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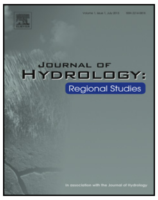

Bi-decadal groundwater level trends in a semi-arid south indian region: Declines, causes and management

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ABSTRACT

Study region: Three districts in crystalline aquifer region of semi-arid south India.
Study focus: India, world's largest groundwater user (250 billion m^3 yr^{-1}) has been reported to experience declining groundwater levels. However, the statistical significance of the decline has not been analyzed to separate human effects from natural variability. Trends in groundwater levels in three administrative districts of south India were analyzed and explained through changes in irrigation, rainfall, and agricultural power subsidy.
New hydrological insights for the region: Contrary to common perception of widespread groundwater declines only 22–36% of the wells showed statistically significant declines. The use of well depth during dry well periods may slightly underestimate the number of declining wells (by 1%) and rate of decline. Increase in groundwater irrigated area combined with rainfall and power subsidy policy, were the main causative factors for the decline. Groundwater decline after implementation of free-electricity policy in 2004 confirmed the nexus between power subsidy and groundwater. These declines are likely to worsen due to future well drillings. Trends in other regions with similar hydro-geologic conditions need to be analyzed to verify groundwater declines and its linkages with power subsidy. Once established, reforms in power subsidy and well permit policy along with conversion to efficient micro–irrigation may be needed to maintain or enhance groundwater availability in the crystalline aquifer region of India (240 million ha).

1. Introduction

India, home to 17% of the world's population, is facing water scarcity. Ranked highest in groundwater use globally, its groundwater use is 250 billion m^3 per year (AQUASTAT, 2010; Shah et al., 2007). India uses 80% of its water for irrigation (Mall et al., 2006) and 65% of irrigation supply is provided by groundwater (Siebert et al., 2010). Such large-scale withdrawals are mainly due to an increase in the number of irrigation wells equipped with diesel or electric pumps; there has been a 130 fold increase in the irrigation wells from 0.15 million in 1960 to nearly 20 million by 2000 (Shah, 2009). This groundwater development has caused groundwater depletion and several other environmental problems in many regions of India (Ambast

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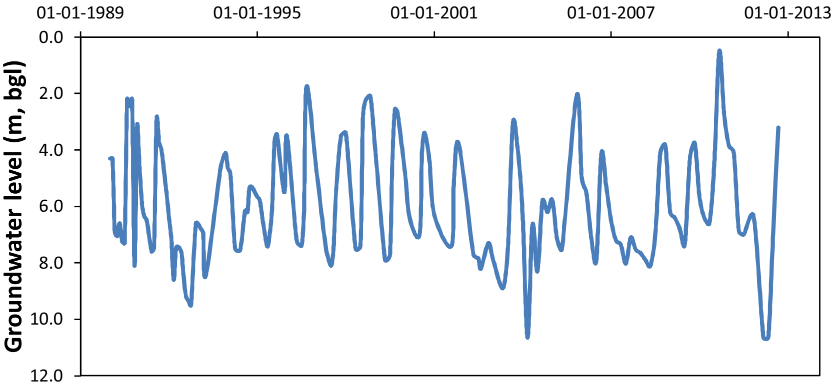

Fig. 1. Seasonal and annual groundwater level (below ground) fluctuations in a monitoring well in Rangareddy district, Telangana.

et al., 2006; CGWB, 2006; Rodell et al., 2009; Singh and Singh, 2002; Tiwari et al., 2009). Most of the states (e.g. Punjab and Telangana) where the groundwater depletion has been reported also provide free electricity to farmers. Free or subsidized electricity has frequently been cited as one of the main factors causing groundwater depletion in many regions of India (Shah et al., 2012). However, this qualitative assessment of relationship between subsidy and groundwater decline has not been field-verified.

Unlike other regions of India (e.g. eastern regions including Indo-Gangetic plains) which have plenty of surface water from Himalayan rivers, the semi-arid southern India mainly relies on ground water for irrigation. Northern and north western states (e.g. Punjab and Haryana) are located in alluvial aquifers while almost the entire region of southern India is underlain by hard crystalline rocks (CGWB, 2011). Deep alluvial aquifers found in Punjab and Haryana have higher specific yield and storage as compared to the shallow weathered fractured aquifers in southern India. While the declining water table may not affect the water availability, in a short run, for the farmers of Punjab (due to periodic well deepening) the groundwater declines are likely to deplete the shallow low storage aquifers of south India and limit the water availability (Fishman et al., 2011). While many studies have addressed the groundwater depletion in the north-west (Ambast et al., 2006; Rodell et al., 2009; Tiwari et al., 2009) and south (CGWB, 2011; Kumar et al., 2011; Massuel et al., 2007; Reddy and Reddy, 2010; World Bank 2010) India, none of these studies have tested the statistical significance of groundwater level trends in the semi-arid south Indian context. In addition, while the qualitative and some quantitative assessments have been made on the groundwater decline, it is not clear if these declines are due to groundwater withdrawals, power subsidy and/or rainfall. Systematic analysis of statistical significance of long-term trends in groundwater level change is needed to identify realistic groundwater management strategy in specific regions.

The former state of Andhra Pradesh, divided into two states namely Telangana and Andhra Pradesh on 2nd June 2014, officially implemented the free electricity policy for farmers in May 2004. Free or subsidized electricity causes wasteful use of groundwater as well as the electricity (Kumar et al., 2011). Use of automatic switches by the farmers turns the pumps on instantaneously as soon as the power comes, often causing the water to run unattended in the fields particularly at night. Although it has been argued that free electricity has triggered extensive well drillings in Telangana, it has also been reasoned that most of the well drillings already took place before 2004 and that free electricity didn't accelerated the drilling of wells (Fosli, 2014). Statistical analyses testing this cause-effect relationship (electric subsidy-groundwater declines) are lacking.

The groundwater system in the semi-arid crystalline aquifer regions of central and south India is highly dynamic where groundwater levels rise and decline quickly in response to recharge in the wet season (June-Oct) and pumping in the dry season (November–May) (Fig. 1). Seasonal and annual water level fluctuations in these fractured aquifers depend primarily on groundwater abstractions and recharge (Maréchal et al., 2006a, 2006b; Pavelic et al., 2012). Using six-year (2002–2008) GRACE satellite data and measured groundwater levels, Tiwari et al. (2011) examined temporal changes in groundwater storage in the semi-arid southern India including the former state of Andhra Pradesh. Both decline (1998–2004) and increase (2005–2008) were observed with overall increased groundwater storage in most parts of southern India. While they suggested that these changes in the groundwater storage are likely to be associated with inter-annual variability in rainfall, there were no statistical analyses to detect if these changes in groundwater storage or rainfall were significant. Fishman et al. (2011) argued that while there may be a short-term water stress due to low rainfall and increased withdrawals, the groundwater declines cannot continue in long-run because a good rainfall year can completely fill these shallow aquifers. With their simple groundwater budget model, Fishman et al. (2011) showed that groundwater levels in these weathered aquifers cannot keep declining in the long run because the levels rapidly approach the bottom of shallow aquifer and thus it becomes completely depleted. The dynamic nature of these aquifers and rainfall variability in the region requires statistical analyses of the long-term trends to differentiate natural or short term cyclic changes from anthropogenic or long term declines.

We used long-term (23 years) groundwater level data for the semi-arid south India to test if the groundwater level trends are significant and whether the observed trends are due to natural variability or anthropogenic factors. Specific objectives

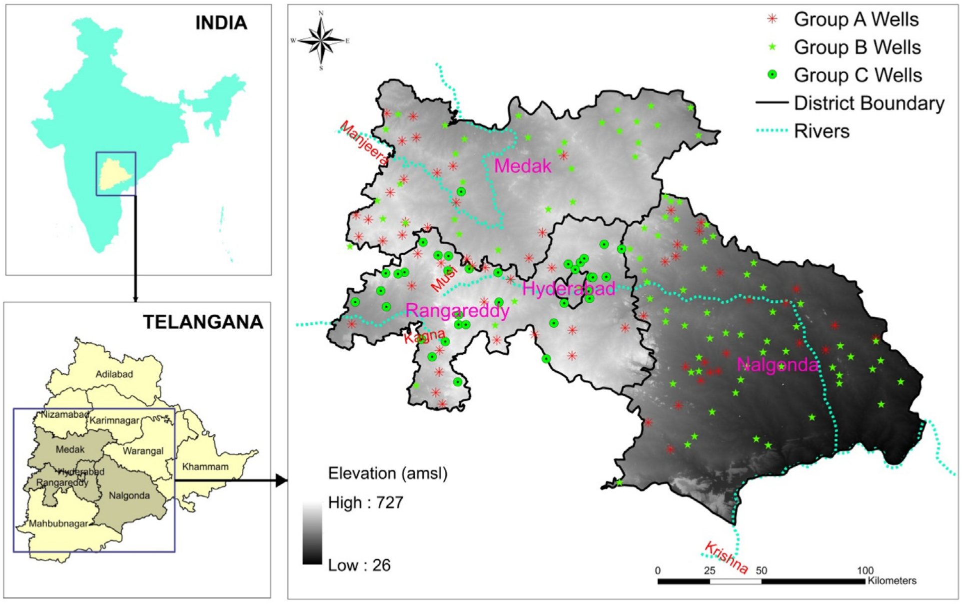

Fig. 2. Map of the study area with location of wells selected for study. Almost the entire Nalgonda and most of the Rangareddy regions drain to the Krishna River which flows along the southern edge of Nalgonda district. The Manjeera River, which flows through Medak district, is a tributary of Godavari River.

were: (1) analyze the long-term (1990–2012) groundwater level trends in a representative crystalline aquifer of southern India; (2) identify whether the changes in groundwater levels are due to natural variability in rainfall and/or other factors including power subsidy and (3) identify and discuss possible policy mechanisms for sustainable use of groundwater.

2. Methods

2.1. Study area

The study area (3.15 million ha), located between 16°21′60″–18°17′33″N and 77°21′15″–80°04′53″E, is a three-district region (Rangareddy, Medak, and Nalgonda) in semi-arid Telangana state of southern India (Fig. 2, also see Supplementary material). A Mandal is an administrative unit and a district is composed of several Mandals; for example, our three district study region encompasses 142 Mandals. The area includes the city of Hyderabad, the capital of Telangana state and fourth most populous city (2011 population = 6,809,970) of India. The area has a typical semi-arid climate where maximum temperature can reach 44 °C during May and minimum temperature can dip to 4 °C in December. The average annual (1990–2012) rainfall is 740 mm, 75% of which occurs during the monsoon season (June–September). The rainfall distribution exhibits high intra-season and inter-annual variability.

The study region lies within the Krishna and Godavari river basins. The Krishna River forms the southern boundary of Nalgonda district (Fig. 2). The Nalgonda and Rangareddy districts lie in the Krishna basin while the Medak district falls within the Godavari basin. The soils are mainly classified as red soils (Alfisols) and black soils (Vertisols) usually developed from granitic and basaltic parent material, respectively. Saturated hydraulic conductivity of red soils (≈1 cm h^{-1}) is generally higher than the black soils (≈0.04 cm h^{-1}) (Pathak et al., 2013).

As of 2005, land uses in the study area include cropped area (37%), fallow (33%), non-agriculture uses (10%), forest (8%), barren land (6%), permanent pasture (4%) and culturable waste (2%) (DES, 2006). Main crops include rice, sugarcane, vegetables, groundnut, and maize. Crops are grown during both wet (June–October) and dry seasons (November–May) and groundwater is primarily used during dry season to irrigate the crops. Groundwater is the main source of irrigation water supply which provides water to 72,824, 145,452 and 192,350 ha of area in Rangareddy, Medak and Nalgonda districts, respectively (DES, 2013a,b). A small fraction of the Rangareddy and Medak districts' agriculture rely on canal-based irrigation (3541 ha); however the Nalgonda district has a significant area (76,036 ha) served by the canals linked to the Krishna River. Another source of irrigation in the area includes small reservoirs (locally known as tank) which store excess runoff during the monsoon and provide irrigation water during the dry period.

The geology of the area is dominated by Archean granite and gneiss with Cretaceous Deccan Trap basalts in some places. Prolonged weathering and tectonic disturbances in the granites have created an upper weathered layer of thickness ranging from 1 to 20 m. Outcrops and hill slopes usually have a smaller weathered layer thickness due to erosion (Sukhija et al., 2006). Groundwater mostly occurs under unconfined conditions in the single composite weathered fractured aquifer. Two types of groundwater wells are used in the region, open dug wells (shallow) and closed drilled wells (shallow and deep). Closed

Table 1
Sources and characteristics of groundwater level, rainfall and land use data used in the study.

Data	Source	Frequency	Duration	Scale/Resolution
Groundwater levels (Open Wells)	Former Andhra Pradesh State Groundwater Department	Bi-monthly	1990–2012	Point/Mandal
Rainfall	Former Andhra Pradesh Directorate of Economics and Statistics (DES)	Daily	1990–2012	Point/Mandal
Irrigated areas	DES publications	Annual	1990–2012	District & State
Number of wells and corresponding irrigated area	2nd, 3rd and 4th Minor Irrigation Census (MIC) reports by former Andhra Pradesh Directorate of Economics and Statistics (DES)	Variable	1993–94, 2000–01, 2006–07	District & State

Table 2
Grouping of the groundwater level data, according to the record length and monitoring period.

Group	Time period	Number of wells	Data measured as
A	1990–2012	64	Depth of water below ground level (bgl)
B	1990–2005	159 (Includes 64 wells in group A)	
C	1997–2012	99 (Includes 64 wells of Group A)	

drilled wells are commonly referred as “tube” wells. Open wells, generally 3–10 m in diameter and 10–20 m deep, were the main source of water for irrigation until 1990. Presently, tube wells serve as a major source of groundwater for irrigation, domestic, and industrial purposes. Tube wells are usually drilled to 50–100 m depth in the fractured zone. Shallow tube wells are generally drilled up to 60–70 m while deep tube wells are drilled up to 100 m or more. Wells are drilled deeper with the expectations of increased discharge volume however, well yields seldom increase beyond active weathered fractured layer (50–70 m) (Maréchal, 2010).

Low specific yield, low specific storage capacity and frequent failures in well installation are some of the notable characteristics of the crystalline rock aquifers in the region. Specific yield of the upper weathered layer generally ranges from 1 to 4% and the storage coefficient of the fractured layer varies from 10^{-2} to 10^{-4} in the region (CGWB, 2007a,b,c; Dewandel et al., 2006; Ferrant et al., 2014; Maréchal et al., 2006a,b). Low hydraulic conductivity of the upper weathered layer restricts the flow in response to lateral and vertical flow gradients and helps retain recharged groundwater in open wells. Major aquifer zones are usually found up to the depth of 100 m below ground (CGWB, 2007a,b,c). Fresh granite basement lies at the lower boundary of the fractured zone which is usually impermeable with some local fractures. Regional as well as local lineaments and dykes play an important role in groundwater movement and availability at various locations (Dewandel et al., 2011; Perrin et al., 2011a,b).

The land use, variability in climate and hydro-geologic properties of the three district regions are representative of most of the Telangana state and greater semi-arid south India. The percentage of area irrigated by groundwater is similar in the three district area (12.70% of 3.15 million ha) and Telangana state (12.25% of 11.50 million ha) (DES, 2013a). Net groundwater recharge and trends in groundwater levels in these low storage aquifers are primarily dependent on recharge and pumping fluxes (Maréchal et al., 2006a,b; Perrin et al., 2012) which depends on rainfall and irrigation. About 85% of the three district area in this study is composed of Archean granite and gneiss while the rest is Deccan basalts, laterites and Cuddapah and Kurnool system rocks of limestone, quartzite and shales. This mixed system of hard rocks in three districts is similar to the larger crystalline aquifer system in semi-arid south India which mainly comprises of Archean granite, gneiss, Deccan traps, limestone and quartzite.

2.2. Study data

Groundwater level data for the Rangareddy, Medak and Nalgonda districts were obtained from the former Andhra Pradesh State Groundwater Department (Table 1). The department has a network of monitoring wells comprising of open observation wells and piezometers. Groundwater level data for 250 open wells were obtained from the state department for 1990–2012. The length of record for these monitoring wells ranged from 5 to 23 years. Open observation wells are not used for irrigation therefore these observations usually represent the natural groundwater level of the surrounding area.

Only wells with 12 years or more of data, with less than 50% missing data in the record, were used for trend analyses. This screening reduced the number of wells to 194 distributed throughout the three districts (Fig. 2). Depending on the record length and monitoring period, the well data were categorized into three groups A, B and C (Table 2). These observation wells (10–20 m deep) are located in more homogenous top weathered (saprolite) layer. The groundwater flow network at this shallow depth is generally well connected at watershed scale (Guihéneuf et al., 2014) and thus water levels in these wells are representative of the climate, land use, and hydro-geologic characteristics at the Mandal scale (≈160 km^2). Several studies have used similar resolution groundwater level and rainfall data in the crystalline aquifer region of India to evaluate the importance of groundwater in buffering the agricultural production (Pavelic et al., 2012; well density ≈ one per 130 km^2

and rain gauge density ≈ one per 580 km^2), the climate change effects on groundwater resources (Surinaidu et al., 2013; well density ≈ one per 150 km^2, rain gauge density ≈ one per 500 km^2) and the groundwater level trends (Panda et al., 2007, 2012; well density ≈ one per 160 and 350 km^2 respectively, rain gauge density ≈ one per 500 km^2).

Daily rainfall data (1990–2012) for 136 Mandals located within the study area were obtained from the former Andhra Pradesh Directorate of Economics and Statistics (DES) to investigate whether the trends in groundwater levels were correlated with rainfall trends. Daily rainfall data were temporally and spatially aggregated to develop annual rainfall time series for each of the Mandal, and the entire study area. Trend tests were performed on the annual rainfall time series of each of the Mandal as well as the entire study area. District level irrigation and land use data (Table 1) were also compiled for the period of 1990–2012 to investigate the effects of anthropogenic factors on groundwater level trends. Area irrigated by different sources, number of irrigation sources (e.g. number of wells) and land use changes were analyzed to relate them with groundwater levels changes.

2.3. Statistical tests

The Mann-Kendall (Mann, 1945; Kendall, 1975) test was used to test the significance of trends in groundwater levels. Being a rank-based test, the Mann-Kendall (MK) test is more powerful than the parametric methods when the data is not normally distributed (Hirsch et al., 1991; Yue et al., 2002a). Non-parametric techniques can be as powerful as parametric methods in the case of moderately skewed data (Onoz and Bayazit, 2003). The MK test can also be performed on a time series containing missing data. However, serial correlation in the time series affects the MK test results and the application of this test requires the assumption of serial independence (Von Storch, 1995; Yue et al., 2002b). Groundwater level time series (mean annual, pre-monsoon and post-monsoon for each well) were tested for autocorrelation in R Studio software version 0.98.1091 (R Core Team, 2015; Racine, 2012). Mean annual groundwater levels are the average of all the observations in a certain year and pre- and post-monsoon groundwater levels are observed levels in May and November, respectively. Pre- and post- monsoon groundwater levels were also analyzed separately because groundwater depths are usually deepest in May (pre-monsoon) and shallowest in November (post-monsoon). The autocorrelation plots showed that a few (less than 5%) of the well time series showed an autocorrelation function lying outside the 95% confidence interval for one, two and three year (lag) distances. In addition, almost all the wells showed an autocorrelation function lying within 95% confidence interval for higher than three lag distances. Therefore, MK test was considered appropriate to test the trends in our groundwater level data.

2.3.1. Mann-Kendall test

The MK test is used to evaluate whether the observed data are increasing or decreasing with time through what may be called a non-parametric regression analysis. This method compares the later measured values with earlier measured values to compute the Kendall statistics S. Thus, total n $(n-1)/2$ possible pairs of data are compared for n observations. The Kendall statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(y_j - y_i\right) \tag{1}$$

where

$$sign\left(y_j - y_i\right) = \begin{cases} = +1 if \left(y_j - y_i\right) > 0 \\ = 0 if \left(y_j - y_i\right) = 0 \\ = -1 if \left(y_j - y_i\right) > 0 \end{cases} \tag{2}$$

Large positive values of S indicate an increasing trend and large negative values indicate a decreasing trend with time. Trends were tested at $\alpha = 0.05$ significance level. The MK test was used with the Thiel-Sen Slope (Thiel, 1950; Sen, 1968), commonly referred as Sen slope, to measure the magnitude of the trend. The Sen Slope is the median of the slopes obtained from all the data pairs compared and is calculated by:

$$\beta_1 = median\left(\frac{y_j - y_i}{x_j - x_i}\right) \tag{3}$$

where j > i and j = 1 to n, i = 1 to n − 1, and n is total number of observations.

The package "WQ" (Jassby and Cloern, 2015) written in R was utilized to perform the MK test in open source R Studio. Some of the monitoring wells were observed to dry frequently, especially in the dry season. For analysis, these "dry" well observation data points were replaced with the bottom of the corresponding well, where available, or with the deepest observed level during the entire period of record for the concerned well. A linear interpolation method was used to determine the nature and extent of bias introduced due to the use of well depth as a proxy for dry well condition. Average groundwater level decline/gradient (m/month or season) during non-dry-well years for each of the dry wells were used to determine the levels under dry well conditions. The 2002–2003 period was one of the driest (2002 rainfall = 564 mm) when 46 wells (of the total 194 wells) became dry during the 2003 dry season. When the well depth was used to represent dry well condition, 18 of these 46 wells showed a statistically significant decline. Use of linearly interpolated groundwater level data increased the number of wells showing a statistically significant decline by only one (19 wells). The average magnitude of groundwater decline also increased slightly (0.01 m/yr). Use of the well depth under dry well conditions may slightly underestimate the number of declining wells (by 1%) and the rate of decline.

2.3.2. Local regression (LOESS)

Locally weighted least square regression (Cleveland 1979; Cleveland et al., 1988) was performed on mean annual groundwater levels to develop a rainfall adjusted groundwater level (residual) time series for all the wells. This rainfall adjusted (residual) time series can be used to better relate the groundwater level variation with the temporal changes in pumping and/or other anthropogenic factors. Mean annual groundwater levels for each monitoring well were regressed with the annual rainfall of the corresponding Mandal. Almost all the Mandals, except a few, have only one monitoring well and one rain gauge station installed.

Since LOESS is a non-parametric method, it is not limited by assumptions of the parametric form of the regression line. The “loess” function in R was used to perform the local regression (R Core Team, 2015). The LOESS utilizes weighted linear least square regression to determine the value of regression function at each data point. A low degree polynomial is fitted to a subset of data near each data point. A smoothing parameter (0.75 in our analyses), which is usually a proportion of total data points, is used to determine the number of points in the subset. Each fitted polynomial for a subset of data thus provides a value of regression function for one data point. The MK test was then applied to the rainfall adjusted groundwater level residual time series to discern the underlying trends.

2.3.3. Step trend test: Mann-Whitney-Wilcoxon Rank Sum

The Mann-Whitney-Wilcoxon Rank Sum test (R Core Team, 2015) was performed on pre-monsoon groundwater levels and annual groundwater level LOESS residuals to test the presence of step trends from pre-free electricity (1990–2004) to post-free electricity (2005–2012) period. The Mann-Whitney-Wilcoxon test (Conover, 1971; Lettenmaier, 1976) is used to test the difference in median of two samples. The Mann-Whitney test is considered to be suitable for determining presence of step trends in environmental time series data (Lettenmaier, 1976; Hirsch et al., 1991).

2.3.4. Change point and rainfall homogeneity tests

To further explore the effects of free-electricity policy or other potential causative factors, a change point analysis was performed to find years of abrupt change in groundwater levels or trends during 1990–2012. The “segmented” package (Muggeo, 2003, 2008) in R studio was used to perform piecewise linear regression to detect change point(s) in the data. In addition, to evaluate the rainfall effect on groundwater trends, the Brown-Forsythe Levene’s-type test (Fox et al., 2009; Fox and Weisberg, 2010) was performed in R Studio to test the homogeneity of rainfall variance in the study region.

3. Results and discussion

3.1. Groundwater level trends

3.1.1. Annual trends

The MK test on selected 194 wells showed that 34% of the wells have a statistically significant declining (increasing groundwater depths) trend and 9% of the wells have a significant rising (decreasing groundwater depths) trend in the mean annual groundwater levels. Depending on group, 22%–36% of the wells had a statistically significant declining trend in mean annual groundwater levels (Table 3). For the wells showing a significant trend in groundwater levels, the rate of decline (Sen Slope) ranged from 0.02 to 1.31 m yr^{-1} while the rate of rise ranged from 0.08 to 0.56 m yr^{-1}. About 15% of the wells in group A showed a statistically significant decline of more than 0.20 m yr^{-1} in mean annual groundwater levels. About 30% of the wells in group B showed a statistically significant decline of 0.20–1.31 m yr^{-1} in mean annual groundwater levels which is a cause of concern. Although the statistical significance of the trends was not analyzed, in 2006 the Central Ground Water Board (CGWB) also reported 30% of the Mandals under critical and over-exploited category in these three districts (CGWB, 2006). The CGWB classifies a Mandal into critical and over-exploited category when there is more than 0.10–0.20 m yr^{-1} decline in long term ($\approx$10 years) groundwater levels and the stage of groundwater development is more than 90%. The spatially aggregated groundwater level time series for the entire study area showed a declining trend for all the groups, however, it was statistically significant for only group B (Table 3). Although we didn’t find a statistically significant declining trend for majority of the wells, which is against the common perception, 22%–36% of the wells are still experiencing a long-term decline in mean annual groundwater levels.

Monitoring in more than 60 wells in group B was discontinued during the 2003–2006 period. More than half of these group B wells, showed a declining trend in groundwater levels. Water level dropping below the bottom of these wells was likely the reason for the discontinued monitoring as these wells became frequently dry during 2003–06. This indicates that in reality the number of Mandals/areas experiencing the long term decline are much more than that showed by group A and C wells. As compared to group B, group A and C showed a smaller proportion of wells with a significant decline. It also

Table 3
Mann-Kendall test results for the wells in Group A, B and C. Sen Slope value for a group time series is obtained by MK test on spatially averaged annual groundwater level time series for the entire study area.

Group	Number of Wells	Time series	Number of Trending Wells ($p < 0.05$)		Sen Slope[b] (m yr^{-1})
			Decline (%)[a]	Rise (%[a])	
A 1990–2012	64	Mean Annual	14 (22%)	10 (16%)	+0.06
		Pre-monsoon (May)	15 (23%)	8 (12%)	+0.06
		Post-monsoon (Nov)	7 (11%)	8 (12%)	+0.06
B 1990–2005	159	Mean Annual	57 (36%)	6 (4%)	+0.25[c]
		Pre-monsoon (May)	37 (23%)	3(2%)	+0.16[c]
		Post-monsoon (Nov)	25 (16%)	6 (4%)	+0.12
C 1997–2012	99	Mean Annual	25 (25%)	10 (10%)	+0.08
		Pre-monsoon (May)	23 (23%)	8 (8%)	+0.07
		Post-monsoon (Nov)	15 (15%)	5 (5%)	+0.10

[a] Numbers in the parenthesis show the percent of trending wells to total number of wells in the corresponding group.
[b] Positive value of Sen Slope indicates increasing groundwater depths i.e. declining groundwater levels.
[c] Trend is significant at $\alpha = 0.05$

indicated that the decline in groundwater levels has caused the abandonment of many open wells in the region that have gone dry.

3.1.2. Pre- and post- monsoon trends

Pre-monsoon groundwater levels are indicative of the amount of pumping during the dry season (November–May); the more the pumping the higher the decline in pre-monsoon levels in May. The MK test shows that comparatively higher number of wells have a statistically significant decline in pre-monsoon (May) than post-monsoon (November); 15 wells in group A showed a significant decline in pre-monsoon as compared to 7 wells in post-monsoon. This implies that increased pumping in the dry season is causing a larger number of wells to have a declining trend in the pre-monsoon (Table 3). Relatively lower pumping and the rainfall induced natural recharge during the monsoon explains the fewer number of declining wells in the post monsoon time series.

3.1.3. Spatial trends

A map of trend by Mandal was used to interpret the spatial structure in trends (Fig. 3). This map was prepared from Sen Slope values obtained by MK test on Mandal averaged annual groundwater levels time series. Since the Mandal is an administrative unit, these trends help to identify specific zones for planning and implementation of groundwater management policies. Regardless of the time period, 36% of the analyzed Mandals showed a statistically significant declining trend in mean annual groundwater levels while only 8% Mandals showed a significant rising trend. All the Mandals surrounding the capital city, Hyderabad, showed a statistically significant declining trend in mean annual groundwater levels (Fig. 3). Unlike rural Mandals where irrigation withdrawals may be the main causative factor, growing domestic and industrial water consumption related to the expansion of the city and reduced groundwater recharge due to increased impervious areas are likely the reasons for this decline in groundwater levels around Hyderabad. Human settlements or built-up areas in Hyderabad have more than doubled during 1997–2013 (Kalyani and Govindarajulu, 2013). Some of the Mandals on the south eastern side of Nalgonda district (Fig. 2), which have shown rising trends in groundwater levels (Fig. 3), are located in areas where the source of irrigation is a canal which receives water from the Krishna River. For example, Miryalguda, one of the Mandals in this region where groundwater levels are rising, has highest rice growing area in the district, however the area irrigated from open wells is negligible. Recharge from the irrigation return flow, generated at these canal-irrigated paddy farms, is likely the reason for groundwater level rise. Irrigation return flow from flooded rice has been reported to be almost 50% of the irrigation volume for both wet and dry seasons (Dewandel et al., 2008).

3.2. Rainfall and groundwater dynamics

High rainfall is generally associated with shallow groundwater depths in post monsoon as well as during the following year's pre monsoon period (Fig. 4). On the other hand, deficit rainfall during monsoon increases the number of dry wells in the following pre-monsoon period (inset, Fig. 4). The well drying suggests that the number of declining wells and rate of decline in the monitored wells may have been underestimated (≈1%). Although aquifers work as a resilient buffer against climatic variability, low specific yield of the hard-rock aquifers limit their resilience. High correlation ($r^2 = 0.87$ and 0.80 for pre-and post-monsoon, respectively) between rainfall and groundwater levels (Fig. 4) shows the influence of rainfall on groundwater levels. Results from the Brown-Forsythe Levene's test for rainfall homogeneity showed the homogeneity of rainfall variance ($p = 0.98$) across all Mandals in the study area. The Levene's test results indicate that spatial variability in rainfall may not be a likely cause of groundwater declines in the region. Compared to the rainfall variability among Mandals, the variability within a Mandal is likely to be much less and hence the use of Mandal level rainfall is representative of the rainfall in the vicinity of the observation wells.

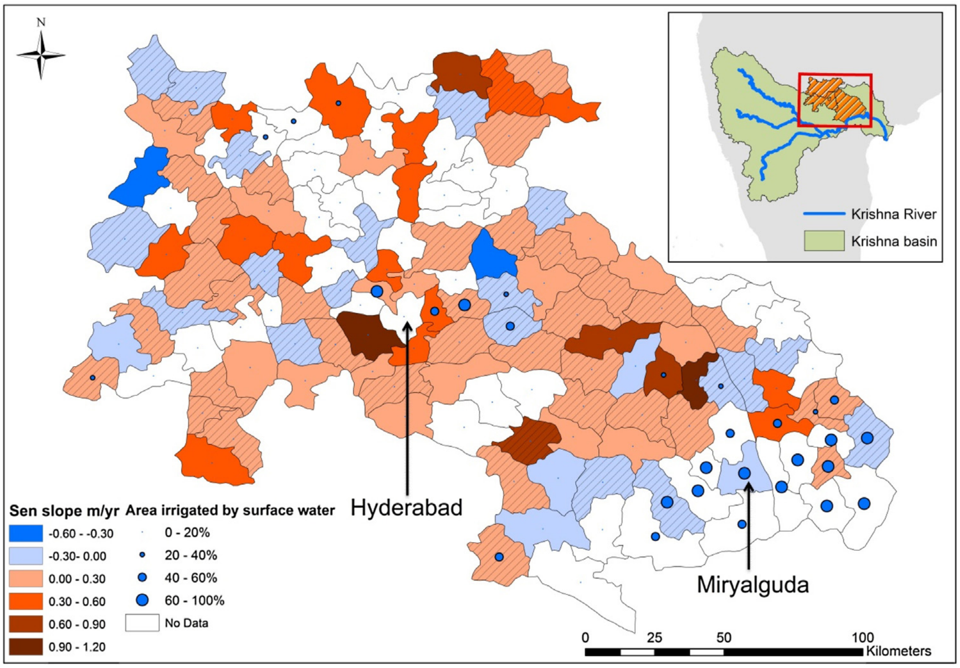

Fig. 3. Trend in groundwater levels obtained from all the wells in group A, B and C by Mandal. All the Mandals surrounding Hyderabad city show a statistically significant decline in groundwater levels which is likely due to increased urban groundwater use related to city expansion. Trends in the hatched Mandals were not statistically significant ($p > 0.05$). Negative Sen Slope indicates rising groundwater levels and positive Sen Slope indicates declining groundwater levels. Size of the blue circle inside each Mandal represents the surface water irrigated area as percent of total irrigated area. Inset plot in upper right shows study area in relation to Krishna River basin in south India.

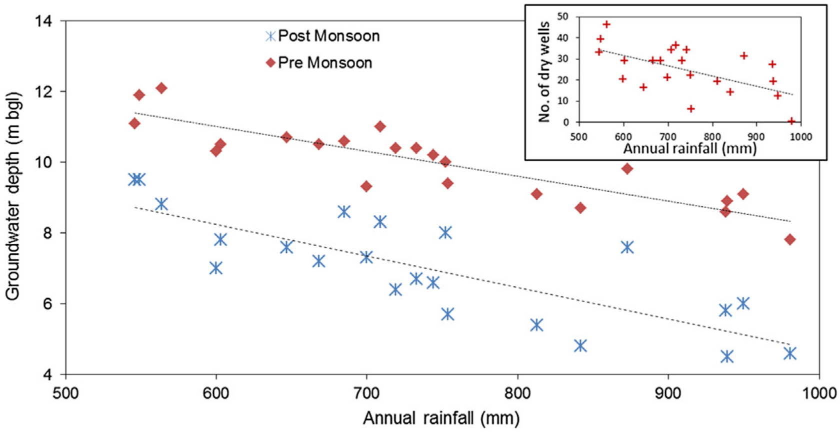

Fig. 4. Pre-monsoon (May) and post-monsoon (November) groundwater levels (1990–2012) in relation to annual rainfall in the study area. Pre-monsoon groundwater levels in the following year are correlated with annual rainfall. Inset graph shows the number of dry wells in pre-monsoon in relation to annual rainfall during previous year.

The MK test results showed that during 1990–2012, eight Mandals (6% of total 136 Mandals) had a statistically significant declining trend while none of them had a statistically significant increasing trend in annual rainfall. Spatially averaged annual rainfall time series for the entire study area showed no statistically significant change in rainfall. Eleven Mandals in group A (1990–2012) showed a statistically significant declining trend in mean annual groundwater levels, however only one of these Mandal showed a statistically significant decline in the annual rainfall during 1990–2012. These results suggest that the trends in rainfall cannot account for the groundwater level declines in most wells.

3.2.1. *MK test on LOESS regressed groundwater level residuals*

The MK test on the residual groundwater levels showed that 20, 22, and 26% of the wells in group A, B, and C, respectively had a statistically significant declining trend in mean annual groundwater levels (Table 4). The rate of decline in significantly

Table 4
Mann-Kendall test results on LOESS residuals of rainfall regressed mean annual groundwater levels. The values in parenthesis show the wells having a statistically significant trend in non-regressed groundwater level time series.

Group	Total number of wells	Wells with significant trend ($p < 0.05$)			
		Decline		Rise	
		Number	Percent of total	Number	Percent of total
A (1990–2012)	64	13 (14)	20% (22%)	6 (10)	9% (16%)
B (1990–2005)	159	35 (57)	22% (36%)	1 (6)	0.6% (4%)
C (1997–2012)	99	26 (25)	26% (25%)	8 (10)	8% (10%)

Table 5
District-wide net-area irrigated (ha) by different sources. The data is compiled from Season and Crop Report Andhra Pradesh 2011–12 and Compendium of Area and Land Use Statistics of Andhra Pradesh (1955–56 to 2004–05) published by DES.

District	Groundwater				Surface Water				Total Irrigated	
	Tube wells[a]		Open wells[a]		Reservoirs		Canals			
	1990–91	2011–12	1990–91	2011–12	1990–91	2011–12	1990–91	2011–12	1990–91	2011–12
Rangareddy	5293	68,499	42,097	4325	11,900	2208	2459	765	64,238	76,985
Medak	5241	138,298	62,995	7154	50,720	6549	5618	2776	127,562	157,472
Nalgonda	1756	167,616	77,391	24,734	22,792	16,301	95,040	76,036	206,323	297,796
Total Area	12,290	374,413	182,483	36,213	85,412	25,058	103,117	79,577	398,123	532,253

[a] Open wells are shallow (10–20 m deep) open dug wells and tube wells are shallow (<70 m deep) and deep (>70 m deep) drilled wells. Reservoirs locally known as tanks are water retention structures that store excess runoff during the monsoon and provide irrigation water during the dry period. Net irrigated area is the area irrigated in a year for a particular crop.

trending wells ranged from 0.05 to 0.89 $\mathrm{m\,yr^{-1}}$ and the rate of rise ranged from 0.08 to 0.42 $\mathrm{m\,yr^{-1}}$; both rates of decline and rise decreased as compared to the non-regressed groundwater level time series results.

As compared to the non-regressed groundwater level time series, group A and C showed only slight changes in number of declining wells (Table 4). However, the numbers of wells showing a declining trend were decreased from 36% to 22% in group B. Thus, the rainfall variation may explain more of the declining trends in group B wells than in group A and C wells. 2002 and 2004 were dry years during which the study area received only 550 and 538 mm of rainfall; all the years during 1999–2004 were also below normal rainfall years except 2003 (743 mm rainfall in 2003). Groundwater level adjustment for this low rainfall effect reduced the number of declining wells in group B (1990–2005) wells as compared to other groups. Nevertheless, it may be inferred that groundwater level decline in at least 20% of the wells across all groups are not related to the annual rainfall variation.

3.3. *Groundwater irrigation*

In the study area, the area irrigated by groundwater is increased by 110% during 1990–2012 (Table 5). This change has mainly been brought by a 30-fold increase in the area irrigated by tube wells with an accompanying decrease in the area irrigated from reservoirs and open wells. Greater reliability of the drilled wells, as compared to the surface water sources, and low installation costs, has promoted the use of drilled wells in the region. Surface reservoirs and open wells usually become dry before the end of dry season and are unable to meet the irrigation demands in the post-rainy season. Currently, groundwater irrigates more than 90% of the irrigated area in Rangareddy and Medak districts while it accounts for 65% of net irrigated area in Nalgonda district. This increase in groundwater irrigated areas is likely a major reason for groundwater level declines in the region.

The MK test result showed that the area irrigated by groundwater has a statistically significant ($p < 0.01$) increasing trend of 9182 ha/year during 1990–2011. However, the area irrigated by groundwater appears to decrease or become stagnant during low rainfall years especially during consecutive below average rainfall years such as during 1998–2006 (Fig. 5). Annual rainfall during 1999–2004 was below average, except in 2003 when it was 743 mm, just above the 1990–2012 average of 730 mm. The number of shallow tube wells increased from 180,228 to 269,641 and number of shallow wells decreased from 192,000 to 116,000 during 2000–2007 (DES, 2013b). This suggests that the area irrigated per well declined during the low rainfall years especially during consecutive low rainfall years. Table 6 shows the changes in area irrigated per well during 1993–2007 in the study region and Telangana. Shallow tube wells, which serve most irrigated area in the region, showed a decline in area irrigated per well by 25% in both the study area and state. Increased number of new wells in the region are likely the reason for these declines in area irrigated per well.

Although rainfall affects the groundwater-irrigated area, it doesn't explain the disproportional and consistent rise after 2004 (Fig. 5). Free electricity, which the state began to provide in 2004, is one of the likely reasons for this steady increase in groundwater irrigated areas after 2004 (Fig. 5). Better rainfall after 2004 and an absence of consecutive low rainfall years resulting in improved well yields and water availability, is another likely reason behind this steady increase in groundwater irrigated area after 2004. Gross irrigated area for rice has increased by more than 100% from 185,000 ha in 2004 to 377,000 ha

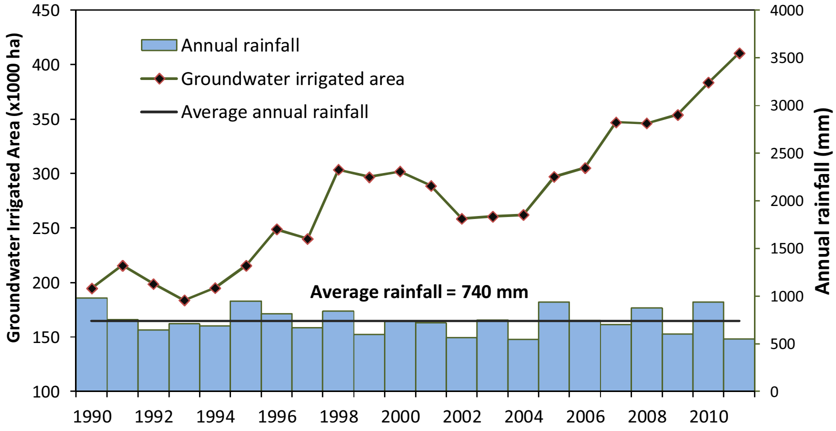

Fig. 5. Net area Irrigated by groundwater wells in relation to annual rainfall for the study area. The horizontal line shows average rainfall (1990–2012) in the study area.

Table 6
Area irrigated per well (ha/well per year) for different well types derived from 3rd (2004) and 4th (2013) Minor Irrigation Census of Andhra Pradesh, Directorate of Economics and Statistics.

Year	Open Well		Shallow Tube Wells		Deep Tube wells	
	Study Area	Telangana	Study Area	Telangana	Study Area	Telangana
1993–1994	1.02	0.85	1.32	1.59	1.77	3.90
2000–2001	0.88	0.65	1.02	1.32	1.20	1.93
2006–2007	0.88	0.78	1.00	1.21	1.00	1.10

in 2011. Area under irrigated maize and vegetables also increased (by 11,500 ha for maize and 10,000 ha for vegetables), but it was nowhere near the increase in rice area. As of 2011, rice irrigated area constitutes 61% of gross groundwater irrigated area. Rice is a high water demanding crop and this increase in irrigated areas is likely to decline the groundwater levels and decrease the water availability in the region. Field water use for rice typically ranges from 1000 to 2000 mm depending on the management, soils and planting season (Bouman and Tuong, 2001) while most of the other crops only require about 500–800 mm of irrigation in the dry season.

3.4. *Electric subsidy*

Results of the Mann-Whitney test on pre-monsoon groundwater levels showed that 60% and 70% of the declining wells in group A and C, respectively had a statistically significant step-up trend during the post-subsidy period (groundwater depths significantly increased during the post-subsidy period). Fig. 6 shows six example wells in group A and C which showed a step-up trend in rainfall adjusted mean annual groundwater levels (LOESS residuals). Results of the Mann-Whitney test on rainfall adjusted mean annual groundwater level residuals showed that 46% and 65% of the declining wells in group A and C showed a statistically significant step-up trend during post-subsidy period. Mann-Whitney test on unadjusted mean annual groundwater levels showed a statistically significant step-up trend in 57% and 76% of group A and C wells. Overall, 46% to 76% of the wells, which showed statistically significant downward trends in groundwater levels, showed step declines after the free electricity policy implementation.

Provision of free electricity is likely to increase the numbers of new drilled wells and overall increased groundwater withdrawals thereby resulting in groundwater level declines. As compared to the mean annual LOESS groundwater residuals, higher proportion of wells showing a step decline in pre-monsoon (May) groundwater levels indicate increased dry season (November–May) pumping during the post-subsidy period. Slightly smaller proportion of wells showing a step decline in LOESS adjusted mean annual groundwater levels, as compared to the unadjusted mean annual groundwater levels, indicate that the rainfall could also explain the step decline in few declining wells.

Results of the change point analyses revealed three rainfall driven change points at 1993, 1998 and 2002 (Fig. 7a) i.e. groundwater decline during or after below average rainfall years (1990–1993 and 1999–2002) and rise during or after above average rainfall years (1995–1999 and 2003–2012). Similar change points were observed for declining wells with one exception, there was no rise during 2003–2012 (Fig. 7b). This disparity could not be explained solely from rainfall differences; the average rainfall for the study region (724 mm) was similar to the rainfall for the areas with declining wells (703 mm) during 2003–2012 (Fig. 7e and f). Increased groundwater irrigated area (Fig. 5) influenced by the free electricity

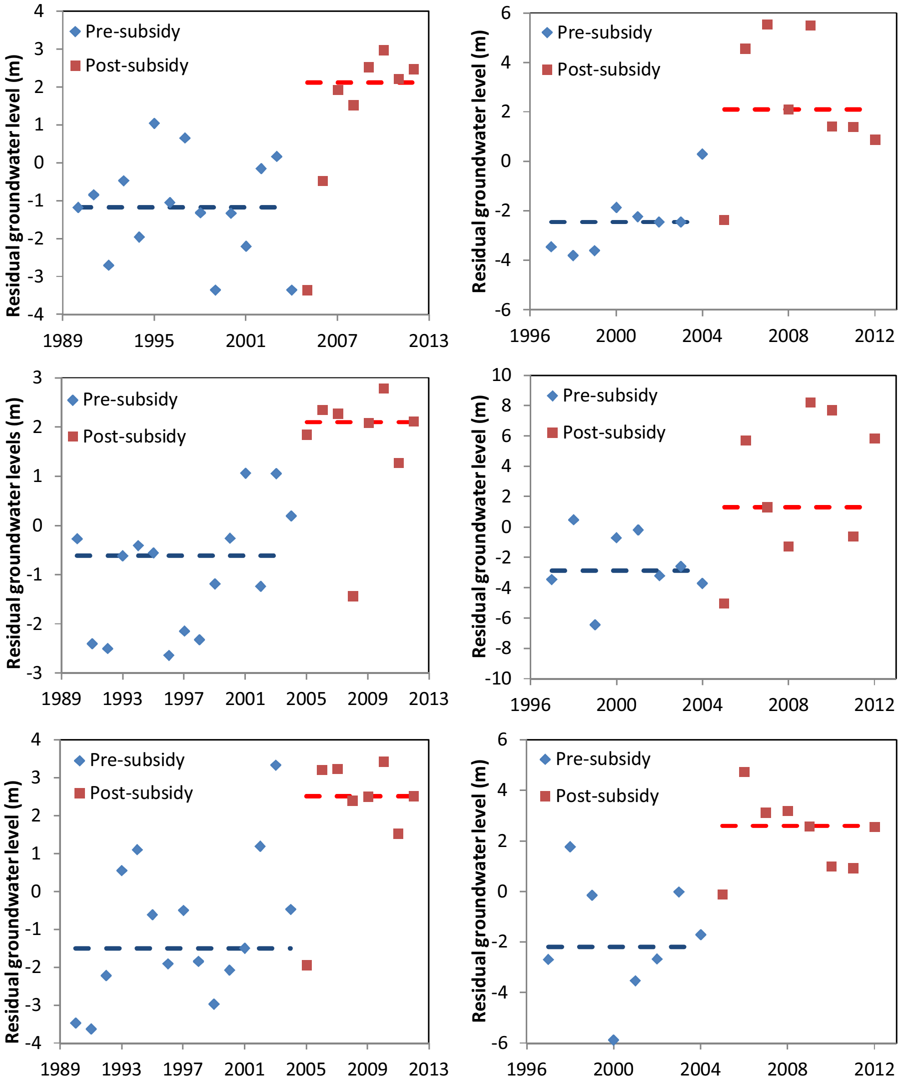

Fig. 6. Group A (1990–2012, left side) and C (1997–2012, right side) wells which showed a statistically significant step-up trend in rainfall adjusted LOESS groundwater level residuals during the post-subsidy (2005–2012) period. The dashed line shows the median for pre- (1990–2004) and post-subsidy (free electricity) period.

policy implemented in 2004 is a likely reason for these declines after 2004. Overall, free-electricity policy implemented in 2004 and the rainfall are the main causative factors for the observed declines in the groundwater levels.

4. Groundwater management: current status and way forward

During 1960s, subsidized agricultural inputs such as fertilizer, seeds and electricity spurred green revolution in India. To enhance the agricultural production, the government promoted groundwater irrigation through development and distribution of affordable pumps and subsidized electricity (Briscoe and Malik, 2006). However, during later decades (1970–2000), when farmers began to organize themselves in favor of agricultural subsidies, politicians started to use the subsidies as a political instrument to win the popular farmers vote bank. Former undivided Andhra Pradesh was the first state where flat rate tariff was promised during the election campaign in 1977 (Dubash and Rajan, 2001). Later during 2004 elections, another political party promised free electricity to win the election and implemented it in May 2004 soon after coming to power. Politicians persist for the subsidized electricity for their vote bank and farmers persist for subsidy for their perception that free or subsidized electricity is good for them. Although subsidized electricity made the agriculture profitable for many farmers, it also promotes wasteful use of electricity and water. For example, farmers in Punjab over-irrigate the fields because they think that in hot climatic conditions the more water they give the better it is for plants (Birner et al., 2011).

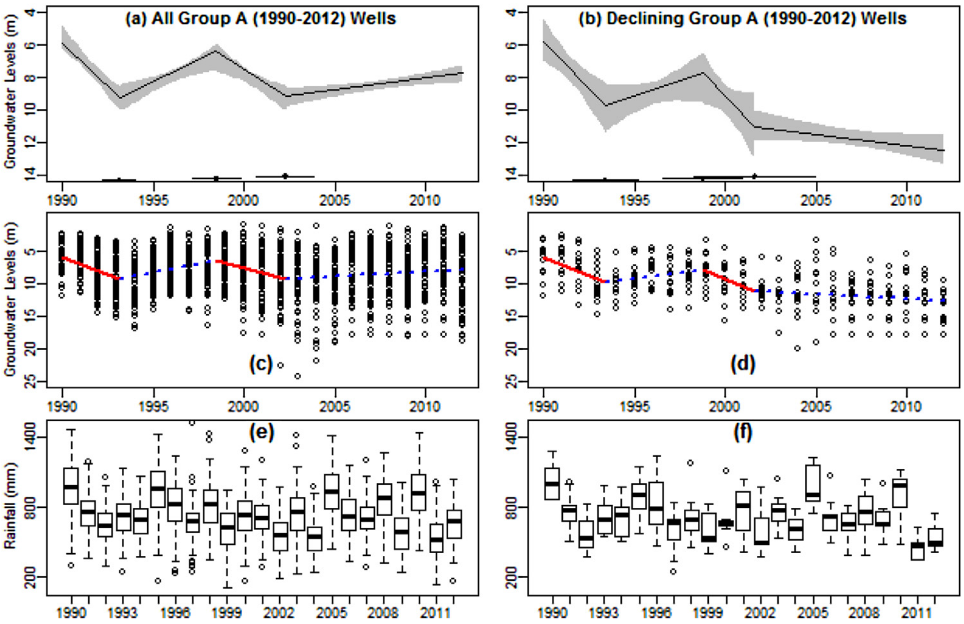

Fig. 7. Fitted (a and b) and observed (c and d) groundwater levels for all (a and c) and declining (b and d) group A wells, respectively. The grey shading around the fitted line in plot a and b shows 95% confidence interval for observed groundwater levels. Middle dots on the horizontal lines parallel to X-axis in plots a and b shows the change-point years. Solid and dashed line in c and d plots show the fitted groundwater levels same as in a and b, respectively. Plots e and f are Tukey box-plots of annual rainfall for entire study region (e) and declining Mandals (f), respectively. The bottom and top of the box (e and f) represents first and third quartile, respectively and the whiskers of the box extend up to 1.5 times the interquartile range. Dots beyond the whiskers represent the outliers.

As of 2006–07, more than 98% (293,080) of the tube wells in the study area use electric pumps (DES, 2013b). In a study over 370 districts in India, Badiani and Jessoe (2013) indicated that a 10% reduction in electric subsidy could decrease the groundwater demand by 6.8%. Shah et al. (2012) argue that the major problem lies in the way the subsidized electricity is administered and not the subsidy itself; they suggest that instead of complete removal of subsidy, an intermediate approach involving better administration of subsidy which encourages efficient use of power would be a more practical option in reality. The Telangana state provides 5–7 h of daily free electricity for pumping. Instead of unreliable 5–7 h of low quality electricity (night hours, fluctuating voltages and intermittent supply), timely 2–3 h of high quality (continuous and stable voltage) electricity could help reduce the wastage of electricity as well as reduce the groundwater withdrawals. Untimely and low quality electricity causes wasteful groundwater use, high electricity consumption and increased pump repair costs; which is lose-lose situation for both farmers and state electricity boards (Dubash, 2007; Kumar et al., 2011). It has been argued that free electricity may not cause groundwater decline because the policy was implemented with rationing of electricity and the aquifer can't be over-exploited with such small number of daily electricity hours (Fosli, 2014). This may be true if the groundwater withdrawals didn't increase after 2005. However, the region has been experiencing steady increase in groundwater irrigated area (Fig. 5) which is likely to increase the aggregated groundwater withdrawals and worsen the groundwater decline problem.

It can be argued that the free electricity policy, which was targeted towards the benefit of small farmers, has benefited a disproportional more number of medium and large farmers because almost 90% of small and marginal farmers in the state do not own irrigation well (Kumar et al., 2013). The financial and risk taking capacity (cost of well and pump) of marginal and small scale farmers is limited and as the wells become unproductive due to declining water levels, small farmers cannot afford the competitive drilling for deeper well installation and ultimately may suffer most from the subsidized power policy itself. In essence, the free electricity policy may in fact be detrimental for small farmers which make up 80% (Fosli, 2014) of the farmers in former Andhra Pradesh. In addition to subsidy-related declines, future increase in high intensity rainfall events is likely to promote the runoff and decrease the natural groundwater recharge in this crystalline aquifer region of Telangana (Dourte et al., 2013). This decrease in natural groundwater recharge combined with increased groundwater uses can further exacerbate the groundwater declines and well drying.

Various regulatory acts and guidelines have been developed for proper management of surface and groundwater resources in the Telangana state. One of the notable acts, Andhra Pradesh Water, Land and Trees Act, was enacted in 2002 for integrated management of surface and groundwater resources. According to this act, the farmers are required to register the existing bore wells and receive permission to drill new irrigation tube wells. While the act was reasonably successful in registering existing bore wells, very few farmers complied with the permit requirement for drilling new tube wells (Ramachandrula, 2008). Only 2500 new wells were granted permission during 2005–06 under this act, while the Transmission Corporation of

Andhra Pradesh Limited has reported an increase of 66,000 individual agricultural electrical service connections during the same period. The purpose of these agricultural electric service connections is to pump the water from the tube wells and it indicates that in reality 66,000 new tube wells were drilled during that period. To regulate the groundwater withdrawals, an appropriate policy should be designed and effectively implemented to restrict the expansion of new tube wells in the decline affected areas. Effective implementation of this policy would require proper coordination between the state electricity board and the agency which grants permission for new well drillings.

Deeper and increased extraction of water from the tube wells may also increase the groundwater quality problems. Almost all districts in the state, including Rangareddy, Medak, and Nalgonda locally suffer from excess fluoride and nitrate content in these shallow aquifers (CGWB, 2010). Excessive fluoride in drinking groundwater has caused dental and skeletal fluorosis in parts of the Telangana state (Radhika and Praveen, 2012). Granitic igneous rocks are usually high in fluoride content and the aquifers in this region possess high fluoride content as compared to other granitic aquifers elsewhere in the world (Brindha et al., 2011). Deeper and increased pumping may result in drying of these rocks and subsequent saturation due to recharge would result in leaching of the fluoride from rock minerals to groundwater (Subba Rao, 2003). Increased return flows due to irrigated area expansion are likely to exacerbate water quality (e.g. salinity and fluoride) problems in these shallow aquifers (Perrin et al., 2011a,b; Pettenati et al., 2013).

It has been argued that resource efficient technologies such as drip irrigation could result in irrigation water savings of over 80% as compared to conventional flood method of irrigation while maintaining or even improving the crop yields in some situations and crops (Narayanamoorthy, 2004a). However, the water savings are likely to be lower at the basin scale because water lost though deep percolation and tail water runoff at one location is available for reuse at another location in the basin. The magnitude of real water savings, and hence reduction in declines, would depend on reduction in unproductive crop consumptive water use (e.g. soil evaporation) (Howell, 2001; Pereira et al., 2002; Ward and Pulido-Velazquez, 2008). Inefficient irrigation systems such as flood irrigation wet the entire field rather than the root zone area as is the case with drip irrigation. Shukla et al. (2014) showed that this localized wetting by drip system reduces the unproductive evaporation from the plant row middles (and between the plant) thereby reducing the crop evapotranspiration by 34%. Studies have shown potentially significant basin-scale water savings from adoption of efficient irrigation such as drip irrigation (Törnqvist and Jarsjö, 2012). Therefore, switching from flood to drip irrigation will reduce the consumptive water use and help reduce the groundwater declines. Water efficient drip irrigation management is also likely to reduce the operation costs (e.g. electricity) and enhance the water productivity (crop yield per unit of water used) and improve water quality.

A preliminary economic analysis was performed to evaluate the feasibility of drip conversion in former Andhra Pradesh. Initial installation cost for drip irrigation is approximated to be 1600 US$ per ha (Kakhandaki et al., 2012). In 2013–14, the electric power subsidy to agricultural consumers in former Andhra Pradesh was about 2 billion US$ (GOI, 2014). If the power subsidy were removed completely, the money saved over two years could bring the entire groundwater irrigated area in the state under drip irrigation without incurring any cost to the farmers. Although, practically it may not be possible to eliminate the power subsidy in one year, a phased implementation of drip irrigation and reduction in power subsidy may help control the groundwater declines. Along with the promotion of drip irrigation, some policy measures, such as reduced number of free electricity hours, reasonable flat rate tariff and effective policy on well drilling may be needed to limit the aggregated groundwater withdrawals. Even with reduced electricity hours, drip irrigation is likely to provide sufficient irrigation to areas currently irrigated with flood irrigation. Lesser duration but high quality power supply hours are also likely to reduce the electricity wastage and carbon footprint of irrigation.

5. Conclusions

Crystalline aquifers, including peninsular granites and Deccan basalts, occupy about 65% (240 million ha) of India and provide the means of livelihood for many of the small and medium scale farmers. Proper planning and management of groundwater in these low storage aquifers is a key to enhance the reliability and resilience of this resource as well as to ensure the food security. Against the common perception that majority of the wells in this crystalline aquifer region have a declining trend, only about one third of the wells in the three-district study region showed a statistically significant decline in groundwater levels. The results may be slightly conservative (by 1%) considering the limitations of using the level data from open wells that became dry on few occasions. Increased irrigated area mainly due to free electricity policy and rainfall are the main reasons for these declines. Similar to our three district study region, parts of south, central and western India with the crystalline aquifer system are also located in semi-arid low rainfall climatic region where the groundwater recharge is limited. Demand side management of groundwater can increase the overall reliability of the wells in this semi-arid crystalline aquifer region. Our results for the three district study region suggest a need to carefully consider a reform in existing power subsidy policy. Similar groundwater trend and its linkages with power subsidy may exist but will need to be analyzed for entire Telangana or greater semi-arid hard-rock regions of India with power subsidy. Once the groundwater decline and power policy nexus is verified, appropriate policy reforms and conservation measures (e.g. microirrigation) such as those identified here will need to be considered to improve water sustainability. Promotion of drip irrigation, along with reduced electric subsidy and regulated drilling in decline affected areas may help reduce the groundwater withdrawals and declines as well as improve the groundwater and surface water quality. A similar management strategy could be implemented in the states such as Punjab where power subsidy is provided. Careful and detailed region-specific water balance and modeling studies should be undertaken to identify management systems that can lead to improved water and agricultural sustainability.

Anticipated increase in extreme weather events such as high intensity rainfall events under future climate may promote the runoff and reduce the groundwater recharge thereby further exacerbating the groundwater declines and water scarcity. There is a need to carefully consider the existing groundwater management policies including electric subsidy to control further groundwater declines and maintain sustainable water supply.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2016.09.005.

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