

Groundwater Storage and Depletion Trends in Tamil Nadu State, India

Pennan Chinnasamy · Govindasamy Agoramoorthy

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Abstract Groundwater irrigation is the most predominant method used across India. The south Indian state of Tamil Nadu is one of the largest producers of agricultural products, and is largely dependent on groundwater for irrigation. The impact of increased irrigation due to intensification of agricultural activities on groundwater levels has not been well researched, both spatially and temporally. Hence this study has used remote sensing data from NASA's Gravity Recovery and Climate Experiment and the Global Land Data Assimilation Systems to assess the total change in groundwater storage across the state of Tamil Nadu over a period of 11 years, from 2002 to 2012. The results show groundwater depletion at the rate of $21.4 \text{ km}^3 \text{ yr}^{-1}$, which is 8% more than the annual recharge rate ($19.81 \text{ km}^3 \text{ yr}^{-1}$) owing to the total rainfall of 1016 mm yr^{-1} . Maximum depletion was observed in 2008, while the least depletion was observed in 2002 with rates of 41.15 and 0.32 cm yr^{-1} , respectively. Districts such as Dharmapuri, Vellore and Thiruvannamali encountered intense groundwater depletion. Observed spatiotemporal groundwater storage will benefit India's water resource managers and policymakers for the future management of groundwater resources to enhance food and water security.

Keywords Green revolution · Groundwater use · GRACE · GLDAS · Remote sensing · India

1 Introduction

Groundwater is a common-pool resource with no ownership, hence taken for granted and depleted recklessly by human societies across continents over millennia (Burness and Brill 2001; Qureshi et al. 2010). In the rapidly urbanizing globalized world, issues surrounding the availability, accessibility, and security of drinking water have emerged as major stumbling blocks for sustainable development (Groenfeldt 2013; Qureshi et al. 2010). Scientists have already predicted that by 2025, nearly two billion people will be forced to live in areas with

P. Chinnasamy

International Water Management Institute, GPO 8975 EPC 416, Kathmandu, Nepal

e-mail: p.chinnasamy@cgiar.org

G. Agoramoorthy (✉)

College of Environment and Health Sciences, Tajen University, Yanpu, Pingtung 907, Taiwan

e-mail: agoram@mail.nsysu.edu.tw

absolute water scarcity (United Nations Water 2007). Hence, are mitigating water insecurity has become a thorny environmental challenge for policy makers of the 21st century. This notion was indeed reflected when over 80% of the decision-makers, who attended the World Summit on Sustainable Development at Johannesburg in 2002, identified freshwater as a key issue that deserves to be tackled by Heads of States (United Nations 2002). Furthermore, the agriculture sector alone uses nearly over 70% of the freshwater supply worldwide. Therefore, there is no longer any difference between agriculture decision and water decision. For example, the enormous water footprint involved in wheat irrigation that uses both surface and groundwater has been reported to reach over a trillion m^3 per year between 1996 and 2005 (Hoekstra 2013).

Based on the annual water withdrawal-to-availability ratio, most of India's land areas can be categorized as highly water-stressed (CGWB 2011; Poddar et al. 2014). India is one among the greatest consumer of groundwater in the world with an estimated annual withdrawal exceeding over 230 km^3 . Besides, agriculture sector consumes over 60% of the groundwater (Hoekstra 2013). Estimations of groundwater use and demand for agricultural productivity are important to identify future food security measures and sustainable farming methods. Since most policy decisions are based on land use and land cover data, insights on groundwater storage is often ignored. The groundwater use for agriculture should be at sustainable rates to ensure long-term food and water security (Maheshwari et al. 2014). The green revolution was one of the major factors responsible for converting India from a "food importer" to a "food exporter". However, if agriculture continues to use groundwater resources at unsustainable levels, then the aforementioned trend might reverse eventually leading to economic and social complications.

Predicting India's groundwater availability has become increasingly problematic for scientists and water resource managers in recent decades. 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 collection besides problems to access observation data from government agencies. As a result, water resource scientists have started to rely more on satellite-based remote sensing data to extrapolate ground water realities (Rodell et al. 2009; Jha et al. 2007; Awange et al. 2008; Chowdary et al. 2009).

Among the Indian states, Tamil Nadu has seen tremendous increase in groundwater use for agriculture in the past decade (Tamil Nadu Agricultural Department 2010). This study has used, for the first time, seasonal and annual hydrological signals obtained by NASA Gravity Recovery and Climate Experiment (GRACE) satellites, and simulated soil moisture variations from Global Land Data Assimilation Systems (GLDAS) to show the extent of depletion in groundwater trends in Tamil Nadu. As a matter of fact, many studies have used GRACE to understand groundwater decline (e.g., Rodell et al. 2009; Chinnasamy et al. 2013; Awange et al. 2008). In a study by Rodell et al. (2009) for example, GRACE data showed favorable comparisons between 58 CGWB well based groundwater time series. In the same study, the GRACE remote sensing data was used to estimate groundwater depletion rates in the north Indian states of Rajasthan, Punjab and Haryana. The estimated groundwater depletion rate was 13.2 km^3 greater than that reported by the Ministry of Water Resources. We have also shown that the GRACE groundwater estimated trends for Gujarat are in agreement with the CGWB groundwater trends (Chinnasamy et al. 2013). Hence we have commended the need for CGWB data and remote sensing data to be used in unison in the Indian subcontinent with scarce observed data, both spatially and temporally. Velicogna and Wahr (2006) monitored the Greenland glacial retreat using GRACE and reported a 250% increase in glacial melt over a two-year period: April 2002 to April 2004 (Velicogna and Wahr 2006). Morrow et al. (2011), in a study conducted in the Mackenzie River basin located in Canada, showed that there was insignificant glacial recovery over a 7 year period (October 2002 to September 2009). The aforementioned studies, and many more, have increased the confidence in using GRACE data

for estimating changes in groundwater storage, thus aiding in better formulation of management plans.

The primary objective of this study is to estimate the groundwater storage trend during the agricultural intensification period (2002 to 2010) and compare with natural groundwater recharge rates, thus leading to a better understanding on sustainability of current agriculture practices. The results of this study will enable land managers and policy makers to have an understanding on the long-term impact that agricultural intensification has on groundwater. As a result, better sustainable measures such as acceleration of groundwater recharge and drip irrigation can be applied in using groundwater storage. Such information on the impact on groundwater is unavailable in the current scenario, and hence the results of this study will encourage the concept of sustainable agricultural intensification.

2 Datasets and Methods

2.1 GRACE Datasets

This study has assessed groundwater trends extending over a period of 11 years from 2002 to 2012 using Gravity Recovery and Climate Experiment (GRACE) mission and Global Land Data Assimilation Systems (GLDAS) missions by examining remote sensing images of captured groundwater usage trends across Tamil Nadu state, India. The groundwater storage change during the peak summer season (May), monsoon or *kharif* season (August), and winter or *rabi* season (December) for the 11-year period was also assessed. Furthermore, data were compared of the groundwater usage versus natural groundwater recharge via rainfall to determine the net pressure on the groundwater resources of Tamil Nadu state.

2.2 Study Site

Tamil Nadu is located in the south-eastern of part of peninsular India. It also forms the south-eastern boundary of the Indian subcontinent. It extends from 8.01°N, 77.33°E to 13.24°N, 80.18°E (Fig. 1) and it is considered to be the 11th largest state in the country encompassing an area of 130,000 km² divided into 32 administrative districts (Fig. 1). Villupuram (area 7185 km²) is the largest district, while Chennai (area 174 km²) is the smallest in the state. However, Chennai city located at 13.09°N 80.27°E is the capital of Tamil Nadu state and an important international sea port. The geologic setting of the state is a combination of hard rock and fissured crystalline rock systems, especially charnockite, gneisses and granites (Subramanian and Selvan 2001). The sedimentary composition of Tamil Nadu consists of sand stones, lime-stones and shales, while the quaternary sediments are composed of alluvium. Most of the coastal region of Tamil Nadu is reported to have alluvium extending up to an average of 50 km from the sea. The most productive agricultural areas are located in the centre of the state and along the Cauvery delta region.

The climate of Tamil Nadu is of tropical wet and dry type with an average maximum temperature recorded in May (35–40 °C) and minimum recorded in January (15–22 °C). It gets an average rainfall of 984 mm per year (2000 to 2011; IMD 2012). The dominant rainfall periods in Tamil Nadu are the South-West monsoon (from June to September) and the North-East monsoon (October to December), with the majority (36% more) occurring in the latter period. According to the population estimates (Census, 2011), Tamil Nadu is the 7th most populated state in the country harbouring 72 million inhabitants, of which 44% reside in urban areas, while the rest distributed among rural and semi-urban areas. About 20% of the



Fig. 1 Map of India with Tamil Nadu state. Inset shows the 32 districts of Tamil Nadu State

population or 14 million depend on agriculture for a living (Census 2011). Furthermore, the agriculture sector contributes nearly 21% to the economic growth of the state.

The Cauvery delta of Tamil Nadu has been historically known as the “Rice bowl” and is the fifth major producer of rice in India (Tamil Nadu Agricultural Department 2010). In 2009–2010, an area of 56,000 km² (44% of the total land area) was cultivated with rice. In addition, Tamil Nadu is the largest producer of bananas, flowers, tapioca, and the second largest producer of mangoes, natural rubber, coconut and groundnut in India. It is the third largest producer of tea, coffee, sapodilla and sugarcane in the country. Furthermore, the state has 170 km² area of palm oil plantation, the second highest in India. The aforementioned statistics show the state’s prominence in agricultural growth (Tamil Nadu Agricultural Department

2010) therefore scientific management of irrigation water sources is not only essential but also mandatory.

2.3 GRACE Estimations of Terrestrial Water Storage (TWS)

The Gravity Recovery and Climate Experiment (GRACE) mission was launched on the 17th of March 2002, due to a combined effort from the National Aeronautics and Space Administration (NASA) and the German Aerospace Center Deutschen Zentrum für Luft- und Raumfahrt (DLR). The GRACE mission is the first of its kind that can estimate groundwater storage globally on a monthly scale (Tapley et al. 2004a, b). The GRACE satellite mission has two satellites working in unison. The mass anomalies (due to changes in groundwater volume) cause changes in the gravitational field which in turn causes perturbations in the satellite orbits of the GRACE satellite. While one satellite undergoes changes in the orbit, the other satellite records these perturbations as changes in stored terrestrial water (Rodell and Famiglietti 2002; Rodell et al. 2004a, b, 2007, 2009). Thus, the GRACE team of scientists have used the fact that the composition and structure of the planet Earth can be inferred from the planet's gravitation field (Tapley et al. 2004b). With this working principle, changes in Terrestrial Water Storage (TWS) can be estimated over the globe at monthly resolution, as the satellite orbits each location once a month. Many studies have validated GRACE data for groundwater studies (Rodell and Famiglietti 2002; Rodell et al. 2004a, b, 2007, 2009; Tapley et al. 2004a, b; Tiwari et al. 2011; Chinnasamy et al. 2013).

2.4 GLDAS Estimations of Total Soil Moisture (SM)

The Global Land Data Assimilations Systems (GLDAS) was developed jointly by NASA Goddard Space Flight Center (GFC) and National Oceanic and Atmospheric Administration (NOAA) to provide estimates and archives on land surface states and fluxes (Rodell et al. 2004a, b, 2009). In the GLDAS, the total soil moisture can be estimated using Land Surface Models (LSMs) which are driven by remote sensing data on global scales. Of the LSMs, the National Centers for Environmental Prediction/Oregon State University/Air Force/Hydrologic Research Lab Model (NOAH), Common Land Model (CLM), MOSAIC and Variable Infiltration Capacity (VIC) are well known. For the current study, Noah 2.7.1 - a land hydrology LSM in the GLDAS is used to estimate soil moisture (as an equivalent thickness) from the surface up to a depth of 200 cm. The Noah estimates of total soil moisture (SM) are coupled with GRACE estimates of TWS to arrive at net groundwater storage. Details about the Noah, GLDAS and LSMs can be obtained from Goddard Earth Sciences Data and Information Services Center (GES DISC).

2.5 Rainfall and Terrestrial Water Storage (TWS)

The monthly district level rainfall data from 2000 to 2011 was obtained from the Indian Meteorological Department (IMD, 2012) for the state of Tamil Nadu (with 32 districts). The IMD records daily rainfall and aggregates to monthly rainfall data. Monthly rainfall data was used to construct annual hyetographs. The critical groundwater extraction districts were identified using the Central Ground Water Board's (CGWB) report on groundwater resource assessment (CGWB, 2011). The monthly land mass grids of GRACE data are archived by the University of Texas Center for Space Research (CSR) (Landerer and Swenson 2012), GeoForschungsZentrum Potsdam (GFZ), and the Jet Propulsion Laboratory (JPL) and can be accessed online (<http://gracetellus.jpl.nasa.gov/data/>) (Landerer and Swenson 2012;

Swenson and Wahr 2006). GRACE land data (<http://grace.jpl.nasa.gov>) processing algorithms were provided by Sean Swenson, and supported by the NASA MEaSUREs Program. The current GRACE data was based on the level V (RL05) spherical harmonics from Center for Space Research (CSR – Texas), Jet Propulsion Lab (JPL- NASA) and Geo Forschung Zentrum (GFZ – Potsdam, Germany). Information regarding the GRACE data solutions (Cheng et al. 2011), degree one coefficients (Swenson et al. 2008) and glacial isostatic adjustments (Geruo et al. 2013) performed on the data can be inferred from the GRACE data download page. Mass variability due to plant biomass and snow water equivalent were neglected in this study, as latter was unimportant owing to the temperate climate of Tamil Nadu. The collected data was then processed using the Quantum Geographic Information System (2.2 QGIS), which is an open source free software for mapping exercises. Scaling coefficients were multiplied to the collected data to minimize error due to attenuation of signal (Swenson and Wahr 2006).

2.6 Total Soil Moisture (SM) and Groundwater Storage (GW)

The processed GLDAS data was accessed online (<http://grace.jpl.nasa.gov>), which used the services of the Goddard Earth Sciences Data and Information Services Center. The collected data is formatted and grids for average monthly soil moisture are prepared by the GES DISC team (Rodell et al. 2004a, b). Since the GLDAS data is provided in different spatiotemporal resolutions, care was taken to download similarly formatted spatial (1°) and temporal- (monthly) resolution Noah data. Total soil moisture, as collected from Noah, represents the sum of soil moisture estimates from four data sets that represent soil moisture from 0 to 10, 10 to 40, 40 to 100, and 100 to 200 cm, respectively. The data was summed to arrive at total vadose zone soil moisture. All data processing was done using QGIS. Finally, GRACE-based estimates of terrestrial water storage (TWS) and GLDAS-based soil moisture (SM), equivalent water thickness or groundwater storage (GW) were calculated as per (Rodell et al. 2007, 2009; Chinnasamy et al. 2013)

$$GW = TWS - SM \quad (1)$$

where, TWS, SM and GW are estimated in centimeters.

Since the study aimed at identifying groundwater trends during peak summer, Kharif and Rabi growing seasons, GRACE and GLDAS data was downloaded for the months of May, August and December for the years spanning from 2002 to 2012.

The annual GW depletion due to the combination of summer and agricultural activities was estimated from the difference in groundwater storage thickness (GW) between peak summer (May) and the high rainfall (December) months. In addition, the post monsoon depletion of groundwater storage was estimated by calculating the difference in GW thickness between winter (December) and monsoon (August) seasons.

3 Results and Discussion

3.1 Rainfall Trends in Tamil Nadu State

The monthly rainfall data, analysed across 32 districts of Tamil Nadu state from 2002 to 2012 indicate an annual average of 1010 mm per year. The highest rainfall amount was registered during 2005 with 1386 mm, while 2002 recorded the lowest rainfall with 731 mm. The maximum monthly rainfall was observed at Cuddalore district in November of 2005 with a total rainfall of 824 mm. March had the most number of non-rainfall recordings, making it the

driest month in the period (2002 to 2012). The rainfall descriptive statistics that include minimum, maximum, standard deviation and average are shown in Table 1. The rainfall trend indicates an increase in rainfall at the rate of 17 mm per year from 2000 to 2012. Hence, any depletion in groundwater storage can be attributed to increased use of groundwater resources and not due to climate change (especially a decrease in rainfall).

3.2 Groundwater Storage Trends in Tamil Nadu State

GRACE estimates groundwater storage as equivalent thickness of water, in cm thickness. The Tamil Nadu state groundwater storage (GW), in equivalent water thickness (cm), is shown in Figs. 2, 3 and 4. Figure 2 shows the groundwater storage trends across Tamil Nadu during the peak summer month (May), while Figs. 3 and 4 show the groundwater storage trends in monsoon (August) and winter (December) seasons, respectively. The GW data was normalized using the average GW levels from January 2004 to December 2009 (baseline average). The baseline was created to understand the trend of specific month data, when compared against the long term monthly data. Hence, a negative sign in GW indicates a negative deviation from the average baseline. On the same note, the average GW for the summer month was -11.05 cm (lower than baseline), while the averages for monsoon and winter seasons were -4.01 and 5.54 cm, respectively. The negative signs indicate that the GW is progressing on a negative trend, which is similar to the groundwater estimates as reported by Central Ground Water Board (CGWB) for the state of Tamil Nadu (CGWB 2011). May month has the most groundwater depletion due to the hot weather conditions and less rainfall during the summer season. The winter seasons show an increase in GW due to the higher rainfall amount, 17% more than summer, during the month of December. Using a baseline value of 40 cm (from the average trend), the baseline removed data indicate average GW storage values of 29, 36 and 45 cm for summer (May), monsoon (August) and winter (December) seasons, respectively. Hence, the winter season (post monsoon) has a higher than average, while the summer and the start of monsoon exhibit lower than baseline conditions.

3.3 Groundwater Storage in Agriculture-intensive Districts of Tamil Nadu

The districts namely Dharmapuri, Vellore and Thiruvannamali are some of the most agriculturally-intensive districts in Tamil Nadu. In addition, the CGWB has identified many blocks in the aforementioned districts as over exploited in groundwater resources (CGWB 2011). When compared with baseline, the GW thickness is depleted in Dharmapuri (-3.27 cm), Vellore (-7.12 cm) and Thiruvannamali (-4.39 cm). The average rainfall is more in Thiruvannamali (by 22 %) when compared to Dharmapuri and Vellore, with average annual rainfall of 1190, 980 and 978 mm yr^{-1} , respectively. The average GW thickness in the aforementioned districts is 164% lower than the GW thickness average for the entire state of Tamil Nadu during the study period, even though the annual rainfall is 17 % more in the aforementioned districts (1190 mm yr^{-1}) than the average Tamil Nadu rainfall (1010 mm yr^{-1}).

Table 1 Rainfall data from 2000 to 2011 for Tamil Nadu state, India

Descriptive statistics	Value
Minimum (mm)	1386
Maximum (mm)	731
Std. Dev (mm)	198
Average (mm)	1016

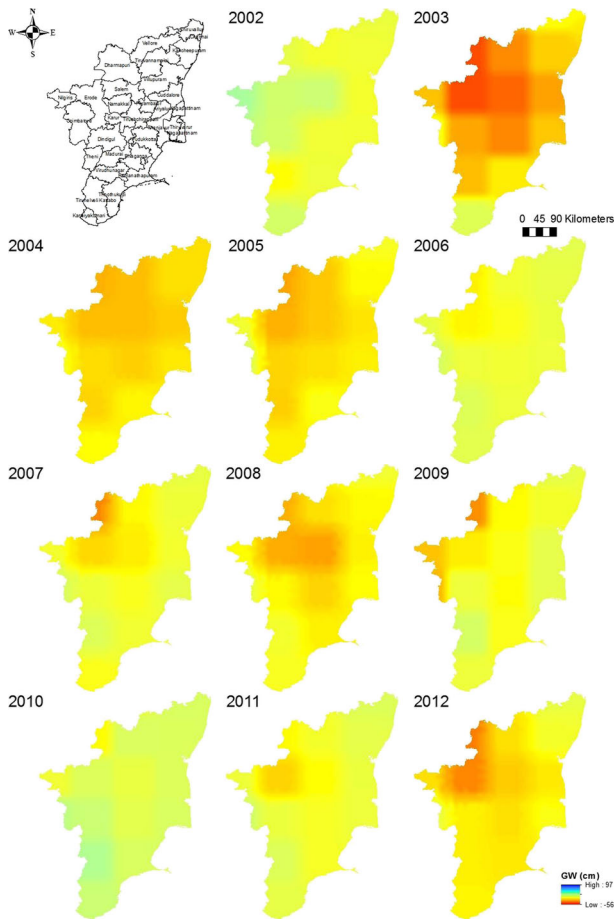


Fig. 2 GRACE/GLDAS gravity solutions for equivalent groundwater storage thickness for the state of Tamil Nadu during peak summer month (May) for the years 2002 to 2012

Table 2 shows details of GW trends across the aforementioned districts in Tamil Nadu. The annual average rainfall from 2002 to 2012 indicates an increasing trend with an increase of 17 mm yr^{-1} . Hence, the above mentioned decrease in groundwater storage (from baseline) can be attributed to an increase in groundwater use, especially in the agricultural sector.

3.4 Estimations of Depletion Rates for Groundwater Storage

The average difference in groundwater thickness is of the order of $-16.48 \text{ cm yr}^{-1}$, for the entire study period from 2002 to 2012. The maximum depletion rate was observed during 2008 ($-41.15 \text{ cm yr}^{-1}$) while the minimum was observed during 2002 (0.32 cm yr^{-1}). The groundwater withdrawals for irrigation have caused an average water volume depletion of $21.4 \text{ km}^3 \text{ yr}^{-1}$ across the entire state of Tamil Nadu (area of $130,000 \text{ km}^2$), for the study period. As per the recommendations of the groundwater estimation committee (GEC 2009), a 15 % of annual rainfall recharges groundwater for Tamil Nadu. Using this assumption, a net water volume of $19.81 \text{ km}^3 \text{ yr}^{-1}$ of groundwater is recharged. As a result, the groundwater usage

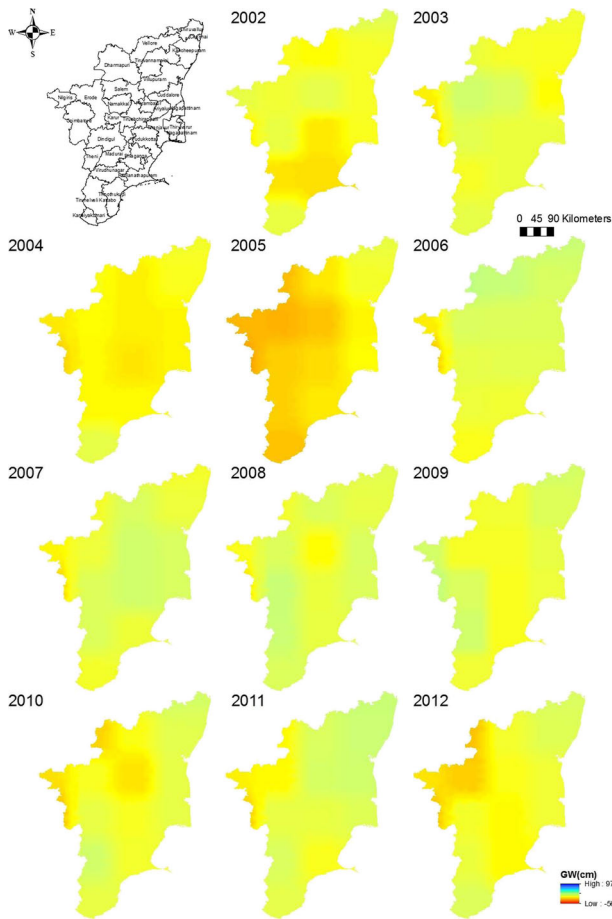


Fig. 3 GRACE/GLDAS gravity solutions for equivalent groundwater storage thickness for the state of Tamil Nadu during peak monsoon crop (August) for the years 2002 to 2012

exceeds the annual recharge by 8 % ($1.59 \text{ km}^3 \text{ yr}^{-1}$). Groundwater depletion at such rates will lead to unsustainable groundwater levels, resulting in socio-economic stress, vulnerability to climate change and unbearable stresses to food and water security. Similarly, the average groundwater depletion rate is -9.45 cm yr^{-1} between monsoon and winter seasons (from 2002 to 2012). The maximum depletion rate was observed during 2010 ($-26.95 \text{ cm yr}^{-1}$) while the minimum was observed during 2003 (2.69 cm yr^{-1}). The intense agricultural activities between monsoon and winter seasons have resulted in a net groundwater depletion volume of $12.29 \text{ km}^3 \text{ yr}^{-1}$.

3.5 Mitigating Future Irrigation Water Stress in Tamil Nadu

Irrigation water use has grown rapidly in India. In 1951, India had only 17% of permanently irrigated area. However, the irrigation potential increased from 22.6 million ha in 1951 to nearly 90 million ha by the end of 1995 mainly due to the impact of green revolution that spread across the country during the late 1960s supported by new seed varieties, pesticides,

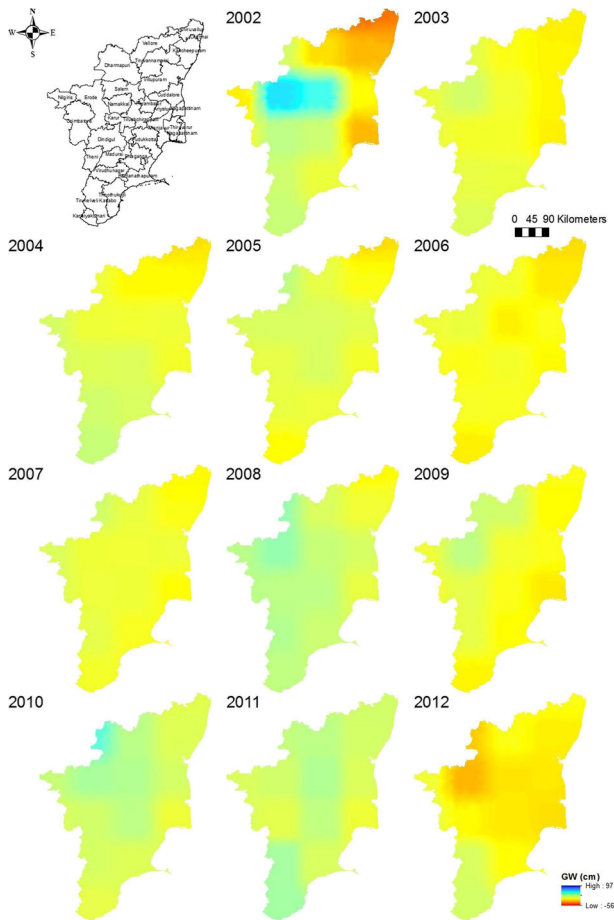


Fig. 4 GRACE/GLDAS gravity solutions for equivalent groundwater storage thickness for Tamil Nadu during peak winter crop month (December) for the years 2002 to 2012

fertilizers and canal irrigation systems linked to large and medium-sized dams (Jain 2010). Although green revolution has helped India to increase self-sufficiency in grain production, several studies have confirmed that the revolution has severely affected groundwater resource availability (Shah et al. 2003; Singh 2000; World Bank 1999). In a study conducted in Haryana State of north India, for example, Singh (2000) showed that the green revolution resulted in an average groundwater table decline of 7 m across the state. The decline was due to the promotion and increase of rice and wheat cultivation through green revolution to 95% of the total agricultural crops, of which 65% was irrigated by groundwater. The World Bank report (1999) also showed that the groundwater table dropping by 3 m in major areas across the state of Punjab in north India, owing to over-exploitation of water for agriculture influenced by green revolution practices. Similarly, our study has shown groundwater depletion during agricultural intensification period in Tamil Nadu, south India. Assuming an average specific yield of 0.12 (GEC 2009), our study estimates the regional groundwater decline to be 1.4 m per year.

Table 2 Groundwater storage change (post monsoon-summer) across major agricultural districts (Dharmapuri, Vellore and Thiruvannamali) of Tamil Nadu (from 2002 to 2012)

Year	Average rainfall (mm)	Dharmapuri (cm)	Vellore (cm)	Thiruvannamalai (cm)
2002	731	0.80	-0.39	0.47
2003	1035	-31.92	-27.90	-15.86
2004	1126	-20.86	-18.29	-15.14
2005	1386	-19.41	-15.57	-10.42
2006	956	-1.27	0.95	-2.51
2007	1019	-16.59	-4.50	-1.58
2008	1252	-19.13	-8.65	-8.27
2009	982	-15.20	-4.47	-2.12
2010	1190	4.28	9.48	9.08
2011	937	-4.75	0.98	3.03
2012	932	-21.95	-7.12	-4.95
Descriptive statistics				
Minimum (cm)	731	-31.92	-27.90	-15.86
Maximum (cm)	1386	4.28	9.48	9.08
Std. Dev (cm)	190.86	11.36	10.46	7.59
Average (cm)	1010	-13.27	-6.86	-4.39

The authors of the aforementioned studies have urged for groundwater interventions, to increase groundwater recharge and augment groundwater resources to secure future availability of water. Even though interventions can aid, considerate and sustainable use of groundwater resources is more important for the success of green revolution in the future. Such use plans can be formulated if better estimates of groundwater storage and recharge are available at micro and macro watershed scales. However, due to limited field data, larger scale estimates are currently unavailable. Hence, the groundwater intervention programs should aim at improving groundwater resources to combat steady declines, along with improvements in agricultural practices.

Punjab and Haryana states in north India have been the flag-bearers of India's green revolution to achieve maximum agricultural output to eradicate hunger, famine and malnutrition. Nonetheless, in recent years Gujarat in northwest India has also increased its agriculture productivity. However, the question is how did the semi-arid state of Gujarat improve its agriculture productivity? The reason seems to be simple. The Gujarat state has given emphasis on market orientation to ensure farmers of fair economic returns. Besides, the bottom line for agriculture is irrigation water and Gujarat has built several large and medium-size dams across major rivers connected by canal irrigation system. The numerous hydroelectric dams have made Gujarat one of the few electricity-surplus states in India. Furthermore, the government of Gujarat has given equal importance to build numerous small dams (also called check dams) across small, medium and large rivers and these ecofriendly check dams have increased not only groundwater recharge in rural villages but also provided irrigation water to dryland farms that cannot be reached by canal irrigation system (Agoramoorthy and Hsu 2008).

The check dams are connected to lift irrigation system and the farming communities manage the minor irrigation structures (Agoramoorthy and Hsu 2013). The concept of check dam is based on the Grant Anicut built by the ancient Chola Dynasty king Karikalalan during the 2nd Century AD. The 4.5 m tall check dam is considered the world's oldest and still

functioning irrigation dam. Nevertheless, the Tamil Nadu state has not been able to replicate the model like in Gujarat to build more check dams to mitigate irrigation water crisis locally. Instead, Tamil Nadu continues to legally challenge the neighboring state of Karnataka to release more water from its large dams built upstream of the Cauvery river (Agoramoorthy and Hsu 2008). The precipitation in Tamil Nadu is concentrated mainly during the monsoon season. Some areas of the Western Ghats rainforest region in south India for example receive heavy rainfall during the summer monsoon—sometimes the daily rainfall even reaching 152 mm, causing extensive damage (Francis and Gadgil 2006). However, most of the water cannot be harvested for later use owing to inadequate surface and ground storage infrastructures. For instance, the large and medium-size dams store about 1150 km³ out of an annual rainfall of 4000 km³—the remainder (71%) runs off without being used. Therefore, the study urges the Tamil Nadu government to pilot test smaller check dams across the river Cauvery and also in other major and minor rivers across the state to harvest rainwater. If the pilot tests are successful in increasing the net surface and groundwater storage, the check dams can be introduced in large numbers. This will certainly increase storage of monsoon water, which is crucial and necessary to mitigate future irrigation water crisis. The current study results will increase the understanding of the current water depletion, and the storage available in the groundwater that can be recharged using artificial recharge structures.

4 Conclusions

Groundwater is being depleted rapidly to increase agricultural yield in Tamil Nadu. This study alarmingly shows the reality of an average groundwater decline of 1.4 m yr⁻¹ across the state of Tamil Nadu from 2002 to 2012 owing to a groundwater usage that is nearly 8% more than the annual recharge rate. To aid formulation of better groundwater management plans, an interdisciplinary approach is urgently needed to quantify sustainable agricultural practices and artificial water storage in Tamil Nadu state of India. Future methods need to include cropping pattern scenarios, climate projection scenarios, social stress for groundwater and governance of groundwater while formulating net groundwater demand and groundwater use projections. Remote sensing data, given its cost effective usefulness, needs to be used along with field based physical measurements to improve groundwater estimation methodology.

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