Using Remote Sensing Data to Improve Groundwater Supply Estimations in Gujarat, India

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ABSTRACT: India is the greatest groundwater consumer in the world, with estimated annual withdrawals exceeding 230 km^3. More than 60% of irrigated agriculture, 85% of drinking water supplies, and 50% of urban and industrial water needs are dependent on sustainable groundwater management. Regardless, groundwater overextraction is a growing problem in many regions. Predictions of groundwater resource availability in India are problematic in part because of a limited number of monitoring sites and insufficient data quality and quantity. Regional groundwater assessments are further complicated because of sporadic and low-frequency data. To help overcome these issues and more

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accurately quantify groundwater resource availability, scientists have begun using satellite-derived remote sensing data. In this study, the authors used seasonal and annual hydrologic signals obtained by NASA Gravity Recovery and Climate Experiment (GRACE) satellites and simulated soil moisture variations from land data assimilation systems to show groundwater depletion trends in the northwest state of Gujarat (surface area of 196 030 km^2), India. Results were evaluated using direct measurement data from 935 wells. Remote sensing generated results compared favorably with well data (e.g., $r^2 = 0.89$ for Gandhinagar, a representative highly urbanized district in Gujarat: confidence interval (CI) = 0.05 and $P = 0.002$). Results show that remote sensing is an effective tool to compliment and interpolate observed regional groundwater well data and improve groundwater storage estimations in Gujarat, India. Properly implemented, the method will supply reliable science-based information to enhance management of groundwater resources in India and other geographic locations.

KEYWORDS: India; Gujarat; Groundwater depletion; Remote sensing; Education; Agriculture

1. Introduction

Groundwater is the primary source of freshwater in many regions globally (Rodell et al. 2009). However, in many locations groundwater is consumed unsustainably to the detriment of quantity and quality of the resource. Regulations governing the use of groundwater are not well developed, even in many developed nations (Livingston and Garrido 2004). Lack of regulations is largely attributable to insufficient knowledge of groundwater supplies and rates of recharge. In many regions, groundwater recharge responds slowly to meteorological conditions, relative to surface water reservoirs (ponds, lakes, rivers, etc.) (Livingston and Garrido 2004; Rodell et al. 2009) because of physical characteristics of the underlying soil and geology (Postel 1993; Postel and Carpenter 1997).

In recent decades, increasing agricultural practices in arid and semiarid countries have included dramatic increases in groundwater extraction (Llamas and Martínez-Santos 2005). Electric power subsidies provided to farmers in many countries have encouraged overexploitation of groundwater resources by means of inexpensive pumping costs (Shah 2008). Despite increasing groundwater withdrawals, participation of government agencies in planning, control, and regulation of groundwater use remains limited (Llamas and Martínez-Santos 2005; Rodell et al. 2009; Rodell et al. 2007). While surface water irrigation is commonly regulated by local government agencies in many countries, farmers acting independently from each other often collectively increase and consequently overuse groundwater supplies (Shah 2008; Shah et al. 2008; Tiwari et al. 2011). Thus, agricultural overuse of groundwater resources is often attributable to a general lack of understanding of supplies and long-term impacts of groundwater overwithdrawals (Llamas and Martínez-Santos 2005; Postel and Carpenter 1997; Rodell et al. 2009). Ultimately, lack of quantitative understanding of groundwater supplies may be resulting in human overuse of the perceived "unlimited" resource in many regions, globally.

In India, groundwater resources are declining rapidly because of agricultural overexploitation (Central Groundwater Board 2004; Central Groundwater Board 2011; Groundwater Resource Estimation Committee 2009; Rodell et al. 2009; Tiwari et al. 2011). India is the largest groundwater consumer in the world with estimated annual withdrawals of 230 km^3 (Central Groundwater Board 2004; Central Groundwater Board 2011; Groundwater Resource Estimation Committee 2009; Ministry of Water Resources 2008). However, groundwater supplies in the Indian subcontinent are difficult to quantify because of complex hydrogeological formations with considerable lithological and chronological variability and complex tectonic framework, coupled to variations in hydroclimate and hydrochemical conditions (Central Groundwater Board 2004; Central Groundwater Board 2011). In addition, India's increasing human population and rapid industrial and economic growth has placed enormous demands on groundwater resources (Agoramoorthy 2007; Agoramoorthy 2008; Agoramoorthy and Hsu 2008; Agoramoorthy et al. 2008; Agoramoorthy et al. 2009). In spite of adequate rainfall in many regions (1200 mm yr^{-1}, as reported by Kumar et al. 2005), India regularly suffers severe water shortages in many of its states (Agoramoorthy 2007; Agoramoorthy 2008; Agoramoorthy 2009; Agoramoorthy and Hsu 2008; Agoramoorthy et al. 2008; Agoramoorthy et al. 2009; Groetschel et al. 2000; Rodell et al. 2009). Given this scenario, it is not surprising that many states in India (Tamil Nadu, Karnataka, Gujarat, and Uttar Pradesh; Central Water Commission 2008) have become overly dependent on groundwater resources, consuming groundwater faster than natural recharge rates (Central Groundwater Board 2004; Central Groundwater Board 2011; Agoramoorthy 2007; Agoramoorthy 2008; Agoramoorthy 2009; Agoramoorthy and Hsu 2008; Agoramoorthy et al. 2008; Agoramoorthy et al. 2009; Mall et al. 2006; Shah 2008).

In response to growing concerns pertaining to unsustainable groundwater withdrawal practices, the Indian government established the Central Groundwater Board (CGWB) (Central Groundwater Board 2004) in 1970 under the Ministry of Agriculture to quantify and regulate groundwater resources nationwide. The CGWB, along with the Groundwater Resource Estimation Committee (Groundwater Resource Estimation Committee 2009), formulated scientific methods to monitor groundwater resources in collaboration with state groundwater departments. Many state- and district-scale scientific reports have been published to date (e.g., Central Groundwater Board 2004); however, implementation of the recommendations from such reports are very limited. Currently, the CGWB monitors approximately 15 000 wells distributed across India (Central Groundwater Board 2011; Groundwater Resource Estimation Committee 2009). However, there remains spatial and temporal groundwater data gaps in many districts. Instrumentation errors and maintenance and project costs supply many reasons for low-frequency and unreliable data collected from district wells. Consequently, developing a regional assessment of groundwater depletion, which is necessary to better manage groundwater resources, has been problematic. Obviously, implementation and validation of best groundwater management practices depends on the quality and availability of systematically collected data (Agoramoorthy 2007; Agoramoorthy 2008; Agoramoorthy 2009; Agoramoorthy and Hsu 2008; Agoramoorthy et al. 2008; Agoramoorthy et al. 2009; Tiwari et al. 2011). In addition, long-term and extensive groundwater resource campaigns are needed throughout India to educate the human population, including (but not limited to) industrialists, village people, and rural farmers, about proper groundwater consumption strategies (Agoramoorthy 2007; Agoramoorthy 2008; Agoramoorthy 2009; Agoramoorthy and Hsu 2008).

The state of Gujarat in India provides an example where 66% of the population (Groetschel et al. 2000) lives in villages and depends on the agricultural industry for their primary source of income. According to the Groundwater Resource Estimation Committee (GEC) (Groundwater Resource Estimation Committee 2009) and CGWB (Central Groundwater Board 2004), there is a continuum of freshwater withdrawal scenarios in India, including that in which (i) the entire water supply is provided from surface water; (ii) the entire water supply is provided from groundwater; and (iii) there is a mixed supply, a combination of both (Central Groundwater Board 2004). Although the state of Gujarat has several large dams built on rivers such as Narmada that supply irrigation water to millions of acres of farmlands, the state relies heavily on groundwater resources and falls within the second category.

According to the Indo-German Watershed Development Programme (IGWDP), the most common and pressing problems in the state of Gujarat are water related (e.g., access to quality water, irrigation, and soil erosion) (Groetschel et al. 2000). Similar to conditions in other states, impoverished village people do not fully understand the hydrogeologic regime. They therefore often exploit the groundwater resources, leading to depletion and environmental deterioration, which can then lead to further impoverishment (Agoramoorthy and Hsu 2008; Agoramoorthy 2007; Agoramoorthy 2008; Agoramoorthy et al. 2008). The geology of the semiarid state of Gujarat promotes low groundwater recharge. Therefore, groundwater in many regions of Gujarat is slower to recover from natural or anthropogenic disturbances relative to other regions in India. Clearly, continued information related to groundwater use and recharge is critical to improve groundwater management in Gujarat. Even though the state has approximately 930 wells to monitor groundwater resources, well locations are opportunistically located (i.e., unequally spaced with variable depth) and groundwater depth is only measured quarterly. Improved groundwater-monitoring methods are necessary to preserve Gujarat's regional groundwater resources. Rodell et al. (Rodell et al. 2009) further explained the situation reporting that regional groundwater assessments in India are difficult to generate from limited well surveys. Similarly, Tiwari et al. (Tiwari et al. 2011) reported that formulation of management plans for groundwater resources for a vast country like India will be challenging because of limited observation sites and data frequency.

While unable to replace direct monitoring, satellite technology may provide a useful indirect method to complement current observed datasets leading to more accurate groundwater resource estimations (Rodell et al. 2009). Rodell et al. (Rodell et al. 2009) used satellite remote sensing data to show that groundwater is being depleted at a rate of $17.7 \pm 4.5\ \mathrm{km^3\ yr^{-1}}$ from the groundwater reserves of Rajasthan, Punjab, and Haryana in northern India. Their estimations were much higher than the groundwater depletion rate ($13.2\ \mathrm{km^3\ yr^{-1}}$) reported by the Indian Ministry of Water Resources (Ministry of Water Resources 2008). Rodell et al. (Rodell et al. 2007) showed favorable comparisons between 58 well-based groundwater time series and total groundwater storage measured by remote sensing vehicles. In both the aforementioned studies, Rodell et al. (Rodell et al. 2007; Rodell et al. 2009) used the National Aeronautics and Space Administration (NASA) Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) to improve estimates of total equivalent groundwater storage. A number of previous studies successfully used GRACE and/or GLDAS remote sensing data to monitor water resources in various geologic settings (King et al. 2006; Bauer et al. 2007; Swenson and Wahr 2006; Awange et al. 2009; Velicogna and Wahr 2006; Morrow et al. 2011). Velicogna and Wahr (Velicogna and Wahr 2006) used GRACE to monitor glacial retreat in Greenland and reported a 250% increase in glacial melt from April 2002 to April 2004, noting the need to continue monitoring. Morrow et al. (Morrow et al. 2011) used GRACE to show insignificant glacial recovery using a 7-yr (October 2002–September 2009) linear trend in the variability of terrestrial water storage within the Mackenzie River basin, Canada.

Given the broad acceptance of the method (e.g., Rodell et al. 2009; King et al. 2006; Bauer et al. 2007; Swenson and Wahr 2006; Awange et al. 2009; Velicogna and Wahr 2006), studies are warranted that will provide higher-temporal-resolution (i.e., seasonal) estimates of groundwater thickness at higher-resolution spatial scales. Rodell et al. (Rodell et al. 2009) considered the northern states of India (Rajasthan, Punjab, and Haryana). However, there are other states (e.g., Gujarat) that have relatively low recharge conditions coupled to extensive groundwater withdrawals by agriculture and industry that will benefit from similarly implemented yet higher-resolution studies. Given that geology, land use, and climate differ vastly among states in India, higher spatial, temporal, and state-specific groundwater storage estimates are necessary to advance understanding and improve groundwater management.

The objectives of this study were fourfold: 1) to determine equivalent groundwater storage thickness using GRACE/GLDAS data for the northwest Indian state of Gujarat; 2) to validate GRACE/GLDAS results against quarterly averaged groundwater levels; 3) to identify spatial trends in groundwater storage/recharge across the state of Gujarat; and 4) to quantify temporal (monthly and seasonal) patterns in groundwater storage/recharge. We hypothesized that a positive trend between GRACE/GLDAS and recorded groundwater data will improve confidence in study results and therefore increase understanding of the current seasonal groundwater regime and will provide additional justification for continued use of remote sensing data to improve estimation accuracy of regional-scale groundwater depletion and supplies.

2. Methods

2.1. Study state

Gujarat is a northwestern state of India (Figure 1), located at 23.2167°N, 72.6833°E. The central and northern regions of Gujarat are dominated by plains lowlands with mountain ranges in the east. Gujarat is the 10th most populated state in India with a population of 60 509 671. Gujarat, on average, receives approximately 840 mm yr^{-1} of precipitation (Mukherji 2006), most of which falls during the months of June through September. The state of Gujarat has a total surface area of 196 000 km^2. A total of 27% of the area of Gujarat is drought prone. Nearly 82% of the state's irrigated land is irrigated with groundwater (Mukherji 2006). Agriculture in Gujarat grew at a rate of 9.6% yr^{-1} between the years of 2002 and 2008. A simultaneous rapid increase in industrialization resulted in sharp increases of groundwater extraction in a region where limited surface water is available for

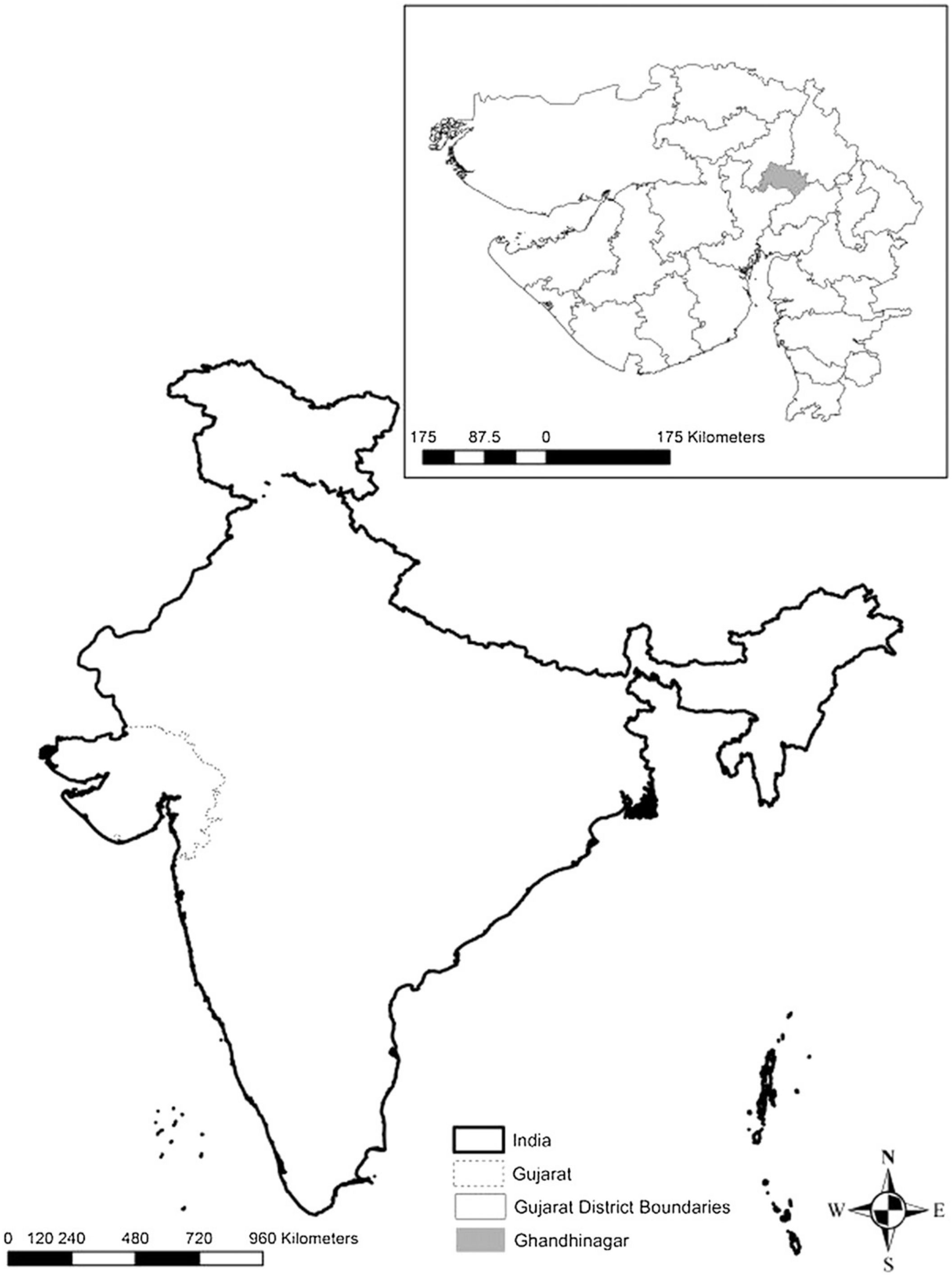

Figure 1. Map of India showing location of the state of Gujarat. Inset figure shows the location of Gandhinagar in Gujarat.

domestic and irrigation purposes (Groetschel et al. 2000). As a result, groundwater levels in Gujarat have fallen at rates 100% faster than recharge rates. Of the number of assessed suburbs, locally known as Talukas ($n = 223$), 69, 12, and 31 are currently classified as semicritical (groundwater withdrawal rates 70%–90% greater than recharge rates), critical (groundwater withdrawal rates 90%–100% greater than recharge rate), and overexploited (groundwater withdrawal rates 100% greater than recharge rates) (Central Groundwater Board 2004; Central Water Commission 2008; Groundwater Resource Estimation Committee 2009). These statistics illustrate the urgency for studies that seek to (i) better characterize current groundwater withdrawal and recharge rates and (ii) identify geographical distribution of supply and demand of groundwater in Gujarat and throughout India.

2.2. Estimating terrestrial water storage using GRACE

The composition and structure of the earth can be inferred from the planet's gravitational field (Tapley et al. 2004b). Seasonal variations in the earth's gravitational field reflect the annual redistribution of the atmosphere and mass of water in the biosphere and lithosphere. Terrestrial water storage (TWS) can be estimated from spatiotemporal variations in the gravitational field measured by the GRACE satellite mission. The GRACE was launched in 17 March 2002 in collaboration between NASA and the German Aerospace Center Deutschen Zentrum für Luft- und Raumfahrt (DLR). The GRACE is the first satellite remote sensing mission, which can be used to asses groundwater storage globally (Tapley et al. 2004a; Tapley et al. 2004b). The GRACE records satellite orbit perturbations caused by gravitational anomalies near the land surface and converts the change in gravitational field to estimate terrestrial water storage (Rodell and Famiglietti 2002; Rodell et al. 2009; Rodell et al. 2007; Rodell et al. 2004). Changes in groundwater storage can be estimated over large regions (130 000 km^2) at monthly resolution (Rodell and Famiglietti 2002; Rodell et al. 2007; Tapley et al. 2004a; Tapley et al. 2004b). Previous studies used land surface models and auxiliary methods to separate groundwater storage from GRACE-derived total mass variations (Rodell and Famiglietti 2002; Rodell et al. 2009; Rodell et al. 2007; Rodell et al. 2004; Tapley et al. 2004a; Tapley et al. 2004b; Tiwari et al. 2011) thereby validating GRACE usefulness for groundwater studies.

GRACE's signal supplies net variation in TWS after the oceanic and atmospheric effects are removed using numerical models (Rodell et al. 2009). Errors could be introduced depending upon the global land data assimilation system used (Howarth et al. 2012). However, a number of recent studies reported improved GRACE data processing and filtering techniques that greatly improve model confidence (Awange et al. 2009; Bauer et al. 2007; King et al. 2006; Swenson and Wahr 2006). GRACE's primary limitations include spatial resolution, where it cannot sample finer than 40 000 km^2 (Velicogna and Wahr 2006), and an inability to distinguish differences between linear ice mass and soil mass displacements (Howarth et al. 2012). The aforementioned limitations were accounted for in the current study by limiting the analysis for areas greater than a few hundred kilometers. Ice was not an issue given the general low elevations of Gujarat, which are well below the snow line. The current work uses methods as outlined by Rodell et al. (Rodell et al. 2009) but differs in spatial (state level rather than national level) and temporal (monthly rather than annual) scales. Therefore, the current study advances recent work by providing higher-resolution (spatial and temporal) estimates of groundwater thickness. Rodell et al. (Rodell et al. 2009) considered northern states of India but did not include Gujarat state, which has low recharge conditions and high groundwater withdrawals for agriculture and industry. Furthermore, seasonal patterns in groundwater storage/recharge can also be evaluated with the current method (GRACE/GLDAS), which is not possible from quarterly groundwater estimates from government agencies alone (Groundwater Resource Estimation Committee 2009). Study results also improve understanding of monthly groundwater recharge/storage trends that can be influenced by seasonal monsoons.

2.3. Estimating soil moisture using GLDAS

The GLDAS is a remote sensing system developed jointly by the NASA Goddard Space Flight Center (GFC) and the National Oceanic and Atmospheric Administration (NOAA) (Rodell et al. 2009; Rodell et al. 2004). The National Centers for Environmental Prediction (NCEP) monitors land surface fields at high spatial resolution (1 km) and in near–real time to produce land surface models (LSMs). Noah, a stand-alone single dimension column model driven by GLDAS, can be used to estimate soil moisture (Rodell et al. 2009; Rodell et al. 2004). Using this technology, the nonnegligible terrestrial water storage sources sensed using the GLDAS, resulting in mass variability in Gujarat, were assumed to be groundwater and soil moisture. In the current study, GRACE results were coupled with GLDAS/Noah to estimate groundwater storage variability.

2.4. Data analyses

Monthly results of GRACE data are processed and released 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). Monthly results from GLDAS, processed and released by the NASA Goddard Space Flight Center, were downloaded online from Mirador (at http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings). Care was taken to download similarly formatted spatial- (1°) and temporal- (monthly) resolution GRACE and GLDAS data, to enable groundwater thickness estimation using total water storage (GRACE) and soil moisture (GLDAS) data. Using GRACE-based estimates of terrestrial water storage and GLDAS-based soil moisture, equivalent water thickness or groundwater storage were calculated as per (Rodell et al. 2007)

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

where TWS, total equivalent soil moisture (SM), and equivalent groundwater storage thickness (GW) are all in centimeters. Monthly solutions for TWS and SM data for the state of Gujarat were accessed from GRACE and GLDAS databases for the year 2008. A destriping filter was applied to the GRACE data by the CSR, to minimize the effect of north–south striping errors identified by Wahr et al. (Wahr et al. 1998). Additionally, a 300-km-wide Gaussian filter was applied to the GRACE and GLDAS data to spatially smooth the data (Swenson and Wahr 2006). The GRACE data were further normalized by subtracting the time-averaged TWS for the period between January 2003 and December 2007 as per methods described by Rodell et al. (Rodell et al. 2004).

Surface soil moisture was estimated using four GLDAS datasets, one for each layer (0–10, 10–40, 40–100, and 100–200 cm). Data were summed to estimate total surface (vadose zone) soil moisture data. Two potential sources of mass variability that were neglected in this study included surface water, plant biomass, and snow water equivalent. The latter was unimportant owing to the temperate climate of Gujarat. GLDAS collects grids of total soil moisture content every 3 h. The grids are then averaged to monthly time series by the NASA Goddard Space Flight Center. To normalize the data, a time-averaged grid for January 2003–December 2007 was subtracted from all the individual grids. Thus, Equation (1) results in a normalized water equivalent thickness (Rodell et al. 2004).

2.5. Groundwater level from monitoring well networks

Monthly groundwater level data ($n = 935$) were used to compare observed (Central Groundwater Board 2004; Central Groundwater Board 2011) and estimated (GRACE and GLDAS/Noah) groundwater levels for the 2008 calendar year. Geographical information systems (GIS) were then used to characterize trends between observed and remotely sensed groundwater level and storage. Groundwater data from Gandhinagar, a district in Gujarat with high groundwater depletion rates, were compared to GRACE/GLDAS observed groundwater storage trends across Gandhinagar.

3. Results and discussion

Figure 2 shows the 2008 monthly normalized equivalent groundwater thickness, as per Equation (1) after removing soil moisture and surface water components, over the entire state of Gujarat. Changes in map color indicate water mass variations in terms of total net groundwater storage. Time series of GRACE/GLDAS data showed a decrease in groundwater supply from May to July and an increase in groundwater from August to October. The increasing trend is likely influenced by precipitation induced aquifer recharge processes, while the decreasing trend is likely driven by hot weather conditions, high evaporation rates, agriculture, and other human-related consumptive uses. Maximum groundwater storage months (September–November 2008) occurred after the maximum precipitation (Figure 3) input months (June–September 2008), indicating the lag time for rainwater to recharge groundwater aquifers. Similarly, minimum groundwater storage months (May–July) coincided with peak drought months and with months when groundwater withdrawals for irrigation are often the greatest. It is noteworthy (Figure 2) that December groundwater thickness approached the groundwater thickness of January, thus validating the expected annual cyclic trend of groundwater recharge and depletion. Quantitative understanding of groundwater recharge trends is important for proper management of seasonally variable groundwater supplies. It will therefore be helpful for future studies to remotely estimate lag times between groundwater depletion and recharge.

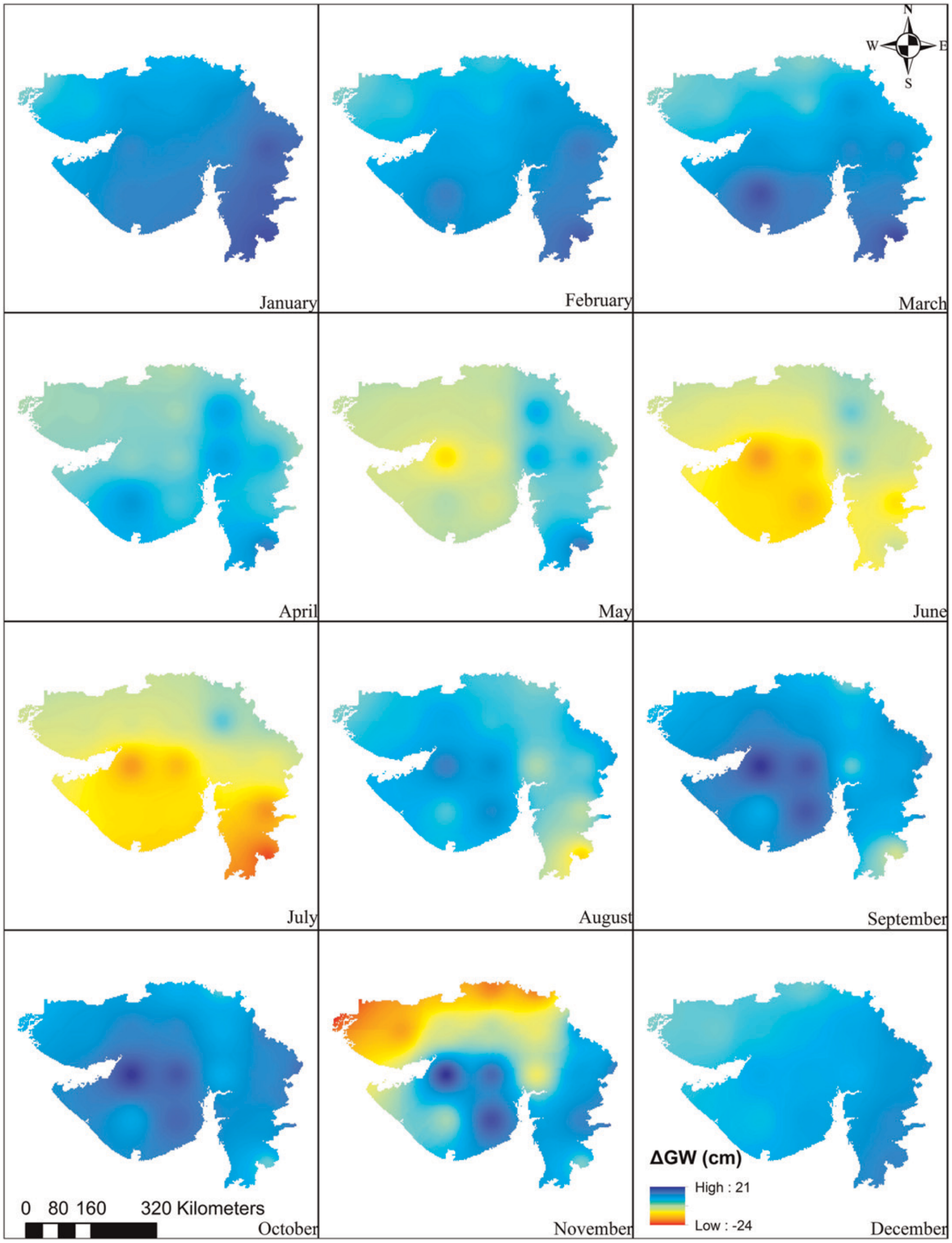

Figure 2. Monthly GRACE/GLDAS gravity solution for total groundwater storage for 2008 in Gujarat, India.

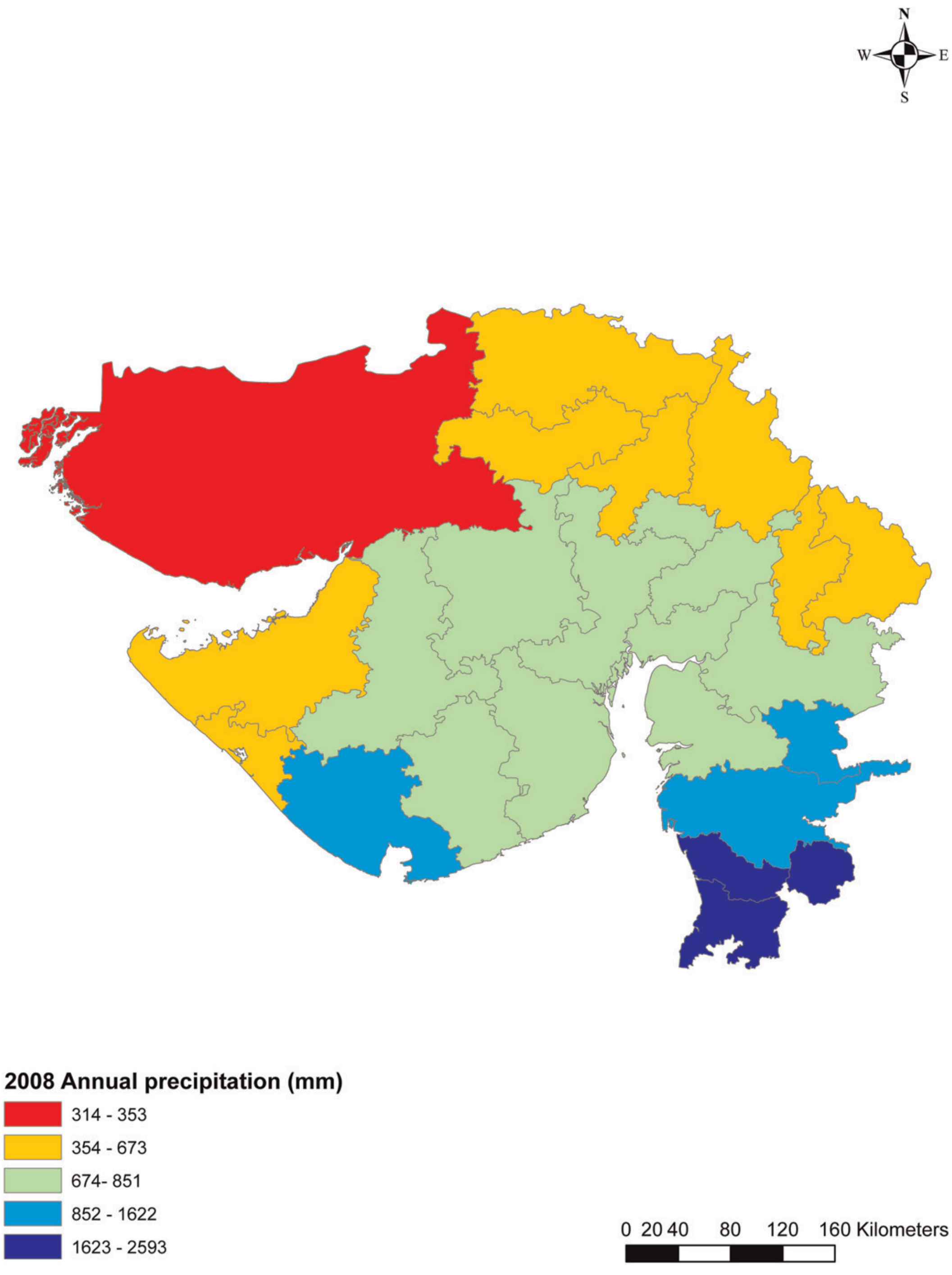

Figure 3. Annual precipitation (mm) in Gujarat, India, for 2008.

Figure 4 shows the groundwater level across Gujarat recorded from observation wells. Figures 2 and 4 show similar trends in groundwater depletion and groundwater recharge, with the lower regions of Gujarat recharging after the monsoon months (July–September). For site-specific comparison, Figure 5 compares the GRACE–GLDAS estimates of groundwater storage against physically recorded groundwater levels. The district of Gandhinagar (Figure 1) was chosen for comparison purposes, as the CGWB (Central Groundwater Board 2011) listed Gandhinagar in the groundwater overexploited regions category indicating groundwater withdrawal rates are greater than groundwater recharge rates. A total of 24 wells were averaged (Tiwari et al. 2011) for every month of data that were available in 2008 (January, May, August, and November). Groundwater wells in Gandhinagar were installed with average distance between wells ($n = 24$) of 19.8 km. The maximum and minimum distances from the center of the district are 30 and 14 km, respectively (standard deviation = 5.8 km). The wells are thus not clustered and are well distributed. Descriptive statistics of well distance, recorded groundwater data, and estimated groundwater thickness are shown in Table 1. Figure 5 shows that the GRACE/GLDAS-derived groundwater storage estimates closely tracked the trend observed in the groundwater-monitoring wells. Even though groundwater was recorded in Gandhinagar by the government only for 4 months during 2008, thus limiting our comparison, we were still able to observe similar groundwater trends between both methods. A positive trend indicated a favorable comparison between GRACE–GLDAS data and observed well data. A subsequent regression analysis, between GRACE/GLDAS-derived groundwater storage and observed groundwater level, yielded a coefficient of determination (r^2) value of 0.89. At the 95% confidence interval, the regression between GRACE/GLDAS-derived groundwater storage and recorded groundwater level was significant ($P = 0.002$). Tiwari et al. (Tiwari et al. 2011) indicated that improved understanding of aquifer hydrological parameters is necessary to convert GRACE–GLDAS water equivalent thickness to mass variation (total volume change). Because of the complex nature of the bedrock underlying Gujarat, it is difficult and costly to estimate regional-scale aquifer parameters. However, as corroborated in previous studies (Rodell et al. 2009; Tiwari et al. 2011), a visual agreement in spatiotemporal variations is observed, and it is shown for the current work in Figures 2–4. This, coupled to the regression value from Figure 5, provides further evidence that GRACE–GLDAS can be a cost-effective alternative or complimentary method to estimate groundwater supply depletion rates.

Future investigations

Precipitation in 2008 was greatest in August with an average of 330 mm across Gujarat due to monsoon rains. Figure 2 shows substantial increases in groundwater storage in September, indicating an approximate recharge lag time of 1 month. The role of streams and rivers likely influence groundwater recharge rates; therefore, future surface flow monitoring may aid in quantifying groundwater recharge sources and rates. In addition, groundwater-monitoring wells should be installed in low recharge regions (e.g., Dahod) where urbanization is rapidly increasing and along densely populated coastal regions (e.g., Mandvi). These wells need to be

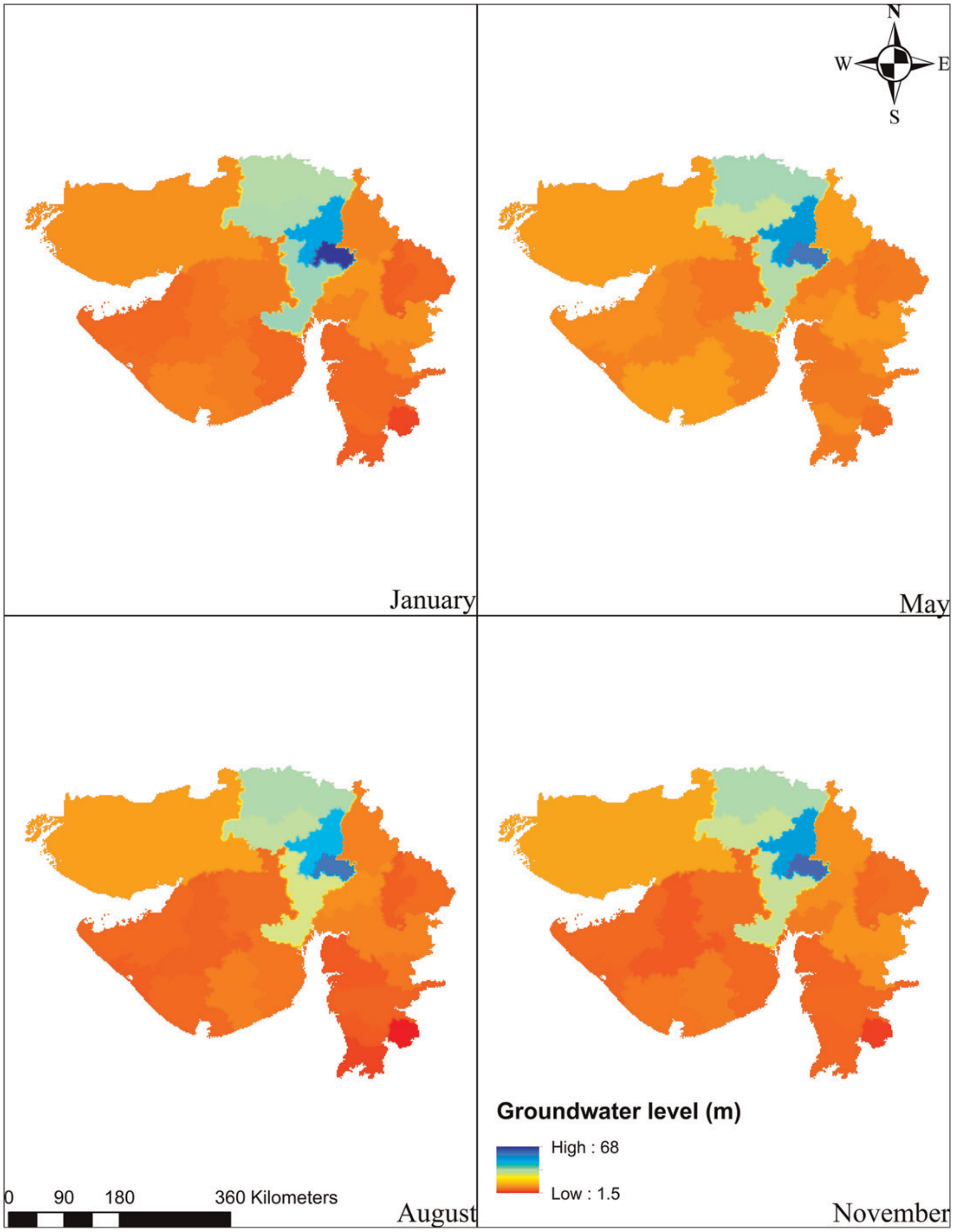

Figure 4. Monthly groundwater level recorded in Gujarat, India, for 2008. Data were obtained from the Central Groundwater Board's groundwater report (Central Groundwater Board 2010).

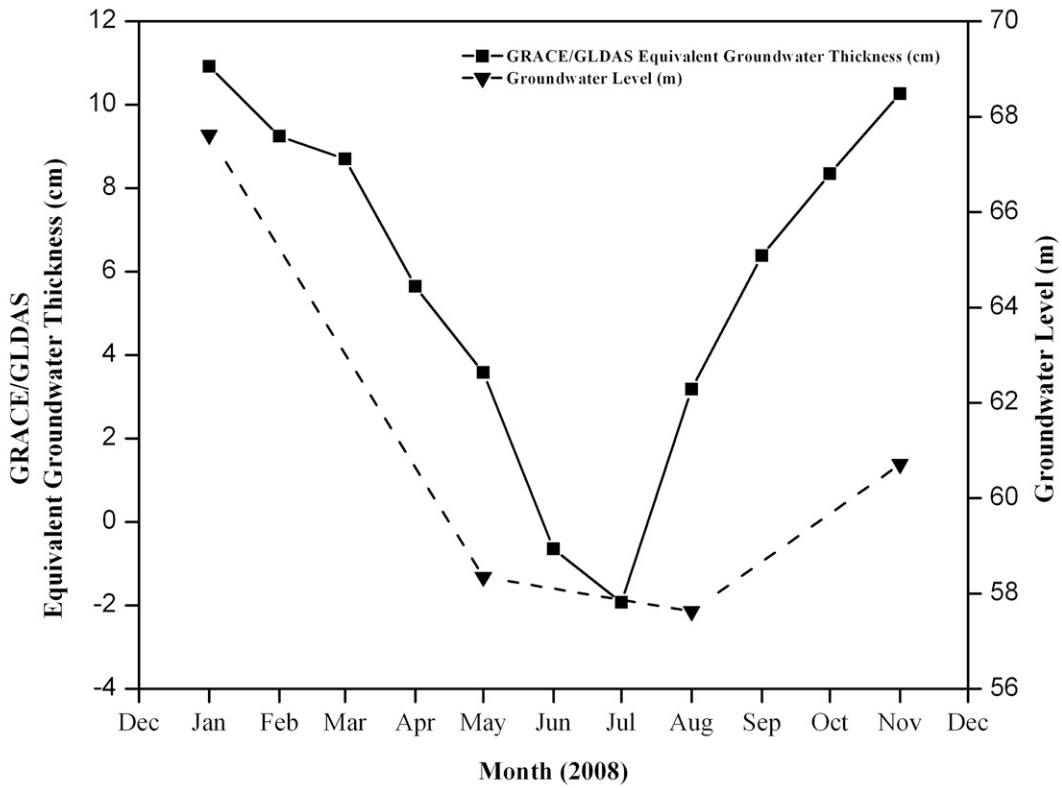

Figure 5. Comparison between GRACE/GLDAS-derived groundwater thickness (cm) and observed groundwater level (m) at Gandhinagar district in Gujarat for the calendar year 2008 (Central Groundwater Board 2010).

installed systematically and monitored at least monthly. Only then will a higher-resolution quantitative assessment be possible to better understand human impacts on groundwater supplies in the arid districts of Gujarat.

Figure 2 shows that coastal regions near the Gulf of Kuchchh have higher groundwater storage anomalies. Because of aggressive groundwater depletion along coastal regions, saltwater intrusion can occur rapidly, leading to contamination of freshwater aquifers. To protect freshwater resources and aquatic ecosystems in such vulnerable coastal areas, it is necessary to physically monitor groundwater and seawater levels using high-frequency instruments in high groundwater depletion zones. The GLDAS sea-grid model (Fukumori 2002; Kim et al. 2007) can be used to estimate sea level across the globe. Tools like the GLDAS, coupled to remote sensing data with available field measurements, will increase physical processes–based understanding of groundwater flow. Such information will help land managers improve saltwater intrusion prevention methods, including levee construction and subsurface-engineered barriers, to dampen seawater velocities. Ultimately, quantitative understanding of groundwater depletion rates can help guide state governments in reconsidering urbanization options and better manage population densities in high groundwater sensitive (i.e., overexploited) areas.

Table 1. Descriptive statistics of groundwater well distance from Gandhinagar district center (km), observed groundwater level (m) at 24 monitoring wells, and estimated groundwater thickness using GRACE/GLDAS (cm) for the year 2008 at Gandhinagar district, Gujarat, India.

Parameter	Well distance (km)	Recorded groundwater level (m)	Estimated groundwater thickness (cm)
Mean	19.83	61.08	5.79
Std dev	5.81	4.56	4.32
Min	14.00	57.63	−1.93
Max	30.00	67.62	10.92

4. Conclusions

This work shows that GRACE satellite gravity data are a relatively cost-effective, high-frequency, and regional-scale groundwater assessment tool. The method is viable when coupled to available recorded groundwater data to understand the groundwater hydrologic regime in many global regions. In the state of Gujarat, India, field groundwater monitoring, using four data points per year per observation well, was shown to be insufficient for establishing regional-scale groundwater resource sustainability and management plans. This work shows that, to improve quantitative assessments and thus management of groundwater supplies, remote sensing data can be used in tandem with available observed well data to better characterize spatial and temporal variations in groundwater depletion and recharge. While 1 year is a short period to infer with confidence a long-term trend, results show a positive relationship ($r^2 = 0.89$) between GRACE/GLDAS and recorded groundwater level, thus strengthening the approach as a viable method for establishing multiyear relationships. At the 95% confidence interval, the regression between GRACE/GLDAS-derived groundwater storage and recorded groundwater level was significant ($P = 0.002$). Results of the present study suggest that groundwater extraction is greater during the premonsoon summer months mostly between May and June, with most groundwater storage variations observed in the southern part of Gujarat, which is highly urbanized.

Groundwater depletion rates are likely to continue unmitigated unless effective measures are taken to identify depletion regimes and identify viable science-based alternative to address groundwater overuse problems (Agoramoorthy 2007; Agoramoorthy 2008; Agoramoorthy 2009; Agoramoorthy and Hsu 2008; Agoramoorthy et al. 2008; Agoramoorthy et al. 2009). Lacking in progressive action, it seems probable that groundwater depletion rates will continue to increase, eventually diminishing access of the resource resulting in post facto measures by policy makers (Rodell et al. 2009). The authors recommend that the Government of Gujarat establish long-term high-frequency groundwater monitoring in rapidly urbanizing areas, particularly along coastal regions. Such work will improve understanding of relationships between groundwater withdrawal rates and saltwater intrusion processes, thereby supplying science-based information to land managers wishing to protect freshwater resources in those regions.

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