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Article

Understanding Groundwater Storage Changes and Recharge in Rajasthan, India through Remote Sensing

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Abstract: Groundwater management practices need to take hydrogeology, the agro-climate and demand for groundwater into account. Since agroclimatic zones have already been demarcated by the Government of India, it would aid policy makers to understand the status of groundwater recharge and discharge in each agroclimatic zone. However, developing effective policies to manage groundwater at agroclimatic zone and state levels is constrained due to a paucity of temporal data and information. With the launch of the Gravity Recovery and Climate Experiment (GRACE) mission in 2002, it is now possible to obtain frequent data at broad spatial scales and use it to examine past trends in rain induced recharge and groundwater use. In this study, the GRACE data were used to estimate changes to monthly total water storage (TWS) and groundwater storage in different agroclimatic zones of Rajasthan, India. Furthermore, the long-term annual and seasonal groundwater storage trends in the state were estimated using the GRACE data and the trends were compared with those in rainfall data. The methodology based on GRACE data was found to be useful in detecting large scale trends in groundwater storage changes covering different agroclimatic zones. The analysis of data shows that groundwater storage trends depend on rainfall in previous years and, therefore, on the antecedent moisture conditions. Overall, the study indicates that if suitable groundwater recharge methods and sites are identified for the state, there is potential to achieve more groundwater recharge than what is currently occurring and, thus, enhancing the availability of water for irrigated agriculture.

Keywords: groundwater recharge; rainwater harvesting; remote sensing; gravity recovery and climate experiment (GRACE); groundwater storage and Indian agriculture

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1. Introduction

Groundwater is a common resource in a watershed, but the absence of an effective framework and measures to sustainably use and maintain groundwater supplies contributes to a complex problem, known as the "tragedy of the commons". Whoever can pump water first owns it and this encourages over-pumping, often in excess of natural recharge to groundwater. Decentralisation and the local-level management of groundwater are not easy since property rights for groundwater are complex. The uncontrolled development of tubewells by individual farmers has been an important factor in the complexity of groundwater management in India [1,2]. Understanding the groundwater system dynamics at regional and district levels is difficult due to the time, effort and expenses involved in monitoring groundwater levels. The monitoring at the village or small watershed scale is useful in understanding changes in groundwater storage at the local level, but such monitoring is of limited value for developing strategies for groundwater management and policy development at the state and national levels. Hence, groundwater resource assessments should be conducted at scales that are already demarcated by government agencies, such as agroclimatic zones, so that management boundaries coincide with strategies identified by the government. Rajasthan state is one such Indian state with complex agroclimatic zones and in urgent need of augmenting groundwater resources.

The Rajasthan state is home to 56 million people and has more than three quarters of its population living in rural areas. It has a total geographical area of 340,000 km^2 and is the largest state by area in India. The state accounts for more than 10% of India's geographical area, supports about 5% of the human population and 20% of the livestock but only possesses 1.2% of the total surface water and 1.7% of the groundwater available in India. The Aravalli hill ranges, running from north east to south-west, divide the state approximately into the western arid and eastern semi-arid regions [3–5].

Rajasthan's economy has undergone considerable transformation in the recent past, with agriculture (including livestock) providing one-fourth of the state's GDP. Approximately 5.4 million households are engaged in farming, while 60% of the state's population depend on agriculture for their livelihood. Nearly half of them are small or marginal farmers, with cultivation land less than 0.01 km^2 (*i.e.*, one ha). Given the size of the agriculture sector, improved agriculture productivity is also one key element for a further structural transformation of the overall economy of the state [6]. As such, agriculture plays an important role in the livelihood of people in the state, but water scarcity is a critical issue.

Like many parts of India, Rajasthan's rainfall during the monsoon season is highly variable and uncertain from one year to the next. Hence, groundwater resources are important for crop production. Managed aquifer recharge by capturing the rainfall runoff to recharge aquifers is therefore imperative to ensure water security for agriculture and other uses. The rainfall season commences at the end of June and may continue until the early part of October; a major proportion of the rainfall occurs between July and September. Due to poor distribution of rainfall, through the year, Rajasthan farmers depend on groundwater resources for much of their irrigation.

Rajasthan is heavily dependent on groundwater for irrigation and about 90% of the drinking water and 60% of the irrigation water is sourced from groundwater supplies. During the 1970s and 1980s, the era of Green Revolution in India, there was widespread use of groundwater in Rajasthan and the pressure on groundwater is further increasing due to population growth and an increased number of industries. About 80% of the State areas have witnessed groundwater depletion and many towns and villages have experienced a shortage of drinking water, particularly in summer months [7].

In recent years, the Government of India has given due impetus to identifying constraints to sustainably increase agricultural productivity through site specific research in each agro-climatic zone. The National Agricultural Research Project (NARP) delineated agroclimatic zones based on soil type, temperature, rainfall (agrometeorological characteristics) and geologic constraints. The scales of each zone were also made appropriate to suit administrative boundaries. The state of Rajasthan has 10 agroclimatic zones (Table 1). Even though the Central Ground Water Board monitors groundwater levels at quarterly intervals (*i.e.*, four times a year), only 5% of the monitoring wells in Rajasthan monitor deep aquifers. As a result, the CGWB analysis on Rajasthan's groundwater status is related to the unconfined (shallow) aquifers. Since many irrigation wells in Rajasthan tap the confined water resources (deep aquifers), it is therefore necessary to have more observations of deep aquifer status across the state. Owing to the paucity of data and limitations in deep aquifer monitoring wells in other global locations, many scientists have used remote sensing data to estimate groundwater storage trends (e.g., [8–10]).

Table 1. Agroclimatic Zone area in Rajasthan.

Agroclimatic Zone	Area (km^2)
Arid western plains	51,237
Flood prone eastern Plains	26,560
Humid southern plains	8808
Humid south eastern Plains	24,170
Hyper-arid partially Irrigated zone	82,475
Internal drainage dry	25,450
irrigated north western plains	20,660
Semi-arid eastern plains	30,256
Sub-humid southern Plains	42,706
Transitional plain of Luni basin	51,013

The launch of the Gravity Recovery and Climate Experiment (GRACE) mission in 2002 has enabled indirect monitoring of different components of the hydrologic cycle and, therefore, it is now possible to estimate total water storage (TWS) at broad spatial scales [9,11]. The overall aim of this study is to evaluate the potential of GRACE data for estimating groundwater storage changes in different agroclimatic zones of Rajasthan on monthly scales. In particular, the study is focussed on identifying the long-term annual groundwater storage trends at the state and agroclimatic zone levels and examining the relationship between actual rainfall and rainfall anomalies. Further, the GRACE data are used to estimate groundwater recharge and discharge at the state and agroclimatic zone levels.

2. The Study Area

The Rajasthan State (Figure 1) has an area of 342,000 km^2 and its climate is marked by frequent droughts, a short monsoon season, from July to September, resulting in annual rainfall ranging from 150 to 900 mm in different parts of the state with an average annual mean of 576 mm, and temperatures ranging from 5 to 45 °C. Agriculture continues to be largely dependent on rainfall, leaving the state highly vulnerable to drought-induced water stress, and, therefore, groundwater plays an important role in agriculture. Notably, the groundwater dependent districts in the state are also experiencing higher levels of competition for groundwater use, suggesting that farmers' demand for groundwater irrigation is unlikely to slow any time soon [3,4]. Except for Sri Ganganagar and Hanumangarh districts, all other districts depend heavily on groundwater for the bulk of their irrigation potential.

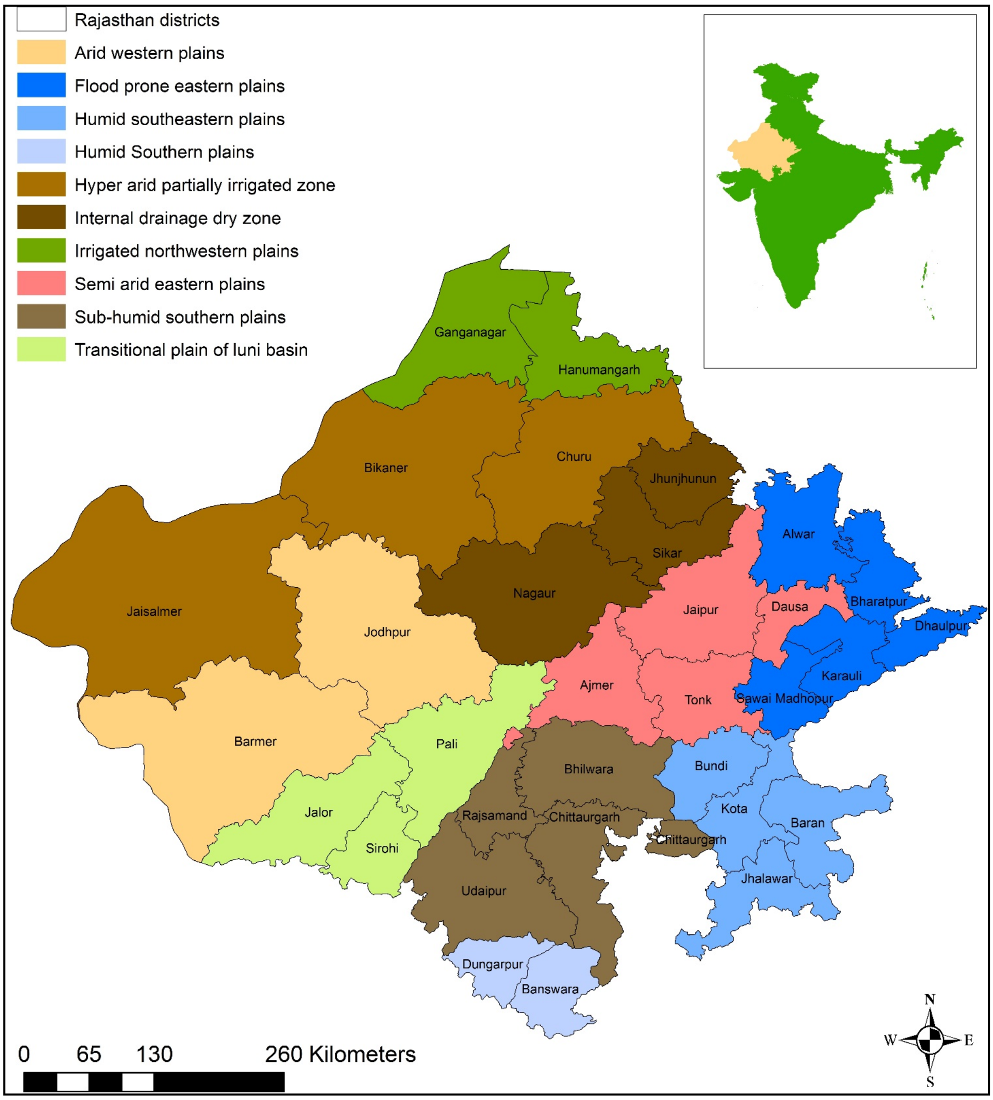

Figure 1. Rajasthan state with different agroclimatic zones. The inset shows the location of Rajasthan state in India.

In order to understand the groundwater use and agriculture, the State can be divided into seven agroclimatic zones: (i) Arid Western Plain; (ii) Transitional Plain of Luni Basin; (iii) Semi-arid Eastern Plain; (iv) Flood Prone Eastern Plains; (v) Sub-humid Southern Plains and The Aravalli Hills;

(vi) Humid Southern Plains and (vii) Humid South-Eastern Plains (Figure 1). The crops grown vary with the zone and include millet, maize, guar, sesame and pulses such as Kharif crops and wheat, rape-seed, gram and mustard as Rabi crops are mostly irrigated.

3. Data Collection and Analysis

3.1. Rainfall Data

Rainfall data, from 2004 to 2013, were obtained from the Indian Meteorological Department (IMD) for the state of Rajasthan. In addition, rainfall data from 1973 to 2013 were obtained from the IMD for the Udaipur district of Rajasthan. A total of 40 stations was recorded in Udaipur. The average of the stations was used for the current study. It is noted that the exact location of the weather stations were not available. IMD avails district averages for each month, which were used in this study. The monthly data were aggregated to obtain annual averages to meet the objectives of the study.

3.2. Terrestrial Water Storage (TWS) Data—Gravity Recovery and Climate Experiment (GRACE)

In-situ monitoring of watertable depth, soil moisture and other parameters provide discrete sampling, whereas gravity observations through the Gravity Recovery and Climate Experiment (GRACE) provides a distinctive quantitative measurement of TWS anomalies that were not available to earlier researchers. In particular, GRACE helps to complete the terrestrial water storage budget by providing a quantitative estimate of total water mass change over time [12]. The GRACE mission was launched on 17 March 2002, as a combined effort between the United States National Aeronautics and Space Administration (NASA) and the Centre Deutschen Zentrum für Luft- und Raumfahrt (DLR) from the German Aerospace agency. GRACE is the first remote sensing satellite that can estimate groundwater storage anomalies for the entire globe on a monthly basis. GRACE records changes in mass that affect the gravitational pull on the two satellites, which is later converted to land mass grid solutions.

For this study, a scaled version of the GRACE data—processed and archived by Landerer and Swenson [13]—were used. This enabled the estimation of TWS at 1° by 1° resolution (approximately 100 by 100 km at the Equator). TWS data, in 1° by 1° grid-cells format and at monthly resolution (version RL05), are available from the NASA Jet Propulsion Laboratory website [14]. The corresponding scaling factors [13] are also available from the aforementioned website. In addition, the scaling factors accounted for the GRACE data errors, *i.e.*, leakage errors (caused by GRACE signal leakage from neighbouring land and ocean grids) and measurement errors (caused by errors in processing the raw GRACE data). The GRACE grids were then multiplied by the scaling grids to arrive at terrestrial water storage estimates for the study site. It is to be noted that the newly released RL05 GRACE data minimizes errors due to leakage and measurement errors and improves the spatial resolution (1 × 1 degree) [13]. This enabled water storage analysis for regional, district [15,16] and even watershed scale (e.g., as in [17] whose study areas were from 30 to 7000 km^2) water resources assessments. In addition, GRACE data are only available as monthly anomalies with a baseline average (from January 2004 to December 2009) removed, to understand long-term trends in terrestrial water storage. The GRACE data processing team defines the baseline period, and hence it cannot be changed. Further information regarding the GRACE data solutions [18], degree one coefficients [19], and glacial isostatic [20] used to process the data were accessed from the GRACE data download page [13]. Monthly data from 2002 to 2013 were downloaded. Land mass variability caused by changes to snow water equivalent was not considered in this study as the amount of snow is negligible in Rajasthan.

3.3. Soil Moisture (SM) Data—Global Land Data Assimilations System (*GLDAS*)

The Global Land Data Assimilations System (GLDAS) was initiated and maintained, in unison, by researchers at the United States NASA Goddard Space Flight Centre (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) in order to estimate and archive changes in land and ocean mass fluxes [9,21–23]. The GLDAS team utilises land surface models (LSMs) to estimate total soil moisture across the globe at different spatial and temporal resolutions. The LSMs are driven by remote sensing data collected from various remote sensing missions and platforms. Of the LSMs, Noah, the Common Land Model (CLM), Mosaic, and the Variable Infiltration Capacity (VIC) model are the widely used models.

In this study, Noah version 2.7.1, was used to estimate soil moisture ranging from 0 to 200 cm in depth. Noah was chosen over the other GLDAS models given the demonstrated successful applications of Noah for the Indian subcontinent, particularly in Northern India (e.g., [8,9]). Information on the Noah model and other GLDAS-LSMs can be obtained from the Goddard Earth Sciences Data and Information Services Centre [24].

For this study, Noah data contained, in gridded format, monthly averages of soil moisture for the state of Rajasthan at spatial and temporal scale (1° grid-cells/monthly resolution) similar to that of the GRACE data. The total zone soil moisture (SM) in the subsurface was estimated by summing soil moisture values from four depths: 0–100 mm, 100–400 mm, 400–1000 mm, and 1000–2000 mm. The soil moisture (SM) estimates were then coupled with GRACE estimates of TWS to arrive at net groundwater storage.

3.4. Groundwater Storage (*GW*)

Similar to the methodology used in earlier studies [8,9,11,25,26], groundwater storage was estimated using TWS (GRACE) and SM (GLDAS) using the following equation:

$$\mathrm{GW} = \mathrm{TWS} - \mathrm{SM} \tag{1}$$

where TWS is terrestrial water storage estimated using GRACE (cm), SM is soil moisture storage using GLASA (cm), and GW is groundwater thickness (cm). Since the intent of this study was to also compare GRACE and CGWB estimates, monthly GRACE and GLDAS grids for the time period from August 2002 to August 2013 were used to estimate net GW for each month.

4. Results and Discussion

4.1. Rainfall Trends

The rainfall hyetograph, for the duration of 10 years (2004–2013), was developed from the monthly rainfall data obtained from the IMD for the entire state of Rajasthan, for all the districts in the state of Rajasthan (Figures 2–4). The average recorded rainfall for the entire state of Rajasthan from 2004 to

2013 (Figure 2) was 572 mm, with 2009 recording the lowest (378 mm) and 2013 the highest (720 mm). The average annual rainfall for the 10 year period was increasing at the rate of 21 mm per year, with a minimum and maximum of 378 and 734 mm per year. The district rainfall analysis for the 10-year period (2004–2013) indicates that the highest rainfall occurred in Banswara district (995 mm), while Jaisalmer district received the lowest rainfall average (231 mm) in the state. For Udaipur district, data for 20 years (1994–2013) were available and were used for developing rainfall hyetograph (Figure 4).

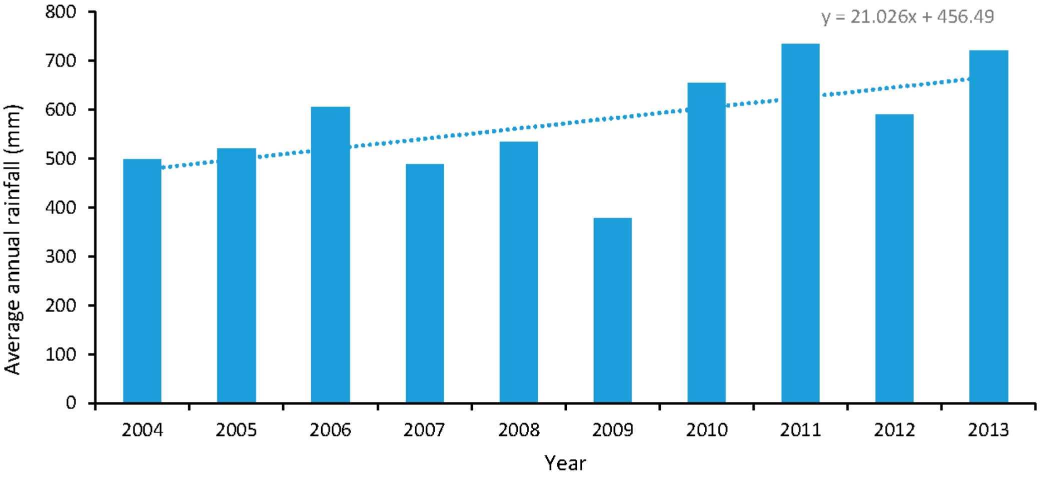

Figure 2. Rainfall hyetograph for Rajasthan state from 2004 to 2013.

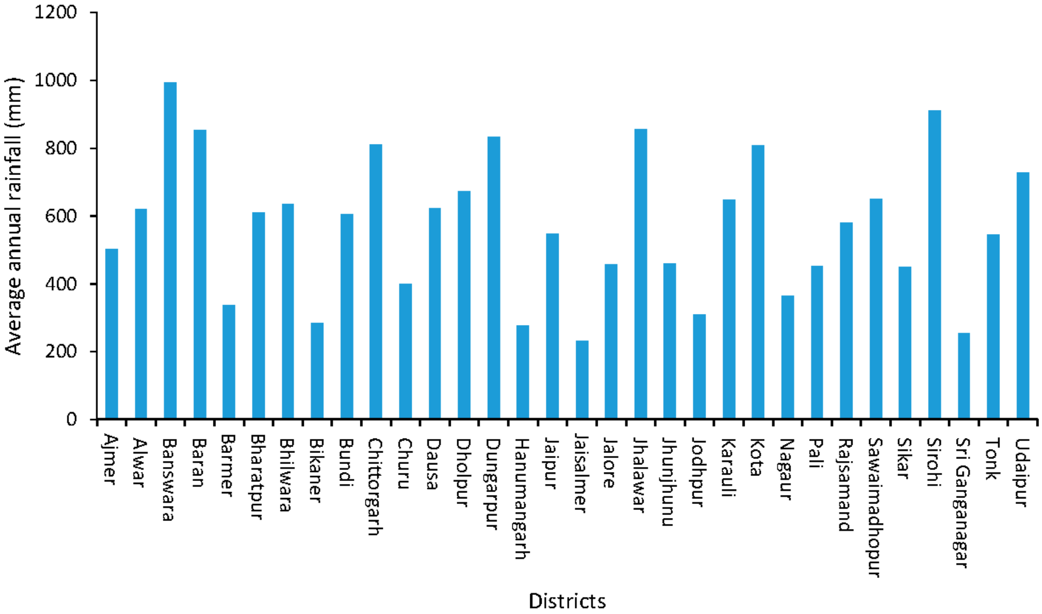

Figure 3. District average annual rainfall hyetograph in Rajasthan from 2004 to 2013.

Figure 5 shows the annual average rainfall distributed between the agroclimatic zones of the state. The humid southern plains have the highest rainfall (914 mm per year) while the irrigated drainage dry zone had the lowest rainfall (265 mm per year). The higher irrigation activity at this zone could be due to the lower rainfall pattern.

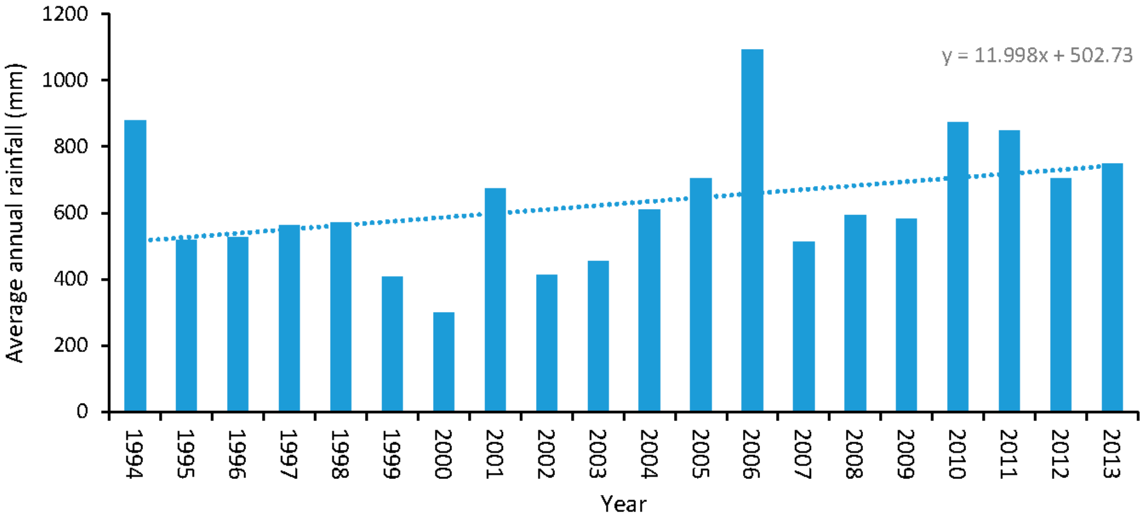

Figure 4. Rainfall hyetograph for Udaipur district of Rajasthan from 1994 to 2013.

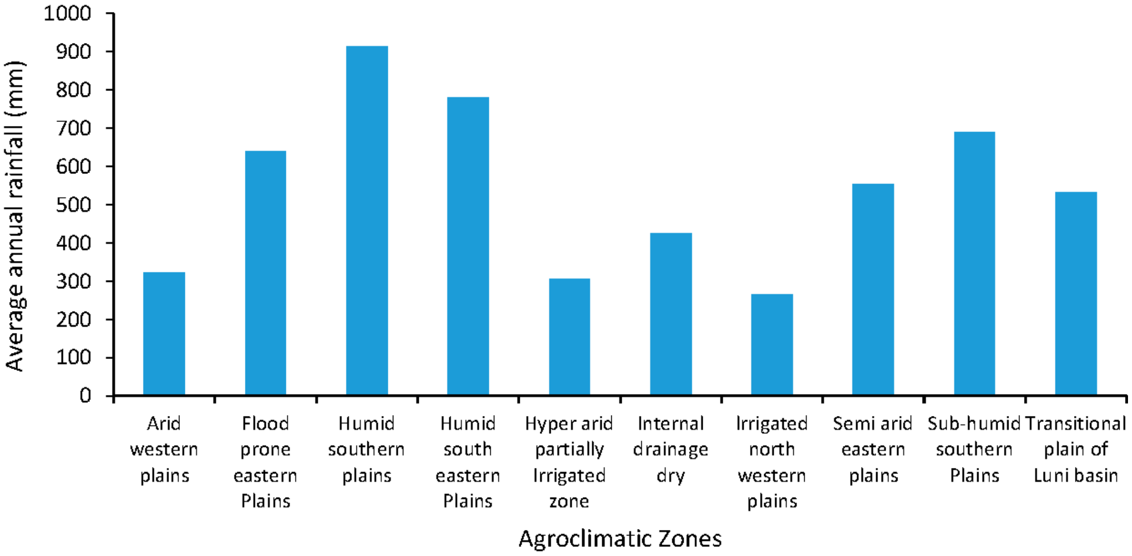

Figure 5. Agroclimatic Zone average annual rainfall hyetograph in Rajasthan from 2004 to 2013.

4.2. State Level Groundwater Storage Anomalies

State level groundwater storage anomaly for the month of October is depicted in Figure 6 for Rajasthan. The average of groundwater storage between 2004 and 2009 is removed to arrive at monthly groundwater storage anomaly values to better understand deviation in groundwater storage trends. Hence, the groundwater storage estimates are provided as anomalies with a positive value if the groundwater storage is above the average, and a negative if below. October represents the end of monsoon for Rajasthan; hence, the current study shows only the image for the October months in Figure 6. The image indicates a more negative trend post 2009. The fact that the groundwater storage trends gradually change to negative indicates that the groundwater storage trends for Rajasthan also depend on antecedent moisture conditions.

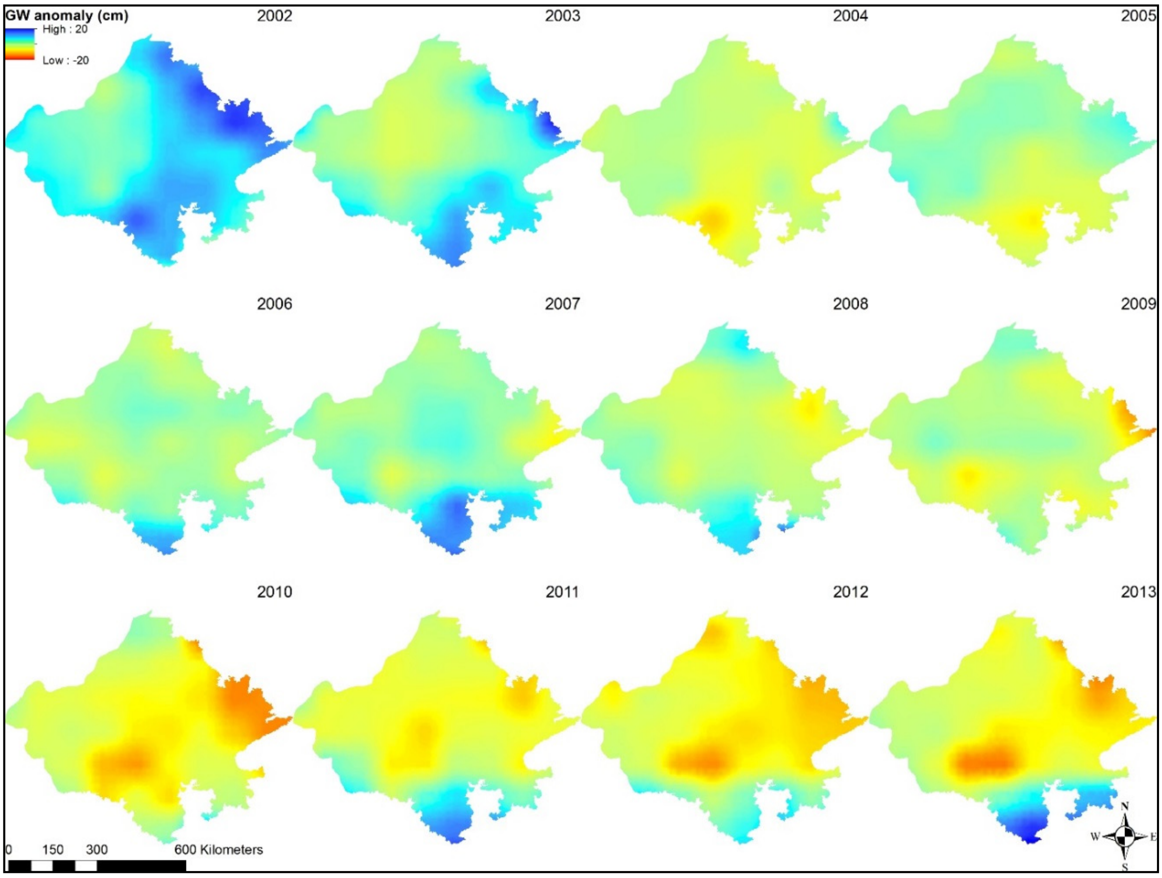

Figure 6. GRACE estimates of groundwater storage anomaly for the Indian state of Rajasthan for the month of October.

4.3. Effects of Rainfall Amounts on Groundwater Storage Change

To analyse the fluctuation of groundwater storage trends due to changes in rainfall patterns, rainfall data were compared against GRACE estimates of net groundwater storage (Figure 7). Net groundwater storage is the difference in GRACE groundwater estimates between October (end of monsoon) and June (end of summer) for the same calendar year. A dry spell during 2002 (53% less rainfall) was responsible for a lower groundwater storage in Rajasthan. Previous year datasets for GRACE were unavailable, as the mission commenced only from the year 2002. Figure 6 indicates a gradual recovery of groundwater storage trends after average rainfall (540 mm) in 2003 and 2004. The lag in response of the aquifer for rainfall in 2003 and 2004 may be explained as follows. It appears that the soil profile was dry during the extended period of drought, and rains in 2003 and 2004 have increased storage closer to their field capacity. Subsequent rains have induced drainage below the soil profile and recharged the aquifer [27].This means a longer recharge time is needed for regions which undergo continuous drought for several years and then experience a series of wet years. Consequently, Managed Aquifer Recharge (MAR) structures can play an important role in capturing available rainfall, preventing flash floods, storing rainfall in the surface/subsurface and increasing infiltration rates leading to increased groundwater recharge and water storage.

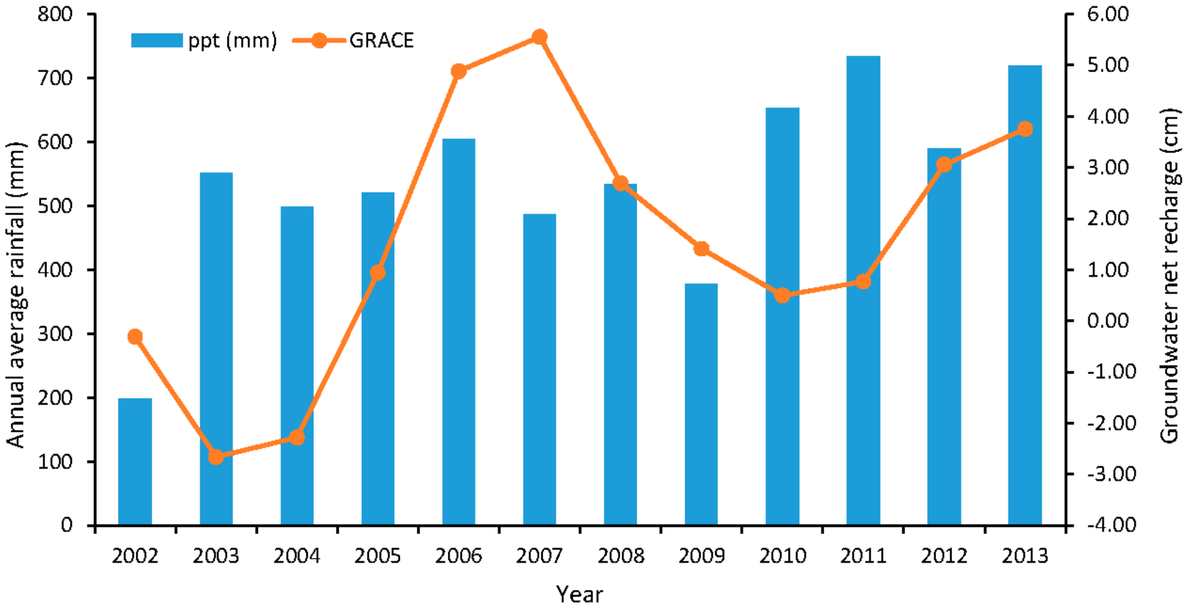

Figure 7. Comparison between annual average rainfall and GRACE net estimated groundwater recharge.

To reconfirm the aforementioned behaviour, the groundwater storage trends were compared against rainfall anomaly for Rajasthan. It is noted that a major drought was experienced over India, including Rajasthan state, in the year 2002 with a seasonal rainfall deficit of 21.5%, a result of 56% below normal rainfall for July [28]. The 12-year (2002–2013) rainfall data was averaged and removed from each year's annual rainfall to arrive at annual rainfall anomaly values. This is similar to the GRACE data anomaly processing. This is done to understand a particular year's rainfall behaviour from long-term average, *i.e.*, if the rainfall is above average or below average. The rainfall anomaly analysis (Figure 8) indicate that 2002–2009 (average rainfall 472 mm) was a drier spell when compared to 2010–2013 (average rainfall 675 mm). Furthermore, the net groundwater recharge trends follow the rainfall anomaly data.

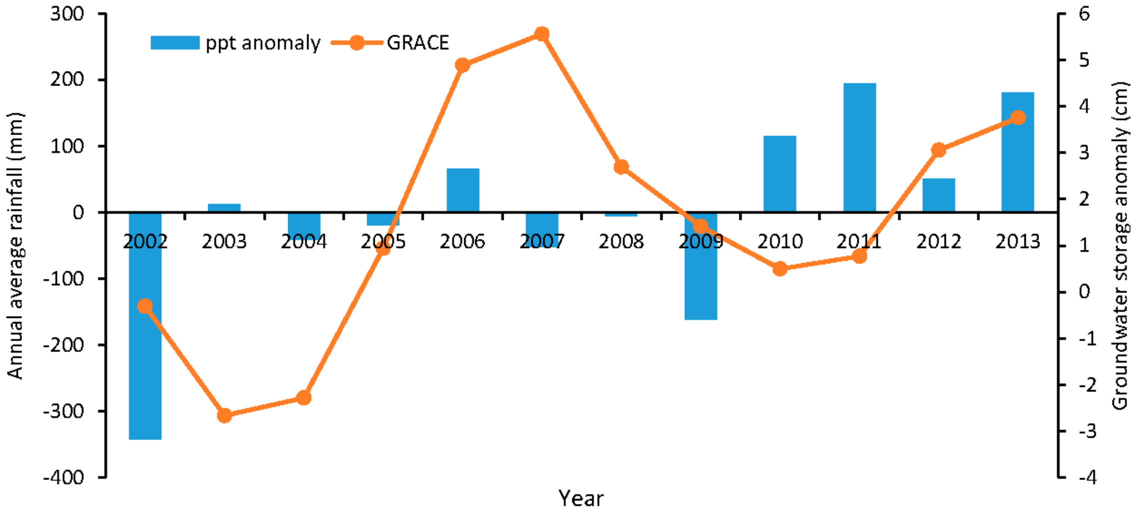

Figure 8. Comparison of precipitation anomaly (anomaly calculated using average of 2002–2013) and GRACE net estimated groundwater recharge.

4.4. Effects of Agroclimatic Zones

4.4.1. Groundwater Storage Changes

The agroclimatic zonal (AGZ) groundwater storage anomaly trends in June (pre monsoon) are shown in Figure 9. Years 2003 and 2013 had above average June storage (*i.e.*, positive anomalies) when compared to the other years for Rajasthan. The flood-prone eastern plains AGZ had the highest groundwater storage of all AGZs in Rajasthan for the 12-year study period. However, during the dry years (e.g., 2012), the flood-prone eastern plains show the least groundwater storage when compared with other AGZs. This could be due to the nature of the flood-prone eastern plains soil that responds more rapidly to precipitation trends. The 12-year groundwater storage anomaly trend indicates an increase in annual recharge (from the average storage for the study period) equivalent to 0.24 cm water depth spread over the entire state or 0.8 billion cubic meters (BCM) of water, which is about 100 mm of irrigation over 8000 km^2 land.

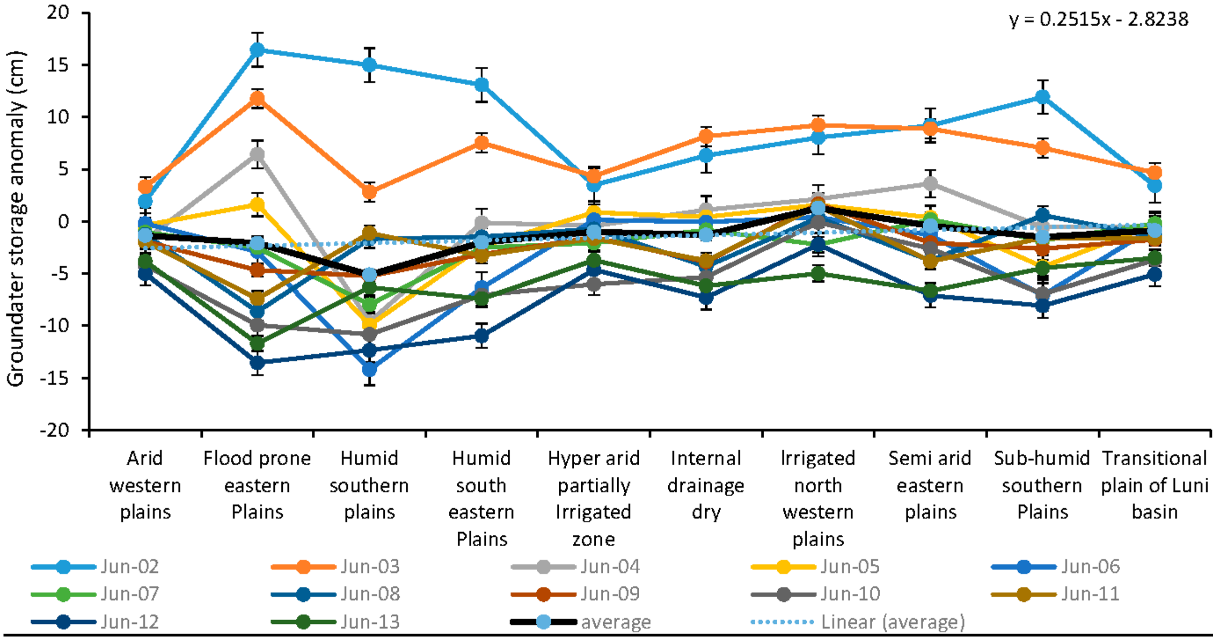

Figure 9. Variations in agroclimatic zonal GRACE estimates of groundwater storage anomaly in the Indian state of Rajasthan for the month of June. Bars indicate standard error.

The AGZ groundwater storage trends for October (post monsoon) are shown in Figure 10. The trends show a similar trend as for the June month. The 12-year average is still above the baseline (2004–2009) indicating an increase in groundwater storage trends (hence positive anomalies). The humid southern plains show the highest increase in groundwater storage (2013) while the flood-prone eastern plains recorded the lowest groundwater storage in 2010. The 12-year groundwater storage trend for October is slightly decreasing from the baseline average at 0.18 cm (0.6 BCM) per year which is equivalent to a loss in irrigation water supply of 100 mm of irrigation on 6000 km^2. The AGZ groundwater storage trend for December (Figure 11) shows the flood-prone eastern plain region having the highest groundwater storage anomaly in 2002 and the least in 2012. The average anomaly trend for all AGZ showed an increase at a volumetric rate of 0.034 BCM per year (thickness increase of 0.01 cm per year).

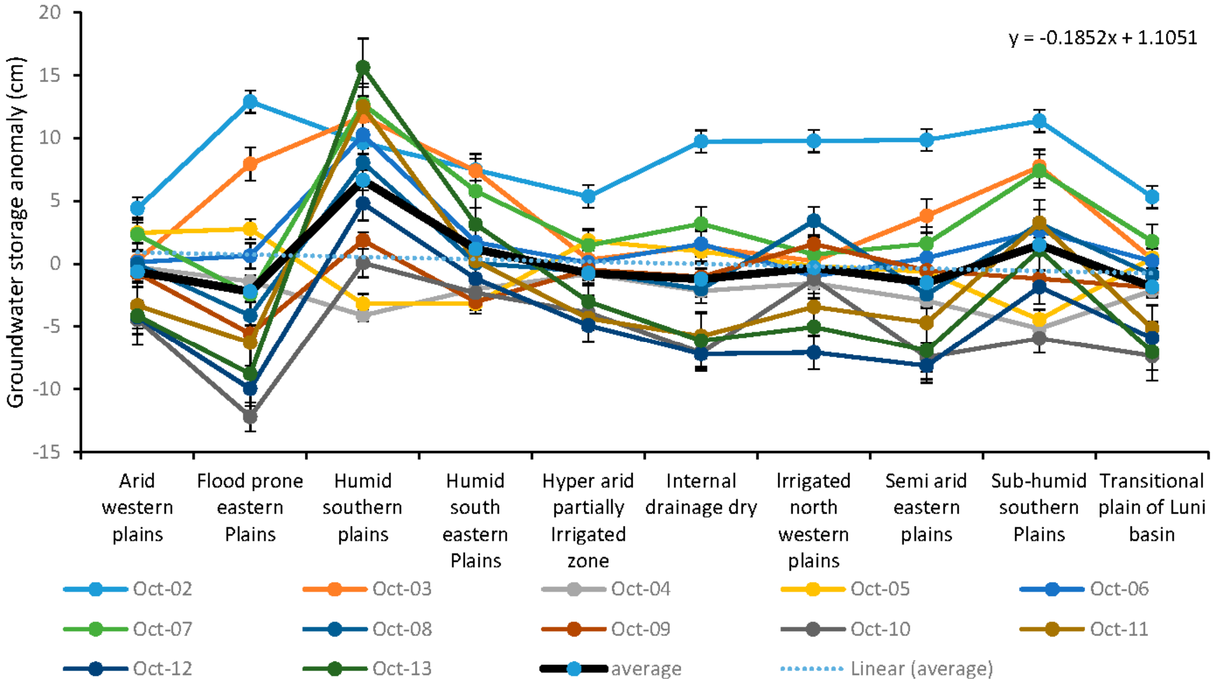

Figure 10. Variations in agroclimatic zonal GRACE estimates of groundwater storage anomaly in the Indian state of Rajasthan for the month of October. Bars indicate standard error.

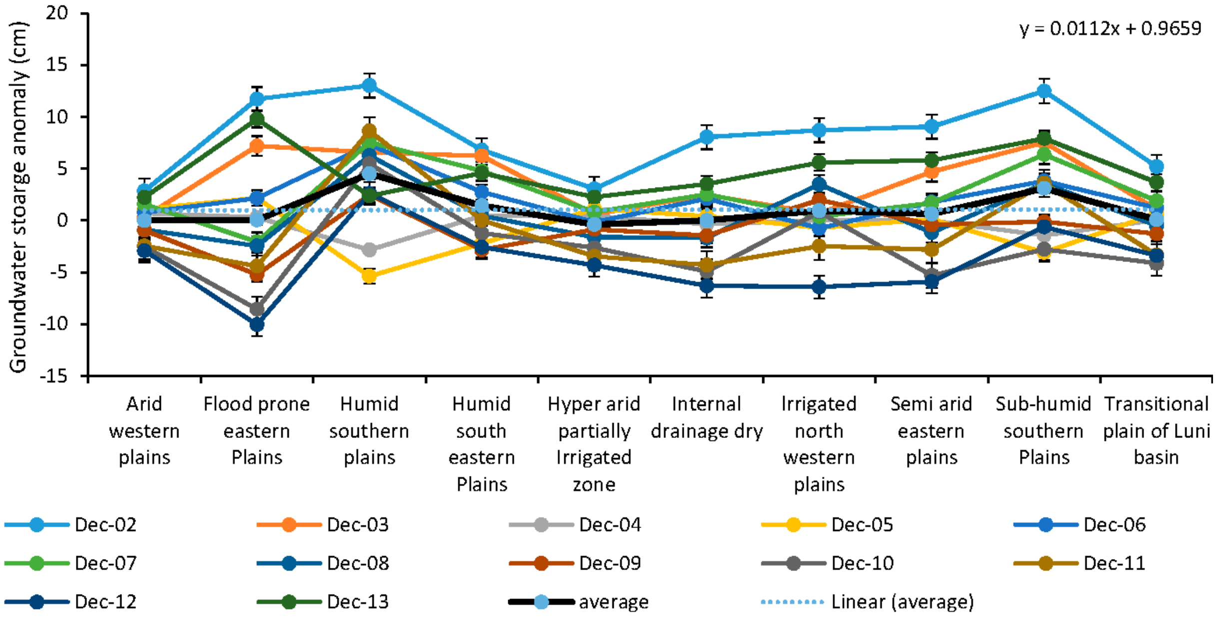

Figure 11. Variations in agroclimatic zonal GRACE estimates of groundwater storage anomaly in the Indian state of Rajasthan for the month of December. Bars indicate standard error.

The aforementioned rates can be compared against CGWB estimated rates [29] to have a perspective on the increasing trend in the state. The [29] report indicates that the net annual replenishable groundwater resource for Rajasthan in 2009 was in the order of 11.860 BCM, of which 9.430 BCM and 2.430 BCM recharge occurred in monsoon and non-monsoon months, respectively.

The CGWB also indicated that the net draft of groundwater was 0.75 BCM more than the natural recharge, and was thus similar to the current paper—stressing the need to augment groundwater recharge activities in the state.

4.4.2. Groundwater Net Recharge and Net Discharge

The net groundwater discharge of the xth year is obtained by subtracting the GRACE GW in the post-monsoon month of the previous year (October of the $(x - 1)$th year) from the groundwater storage anomaly in the monsoon month of the xth year (June of the xth year). Similarly, the net groundwater recharge of the xth year was estimated by subtracting the groundwater storage anomaly in the post monsoon (October of the xth year) from the groundwater storage anomaly in the monsoon month (June of the xth year). The values of net groundwater recharge for all the AGZ are shown in Figure 12. The groundwater recharge trends differ between AGZ only by 3 cm at an average. It is to be noted that the net groundwater recharge trends coincide well with the rainfall trend (Figure 5) for the AGZs. The longer time series average of net groundwater recharge indicates a net increase at a rate of 0.33 cm per year, which is enough to irrigate at least 10,000 km^2 per year at an irrigation depth of 100 mm per year.

According to the Groundwater Estimation Committee [30,31], for hard rock aquifers with limestone, sandstone, phyllite, quartzite and shale as aquifer material, 3%–10% of the annual rainfall will recharge the aquifer. Assuming an average of 7.5% of rainfall recharge in Rajasthan, the recharge due to rainfall is calculated for each AGZ (Table 2). Similarly, the net ground recharge is calculated using GRACE data and the area of the AGZ and listed in Table 2.

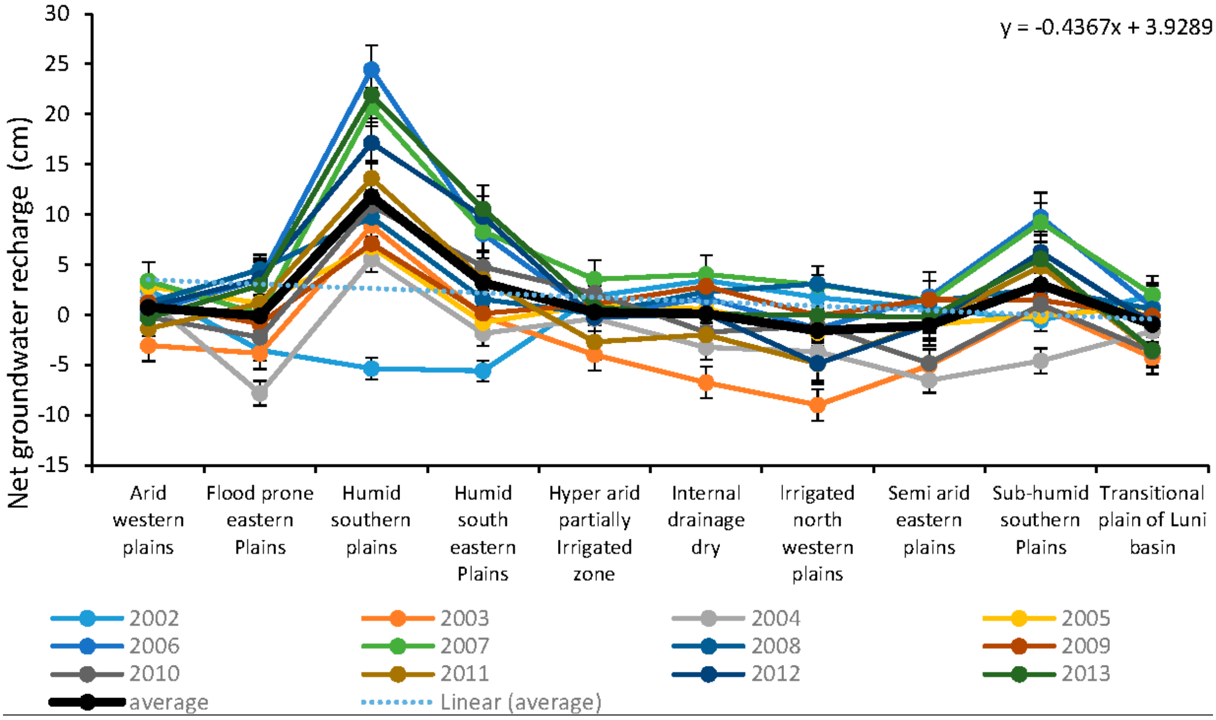

Figure 12. Variations in agroclimatic zonal GRACE estimates of net annual groundwater storage recharge (October–June) in the Indian state of Rajasthan. Bars indicate standard error.

Table 2. Average annual rainfall recharge, net groundwater recharge (GRACE) and net groundwater withdrawal (GRACE) estimates.

Agroclimatic Zones of Rajasthan	Rainfall Groundwater Recharge (BCM)	Net Groundwater Recharge (BCM)	Net Groundwater Withdrawal (BCM)
Arid western plains	1.2	0.37	0.70
Flood prone eastern Plains	0.6	−0.03	0.60
Humid southern plains	0.2	1.04	1.18
Humid south eastern Plains	0.6	0.77	1.17
Hyper-arid partially Irrigated zone	2.0	0.21	0.70
Internal drainage dry	0.6	0.02	0.31
Irrigated north western plains	0.5	−0.33	−0.13
Semi-arid eastern plains	0.7	−0.32	0.07
Sub-humid southern Plains	1.0	1.28	1.82
Transitional plain of Luni basin	1.2	−0.50	−0.09
Total	8.8	2.5	6.3

The net groundwater withdrawal for all the AGZ is shown in Figure 13. The year 2013 showed more variation from the baseline average, as 2013 had a higher rainfall average (including antecedent good wet years). The humid southern plains show a higher withdrawal of groundwater then other AGZs. Furthermore, in the year 2013, the withdrawal trends are lower than the average baseline withdrawal rate. Especially, in the flood prone eastern plains, the withdrawal is −19 cm in 2013, indicating the potential for flooding in this region during that year. The average withdrawal for the 12-year period indicates a net decrease in withdrawal rates by 0.65 BCM (or equivalent water thickness of 0.19 cm) per year.

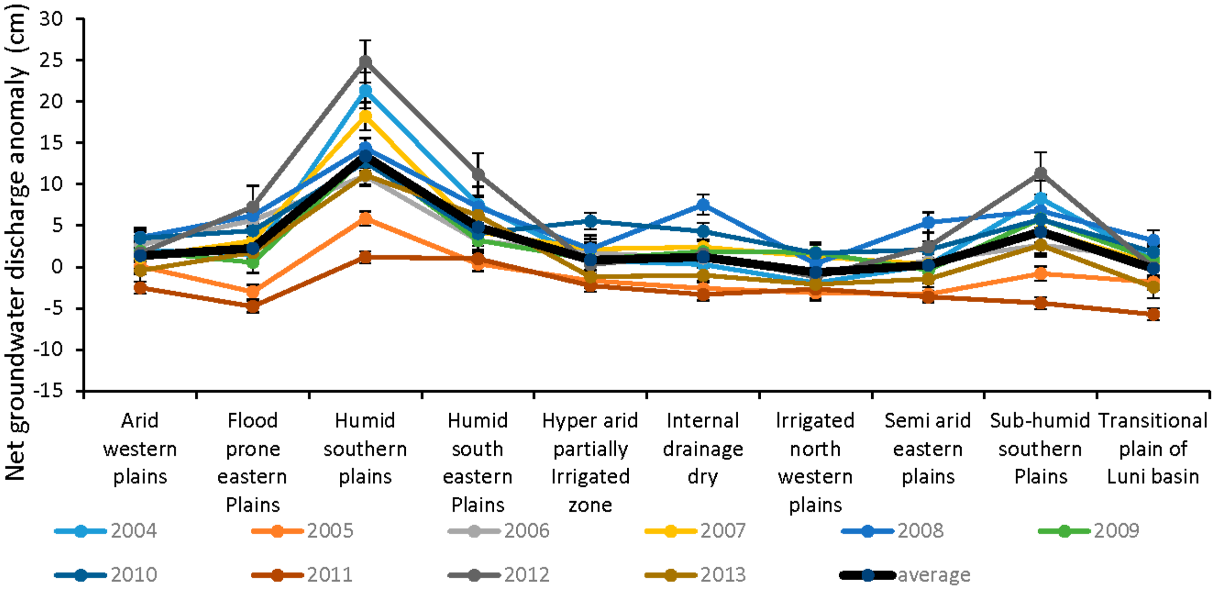

Figure 13. Variations in agroclimatic zonal GRACE estimates of net annual groundwater storage discharge (June–October) in the Indian state of Rajasthan. Bars indicate standard error.

The groundwater withdrawal volume in billion cubic meters is shown in Table 2. The total rainfall recharge should be equal to the sum of the net recharge (recharge available after use) and net groundwater withdrawal (use). The sum of the aforementioned is 8.8 BCM which is the same as that calculated using 7.5% of rainfall recharge for Rajasthan (8.8 BCM). This is an interesting finding, that 7.5% of rainfall recharge equals the total groundwater recharge and use in the state, and, hence, stresses the importance of using remote sensing products in unison with observation records for better inference of groundwater use. The observation wells and estimated groundwater use (e.g., [29]) can give estimates on the potential recharge and use for Rajasthan, while GRACE estimates of groundwater storage status can provide the net volume of groundwater remaining for future use.

4.5. Groundwater Management and Gravity Recovery and Climate Experiment (*GRACE*)

Due to the arid and semi-arid nature of Rajasthan, groundwater is an important resource for agriculture, domestic water supplies and other uses. Watershed development programs and water managers need data and practical information on the dynamics and current status of groundwater storage and use to effectively plan and implement groundwater management strategies and infrastructure. The on-going mapping and monitoring of groundwater storage is expensive, and this combined with the high spatial variability in hydraulic properties of aquifer systems in hard rock areas makes the management of groundwater a difficult and complex task. However, it is critical that some indirect and reliable methodology is available to understand changes in groundwater storage due to rainfall and pumping. This study has demonstrated that GRACE is useful to develop insights into how the groundwater levels fluctuate with rainfall over a longer period (10 years or more) and larger area.

In addition, GRACE provides the net groundwater storage volume that was once emptied and refilled during the 10 year period, without breaching the resilience of the aquifer. For example, the difference between the maximum and minimum GRACE derived GW storage (from 2002 to 2013) was approximately 8 cm of equivalent water thickness, which equates to 27 BCM for the entire state of Rajasthan. This volume is still higher than the CGWB projected annual groundwater draft demand of 16.36 BCM. Currently, the natural recharge is only saving 10.79 BCM of water annually. This indicates that if suitable groundwater recharge methods and sites are identified for the state, there is potential for more groundwater recharge than what is currently occurring and, thus, enhancing the availability of water for agriculture. This important finding has showcased Rajasthan's groundwater storage potential and, hence, future studies should identify methods to augment local natural groundwater recharge rates [32].

In a recent, similar study by Chinnasamy *et al.* [26], GRACE data and remotely sensed land cover data (from MODIS) were used along with rainfall data to understand the groundwater recharge and discharge in Gujarat. The study found that initially the groundwater storage was depleted due to water intensive farming practices. However, after the introduction of water infrastructure, the groundwater recharge rates increased by 29%, thus supplying more water for agricultural growth. Even though there was not a considerable change in the annual rainfall patterns across the state of Gujarat, the small scale water infrastructure (especially check dams) and the increase of the height of the Sardar Sarovar Project (dam) by 10 m resulted in an increase in groundwater storage by 29%, when compared to years with similar rainfall before the introduction of the water infrastructure. Thus, Gujarat, with a similar hydrogeology as Rajasthan, was able to benefit by storing the available rainfall using water infrastructure in the study area. In another similar study by Chinnasamy and Agoramoorthy [11], GRACE data indicated that the groundwater use for irrigation increased the agricultural yield in Tamil

Nadu (Southern state in India), however, the groundwater abstraction rates were not sustainable. As a result, the groundwater levels are continuing to fall and the study indicated that, without proper mechanisms to augment natural groundwater recharge rates, the agricultural yield will be affected due to unsustainable groundwater use. The aforementioned studies, conducted in India, indicate that even though the rainfall patterns did not change much, there is considerable impact of ongoing farming practices on the groundwater system. Hence, policy makers should investigate options to augment groundwater resources to sustain agricultural growth. These studies, similar to the current study, show the potential of remote sensing data to infer behaviour of groundwater storage against changes in rainfall and agricultural demands.

The reliability and accuracy of measurements of groundwater storage changes based on GRACE depends on how accurate the total water storage and the soil moisture content estimates are and whether there are any systematic biases or trends. Errors in groundwater storage estimates derived from this process may stem from the summation of the errors in the GRACE total water storage changes, the soil moisture values and the surface water estimates. Past studies show that the greatest uncertainty in the estimation of groundwater storage relates to how we separate soil moisture and groundwater, *i.e.*, the distinction of storage in the unsaturated and saturated zones [12]. For the region of study, uncertainty errors in GRACE estimates were inferred as per Wahr *et al.* [33]. In a study, Wahr *et al.* [33] estimated uncertainty in GRACE derived water storage anomaly data by using the Gaussian smoothing technique. For the Rajasthan state, this technique computes the uncertainty in GRACE TWS as between 2.4 and 2.6 cm. It is to be noted that since the scaling coefficients were used in processing the data for the current study, adjustments to incorporate these errors were already made to the data and, hence, no additional error analysis was needed.

5. Conclusions

The main aim of this study was to evaluate to what extent the combination of remotely sensed total water storage estimates from GRACE could be used to estimate the changes in groundwater storage for the state of Rajasthan. The study indicates that the methodology based on GRACE data has provided reasonable trends in groundwater storage changes over larger areas covering different agroclimatic zones. The analysis of data shows that groundwater storage trends depend on rainfall in previous years and, therefore, on the antecedent moisture conditions. Further, due to the hard rock geologic conditions with poor connectivity across the aquifer dominant, the groundwater storage does not respond rapidly with rainfall but it gradually changes over time. When plotted against rainfall anomaly trends, the groundwater storage anomalies closely follow the rainfall trends. The study also highlights that due to brief intensive rainfall seasons, there is a need to increase recharge through managed aquifer recharge. The agroclimatic zones, where the annual groundwater anomaly is consistently less than zero, should be given priority for investments in groundwater recharge infrastructure.

Even though there have been many studies using remote sensing methods to assess groundwater depletion, this study is the first to investigate groundwater recharge and discharge behaviour in different agroclimatic zones for Rajasthan. Most studies use administrative boundaries (e.g., country, state, district), but by using agroclimatic zones, this study attempts to relate the climate characteristics (e.g., arid *versus* humid) and hydrogeological characteristics (e.g., well drained soils *versus* flooding) associated with each unique agroclimatic zone. By this first attempt, future researchers are urged to explore options in selecting spatial boundaries while using remote sensing datasets, especially GRACE.

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Author Contributions

Pennan Chinnasamy: Data collection, data analysis, preparation of diagrams, interpretation, writing up of manuscript text. Basant Maheshwari: Data collection, assist in data analysis and interpretation and review and editing of manuscript text. Sanmugam Prathapar: Assist in data analysis and interpretation and review and editing of manuscript text.

Conflicts of Interest

The authors declare no conflict of interest.

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