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The Groundwater Recovery Paradox in South India

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Key Points:
- Reported recovery of groundwater levels in South India is at odds with increasing well failures and reports of groundwater stress
- Apparent paradox is explained by survivor bias, where wells with missing data are routinely excluded from analysis of groundwater trends
- Long-term trend analysis is not appropriate for hard-rock aquifer of South India; alternative metrics developed that highlight groundwater stress

Supporting Information:
- Supporting Information S1

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Abstract Reported groundwater recovery in South India has been attributed to both increasing rainfall and political interventions. Findings of increasing groundwater levels, however, are at odds with reports of well failure and decreases in the land area irrigated from shallow wells. We argue that recently reported results are skewed by the problem of survivor bias, with dry or defunct wells being systematically excluded from trend analyses due to missing data. We hypothesize that these dry wells carry critical information about groundwater stress that is missed when data are filtered. Indeed, we find strong correlations between missing well data and metrics related to climate stress and groundwater development, indicative of a systemic bias. Using two alternative metrics, which take into account information from dry and defunct wells, our results demonstrate increasing groundwater stress in South India. Our refined approach for identifying groundwater depletion hot spots is critical for policy interventions and resource allocation.

Plain Language Summary Over the last century, groundwater has become an important source of freshwater to meet agricultural and drinking water needs. Increasing use of groundwater has contributed to depletion of groundwater reserves around the world, with India being at the forefront of this problem. Recent studies suggest that groundwater levels have been increasing in South India due to increasing rainfall and political interventions. This finding is at odds with local reports of groundwater stress, and increasing well failures. Our study explains this disagreement by showing that previous conclusions have been skewed by the problem of survivor bias, with wells with data gaps being routinely excluded from analysis of long-term groundwater storage trends. We find that traditional groundwater trend assessment methods are not suitable for hard-rock aquifer systems that characterize South India. Indeed, strong correlation exists between climate and groundwater stress and wells with missing data, indicative of a systemic bias. We develop metrics that use data from these wells, and show using these metrics increasing evidence of groundwater stress in South India over the last two decades (1996 to 2016). Our results provide insight into the management of groundwater depletion in India, while highlighting potential biases in groundwater sustainability assessments globally.

1. The Paradox of Rising Farmer Distress in Areas of "Groundwater Recovery"

Food security is inextricably tied to water availability for irrigation. In arid and semiarid regions with high interannual variability in rainfall, a significant fraction of the irrigation water demand is met by mining groundwater. Increasing rates of groundwater usage have led to the drying up of major aquifers around the world (Gleeson et al., 2012), and rapid groundwater depletion has often been accompanied by negative socioeconomic and environmental consequences (Giordano, 2009; Mukherji & Shah, 2005; Srinivasan & Kulkarni, 2014). India has some of the highest groundwater extraction rates in the world, with annual abstraction increasing from ~25 to ~200 km^3/year between 1950 and 2000 (Giordano, 2009; Shah, 2005). These high rates of abstraction are especially alarming as groundwater accounts for 60% of irrigation water and 85% of drinking water in India (World Bank, 2010). Given the societal dependence on this critical resource, accurate identification of hot spots of groundwater depletion is imperative, so as to design effective intervention strategies.

Recent analyses have identified North India (NI) as a hot spot for groundwater depletion (Asoka et al., 2017; Panda & Wahr, 2016; Rodell et al., 2009). In contrast, water levels are reported to be rising in South India (SI; Asoka et al., 2017; Bhanja et al., 2017; Panda & Wahr, 2016). These conclusions are based on a variety of methods, including satellite observations such as those made by the NASA Gravity Recovery Climate

Experiment (GRACE) satellites, water level measurements in groundwater monitoring wells, and global hydrological models. The problem is that these findings contradict on-the-ground field reports and farm surveys that report increasing well failures during the same time period (Merriott, 2015; Srinivasan et al., 2015).

Indeed, using a keyword search on the Dow Jones Factiva database, we found that the number of newspaper articles reporting groundwater depletion in SI have increased by an order of magnitude since the 2000s (Figure S1). Furthermore, farm surveys that are done as a part of the agricultural and minor irrigation census (Government of India, 2014) provide evidence that farmers are drilling deeper wells. Census reports suggest a decline in shallow well irrigated area from 1996 to 2010, and an increase in the deep well irrigated area over the same time frame (Figure S2). The median percent decline in shallow well irrigated area from 1996–2000 to 2006–2010, across the South Indian states of Andhra Pradesh, Telangana, and Karnataka, is 52%, while the median percent increase in deep well irrigated area over these states is 98% over the same time frame. If groundwater rejuvenation is indeed occurring in SI, as claimed by earlier studies (Asoka et al., 2017; Bhanja et al., 2017), why are farmers switching from shallow to deep wells, and why are newspaper mentions of groundwater stress increasing?

We hypothesize that the lack of agreement between large-scale analysis of groundwater vulnerability and on-the-ground reports in South India can be attributed to methodological constraints arising from the unique characteristics of hard-rock aquifers, viz., low storage capacity and heterogeneous spatial patterns of storage. Our objective in this paper is (1) to assess groundwater storage trends in India using traditional data sources (monitoring wells, satellite data), (2) to explain differences in groundwater stress inferred from traditional "hard" hydrological data (monitoring wells, satellite data) versus "soft" nonhydrological data (census surveys, field reports, newspaper searches), and (3) to identify alternate large-scale metrics of groundwater depletion that are consistent and reliable.

2. Methods

District-wise irrigated area from 1996 to 2011 was obtained from the agricultural census database (http://vdsa.icrisat.ac.in/) compiled by the International Crops Research Institute for the Semi-Arid Tropics. This database contains information on district-scale (Figure S3) irrigated area that has been grouped based on the source of irrigation (Table S1). As the number of districts in India has changed significantly since the 1960s, the database aggregates data from new districts into (parent) districts from 1966 for consistent temporal comparisons. Monthly precipitation data was obtained from the Indian Institute of Tropical Meteorology from 1980 to 2016 (https://www.tropmet.res.in/Data%20Archival-51-Page). Monthly precipitation values were converted to standardized precipitation index values to represent region specific dry and wet periods. Standardized precipitation index for 12, 24, and 36 months was calculated by fitting a gamma distribution to the cumulative precipitation amounts for the same time period.

We used monthly GRACE data from 2002 to 2016 to estimate the satellite-derived groundwater storage anomalies. Specifically, groundwater storage anomaly was estimated by subtracting surface water storage from the GRACE-derived terrestrial water storage anomaly. The surface water storage (canopy storage, soil moisture, snow) was estimated using Noah land surface model, available from the Global Land Data Assimilation System (Rodell et al., 2004). We obtained level-3 terrestrial water storage anomaly version RL05 (Landerer & Swenson, 2012; Swenson & Wahr, 2006) from the Centre for Space Research at the University of Texas, Austin (ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land_mass/RL05). The accompanying scaling factors based on the Community Land Model version 4.0 were applied to reduce the signal loss from sampling and postprocessing. We ensured that the GRACE-derived terrestrial water storage anomaly and Global Land Data Assimilation System-derived surface water storage were relative to the same baseline period (2002–2016 in our analysis). The Global Land Data Assimilation System-forcing data showed strong correlation with the Indian Institute of Tropical Meteorology precipitation used in the study (Figure S4).

Observation well data (from 1996 to 2016) was obtained from the Central Groundwater Board (CGWB) database (Figure S5) that contains water level measurements recorded 4 times a year (January, May, August, and November) for 29,513 wells (http://www.india-wris.nrsc.gov.in/wris.html). Of these, 12,279 wells were active in 1996, representing wells with the longest possible records in the database. Based on census reports (Government of India, 2014), we categorized "dug wells" as shallow wells, and "tube wells" (or "bore wells") as deep wells for a region. We used shallow wells with >18 (out of 21) years of data to estimate groundwater trends. For deep wells, this condition was relaxed due to a lack of long-term monitoring wells, and wells with >10 years of data were used. The number of wells used for trend analysis ranged from 6,350 to 7,532, depending on the month of analysis.

We assessed statistical significance of trends in groundwater storage for both satellite and monitoring well data using the nonparametric Mann-Kendall trend test (Mann, 1945), while slopes were estimated using the Theil-Sen slope estimation method (Sen, 1968). We used the trend estimation techniques suggested by Yue et al. (2002), which corrects for the influence of autocorrelation in the data series. Trends and slopes in GRACE data were estimated at the yearly time scale after averaging the monthly groundwater storage anomalies estimates. Trends in observation well data were obtained separately for each of the four months to avoid the influence of seasonality.

3. Results and Discussion

3.1. Groundwater Storage Trends in India

We used GRACE satellite data to estimate trends in groundwater storage in India for two overlapping time periods: 2002–2016 and 2005–2016. Consistent with previous studies, the analysis showed widespread significant (p value < 0.1) decreasing trends in groundwater storage anomalies in NI (above 23°N) for both time periods (Figures 1a and 1b). The SI (below 23°N) regions, however, showed a noteworthy difference in trends between the two periods. A large fraction of the area that showed a positive trend with a 2002 start date showed nonsignificant trends (p value > 0.1) with a 2005 start date. Specifically, the trend analysis from 2005 reveals 23% of the region with significant positive trend, 19% with negative trend, and 58% with no trend, in contrast to 51%, 11%, and 38% of the region with positive, negative, and no trend, respectively, with a 2002 start date (Figure 1c). In fact, only 16% of the cells identified by Bhanja et al. (2017) as improving due to political interventions in Andhra Pradesh based on a 2002–2014 GRACE analysis still showed a significant positive trend in the 2005–2016 analysis. This sensitivity to the choice of initial date potentially arises due to the extreme drought that occurred in India during 2002–2004 (Figure S6), and highlights the sensitivity of the trends to the initial date, especially when the period of analysis is relatively short (10–20 years). Thus, we argue that in a monsoonal climate with high interannual variability in precipitation it is important to consider the starting point of analysis when evaluating the significance of various groundwater trends. The other significant limitation of GRACE analysis is that while it provides an excellent estimate of regional trends in groundwater depletion, it is aggregated at a larger scale, and provides no information on local depletion hot spots. This becomes especially important in a highly heterogeneous, hard-rock aquifer system that characterizes South India (Dewandel et al., 2011; Perrin et al., 2011).

To address this issue and identify local depletion hot spots, we analyzed groundwater monitoring well data available from 1996 to 2016 (Figures 1d–1f). Interestingly, other than the northwestern states of Punjab and Haryana, we found that majority of wells in India show no significant trends (p value > 0.1), and all the South Indian states have >50% wells with nonsignificant trends (Figures 1d and S7). Past studies have tended to draw conclusions based on either wells with only significant trends (Asoka et al., 2017) or by not testing for significance (Bhanja et al., 2017). Further, by only considering wells with significant trends, we find that both shallow and deep wells in NI show declining trends (median trend = −7.6 cm/year for shallow wells and −51 cm/year for deep wells). In contrast, the deep wells in SI show a declining trend (−14 cm/year), while the shallow wells there show an increasing trend (4.4 cm/year). Interestingly, when the wells are not segregated by depth, the median water level trends in all wells more closely mimics that of the shallow wells, given the more extensive network of shallow wells (median trend = −10.8 cm/year for NI and 2.7 cm/year for SI), explaining why previous studies (Asoka et al., 2017; Bhanja et al., 2017) that did not segregate wells by depth found an increase in water levels in SI wells. Our analysis of groundwater level data highlights two critical points. First, there are significant depth variations in water level trends in a multiaquifer system that characterizes the Indian subcontinent, and thus, aggregating information with depth conceals critical trends and stresses in the aquifer system. Second, in shallow, hard-rock aquifer systems with low storage buffers and high interannual variability in water levels that characterizes most of South India, a large fraction of the wells have nonsignificant trends and there is critical information that is missed by not considering them. The GRACE data and the groundwater monitoring data corroborate

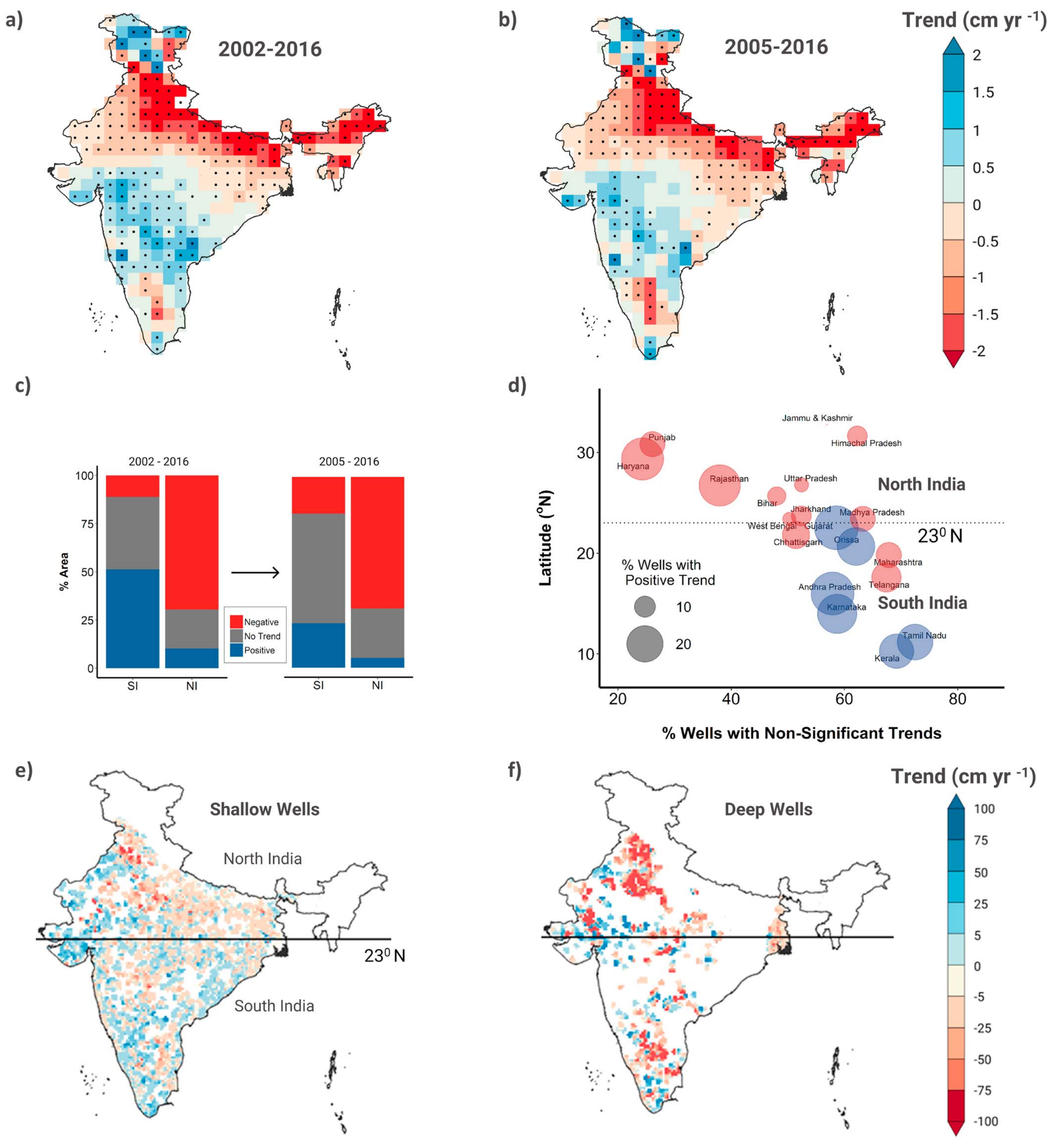

Figure 1. Long-term groundwater storage trends in India: yearly trend (cm/year) in groundwater anomaly from GRACE analysis for (a) 2002–2016 and (b) 2005–2016. Dots represent areas with statistically significant trends (p value < 0.1). (c) Percent change in the distribution of positive, negative, and nonsignificant GRACE-based trends as a function of the analysis time frames in NI (above 23°N) and SI (below 23°N). Results highlight that the percent area with positive and nonsignificant trends are highly sensitive to the period of analysis in Peninsular India. (d) Percentage of wells with nonsignificant trends (p value > 0.1) in May aggregated at the state scale. Each circle represents a state and the size of the circle represents the percentage of wells with positive trends (p value < 0.1). Red circles represent states with greater negative trends than positive, while blue circles represent states with more positive trends. Results show that a majority of states have a large percentage of wells (>50%) with nonsignificant long-term trends. (e) Water level trends (cm/year) in shallow monitoring wells. (f) Water level trends (cm/year) in deep monitoring wells. Note that wells trends (in e, f) are presented for the premonsoon season (May), and all wells used have statistically significant trends (p value < 0.1).

each other over most of India, except parts of northwestern and central India (Figure S8). Furthermore, the GRACE data highlight patterns of large areas with nonsignificant trends in SI, similar to the monitoring well data.

While these issues have never been evaluated at the scale of SI, other local studies have questioned the value of long-term water level trends in highly dynamic hard-rock aquifer systems (Buvaneshwari et al., 2017; Pavelic et al., 2012), and argued for groundwater sustainability to instead be evaluated in terms of short-term water provisioning (Fishman et al., 2011). In a recent field study in the Arkavathy river watershed in Karnataka, SI, Srinivasan et al. (2015) argued that the groundwater monitoring well data that were available from the CGWB reports were not representative of on-the-ground reality. The two wells recording data in the CGWB reports showed water levels at 10–30 m below ground level, and no significant temporal trends. In contrast, their survey of wells in the region found no visible open wells with water. A more focused analysis based on a detailed survey 472 borewells in a small (26 km^2) subcatchment of the Arkavathy watershed revealed that the median depth of the borewells farmers were digging increased from <50 m in 1970s to over 200 m in 2000s (Srinivasan et al., 2017). Deeper borewells are a clear indication of disappearing groundwater, despite CGWB wells recording no significant trends in this region. The lack of trend in this local study is analogous to the large fraction of wells showing no significant trend. Since most studies have ignored wells with no significant trend, they have missed asking the question, *given that a majority of wells show a lack of any significant declining trend in South India, why do irrigation statistics allude to groundwater stress?*

3.2. Stable Water Levels Are Because of Survivor Bias

We contend that this conundrum can be explained using the concept of survivor bias, which is a type of selection bias (Hernán et al., 2004; Simundic, 2013). Survivor bias is an artifact that arises in statistical analysis of data by focusing on data that were filtered based on some selection criteria. Subsequent analysis on the data that "survived" has the potential to significantly skew the interpretation (Aggarwal & Jorion, 2010; Ton et al., 2018). Examples of survivor bias are commonly found in finance where failed hedge funds are excluded from performance studies (Aggarwal & Jorion, 2010), or occupational health studies with inadequate consideration of workers with poorer health status (Buckley et al., 2015).

With groundwater well data, we often use a selection criterion where wells with a certain proportion of missing data are routinely eliminated from the analysis of long-term trends. Missing data in a well record can occur in two ways: (1) the well goes defunct and stops collecting data permanently during the analysis time frame and (2) the well records no data in multiple intermediate months within the time frame. The underlying cause of such missing data can be either (1) physical, where the water level in the well falls permanently or temporarily below the well screen depth, or (2) logistical, where operators neglect maintaining monitoring wells, or they collect or record the data inadequately. We argue that while the latter (operator errors) can contribute to missing data, the former is one of the key underlying reasons for missing data. The aquifer system of SI is known to experience large interannual fluctuations in water level such that a dry well can recover and become functional relatively quickly during wet periods (Fishman et al., 2011; Reddy et al., 2009). Paradoxically, wells that go dry are usually excluded from time series analyses of water level trends that tend to select wells that have the most complete data sets (Asoka et al., 2017; Bhanja et al., 2016).

To test the above claim, we explore the relationship between the % dry wells and metrics that capture climate variability and anthropogenic stress on the groundwater resources. We designate wells as "dry" in a given season and year if they did not record any data in that time frame, and estimate the % dry wells in a region as ratio of the number of dry wells to the total number of monitoring wells in that region. For climate analysis, we aggregate the % dry wells at the regional scale of NI and SI between 1996 and 2016 (Figure S6), and detrend the data using the least squares approach to reduce the effect of systematic changes (e.g., changing technology or groundwater irrigated area) in a region (Hosseini-Moghari et al., 2019; Kumar et al., 2016). Overall, we find a significant negative correlation between the 36-month standardized precipitation index ($r = -0.44$, p value < 0.1; Figure 2a) for each year, and the residuals of the % dry well time series. The higher-percent dry wells in years with a low standardized precipitation index confirms that the missing data are most likely related to dry spells when water level in wells fall below the screen level. These wells might recover in wet years, but the lack of water availability in dry years is an indication of groundwater stress.

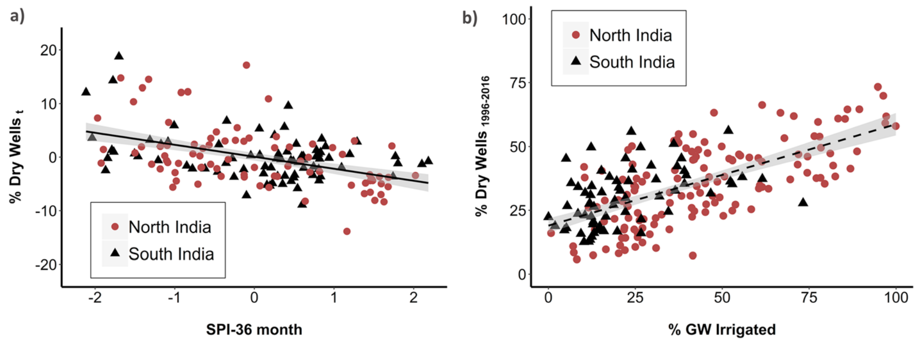

Figure 2. Dependence of dry well density on rainfall and groundwater irrigated area. (a) Percentage of dry monitoring wells (after removing trend) aggregated at the NI and SI scale (referred to as %DryWells$_t$) versus the 36-month standardized precipitation index (SPI) for each month between 1996 and 2016. SPI values and percent dry wells were estimated for each of the four months of available groundwater level data (January, May, August, and November). (b) Percentage of dry monitoring wells at the district scale, aggregated over the 1996–2016 time frame (referred to as %DryWells$_{1996–2000}$) versus the percentage of groundwater irrigation in the district. The % dry well aggregation was done by taking the median % dry well value between 1996 and 2016. The percent groundwater irrigation represents the median percent groundwater irrigated area in each district between 2005 and 2010. Note that only districts where at least 20% of the gross cropped area is irrigated are shown. Figure highlights the dependence of % dry wells on natural (precipitation) and anthropogenic (groundwater irrigation) factors.

To understand the relationship between the % dry wells and the degree of groundwater development at the district scale, we estimate the median % dry wells by aggregating the % dry wells per year over the 20 years of analysis (1996–2016) in that district. We contend that the median percent of "dry wells" over the 1996–2016 time frame is indicative of the degree of groundwater stress in the region. We find a significant positive correlation between the median % dry wells and the % area under groundwater irrigation in a district, aggregated over the same time frame ($r = 0.58$, p value < 0.1; Figure 2b). A higher proportion of dry wells in areas with higher groundwater irrigation is a clear indication that the occurrence of missing data is not random, as it would be if driven solely by human error. This analysis highlights that missing data in well records carry critical information on groundwater stress due to climate and/or anthropogenic factors that are completely missed in long-term trend analyses that routinely filter out this information. Here lies the artifact of survivor bias—the wells that survive the filtering process are wells with the smallest percent of missing data, and are thus preferentially wells at deeper depths, or in pockets of stagnant water in a highly heterogeneous aquifer system. The lack of trend we see in most existing groundwater well data despite reported increasing stress on groundwater resources is most likely due to such survivor bias. Thus, the validity of trends using only wells with continuous long-term records as an indicator of groundwater stress in low-storage, hard-rock aquifers needs to be questioned.

3.3. Alternative Metrics of Groundwater Stress

Given the uncertainty associated with long-term water level trends in hard-rock systems, there is a need for metrics that can measure groundwater sustainability in terms of short-term reliability (Fishman et al., 2011). Based on the above analysis, we propose two metrics: defunct wells and dry wells. We designate monitoring wells as defunct if they stop collecting data permanently within the 1996–2016 time frame, and the % defunct wells in 2016 is estimated as the proportion of wells that started collecting in 1996 that stopped collecting data permanently before 2016. The % dry well is the proportion of wells that started collecting in 1996 that have missing data in the time step of consideration. While other studies have explored trends in groundwater levels, no study so far has explored the trend in the inactivity of the monitoring wells.

We find a steady increase in the % defunct and dry wells in both NI and SI highlighting the increased stress in groundwater (Figures 3 and S9). On average, we see an increase in dry wells at a rate of 104 wells/year in SI, with higher percentages in the drought period of 2002–2003 (Figure S6). Furthermore, we found that nearly 93% of the defunct wells (with at least eight years of data) had either a significant negative trend or no long-

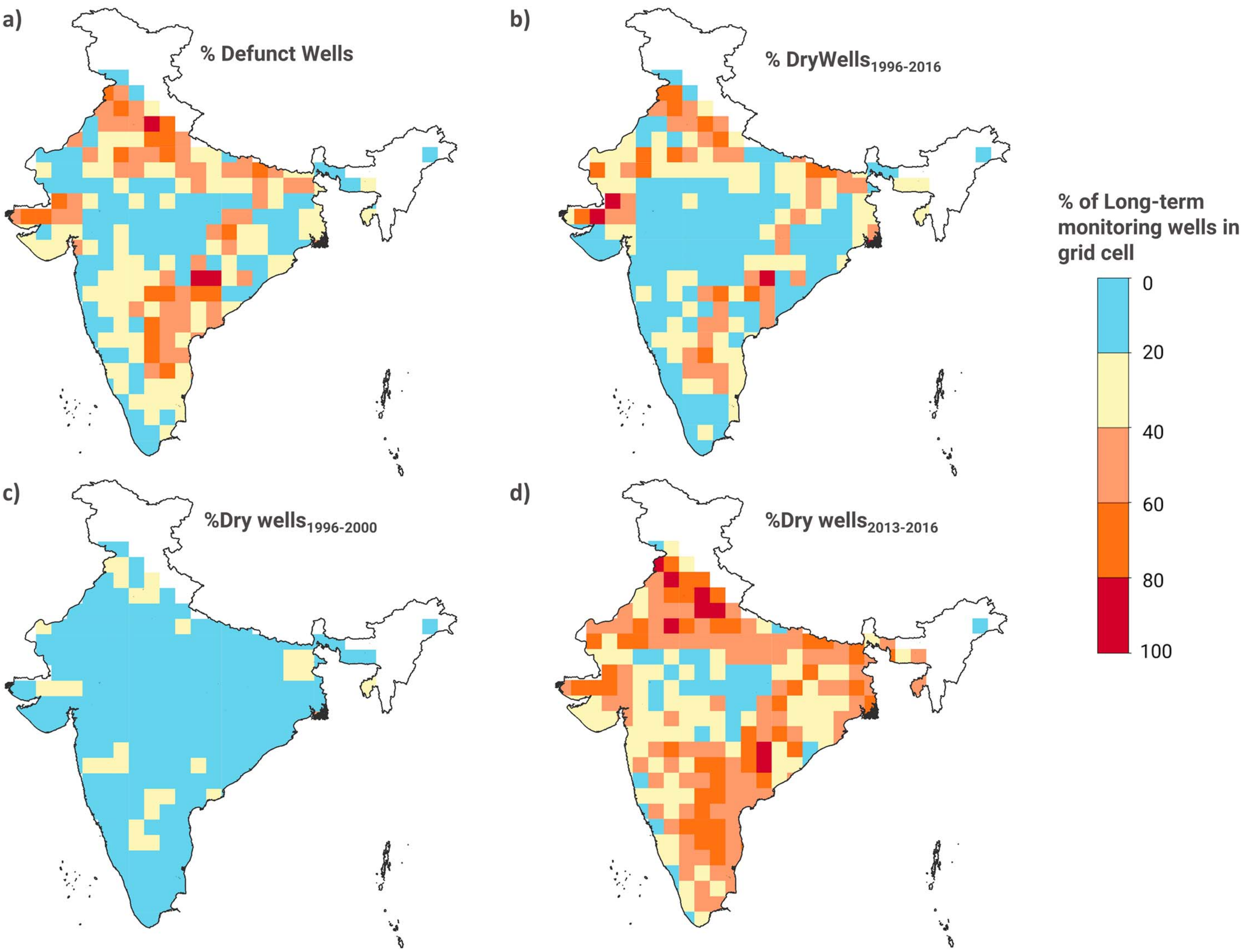

Figure 3. Spatial patterns of dry and defunct wells. (a) Percent of defunct wells in 2016, calculated as the ratio of wells in grid cells (1° by 1°) that permanently stopped collecting data to all the long-term monitoring wells present. (b) Median percentage of dry monitoring wells between 1996 and 2016 in each grid cell. (c) Median percentage of dry monitoring wells between 1996 and 2000. (d) Median percentage of dry monitoring wells between 2013 and 2016. The % dry wells was calculated as a ratio of wells in grid cells (1° by 1°) that did not record data in a time period to all the long-term monitoring wells present there. Higher percentage of dry/defunct wells (orange/red) indicates relatively more groundwater stress, and lower percentage of dry/defunct wells (yellow/blue) indicates relatively less groundwater stress. Please note that long-term monitoring wells in our analysis refer to monitoring wells active in 1996.

term trend. This supports the validity of these metrics as an appropriate indicator for evaluating groundwater stress.

Spatially, dry and defunct wells were found to be uniformly distributed in north and south India, but absent in central India (Figure 3). The distribution of hot spots (areas with >50% dry and defunct wells) in NI correlates well with declining water levels in the monitoring wells, as expected (Figures 3a and 3b). In contrast, there is a significant density of these hot spots in SI despite increasing or stable water level trends in monitoring wells (Figures 1e, 3a, and 3b) that is an artifact of survivor bias. These hot spots in SI also correspond to areas where the proportion of shallow well irrigated area has been decreasing (Figure S2), and where other local studies report occurrences of water stress (Anantha, 2013; Perrin et al., 2011). These results corroborate our initial claim that exploring patterns in monitoring wells going defunct and dry wells may provide critical information on the degree of groundwater stress in a region.

4. Summary and Implications

Our study was motivated by the need to answer why farmer distress is increasing in regions experiencing apparent groundwater recovery. Specifically, analyses of both GRACE and groundwater monitoring data highlight large areas in South India with stable or increasing water level trends (Asoka et al., 2017; Bhanja et al., 2017), which is at odds with findings from social survey data that include reports of well failure and decreases in land area irrigated from shallow wells. Our results highlight that this discrepancy arises due to the problem of survivor bias, where wells with too much missing data are routinely excluded from long-term trend studies. We find that aquifer dryness can manifest itself as data gaps in monitoring well records; thus, these wells carry critical information on the degree of groundwater stress in a region. Given that monitoring well data often underpins government reports and modeling studies, any regional assessment of long-term trends in groundwater systems relying on this information might be prone to such survivor bias. While satellite-based data products can help overcome such biases, the current spatial resolution makes it difficult to highlight local hot spots in heterogeneous aquifer systems.

We argue that in hard-rock aquifer systems with large precipitation-driven interannual variability and significant spatial heterogeneity, water level trends are not an adequate metric to measure groundwater stress. We provide two metrics, % dry and defunct wells, derived from data gaps in monitoring wells that might be better suited for assessing groundwater stress in these regions. In South India, both the % of defunct and dry wells have been increasing over time, and the hot spots identified by them correspond well with areas that have local reports of well failures. Correct interpretation of monitoring well data shows that SI is indeed facing significant groundwater stress, and thus requires improved regulations to help meet local demands for groundwater in a more sustainable manner. Interventions promoting the conjunctive use of surface water from rainwater harvesting structures and groundwater (Siderius et al., 2015), along with policies that change the current structure of agricultural power subsidies (Shah et al., 2012), have the potential to improve the situation in SI. Some practical implications of this analysis are that data collection agencies should prioritize collecting information on these dry/defunct wells, while making available details on why data were not collected from a monitoring well at any time step (using flags in the database).

Groundwater storage and its linkage to socioenvironmental demands in India is a complex, interdisciplinary issue. As we improve our ability to monitor groundwater systems, the interpretation of the data collected and its linkage to on-the-ground reality remains important in developing sustainable groundwater management practices. Government agencies have tended to argue that monitoring data are the only reliable source of data and farmer surveys that rely on recall are unreliable. By triangulating across different official data sets at the national scale, our study uncovers methodological limitations in conventional long-term trend analysis of groundwater levels. Although the study is focused on the Indian subcontinent, our finding related to the analysis of long-term trends in groundwater levels is applicable to hard-rock aquifers that underlie substantial areas in arid and semiarid regions of the world, including the Arabian-Nubian shield (Sultan et al., 2008) and parts of West Africa (Lapworth et al., 2013).

Competing Interests

The authors declare no competing financial interests.

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References

Aggarwal, R. K., & Jorion, P. (2010). Hidden survivorship in hedge fund returns. *Financial Analysts Journal*, *66*(2), 69–74. https://doi.org/10.2469/faj.v66.n2.1

Anantha, K. H. (2013). Economic implications of groundwater exploitation in hard rock areas of southern peninsular India. *Environment, Development and Sustainability*, *15*(3), 587–606. https://doi.org/10.1007/s10668-012-9394-0

Asoka, A., Gleeson, T., Wada, Y., & Mishra, V. (2017). Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. *Nature Geoscience*. https://doi.org/10.1038/ngeo2869

Bhanja, S. N., Mukherjee, A., Rodell, M., Wada, Y., Chattopadhyay, S., Velicogna, I., et al. (2017). Groundwater rejuvenation in parts of India influenced by water-policy change implementation. *Scientific Reports*, *7*(1), 7453–7453. https://doi.org/10.1038/s41598-017-07058-2

Bhanja, S. N., Mukherjee, A., Saha, D., Velicogna, I., & Famiglietti, J. S. (2016). Validation of GRACE based groundwater storage anomaly using in-situ groundwater level measurements in India. *Journal of Hydrology*, *543*, 729–738. https://doi.org/10.1016/j.jhydrol.2016.10.042

Buckley, J. P., Keil, A. P., McGrath, L. J., & Edwards, J. K. (2015). Evolving methods for inference in the presence of healthy worker survivor bias. *Epidemiology*, *26*(2), 204–212. https://doi.org/10.1097/EDE.0000000000000217

Buvaneshwari, S., Sekhar, M., Mohan Kumar, M. S., KumarSharma, A., Duprey, J. L., Audry, S., et al. (2017). Groundwater resource vulnerability and spatial variability of nitrate contamination: Insights from high density tubewell monitoring in a hard rock aquifer. *Science of the Total Environment*, *579*, 838–847. https://doi.org/10.1016/j.scitotenv.2016.11.017

Dewandel, B., Lachassagne, P., Zaidi, F. K., & Chandra, S. (2011). A conceptual hydrodynamic model of a geological discontinuity in hard rock aquifers: Example of a quartz reef in granitic terrain in South India. *Journal of Hydrology*, *405*(3-4), 474–487. https://doi.org/10.1016/j.jhydrol.2011.05.050

Fishman, R. M., Siegfried, T., Raj, P., Modi, V., & Lall, U. (2011). Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India's groundwater irrigation. *Water Resources Research*, *47*, W00L05. https://doi.org/10.1029/2011WR010617

Giordano, M. (2009). Global groundwater? Issues and solutions. *Annual Review of Environment and Resources*, *34*(1), 153–178. https://doi.org/10.1146/annurev.environ.030308.100251

Gleeson, T., Wada, Y., Bierkens, M. F. P., & van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, *488*(7410), 197–200. https://doi.org/10.1038/nature11295

Government of India (2014). *Fourth census of minor irrigation schemes, 2006–07*. New Delhi: Ministry of Water Resources, Minor Irrigation Division.

Hernán, M. A., Hernández-Díaz, S., & Robins, J. M. (2004). A structural approach to selection bias. *Epidemiology*, *15*(5), 615–625. https://doi.org/10.1097/01.ede.0000135174.63482.43

Hosseini-Moghari, S.-M., Araghinejad, S., Ebrahimi, K., & Tourian, M. J. (2019). Introducing modified total storage deficit index (MTSDI) for drought monitoring using GRACE observations. *Ecological Indicators*, *101*, 465–475. https://doi.org/10.1016/j.ecolind.2019.01.002

Kumar, S., Raizada, A., Biswas, H., Srinivas, S., & Mondal, B. (2016). Application of indicators for identifying climate change vulnerable areas in semi-arid regions of India. *Ecological Indicators*, *70*, 507–517. https://doi.org/10.1016/j.ecolind.2016.06.041

Landerer, F. W., & Swenson, S. C. (2012). Accuracy of scaled GRACE terrestrial water storage estimates. *Water Resources Research*, *48*, W04531. https://doi.org/10.1029/2011WR011453

Lapworth, D. J., MacDonald, A. M., Tijani, M. N., Darling, W. G., Gooddy, D. C., Bonsor, H. C., & Araguás-Araguás, L. J. (2013). Residence times of shallow groundwater in West Africa: Implications for hydrogeology and resilience to future changes in climate. *Hydrogeology Journal*, *21*(3), 673–686. https://doi.org/10.1007/s10040-012-0925-4

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, *13*(3), 245. https://doi.org/10.2307/1907187

Merriott, D. (2015). Factors associated with the farmer suicide crisis in India. *Journal of Epidemiology and Global Health*, *6*(4), 217–227. https://doi.org/10.1016/j.jegh.2016.03.003

Mukherji, A., & Shah, T. (2005). Groundwater socio-ecology and governance: A review of institutions and policies in selected countries. *Hydrogeology Journal*, *13*(1), 328–345. https://doi.org/10.1007/s10040-005-0434-9

Panda, D. K., & Wahr, J. (2016). Spatiotemporal evolution of water storage changes in India from the updated GRACE-derived gravity records. *Water Resources Research*, *52*, 135–149. https://doi.org/10.1002/2015WR017797

Pavelic, P., Patankar, U., Acharya, S., Jella, K., & Gumma, M. K. (2012). Role of groundwater in buffering irrigation production against climate variability at the basin scale in South-West India. *Agricultural Water Management*, *103*, 78–87. https://doi.org/10.1016/j.agwat.2011.10.019

Perrin, J., Ahmed, S., & Hunkeler, D. (2011). The effects of geological heterogeneities and piezometric fluctuations on groundwater flow and chemistry in a hard-rock aquifer, southern India. *Hydrogeology Journal*, *19*(6), 1189–1201. https://doi.org/10.1007/s10040-011-0745-y

Reddy, D. V., Nagabhusanam, P., Sukhija, B. S., & Reddy, A. G. S. (2009). Understanding hydrological processes in a highly stressed granitic aquifer in southern India. *Hydrological Processes*, *23*(9), 1282–1294. https://doi.org/10.1002/hyp.7236

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., et al. (2004). The Global Land Data Assimilation System. *Bulletin of the American Meteorological Society*, *85*(3), 381–394. https://doi.org/10.1175/BAMS-85-3-381

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, *460*(7258), 999–1002. https://doi.org/10.1038/nature08238

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, *63*(324), 1379. https://doi.org/10.2307/2285891

Shah, T. (2005). Groundwater and human development: Challenges and opportunities in livelihoods and environment. *Water Science and Technology*, *51*(8), 27–37. https://doi.org/10.2166/wst.2005.0217

Shah, T., Giordano, M., & Mukherji, A. (2012). Political economy of the energy-groundwater nexus in India: Exploring issues and assessing policy options. *Hydrogeology Journal*, *20*(5), 995–1006. https://doi.org/10.1007/s10040-011-0816-0

Siderius, C., Boonstra, H., Munaswamy, V., Ramana, C., Kabat, P., van Ierland, E., & Hellegers, P. (2015). Climate--smart tank irrigation: A multi-year analysis of improved conjunctive water use under high rainfall variability. *Agricultural Water Management*, *148*, 52–62. https://doi.org/10.1016/j.agwat.2014.09.009

Simundic, A.-M. (2013). Bias in research. *Biochemia Medica*, 12–15. https://doi.org/10.11613/BM.2013.003

Srinivasan, V., Thompson, S., Madhyastha, K., Penny, G., Jeremiah, K., & Lele, S. (2015). Why is the Arkavathy River drying? A multiple-hypothesis approach in a data-scarce region. *Hydrology and Earth System Sciences*, *19*(4), 1905–1917. https://doi.org/10.5194/hess-19-1905-2015

Srinivasan, V., & Kulkarni, S. (2014). Examining the emerging role of groundwater in water inequity in India. *Water International*, *39*(2), 172–186. https://doi.org/10.1080/02508060.2014.890998

Srinivasan, V., Penny, G., Lele, S., Thomas, B. K., & Thompson, S. (2017). Proximate and underlying drivers of socio-hydrologic change in the upper Arkavathy watershed, India. *Hydrology and Earth System Sciences Discussions*, 1–28. https://doi.org/10.5194/hess-2017-543

Sultan, M., Wagdy, A., Manocha, N., Sauck, W., Gelil, K. A., Youssef, A. F., et al. (2008). An integrated approach for identifying aquifers in transcurrent fault systems: The Najd shear system of the Arabian Nubian shield. *Journal of Hydrology*, *349*(3–4), 475–488. https://doi.org/10.1016/j.jhydrol.2007.11.029

Swenson, S., & Wahr, J. (2006). Post-processing removal of correlated errors in GRACE data. *Geophysical Research Letters*, *33*, L08402. https://doi.org/10.1029/2005GL025285

Ton, G., Vellema, W., Desiere, S., Weituschat, S., & D'Haese, M. (2018). Contract farming for improving smallholder incomes: What can we learn from effectiveness studies? *World Development*, *104*, 46–64. https://doi.org/10.1016/j.worlddev.2017.11.015

World Bank (2010). Deep wells and prudence: Towards pragmatic action for addressing groundwater overexploitation in India (No. 51,676) (pp. 1–120). The World Bank. Retrieved from http://documents.worldbank.org/curated/en/272661468267911138/Deep-wells-and-prudence-towards-pragmatic-action-for-addressing-groundwater-overexploitation-in-India

Yue, S., Pilon, P., Phinney, B., & Cavadias, G. (2002). The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes*, *16*(9), 1807–1829. https://doi.org/10.1002/hyp.1095