges on the west, and the Arabian Sea on the south. Recent geological and geophysical information suggests that the Indus River system was initiated shortly after the collision between the Indian and Eurasian Plates 45 million years ago. The Indus received water and sediment from several large tributaries, viz. Shyok, Shigar, Gilgit, and Kabul from the north, and the Jhelum, Chenab, Ravi, Beas, and Sutlej from the eastern plains of Punjab. The Indus, Jhelum, and Chenab Rivers are the major sources of water for the Indus Basin Irrigation System. The study is mainly focused on the Indus Basin which spreads over the states of Himachal Pradesh, Punjab, Haryana, Union Territory of Chandigarh, and some parts of Rajasthan (Fig. 1). The study area did not include Jammu and Kashmir, Ladakh, and Uttaranchal parts. The geographical extent of the study area is between 25° 21' to

33° 01' N latitude and 69° 28' to 78° 54' E longitude with an area of 2, 65, 503 km^2. The upper part of the basin lying in Himachal Pradesh mostly consists of mountain ranges and narrow valleys. The basin comprises vast plains in Punjab, Haryana, and Rajasthan which are the fertile granary of the country. The Punjab state is bounded by Jammu and Kashmir in the north, Himachal Pradesh in the northeast and east, Haryana in the southeast and south, Rajasthan in the south, and south-west and shares the international boundary with Pakistan on the western side. The Indian monsoon season in the study area commences at the end of June or starting of July, and may continue until the end of September. The rainfall during the monsoon season is highly variable and uncertain, and a large amount of rainfall occurs between July and August. The major part of the basin is covered with agricultural land. Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) data is used to create elevation maps over the study area and is found to
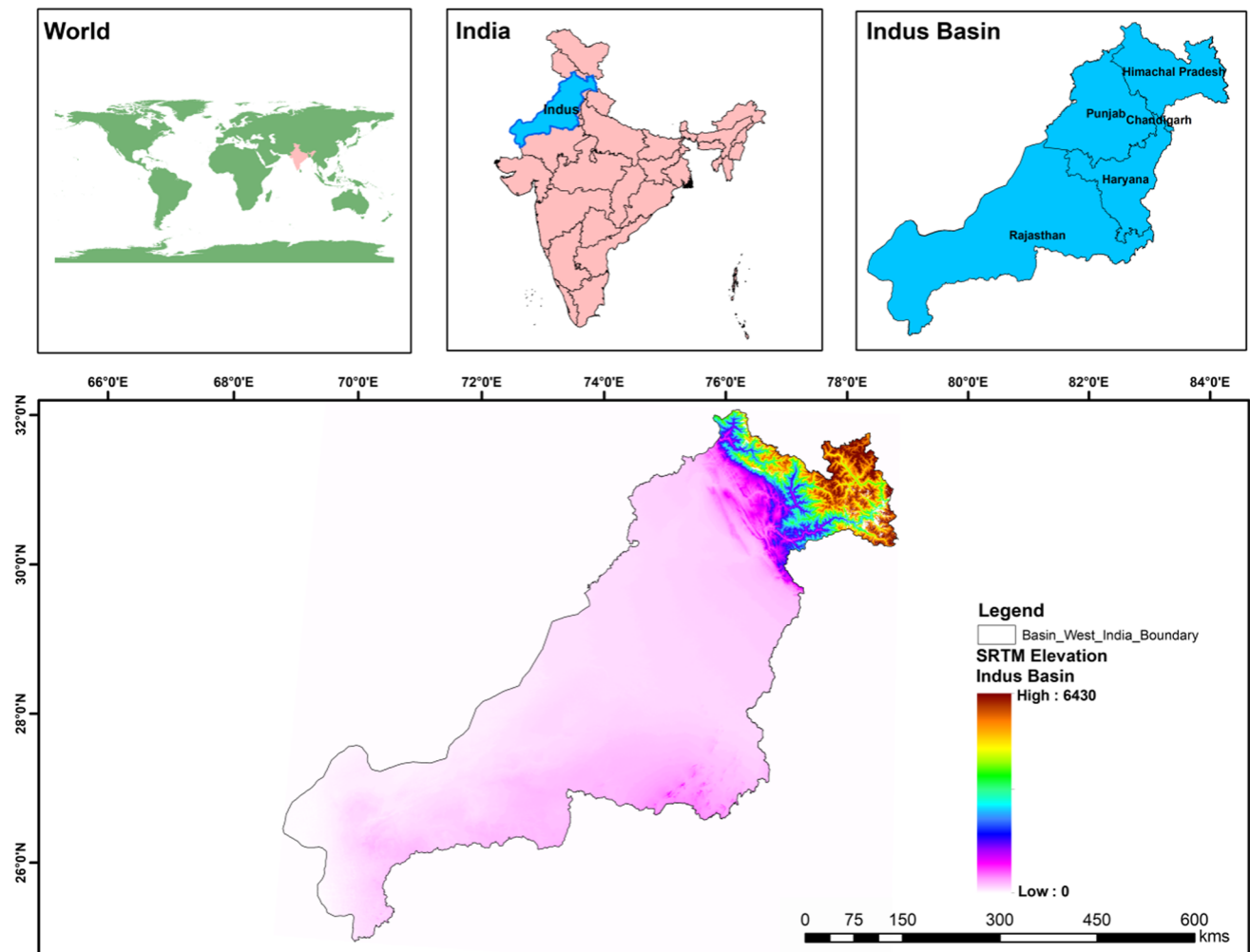

Fig. 1 The study area over a part of the Indus Basin with elevation data covers the part of India, and it spreads over the states of Himachal Pradesh, Punjab, Haryana, Union Territory of Chandigarh, and some parts of Rajasthan

range between 0 and 6430 m. The highest elevation has been observed over the Himachal Pradesh region.

Materials and Methodology

Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (FO) Data

The GRACE and GRACE-FO twin satellites were launched on dated 17 March 2002 and 22 May 2018 as a combined effort between the US agency, NASA (National Aeronautics and Space Administration), and the German agency, GFZ (German Research Centre for Geosciences). GRACE's scientific mission ended on 27 October 2017, but that's not the end of GRACE's story. The GRACE-FO is a successor to the original GRACE mission and measures the Earth's gravity fields every month at a regional scale with a spatial resolution of $1° \times 1°$. The twin satellites follow each other at about 220 km ($\pm$ 50 km) distance in a polar orbit of about ~ 500 km altitude [15] with an inclination of $89.5°$ and constantly send microwave signals to each other to measure the distance between them due to orbital perturbations caused by geographical and temporal variations in Earth's gravity field. The mass anomalies (due to changes in water volume) causes Earth's gravity field changes to affect the distance

of the twin satellites which is measured by the K-band microwave ranging system with great accuracy of $1\mu ms^{-1}$ [5, 22]. The payload of each satellite is also composed of a three-axis accelerometer that provides information on the dynamic effects, including non-dissipative or conservative forces, mainly meaning solar and earth radiation pressure and atmospheric drag. Satellite gravity measurements in the GRACE missions are the first of their kind that can provide time–space variability of the Earth's gravity field, which can indicate the changes in GWS and the amount of water in rivers, lakes, ice sheets, glaciers, sea level, etc. globally [22–25]. Both GRACE missions can only recognize the variations in column-integrated water mass (1 gigaton mass change equivalent to 1 km^3 of water storage).

GRACE and GRACE-FO file consists of a set of spherical harmonics C_{lm} and S_{lm} which are used to derive the physical quantities such as gravity anomaly and TWS of the region. Both datasets are available as monthly anomalies that are computed relative to a time-mean baseline (January 2004 to December 2009). The GRACE and GRACE-FO data processing team defines the baseline period and hence it cannot be changed. The positive anomaly indicates mass gain and the negative anomaly shows a mass loss. The different official processing centers provide three datasets JPL (Jet Propulsion Laboratory), GFZ (Geoforschungs Zentrum Potsdam), and CSR (Center for Space Research

Fig. 2 Flow chart of data processing to extract terrestrial and groundwater storage changes
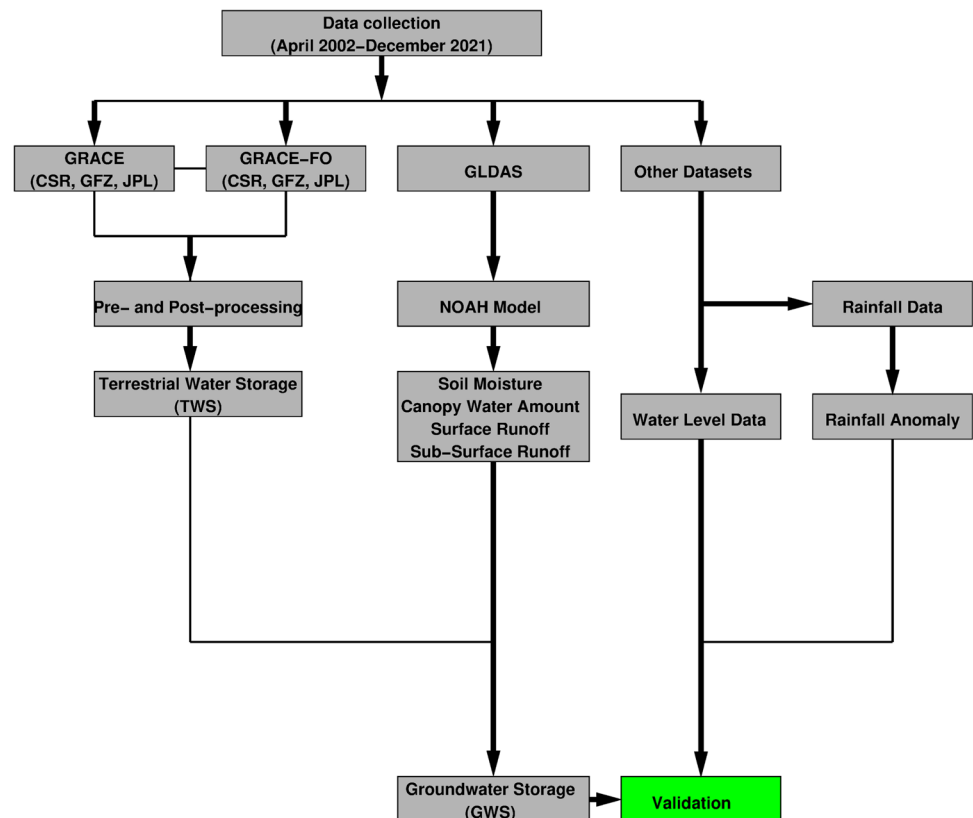
at the University of Texas, Austin) derived from GRACE and GRACE-FO. After filtering to reduce the presence of measurement errors, each data can be converted from spherical coordinates to geographical coordinates. The GRACE mission's grids were then multiplied by the scaling grids to arrive at monthly land mass grids and ocean mass grids. Land mass grids contain land water mass storage given as equivalent water thickness. The equivalent water thickness represents the total terrestrial water storage (TWS) [23]. Equivalent water thickness $\Delta h(\theta, \varphi)$ is calculated as:

$$\Delta h(\theta, \varphi) = \frac{R\rho_{ave}}{3\rho_w} \sum_{l,m} \frac{2l+1}{l+k_l} W_{lm} P_{lm} \tag{1}$$

where l and m are spherical harmonics degree and order respectively, R is the radius of the earth, ρ_{ave} and ρ_w are the average density of Earth (5517 kg/m^3) and density of water (1000 kg/m^3) respectively, θ and φ are the colatitudes and longitude respectively, k_l is the load Love number, W_{lm} is an expression in spherical harmonics for a Gaussian smoothing filter, P_{lm} is the normalized associated Legendre function, and ΔC_{lm} and ΔS_{lm} are the normalized spherical harmonics coefficients after being processed by the decorrelation filter. A glacial isostatic adjustment correction has been applied and standard corrections for geocenter (degree-1), C_{20} (degree-20), and C_{30} (degree-30) are incorporated. A maximum spherical harmonics degree of 60 is used. The amplitude of Δh is further adjusted so that the total amplitude of Δh after decorrelation and smoothing filter is the same as that of initial inputs. The spherical harmonics basis function is a traditional processing approach that has been applied over decades or more to parameterize the Earth's gravity field [26]. Post-processing filters like de-striping and spatial smoothing have been applied to reduce correlated errors.

The GRACE (available at https://podaac.jpl.nasa.gov/grace) and GRACE-FO data (available at https://podaac.jpl.nasa.gov/
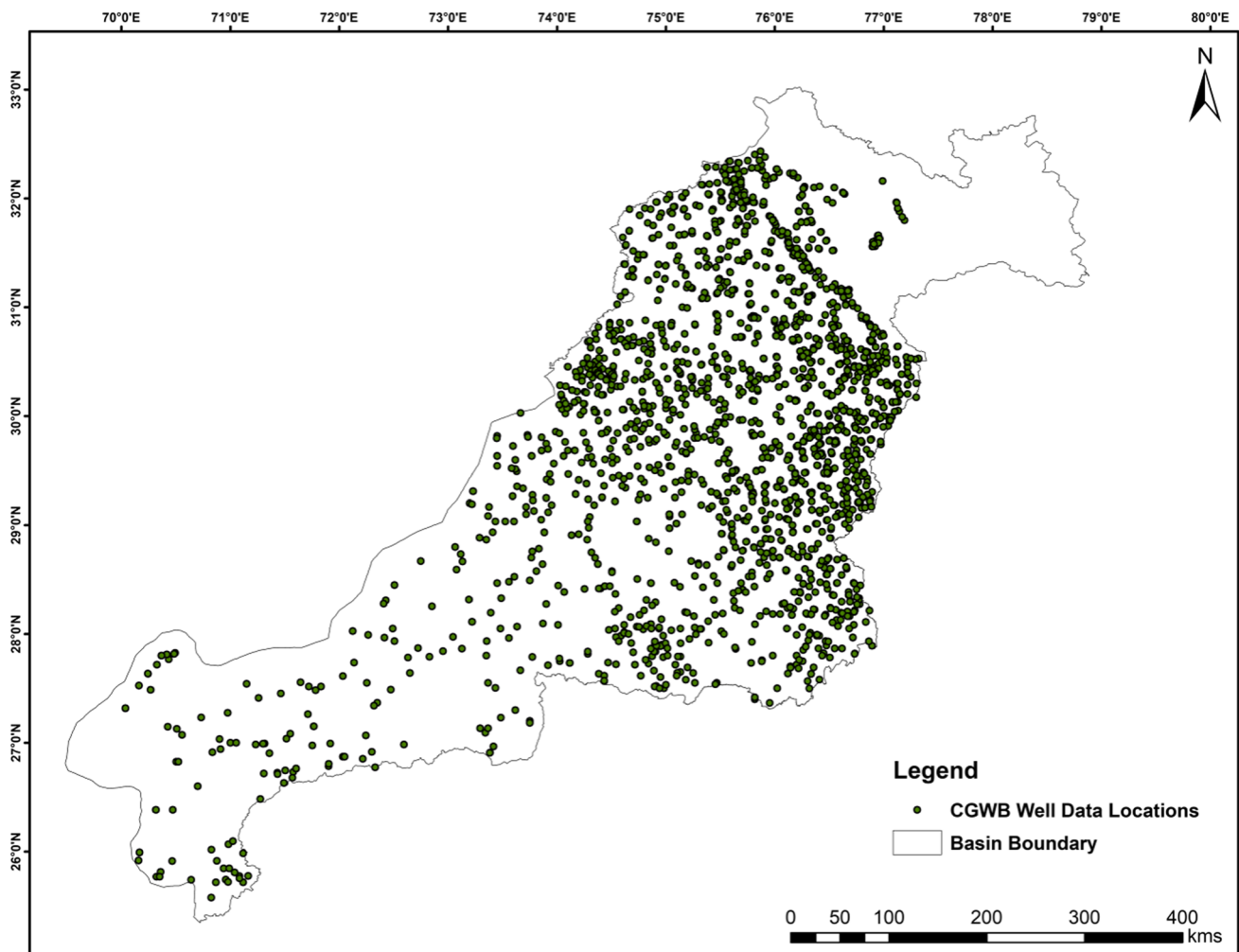

Fig. 3 Groundwater level data taken from the Water Resources Information System over a part of the Indus Basin during the period from 2002 to 2021

data/grace-fo-data) are supported by the NASA MEaSUREs Program [27, 28]. The study considered monthly mass grids inverted from RL06 spherical harmonic coefficients released by the GRACE processing centers. We used averaging all three GRACE and GRACE-FO (Level-3) datasets JPL, GFZ, and CSR to examine the TWS and GWS changes over the study region. The averaging of all three datasets is used in this study for reducing the biasing in the TWS. All data grids are provided in ASCII/netCDF/GeoTIFF formats. GRACE-inferred TWS changes (sometimes referred to as TWSA) are comprised of groundwater, surface water (which includes rivers, lakes, reservoirs, canals), soil moisture, snow, ice, and aquifer. This study also found some missing data and such missing data are filled using linear interpolation.

Global Land Data Assimilations System (GLDAS) Data

GLDAS is an uncontrolled land surface modeling system initiated at Hydrological Science Laboratory and maintained in unison by researchers at the US NASA Goddard Space Flight Centre (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) to estimate and archive changes in land and ocean mass fluxes [7, 21, 29–31]. It uses data assimilation to incorporate various remote sensing missions and observations in advanced land surface models (LSMs) including Catchment, NOAH, Common Land Surface Model (CLSM), and the Variable Infiltration Capacity (VIC). LSMs provide hydrological components, meteorological variables, radiations, and heat fluxes across
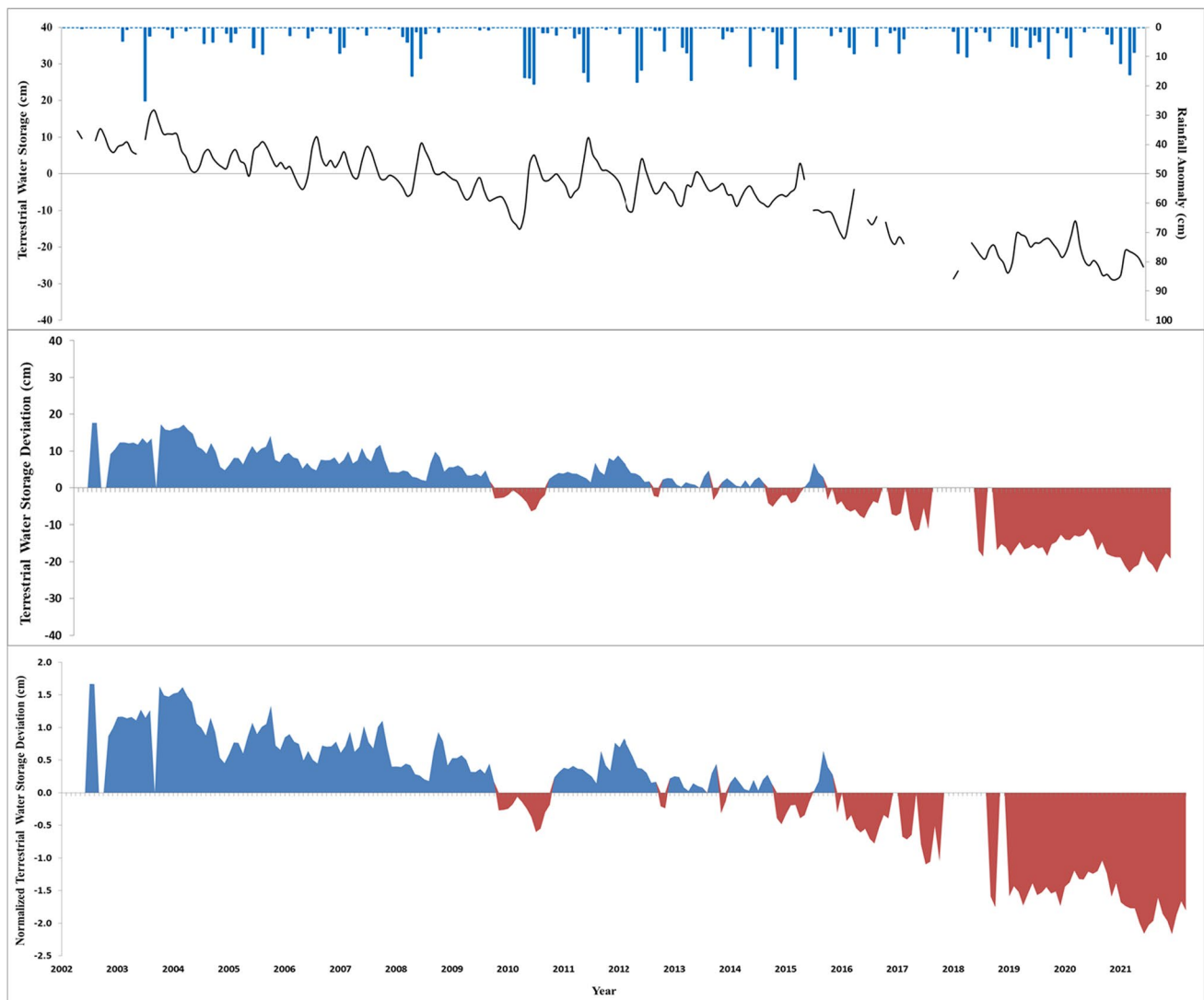

Fig. 4 (upper) Time series of the domain average of the terrestrial water storage, (middle) terrestrial water storage deviations which represent the surplus (in blue) and the deficit (in red), and (lower) normalized terrestrial water storage deviation over a part of the Indus Basin

the globe at different spatial and temporal resolutions since 1948 [2] which can be used widely in water resources and climate studies. The NOAH10-M2.1 model data (available at https://hydro1.gesdisc.eosdis.nasa.gov/data/GLDAS/) contained in gridded format provides monthly data of soil moisture, terrestrial water storage, canopy water amount, surface and subsurface runoff, etc. at a spatial resolution of $1° \times 1°$. This consistent hydro-climatological dataset is widely used in water resources and climate studies, particularly in the region where data are temporally and spatially limited [32, 33]. The study used monthly model data of total vadose zone soil moisture (because soil moisture estimates from four datasets that represent from 0 to 10, 10 to 40, 40 to 100, and 100 to 200 cm respectively), canopy water amount, surface and subsurface runoff for the period

from April 2002 to December 2021 over the study region. The anomaly of these model-based parameters has been derived from each monthly GLDAS model parameter and an average value of each GLDAS NOAH model parameter in the baseline period (January 2004 to December 2009). NOAH was chosen over the other GLDAS models given the demonstrated successful applications of NOAH for the Indian subcontinent particularly in northern India [21].

GWS changes are often disaggregating from GRACE-derived changes of TWS by subtracting changes in soil moisture, canopy water amount, surface, and subsurface runoff (Eq. 2).

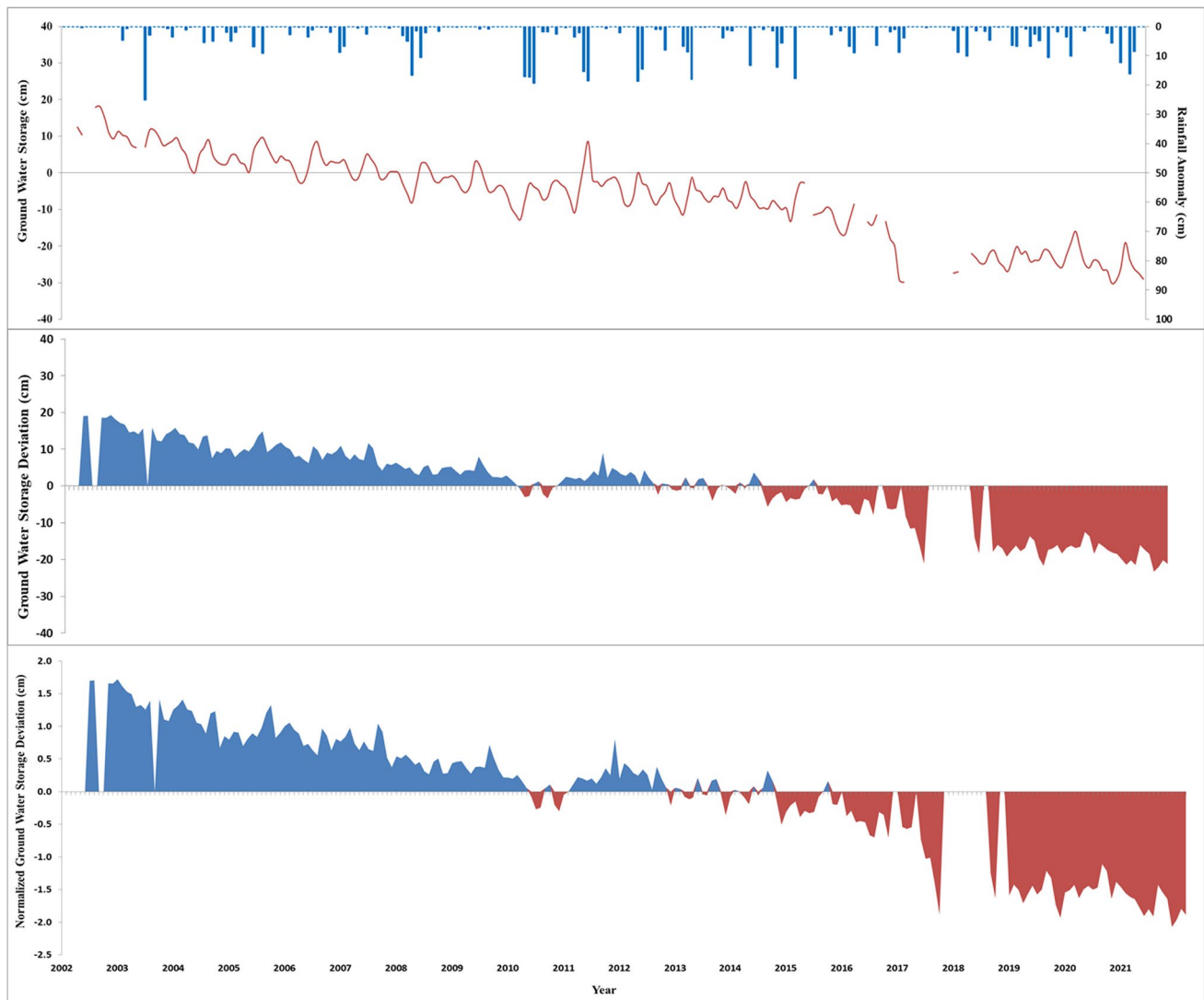$$GWS = TWS - (SM + CW + SW + SbW) \tag{2}$$

Fig. 5 (upper) Time series of the domain average of the groundwater storage, (middle) groundwater storage deviations which represent the surplus (in blue) and the deficit (in red), and (lower) normalized groundwater storage deviation over a part of the Indus Basin

where GWS is the groundwater storage changes, TWS is the terrestrial water storage changes, SM is the soil moisture changes, CW is the canopy water changes, SW is the surface water changes, and SbW is the subsurface water changes. GLDAS product is limited by model physics, model structure, and meteorological data, and it can vary from place to place. The flowchart of data processing to extract GWS has been mentioned in Fig. 2. All collected data has been processed using the MATLAB 2018b software, and ArcGIS 10.4 software has been used for mapping.

Global Precipitation Mission (GPM) Data

The rainfall data has been derived from the GPM satellite for the assessment of the long-term variability of rainfall over the study area. Global Precipitation Measurement is one of the meteorological satellites which provides near real-time rainfall data using dual-frequency precipitation radar (Ku/Ka-band) and a multi-channel GPM Microwave Imager (GMI). Dual-frequency precipitation radar provides

three-dimensional measurements of precipitation structure and characteristics. The GPM Core Observatory launched on February 27, 2014, and is a follow-on, expanded mission to TRMM (Tropical Rainfall Measuring Mission) which provides high spatial resolution (10×10 km) datasets. The study used monthly accumulated rainfall derived from the originally available daily rainfall product during the period from January 2002 to December 2021. The rainfall product presented a reasonable agreement with other datasets and ground-based observations. The study followed a similar pattern of GRACE to derive rainfall anomaly, and rainfall anomaly has been derived from each monthly data and the monthly average value of rainfall in the baseline period (January 2004 to December 2009).

Ground Water Level Data

Central Groundwater Board (CGWB), India, collects the groundwater level data from ~ 32,600 National Hydrograph
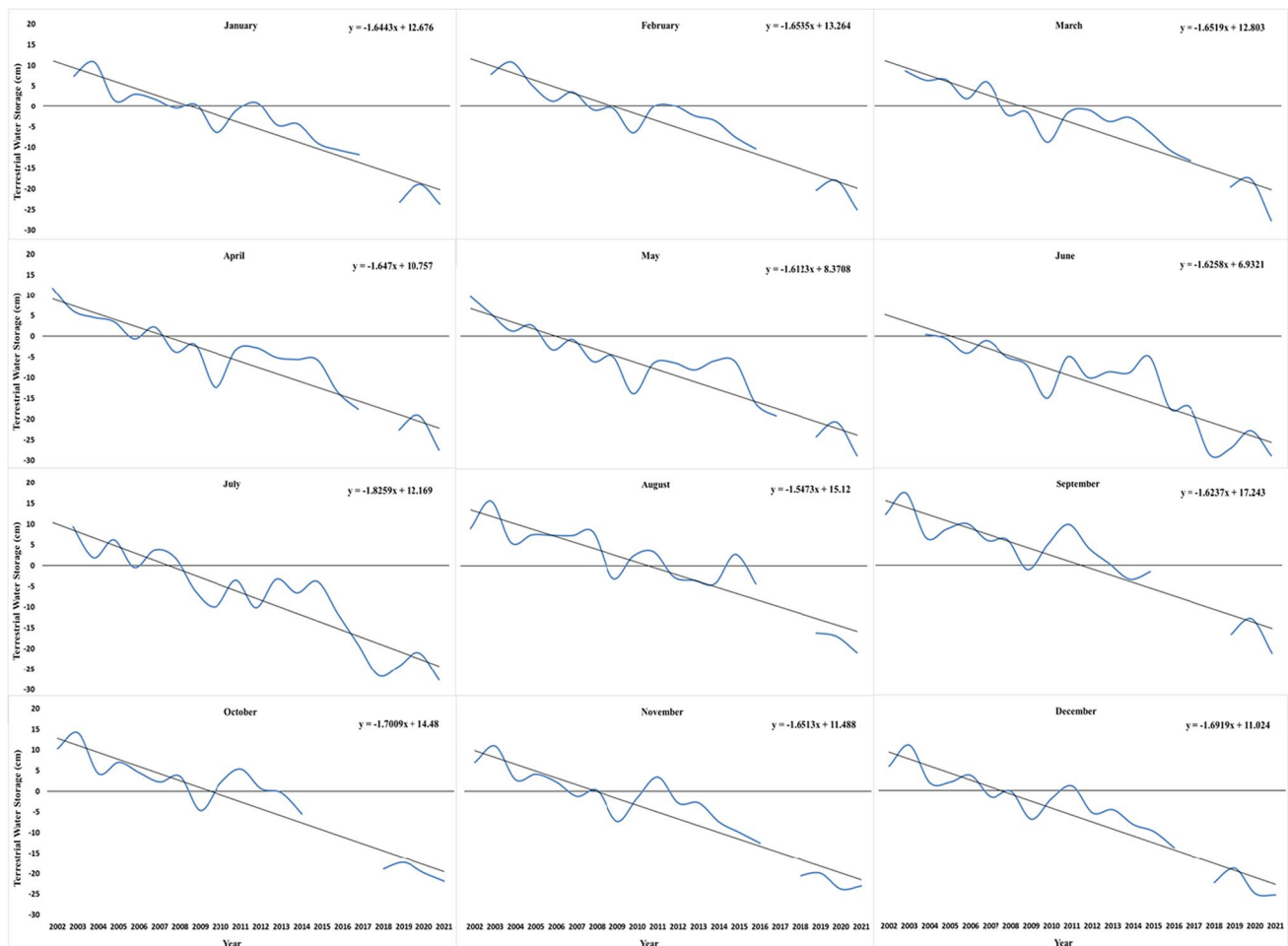

Fig. 6 GRACE and GRACE-FO estimate temporal variations of average terrestrial water storage in different months over a part of the Indus Basin

Stations across the 28 states and 8 union territories under 18 Regional offices in India. The groundwater levels are monitored quarterly in a year, pre-monsoon (1–10 January), monsoon (20–30 May), post-monsoon (20–30 August), and winter (1–10 November). After the collection and analysis of groundwater level data, the CGWB shared its time series data on the National Water Informatics Centre (NWIC) platform, a central repository of nationwide water resource data in India. Groundwater level data from 2002 to 2021 has been derived from the Water Resources Information System (India-WRIS) (a part of the NWIC) over a part of the Indus Basin (Fig. 3). This study also followed a similar pattern of GRACE to derive groundwater level anomaly created from each monthly groundwater level data and the monthly average value of groundwater level in the baseline period (January 2004 to December 2009).

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Results

In this study, we assess the long-term variability of water storage changes (TWS and GWS) using GRACE missions and GLDAS model data to prevent water resources over a part of the Indus Basin, India.

Estimation of TWS and GWS Changes from GRACE and GRACE-FO

GRACE and GRACE-FO monthly datasets have been used to estimate variations of TWS and GWS both spatially and temporally in the different agro-climatic zone over a part of the Indus Basin, India, for the period of 20 years from April 2002 to December 2021. Water storage changes assessment both spatially and temporally is not feasible by ground measurements due to the high cost and limited observations. Field monitoring of soil moisture, surface water changes, groundwater depth, and other parameters provides discrete sampling while GRACE missions can obtain frequent
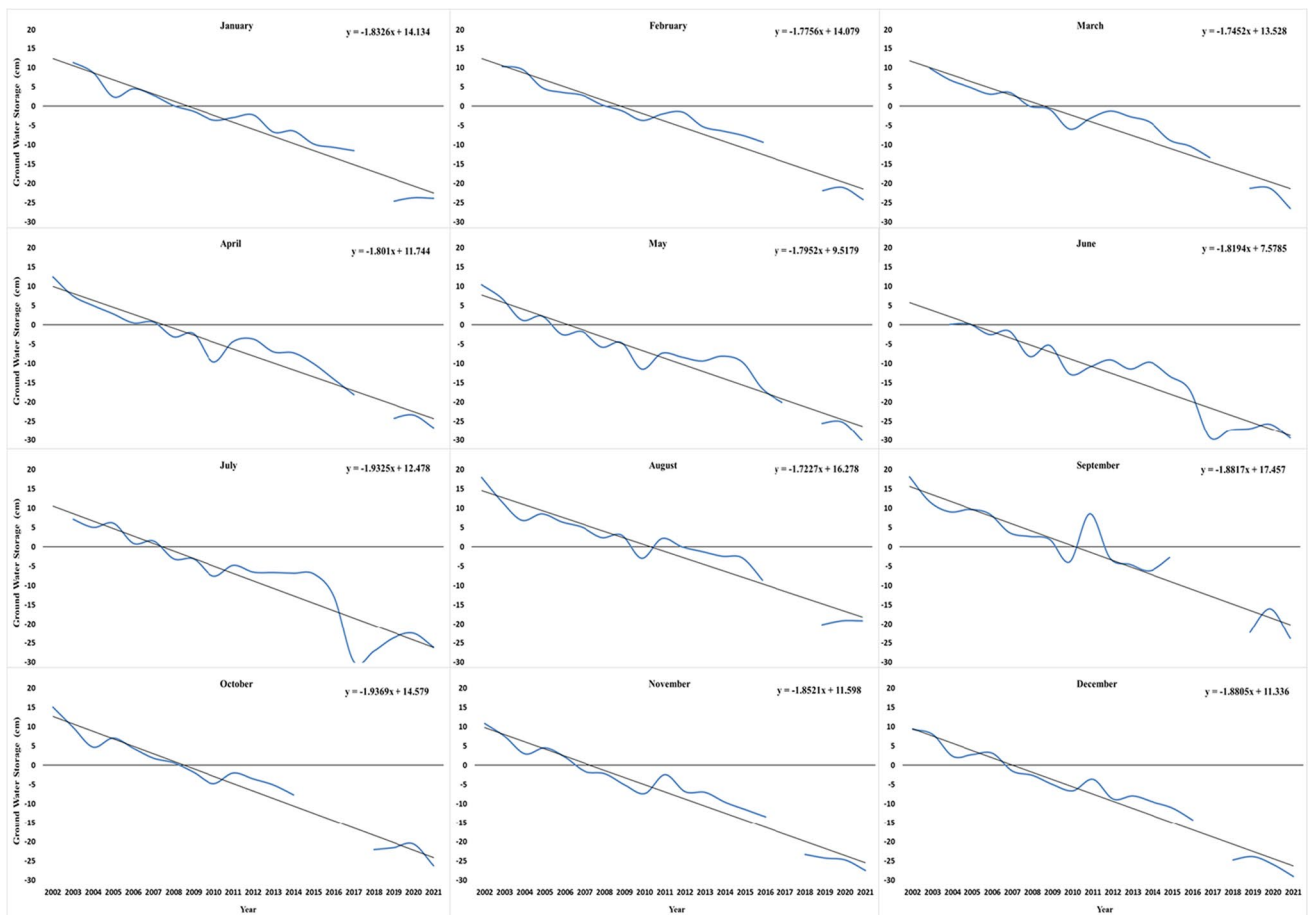
Fig. 7 GRACE and GRACE-FO estimate temporal variations of average groundwater storage in different months over a part of the Indus Basin
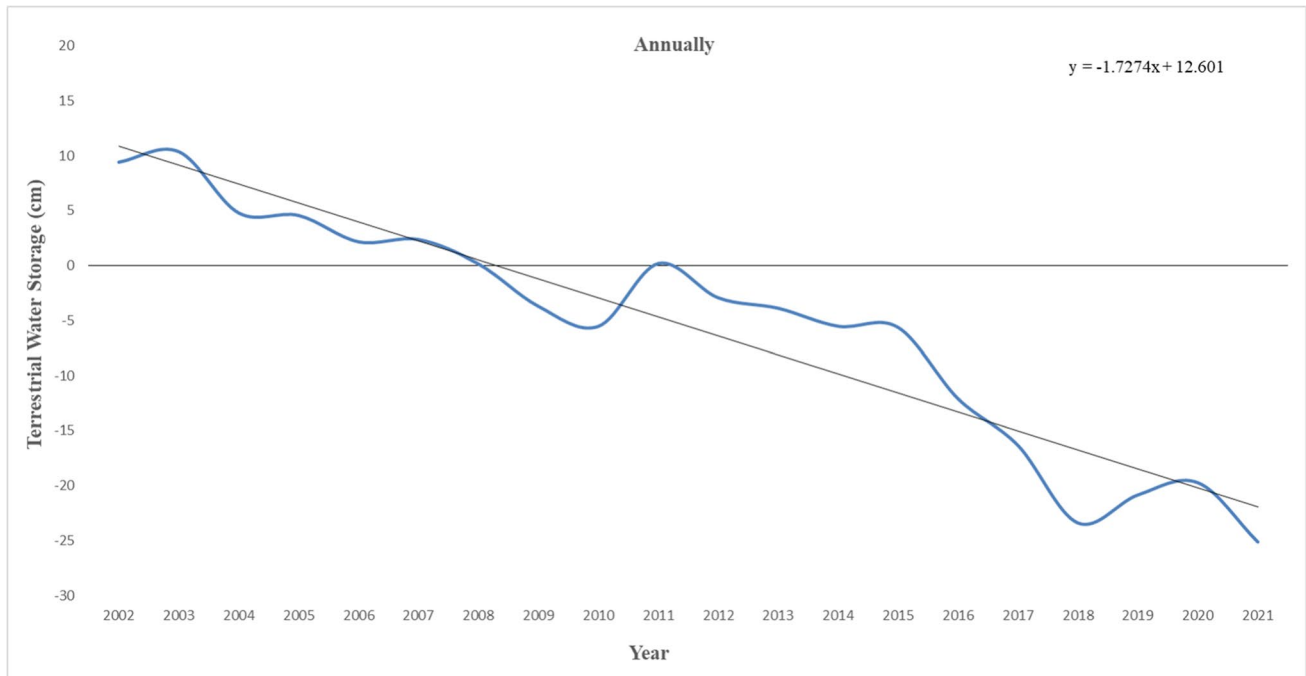
Fig. 8 GRACE and GRACE-FO estimate annual variations of average terrestrial water storage in different years over a part of the Indus Basin

changes in TWS and GWS at broad spatial and temporal scales. The obtained results have been analyzed in three phases: (i) monthly variations; (ii) seasonal variations which include the pre-monsoon season (April/May) and post-monsoon season (October/November); and (iii) annual variations respectively which reflect TWS and GWS characteristics in the entire study area.
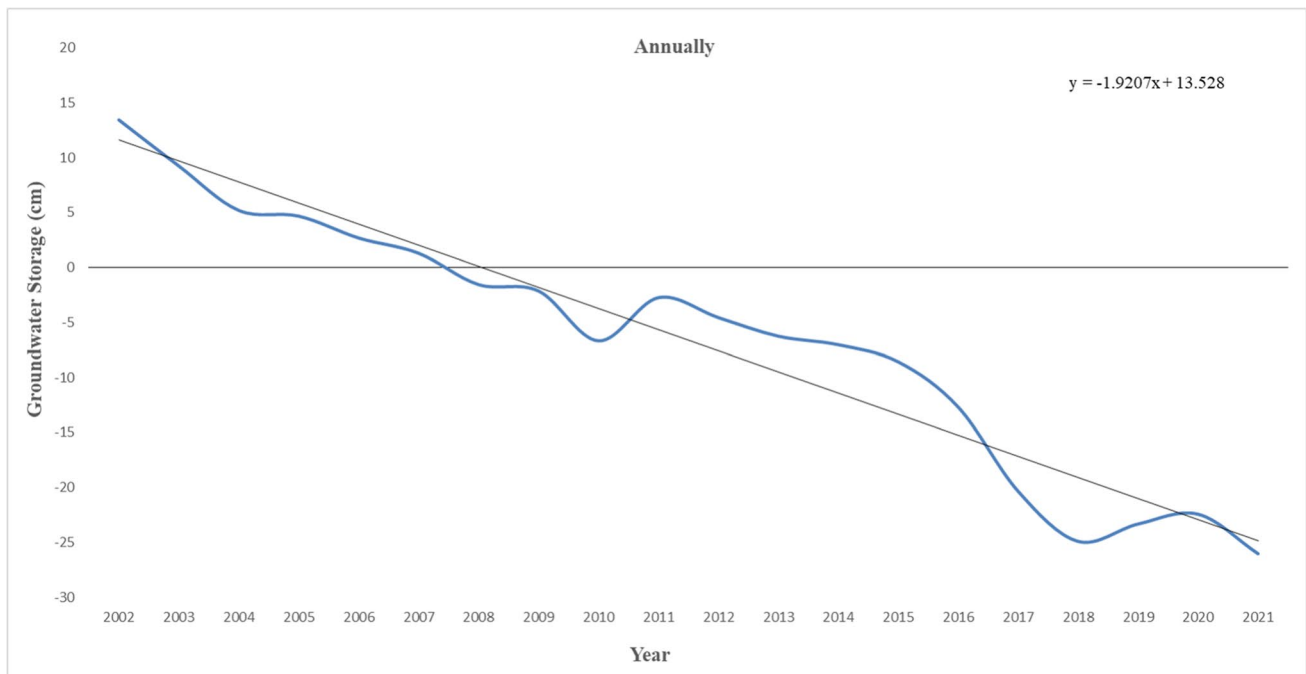

Fig. 9 GRACE and GRACE-FO estimate annual variations of average groundwater storage in different years over a part of the Indus Basin

Spatial and Temporal Variations of TWS and GWS

The monthly trends of TWS exhibit a decreasing pattern of average TWS from + 17.4 to − 28.8 cm, a significant downward trend (at the rate of − 0.06 cm/month), and found completely negative TWS after 2008 with two intermittent breaks in the years 2010 and 2011 (Fig. 4), while GWS exhibits decreasing pattern of average GWS from + 18.1 to − 30.2 cm, a significant downward trend (at the rate of − 0.08 cm/month), and found completely negative GWS after 2008 with two intermittent break in the years 2009 and 2011 (Fig. 5). The downward trends of TWS and GWS have been observed all over the study region. The study found seven downward peaks of TWS, while six downward peaks of GWS and the maximum amount of downward peaks have been observed in 2021 and least observed in 2006 during the period of 20 years. The first negative peak of TWS and GWS has been observed in the years 2005 and 2006. The

highest peak deficit of TWS (− 28.8 cm) has been observed in June 2021 and GWS (− 30.2 cm) has been observed in May 2021. The negative trends of TWS and GWS are indicating a deficit in TWS and GWS compared to its baseline period whereas positive trends signify a surplus in TWS and GWS. The typical time series of GRACE-derived TWS and GWS has a lot of missing values due to the non-availability of GRACE data (because satellites were switched periodically to conserve battery life) and data error occurrence. This study also used monthly climatology TWS and GWS data to remove the influence of seasonality in TWS and GWS changes. The monthly mean climatology data has been subtracted from the monthly TWS and GWS to obtain a TWS deviation (TWSD) and GWS deviations (GWSD) which represent the wet (positive sign) or dry (negative sign) conditions (Eqs. 3–4). Monthly mean climatology is computed by averaging the TWS and GWS data for each calendar month within the span of 20 years period. It represents the
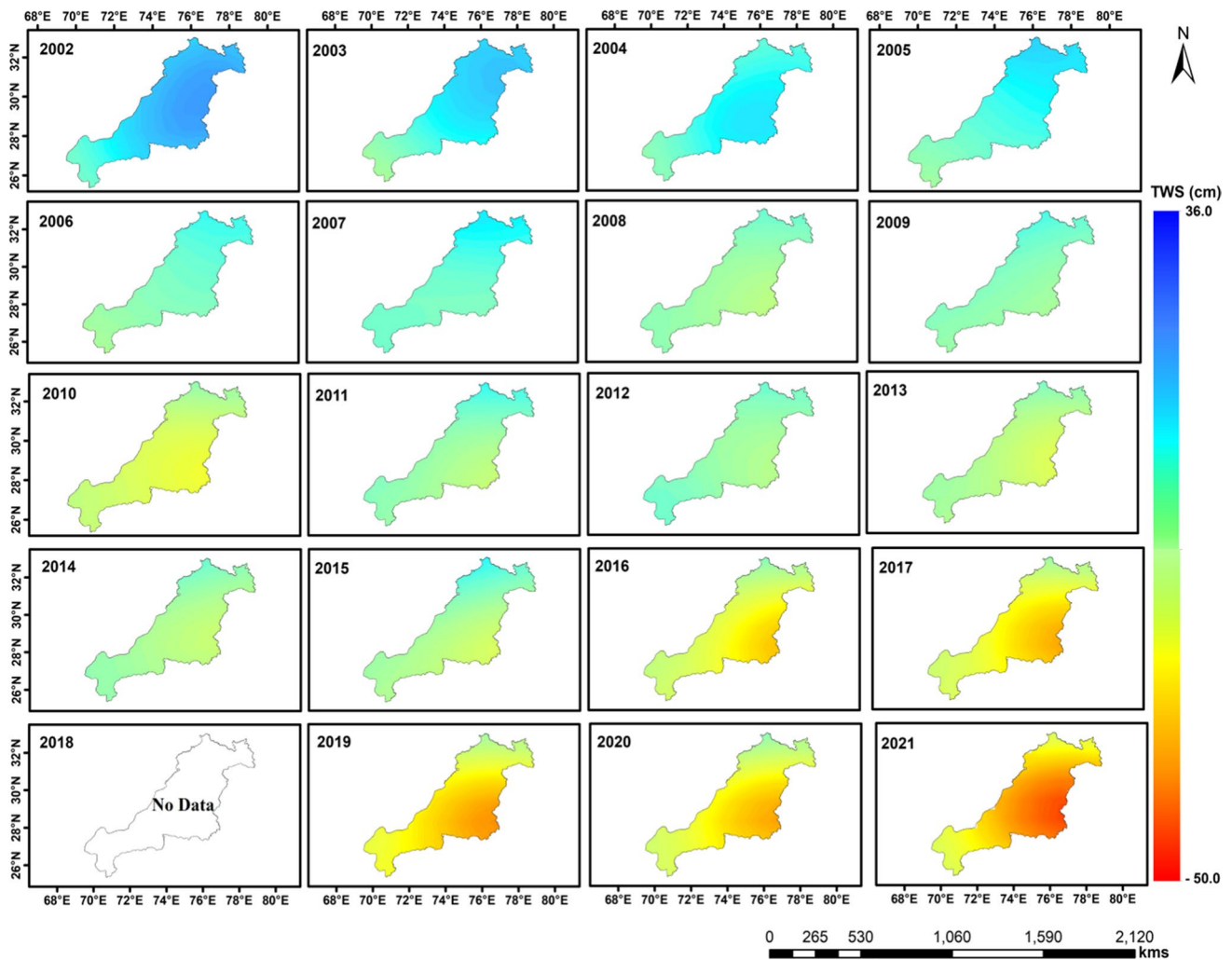

Fig. 10 GRACE and GRACE-FO estimate terrestrial water storage variations during pre-monsoon (April/May month) over a part of the Indus Basin during the period from 2002 to 2021

characteristics variability of TWS and GWS and provides a direct measure of the magnitude from the climatological mean (Figs. 4 and 5). This also represents the net deviation in the TWS and GWS based on seasonal or annual variability and identifies the aberrant variation occurrence over the region. The maximum magnitude of TWS and GWS deviations has been observed after 2016. Seasonal variations play a significant role over TWS and GWS variations but this process is slow as compared with anthropogenic influences. We also computed the normalized net deviation (some referred to as water storage deficit index: WSDI) in TWS and GWS by subtracting the mean net deviation from TWS and GWS and dividing it by the standard deviation (Eqs. 5–6). The negative values of normalized net deviation of TWS and GWS indicate water deficit conditions whereas positive values indicate surplus water storage over a part of the Indus Basin (Figs. 2 and 3).

$$TWSD_i = TWS_i - TWS_j^{climatology} \tag{3}$$

$$GWSD_i = GWS_i - GWS_j^{climatology} \tag{4}$$

$$WSDI_i = \frac{TWS_i - TWS_{mean}}{\sigma_{TWS}} \tag{5}$$

$$WSDI_i = \frac{GWS_i - GWS_{mean}}{\sigma_{GWS}} \tag{6}$$

where TWS_i represents the monthly TWS, $TWS_j^{climatology}$ represents the climatologically mean of TWS for each calendar month, TWS_{mean} stands for the mean time series TWS, and σ_{TWS} stands for the standard deviation of TWS; GWS_i represents the monthly GWS, $GWS_j^{climatology}$ represents the clima-
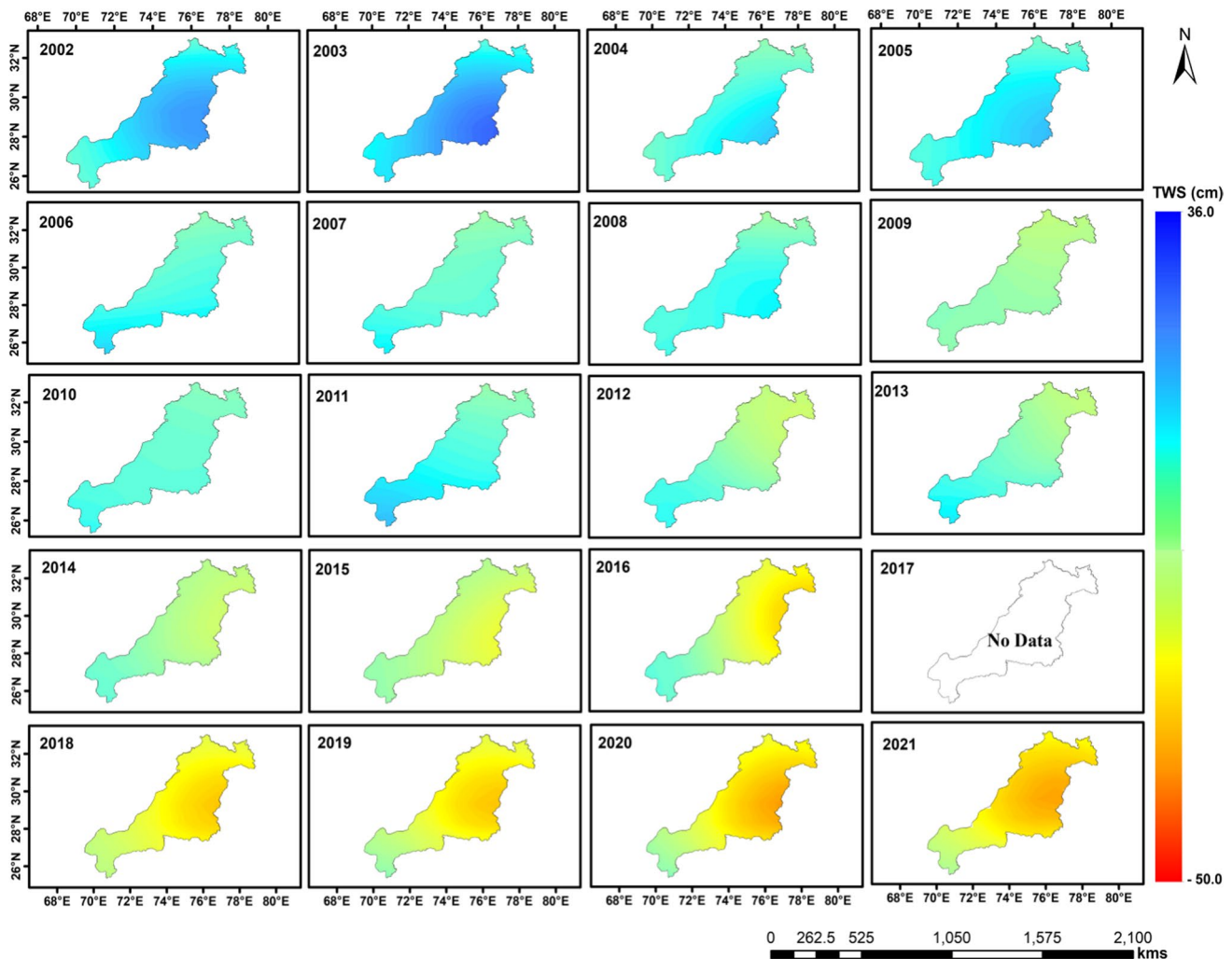

Fig. 11 GRACE and GRACE-FO estimate terrestrial water storage variations during post-monsoon (October/November month) over a part of the Indus Basin during the period from 2002 to 2021

tologically mean of GWS for each calendar month, GWS_{mean} stands for the mean time series GWS, and σ_{GWS} stands for the standard deviation of GWS.

The study also obtained a 20-year time series of the domain average of the TWS and GWS in different months as well as annually to assess the variations and linear trends over the region (Figs. 6, 7, 8, and 9). In the comparative analysis for each month and season with their corresponding month and seasons over the period from 2002 to 2021, we observed some increasing trends of TWS in years 2011, 2012, 2013, 2014, 2015, and 2020, and GWS in years 2011, 2012, 2014, and 2020; after then, we found a continuous decreasing pattern. A significant temporal pattern of TWS has been observed in the years 2010, 2015–2016, and 2019 due to hot weather and less rainfall. This study found less deviation of TWS and GWS in the monsoon season (May, August, and September) which may be due to the higher amount of rainfall.

The study also calculated spatial patterns of TWS and GWS during pre-monsoon (April/May), post-monsoon (October/November), and annually averaged during the period from 2002 to 2021 (Figs. 10, 11, 12, 13, 14, and 15). These results showed TWS and GWS variations in different months and found a decreasing pattern of TWS from +18.4 to −36.5 cm, GWS from +20.4 to −46.4 cm during pre-monsoon period; TWS from +19.1 to −34.4 cm, GWS from +31.9 to −48.7 cm during post-monsoon period; and TWS from +17.0 to −38.5 cm, GWS from +25.1 to −44.6 cm annually (Table S1). The maximum amount of TWS and GWS has been depleted in May and June which may be due to high temperature, less rainfall, and huge demand for water for agriculture and domestic usage. The average TWS during pre-monsoon, post-monsoon, and annually has been computed in the order of −6.6 cm, −4.2 cm, and −6.6 cm respectively and GWS has been computed in the order of −6.0 cm, −2.0 cm, and −5.5 cm respectively.
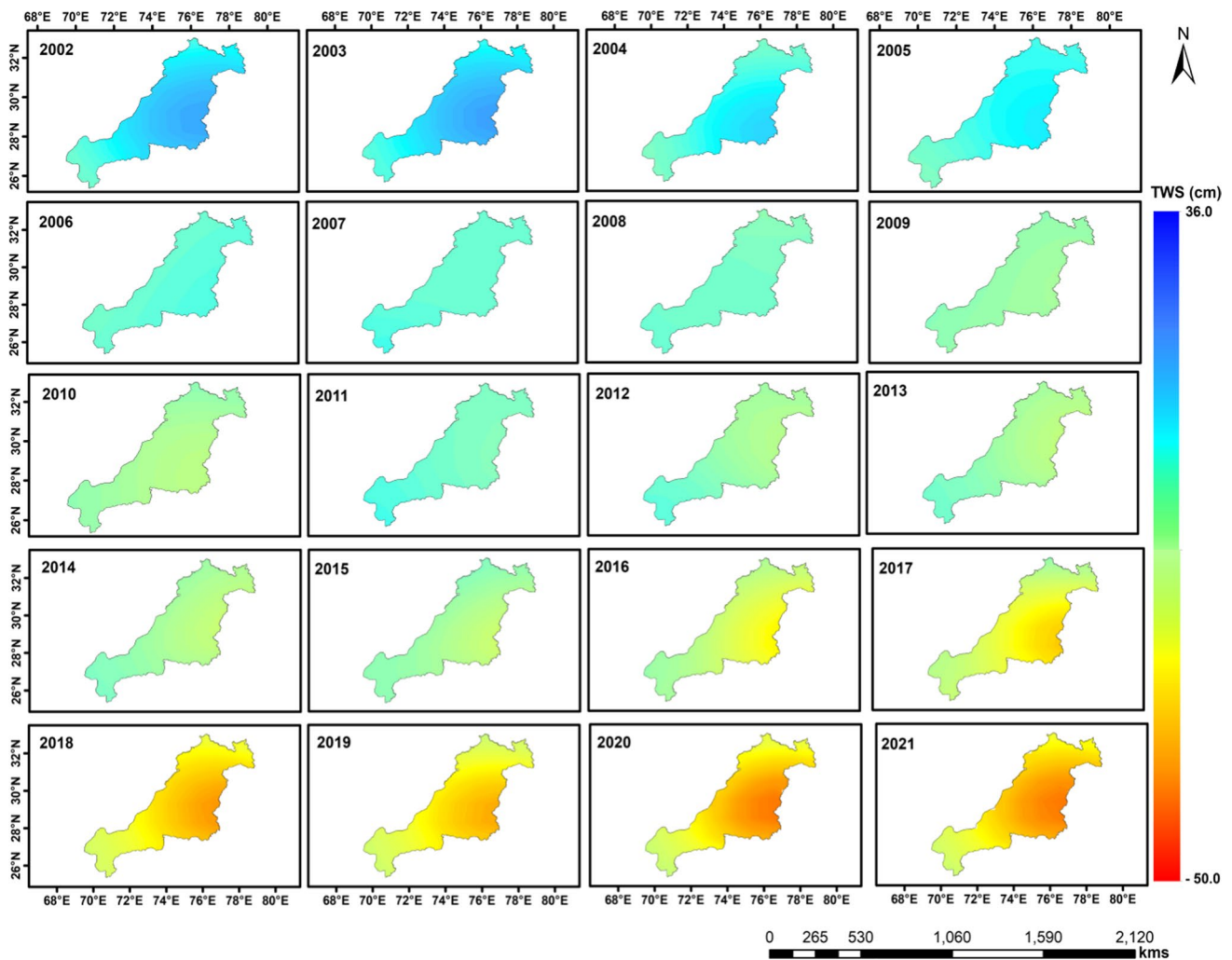

Fig. 12 GRACE and GRACE-FO estimate annual (average of all months) terrestrial water storage variations over a part of the Indus Basin during the period from 2002 to 2021
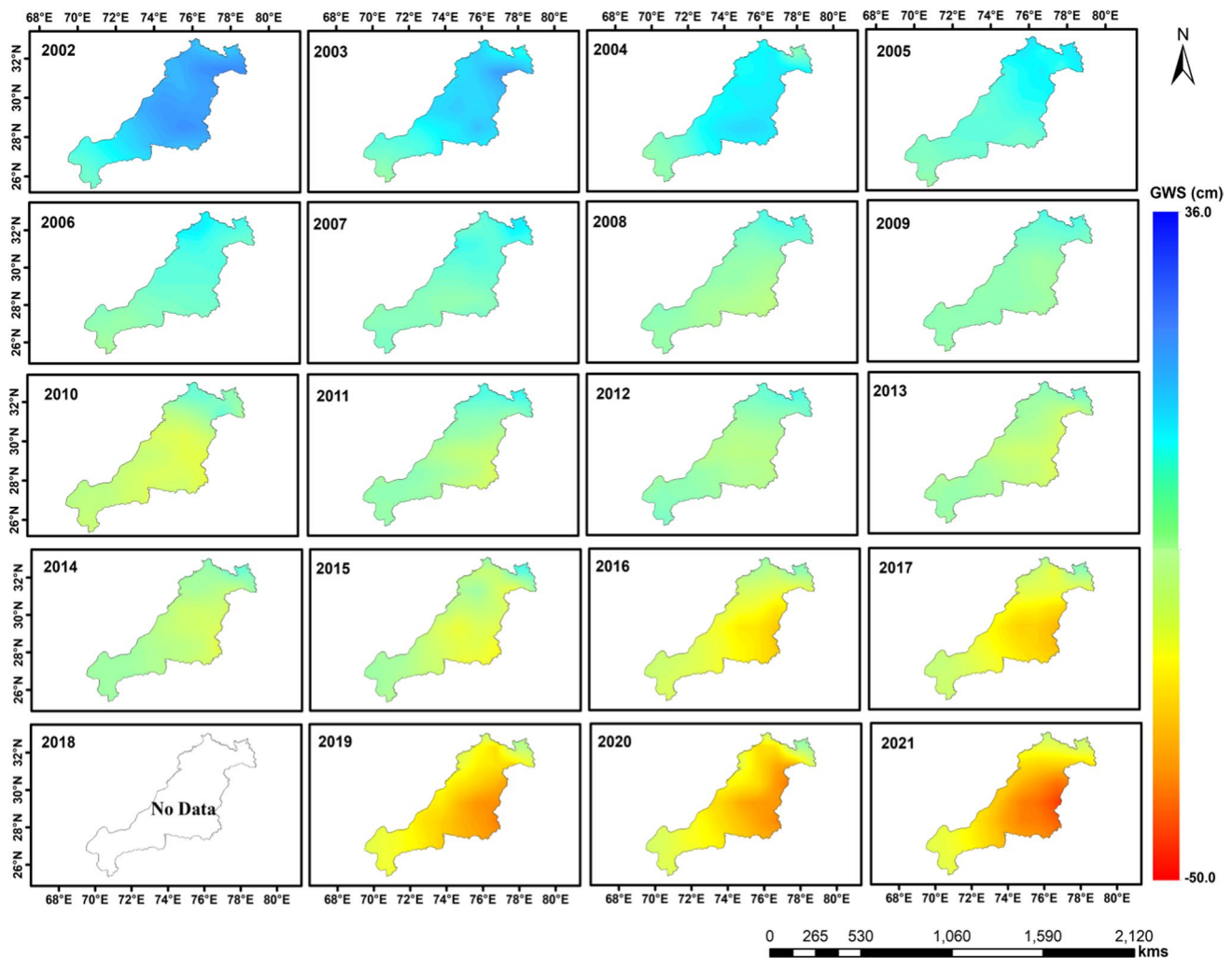
Fig. 13 GRACE and GRACE-FO estimate groundwater storage variations during pre-monsoon (April/May month) over a part of the Indus Basin during the period from 2002 to 2021

The maximum rate of TWS depletion (cm per year) during pre-monsoon, post-monsoon, and annually has been observed in the years 2010, 2004, and 2016 whereas the minimum in the years 2015, 2013, and 2015 respectively while the maximum rate of GWS depletion (cm per year) during pre-monsoon, post-monsoon, and annually has been observed in the years 2010, 2015, and 2010 whereas minimum in the years 2007, 2008, and 2005 respectively. The annual overall TWS changes rate has been computed from a maximum of 6.46 cm/year to a minimum of 0.11 cm/year and the annual overall GWS changes rate has been computed from a maximum of 4.50 cm/year to a minimum of 0.52 cm/year. We also computed the same result for pre-monsoon: TWS maximum 10.2 cm/year to minimum 0.08 cm/year, GWS maximum 7.33 cm/year to minimum 0.22 cm/year; and for post-monsoon season: TWS maximum 9.81 cm/year

to minimum 1.01 cm/year, GWS maximum 7.69 cm/year to minimum 1.10 cm/year.

GPM-Derived Rainfall Trends

The monthly rainfall trends have been computed from the GPM-derived daily rainfall data for the study area during the period from January 2002 to December 2021. The average computed rainfall for the entire study area during the period from January 2002 to December 2021 was 119.5 cm. The annual trends of rainfall exhibit an increasing pattern of cumulative rainfall from 73.4 to 151.2 cm, a significant upward trend (at the rate of 1 cm/year). The highest rainfall has been recorded in the year 2010 which was 151.2 cm while the lowest has been recorded in the year 2002 which was 73.4 cm. The maximum percentage of rainfall has
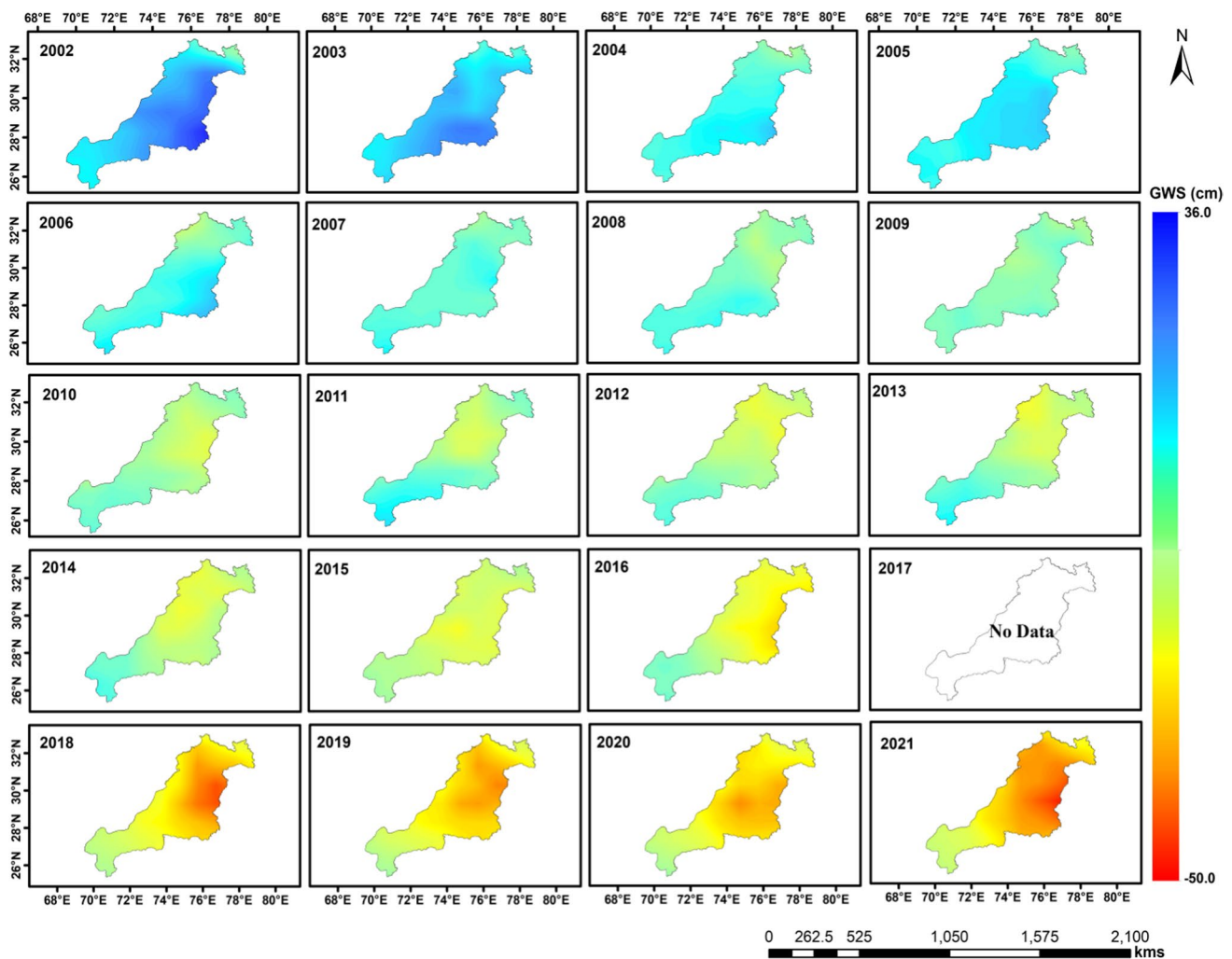
Fig. 14 GRACE and GRACE-FO estimate groundwater storage variations during post-monsoon (October/November month) over a part of the Indus Basin during the period from 2002 to 2021

been concentrated mainly during the monsoon season. The monthly TWS and GWS variations from GRACE and GRACE-FO have been compared with the monthly rainfall anomaly data taken from GPM product over a part of the Indus Basin to analyze the fluctuation of water storage trends. The rainfall anomaly has been derived from each monthly data and the average value of rainfall in the baseline period (January 2004 to December 2009) to understand the rainfall variations. The rainfall variations over the study area are shown in Figs. 4 and 5. This study also included GRACE-derived TWS and GWS over Punjab and Haryana states which lie in the Indus Basin and compared with rainfall anomaly to see the inter-correlation (Figs. 16, 17, 18, and 19). Punjab and Haryana states are two of the largest producers of agricultural products referred to as the "Food Bowl" of the country and are highly dependent on water resources for irrigation.

India-WRIS-Derived Water Level Trends

As mentioned previously, the CGWB monitors groundwater levels at quarterly intervals. Groundwater level data has been taken from the Water Resources Information System over a part of the Indus Basin during the period from 2002 to 2021. A similar month of GRACE and GRACE-FO-derived GWS have been compared with groundwater level anomaly to see the variations over a part of the Indus Basin and this study found almost similar trends in both datasets (Fig. 20). A positive trend in groundwater level data indicates a positive deviation from the average baseline and a negative trend indicates a negative deviation. CGWB groundwater level data has identified that Punjab and Haryana states in the Indus Basin area are over-exploited groundwater. Both states have been the flag-bearers of India's green revolution to achieve maximum agricultural output.
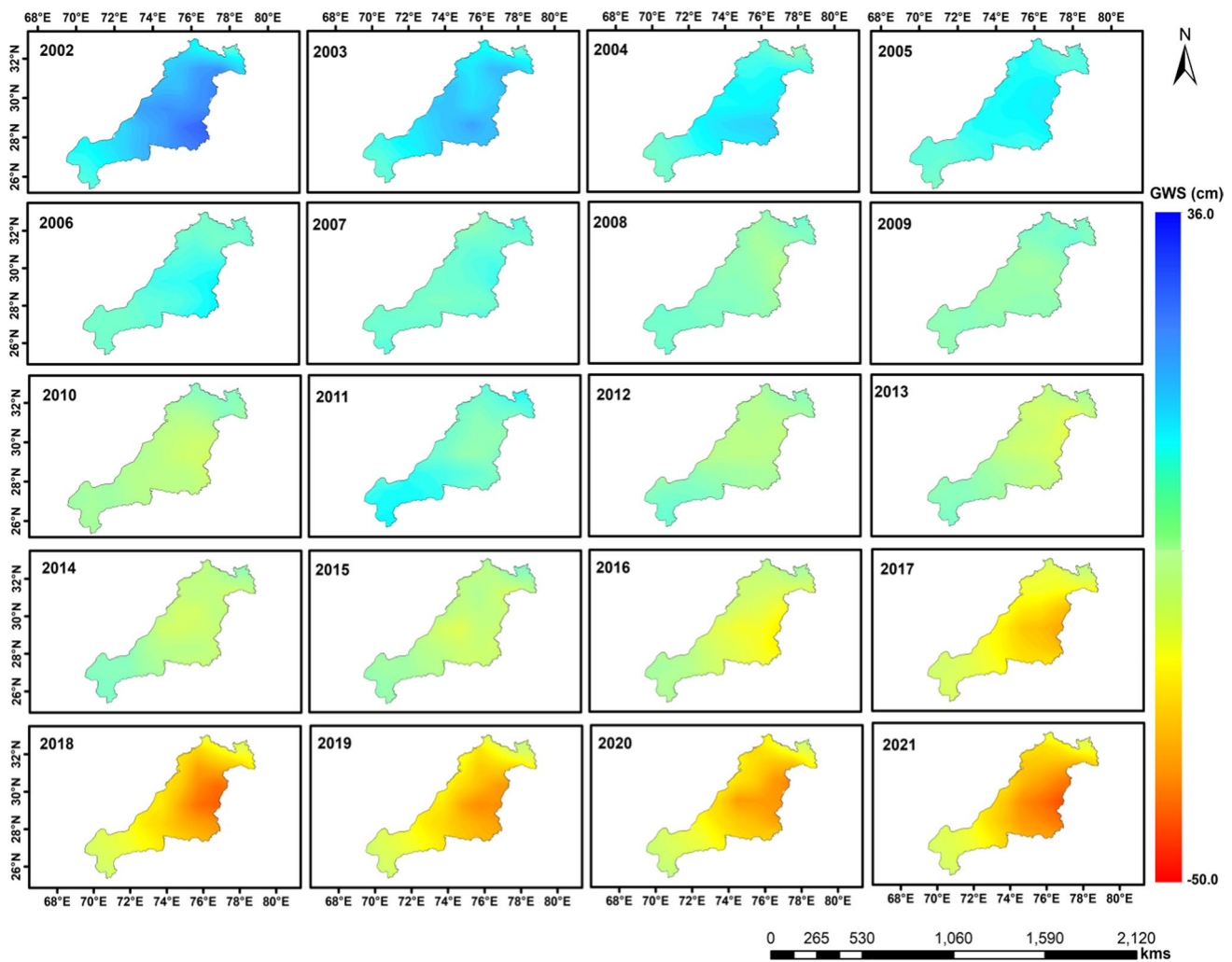
Fig. 15 GRACE and GRACE-FO estimate annual (average of all months) groundwater storage variations over a part of the Indus Basin during the period from 2002 to 2021

Discussion

This study utilized GRACE and GRACE-FO data to track TWS and GWS over a part of the Indus Basin. The results of TWS and GWS in different months have showed a decreasing pattern. The negative TWS and GWS indicate that water storage is progressing towards a downward trend due to the overuse of water (Figs. 8 and 9). The negative sign indicates the deviation from the baseline average (January 2004 to December 2009) which shows a large number of water decreases in the area. The large negative values (red color) show a greater decrease of TWS and GWS over the area. These results show that years 2010, 2016, and 2020–2021 has been identified as high water stress condition which is completely reversed from the year 2002. The north, northeast, and central part of the study area have experienced the highest amount of water storage reduction. The spatial and temporal variabilities of GRACE-derived TWS and GWS

integrate changes in water storage from the land surface to the deepest aquifer. These results also indicate that TWS and GWS decline trends of this magnitude can lead to drought as well as serious threats to agriculture, ecosystems, and socio-economic development.

Many researchers have estimated terrestrial water storage and groundwater storage changes from river basins to global scales through GRACE and GLDAS products [7, 11, 12, 17–19, 22, 24, 29–31, 34–38]. These products have shown a significant reduction in water storage worldwide. Additionally, few studies have shown a favorable comparison between GRACE missions and CGWB groundwater level data. Chinnasamy et al. [11] reported that the GWS trends from GRACE over the Gujarat region were in favorable conditions with the CGWB groundwater level trends. These changes indicate that water resource monitoring is essential for sustainable water management and the detection of any possible disaster. Punjab and Haryana states are one
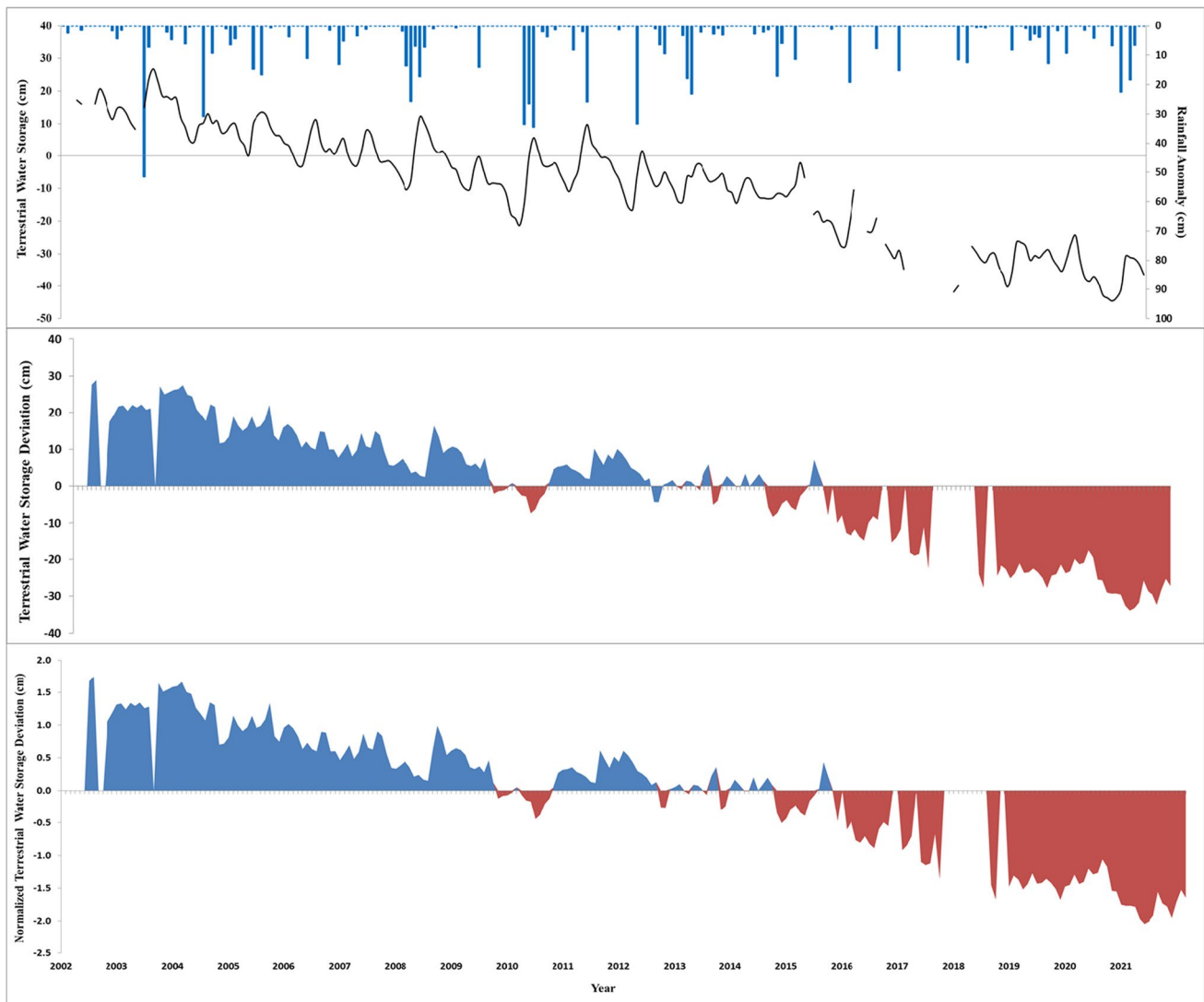
Fig. 16 (upper) Time series of the domain average of the terrestrial water storage, (middle) terrestrial water storage deviations which represent the surplus (in blue) and the deficit (in red), and (lower) normalized terrestrial water storage deviation over Haryana state

of the largest producers of agricultural products (like rice, wheat, jowar, soybean, cotton, and sugar cane) and are highly dependent on water resources for irrigation. Wheat and rice crops use an enormous amount of both surface and groundwater. Punjab and Haryana states produce 50% of the rice crops of the entire India. Out of the 99.9% irrigated area in Punjab, 72% area is irrigated through groundwater pumping and 28% is irrigated through canal water. So, there is a lot of stress on water resources, especially on groundwater resources [39].

The GRACE mission also has the potential for regional water management in response to drought [40]. It provides an integrated measure of the amount of water storage changes on and below the Earth's surface during drought conditions [41]. According to NRAA 2013 [42] report, the most of periods with major downward trends in water storage is coincidental with drought conditions in India. Indian regions have experienced a total of ~24 large-scale droughts during the period between 1891 and 2012 [42] and have caused environmental and socio-economic losses [43–45]. Such severe droughts have affected not only surface water (e.g., reservoirs, lakes, rivers) but also groundwater. Sinha et al. [45] reported that the meteorological drought of 2009–2010 and 2012–2013 was conspicuous in different climate regions of India. Drought is controlled by the spatial–temporal variability of rainfall and the amount of terrestrial and groundwater stored. These changes are further exacerbated by anthropogenic stresses like population
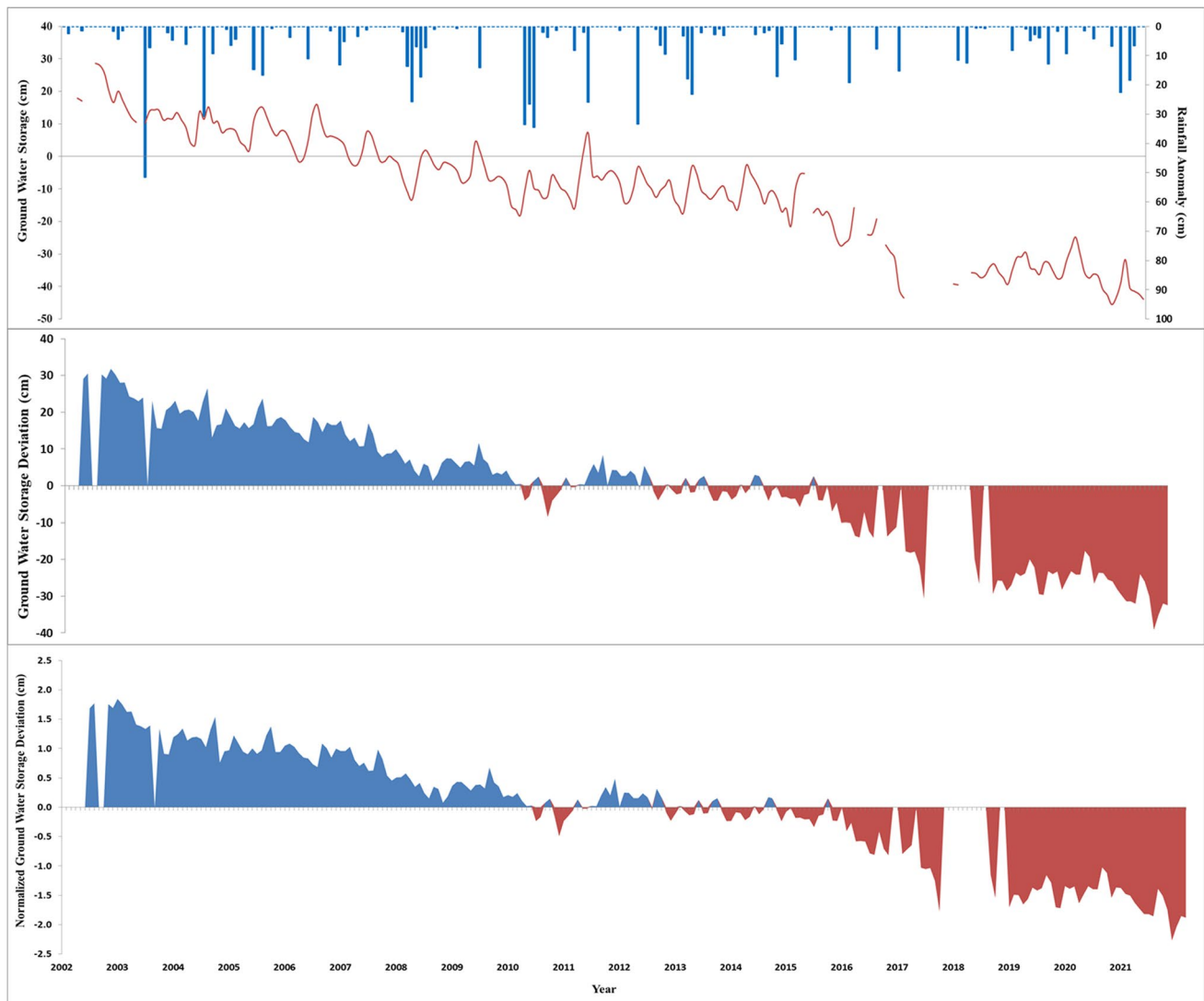
Fig. 17 (upper) Time series of the domain average of the groundwater storage, (middle) groundwater storage deviations which represent the surplus (in blue) and the deficit (in red), and (lower) normalized groundwater storage deviation over Haryana state

growth and growing industrialization and agricultural activities.

The study showed that TWS and GWS derived from GRACE missions and rainfall data derived from GPM are highly correlated (Figs. 4 and 5). We found that when high rainfall has occurred over the study area, there have been experienced some positive changes in the water storage. We have observed a gradual recovery of TWS and GWS. A maximum gradual recovery of water storage trends has been seen in the year 2011 because the year 2010 received a high amount of rainfall over the study area. Tiwari et al. [12] also showed that the positive and negative trends of TWS follow the rainfall pattern. TWS and GWS change measurements are highly difficult to validate with independent datasets due to their integrative nature [26]. This study also included

GRACE-derived TWS and GWS over Punjab and Haryana states which lie in the Indus Basin and compared with rainfall anomaly to see the inter-correlation (Figs. 16, 17, 18, and 19). Managing aquifer recharge by capturing the rainfall-runoff to recharge the aquifer is therefore imperative to ensure water security for agriculture and other uses [21].

The results discussed here illustrate a better understanding of monthly and seasonal TWS and GWS changes over the study region using GRACE missions. This study showed a wide range of variability and magnitude in the TWS and GWS. Both water storage changes occur as a result of complex activities of climate change and anthropogenic activities. The natural changes in TWS and GWS are likely related due to climatic change, hydrological conditions, type of soil deposits, and rock types. Thick soil
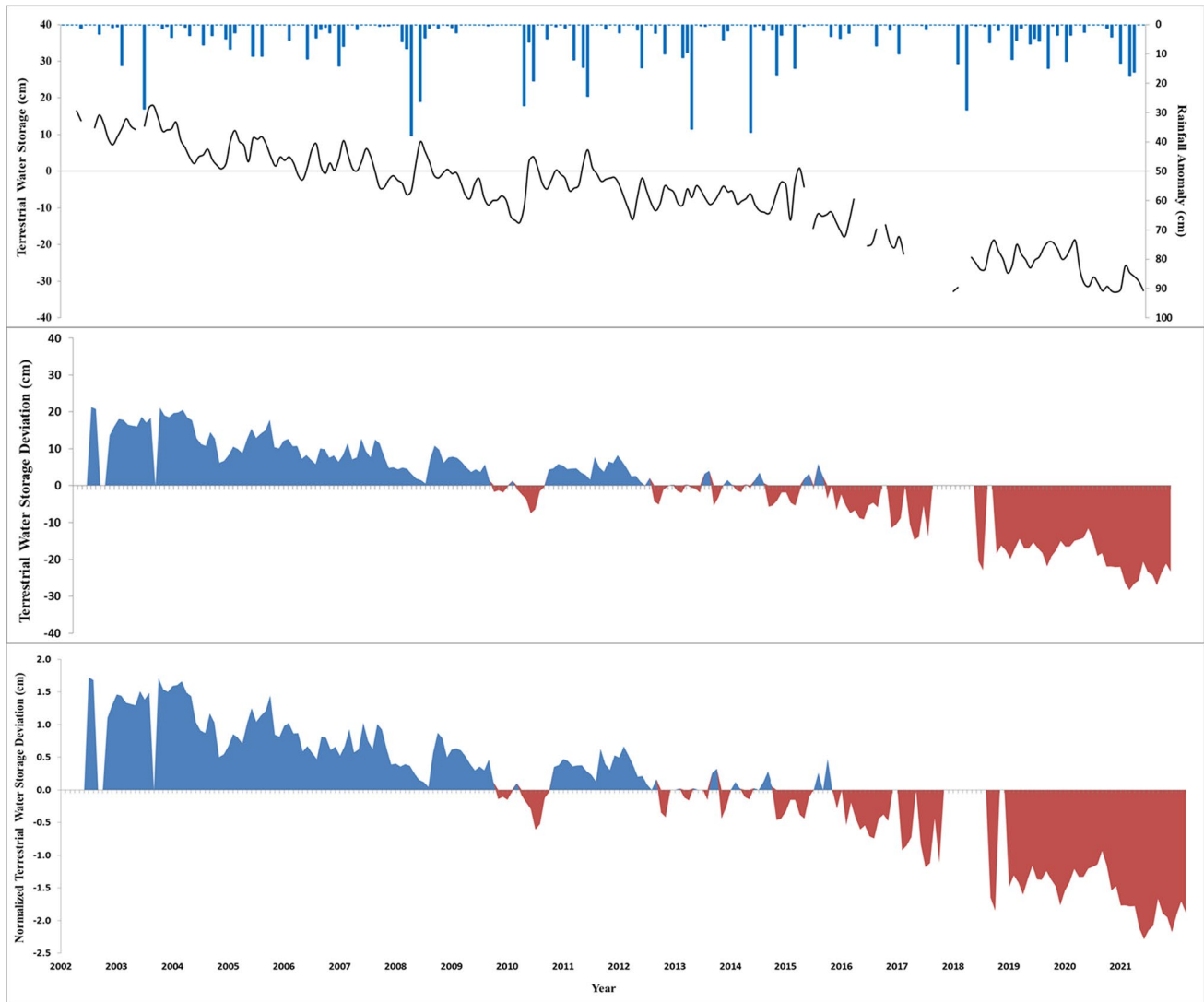
Fig. 18 (upper) Time series of the domain average of the terrestrial water storage, (middle) terrestrial water storage deviations which represent the surplus (in blue) and the deficit (in red), and (lower) normalized terrestrial water storage deviation over Punjab state

deposits have high water retaining capacity as compared to thin soil types and relatively stable groundwater tables [25]. Increasing temperature, evaporation, and less precipitation are the direct effect of climate change which can reduce water storage [2]. Higher temperatures can increase evaporation and thus decrease soil moisture. Climate change can affect not only the frequency and magnitude of precipitation but also the types of precipitation [2]. Syed et al. [35] showed that precipitation, evapotranspiration, and snow melt have a great impact on TWS. Intense agriculture activity, population growth, industrialization, urbanization, dam construction, and improper management are the main anthropogenic factors that influence water storage. The increased irrigation and uncontrolled tube well development have been important factors in the complexity of groundwater management [21]. The use of groundwater has been increasing in the agricultural sector and they are highly dependent on the wells due to the lack of surface water and less precipitation during the monsoon season. If agriculture continues to use groundwater at an unsustainable level then it will lead to social and economic complications. The fluctuations of the groundwater table due to increasing demands and changes in SM and surface water at such rate contribute a dominant role in water storage changes which affect ecosystems, water quality, and soil functionality. GRACE data has gained significant attention for the estimation of TWS and GWS which can be used for sustainable water resource management in the Indus Basin. GRACE missions are helpful to develop insights into how the TWS and GWS change with rainfall over a large area. GRACE and GLDAS data also highlight the potential for improving land surface models.
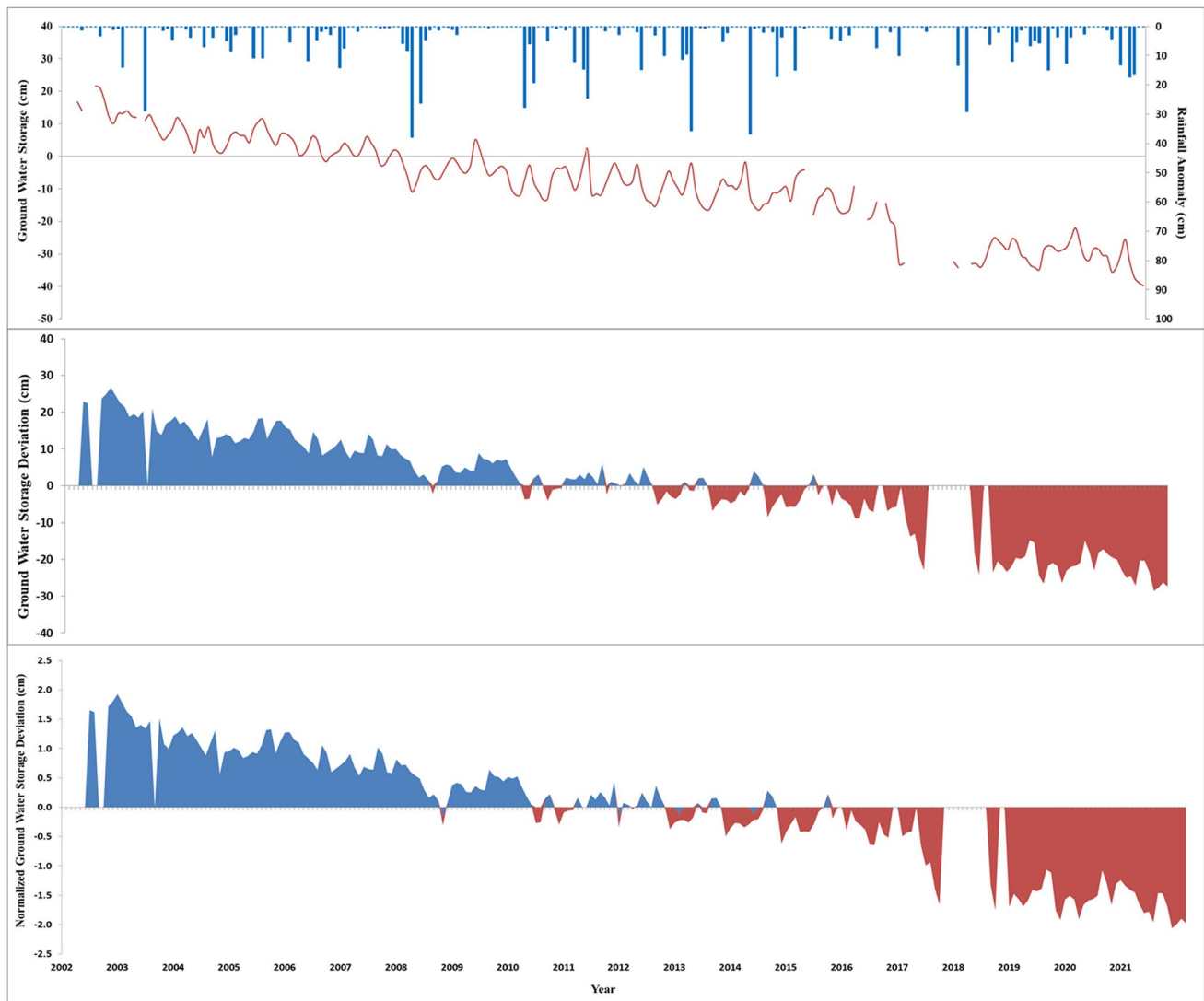
Fig. 19 (upper) Time series of the domain average of the groundwater storage, (middle) groundwater storage deviations which represent the surplus (in blue) and the deficit (in red), and (lower) normalized groundwater storage deviation over Punjab state

Conclusion

The study concludes that GRACE and GRACE-FO data have been used to track TWS and GWS over a part of the Indus Basin where there is a lack of non-spatial data. The downward trends of water storage are a particular concern in the Indus Basin due to pressure from long-term climate change and human activities. Due to limited surface water resources and poor distribution of rainfall over the study area, peoples largely depend on groundwater resources. The intense agricultural activities, uneven rainfall, and domestic consumption have resulted in water resource depletion. GRACE-derived water storage (TWS and GWS) monitoring is particularly useful for the Indus Basin for sustainable water management that lacks sufficient hydrological

monitoring infrastructures on the ground. GRACE-derived water storage changes are also consistent with the meteorological drought. GRACE provides a distinctive quantitative measurement of TWS and GWS while ground monitoring provides discrete sampling. The time series record of GRACE missions revealed that water storage has been decreasing at an alarming rate. Water storage depletion is mainly caused by anthropogenic influences rather than natural over the study area. River flow alteration and dam contraction can be the reason for water resource reduction. The study also concludes that GWS changes may respond slowly to the high amount of rainfall. Management of aquifer recharge by capturing the rainfall-runoff to recharge aquifers is therefore imperative to ensure water security for agriculture and other use. The research indicates that water storage

Fig. 20 Comparison of GRACE and GRACE-FO derived GWS with groundwater level anomaly to see the variations over a part of the Indus Basin
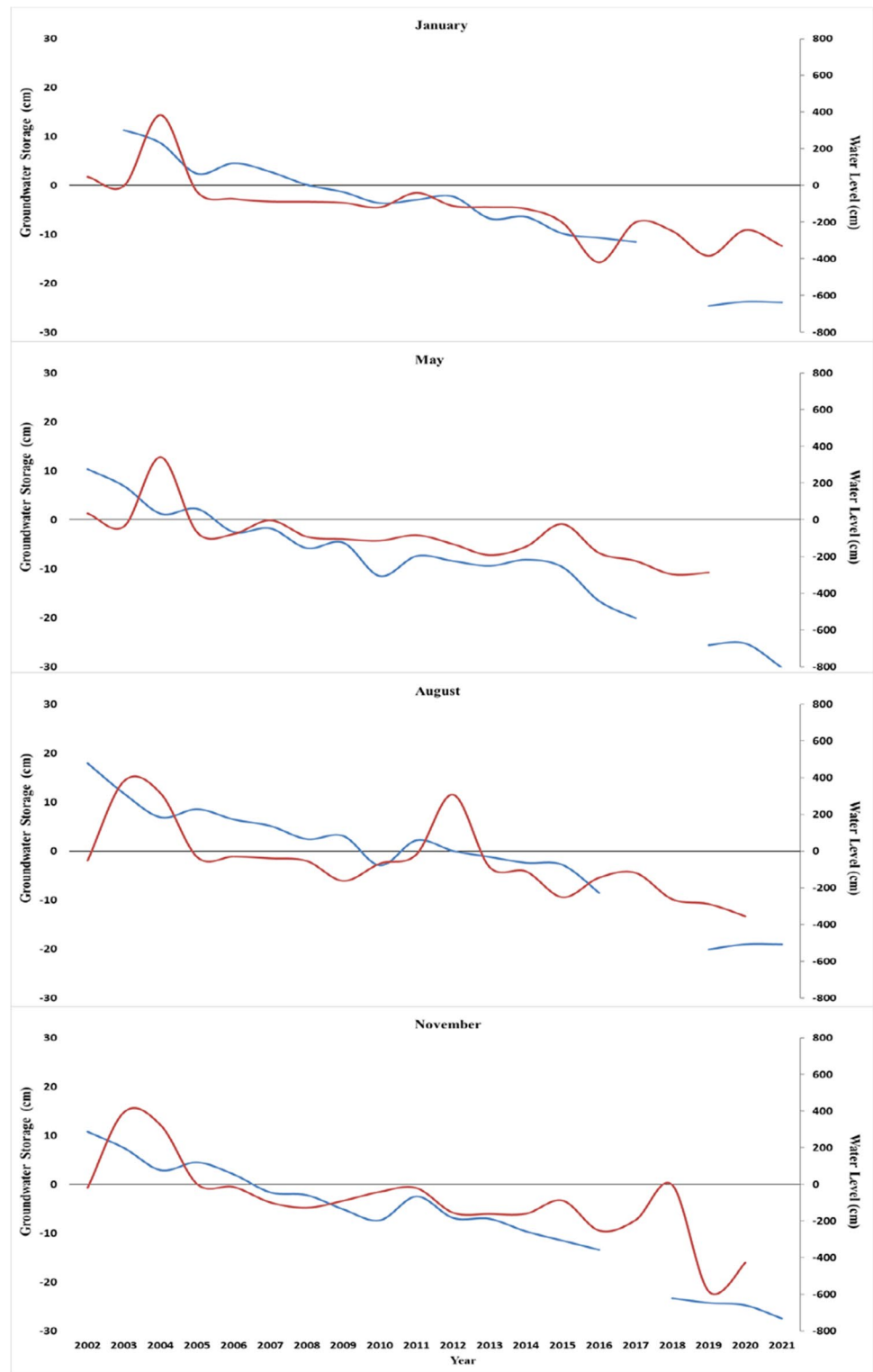
monitoring is essential for sustainable water management and to reduce high-risk impacts in the future. It may aid policymakers to understand the status of water recharge and discharge in each agro-climatic zone.

Declarations

Conflict of Interest The authors declare no competing interests.

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