Hydrological Sciences Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/thsj20

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Version of record first published: 24 Jul 2012.

To cite this article: D.K. Panda, A. Mishra & A. Kumar (2012): Quantification of trends in groundwater levels of Gujarat in western India, Hydrological Sciences Journal, 57:7, 1325-1336

To link to this article: http://dx.doi.org/10.1080/02626667.2012.705845

Hydrological Sciences Journal – Journal des Sciences Hydrologiques, **57**(7) 2012

Quantification of trends in groundwater levels of Gujarat in western India

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Received 24 February 2011; accepted 31 October 2011; open for discussion until 1 April 2013

Editor D. Koutsoyiannis; **Associate editor** K. Hamed

Citation Panda, D.K, Mishra, A., and Kumar, A., 2012. Trend quantification in groundwater levels of Gujarat in western India. *Hydrological Sciences Journal*, 57 (7), 1325–1336.

Abstract The patterns in groundwater level, rainfall and temperature extremes for the western Indian state of Gujarat were examined using water-table records of 555 monitoring wells and daily rainfall and maximum temperature data sets for the period 1995–2005. The results reveal a large number of declining trends in groundwater levels with notable spatial structures; these are unlikely to be associated with the natural climate variability. There is also a noticeable increase in the temperature and rainfall extremes. Our results suggest that the groundwater withdrawal has increased, perhaps due to recurrent droughts and increases in temperature, and this has caused widespread water-table decline that has not been countered by rainfall extremes. Rainfall extremes appear to have caused greater runoff losses in the humid and sub-humid coastal regions, whereas the aquifers of the arid and semi-arid northern regions are more vulnerable to droughts and the warming environment.

Key words groundwater level; rainfall extremes; warming; over-exploited aquifer; agriculture; non-parametric trends

Quantification des tendances du niveau des eaux souterraines du Gujerat (Inde occidentale)

Résumé Les tendances du niveau des eaux souterraines et des extrêmes de précipitations et de températures dans l'État du Gujarat en Inde occidentale ont été examinées à travers les enregistrements du niveau de la nappe dans 555 puits de surveillance et des jeux de données de précipitations journalières et de températures maximales pour la période 1995–2005. Les résultats révèlent un grand nombre de tendances à la décroissance du niveau des eaux souterraines avec des structures spatiales notables. Il est peu probable que ces tendances soient associées à la variabilité naturelle du climat. On observe également un accroissement des extrêmes de températures et de précipitations. Nos résultats suggèrent que les prélèvements en eau souterraine sans doute dus à des sécheresses récurrentes et les augmentations de température ont provoqué une baisse généralisée du niveau de la nappe phréatique, sans qu'elle soit réalimentée par les extrêmes de précipitations. Les extrêmes de précipitations semblent avoir causé davantage de pertes par ruissellement dans les régions côtières humides et sub-humides, alors que les aquifères des régions septentrionales arides et semi-arides sont plus vulnérables aux sécheresses et à l'environnement plus chaud.

Mots clefs niveau des eaux souterraines; extrêmes de précipitations; réchauffement; aquifère surexploité; agriculture; tendances non-paramétriques

1 INTRODUCTION

Groundwater, an important part of the global freshwater resource, is the primary source of irrigation, industrial and drinking water requirements in many parts of the world. This essential subsurface component of the hydrological cycle regulates the large-scale circulation, such as the South Asian summer monsoon climate, through land–atmosphere energy feedback mechanisms (Yuan *et al.* 2008), and also supports the ecosystem in terms of baseflow and spring flow. However, most groundwater systems are subject to both climatic and human stresses. Changes in extremes of rainfall and temperature, changes in evapotranspiration, reduction in snowpacks, and sea-level rise, along with anthropogenic groundwater extraction, influence the recharge to and discharge from aquifers (Rivera *et al.* 2004). Consequently,

ISSN 0262-6667 print/ISSN 2150-3435 online

http://dx.doi.org/10.1080/02626667.2012.705845
http://www.tandfonline.com

groundwater levels have declined in many countries, and this appears to threaten the irrigated agriculture (Alley *et al.* 2002, Konikow and Kendy 2005). In groundwater over-dependent arid and semi-arid regions, the aquifers are over-exploited, as the natural replenishments are not sufficient to balance the groundwater withdrawals (Vörösmarty and Sahagian 2000). In the context of climate change and variability, groundwater is pivotal for sustainable water management, because of its capacity to act as a buffer to large spatial and temporal shifts in climatic extremes. Although there is an urgent need to investigate the influences of climate variability and anthropogenic activities on groundwater systems (Green *et al.* 2007), very little research has been conducted internationally, due to the lack of suitable data sets (McCarthy *et al.* 2001, Kundzewicz *et al.* 2007).

Translation of climate into groundwater responses is a complicated process, because of the interaction of the surface and subsurface hydrology, which is controlled by the physical characteristics of the land surface and the permeability of the rock and soil overlying the aquifer. Moreover, groundwater systems respond to climatic inputs with a time-lag, which makes it difficult to accurately model the impacts of climate change and variability (Chen *et al.* 2004). General circulation model (GCM) studies are also imprecise, as they have no representation of the groundwater (Eltahir and Yeh 1999). For the Indian sub-continent, groundwater extracted for irrigation plays an important role in ensuring food security to the over one billion population; it also contributes 80% of the domestic water use in rural areas and 50% of the water use in urban areas; the estimated annual groundwater extraction is 240 km^3 (Shah *et al.* 2003). The scale and rate of groundwater abstraction have increased substantially in the last five decades, while the number of pumps has increased from 12.58 million in 1990 to a current estimate of more than 20 million (FAO 2003). Consequently, an accumulation of deficits in groundwater storage is observed in many parts of India (CGWB 2006, Panda *et al.* 2007, Jeelani 2008).

A recent study based on the GRACE (Gravity Recovery and Climate Experiment) satellite mission records during the period 2002–2008 reveals large-scale groundwater depletion in north and northwestern India (Rodell *et al.* 2009, Tiwari *et al.* 2009). Rodell *et al*. (2009) attributed the depletion to the likely unsustainable consumption of groundwater for irrigation (i.e. anthropogenic factors only), as annual rainfalls were almost normal and other terrestrial water storage components contributed less significantly during the study period. However, it is important to examine the groundwater depletion in the context of recent climate variability (Tiwari *et al.* 2009). A greater cumulative rainfall in a year may not lead to an increased amount of recharge to the aquifer, as recharge is also influenced by the timing and form of rainfall (Rivera *et al.* 2004). In India, a small change in the monsoon rainfall distribution during June–September, which contributes more than 80% of the annual rainfall, can abruptly alter the irrigation requirement of the large monsoon-dependent agriculture. For example, the deficit in July 2002 rainfall resulted in a widespread agricultural drought and also drinking water scarcity in rural India, although the annual rainfall in 2002 was near the long-term norm (Samra 2004). Furthermore, the recent increases in frequency and magnitude of extreme rainfalls (Goswami *et al.* 2006, Krishnamurthy *et al.* 2009) may stress groundwater resources by causing greater runoff losses as undulating hard rocks cover around 65% of the geography of India. Therefore, climatic extremes are possibly the major influencing factor regarding the overall groundwater requirements for agriculture and other anthropogenic uses. However, it is difficult to distinguish the influence of climatic extremes from that of the human stresses (Hanson *et al.* 2004).

The specific objective of this paper is to assess the trends in groundwater levels and rainfall and temperature extremes to understand the response of groundwater systems to climatic and anthropogenic stresses in the western Indian state of Gujarat. The groundwater level time series are the principal source of information concerning the effect of hydrological and anthropogenic stresses on groundwater systems (Alley *et al.* 2002, Rivera *et al.* 2004). Moreover, a well-conceived monitoring network is capable of informing policy makers regarding sustainable management of groundwater resources (Morris *et al.* 2003). However, groundwater assessments have not been feasible in many parts of the world, as the maintenance of an adequate network of monitoring wells is both labour-intensive and expensive (Rodell *et al.* 2006). Internationally, very little information is available regarding trends in water-table levels and their possible linkages with the extremes of key climatic variables such as rainfall and temperature. In this study, availability of the pre- and post-monsoon water-table data set from a relatively dense network of 555 monitoring stations for the period 1995–2005 and the high-resolution gridded daily rainfall and temperature data set for the corresponding period formed the basis for analysing the trends and variability. Moreover, the study area is characterized by a diverse climatology (i.e. humid, arid and semi-arid climates) and hydrogeology (i.e. hard rocks and over-exploited alluvial regions), which are regionally large and coherent enough to exhibit the forcing of climatic and human stresses.

2 STUDY AREA AND DATA SETS

Based on the climatology and hydrogeology, the state of Gujarat (geographical area: 196 136 km^2) has been divided into four physiographic regions (Fig. 1): the semi-arid north Gujarat (NG), humid south Gujarat (SG), sub-humid Sourashtra Peninsula (SP) and the arid Kachchh Peninsula (KP). The total irrigated area utilizing groundwater, ~89% of the total irrigated area, has more than doubled over 30 years, from 10 000 km^2 in 1971 to 25 000 km^2 in 2001 (Fig. 2). At the same time, the population of Gujarat increased from 26.7 million in 1971 to 51 million in 2001, an increase at a rate of more than 20% per decade (GoG 2005). Groundwater meets 80% of the domestic water requirements of the state. In general, the state shows a north to south contrast in groundwater extraction due to the different water-yielding capacity of the soils. Although the climate of north Gujarat is semi-arid, the large Quaternary alluvial plain of the region has extensive hydraulically-connected aquifers with moderate to large yield (10–40 L s^{-1}) (Kavalanekar *et al.* 1992, Morris *et al.* 2003). The vertical flow from the overlying shallow aquifer, which is primarily recharged by rainfall, contributes 95% of the water withdrawn from the deep aquifer for irrigation (Rushton and Tiwari 1989, Rushton 2003). The soils in the alluvial north Gujarat—having high permeability and infiltration capacity—require a minimum rainfall amount of 40 mm year^{-1} to recharge the shallow aquifer, whereas it requires 355 mm year^{-1} to initiate the recharge in the hard rock (basalts) of the southern parts of the state (Rangarajan and Athavale 2000).

The north Gujarat alluvial aquifer, with a net cropped area of 49 914 km^2 (i.e. 47% of the total cropped area of Gujarat), is recognized as one of the over-exploited aquifers of India based on the classification of the Central Ground Water Board (CGWB 2006), because groundwater abstraction has exceeded the net availability in several administrative blocks of the region. For the whole of north Gujarat, the anthropogenic withdrawal is estimated to be 95% of the annual recharge of 6.88 km^3.

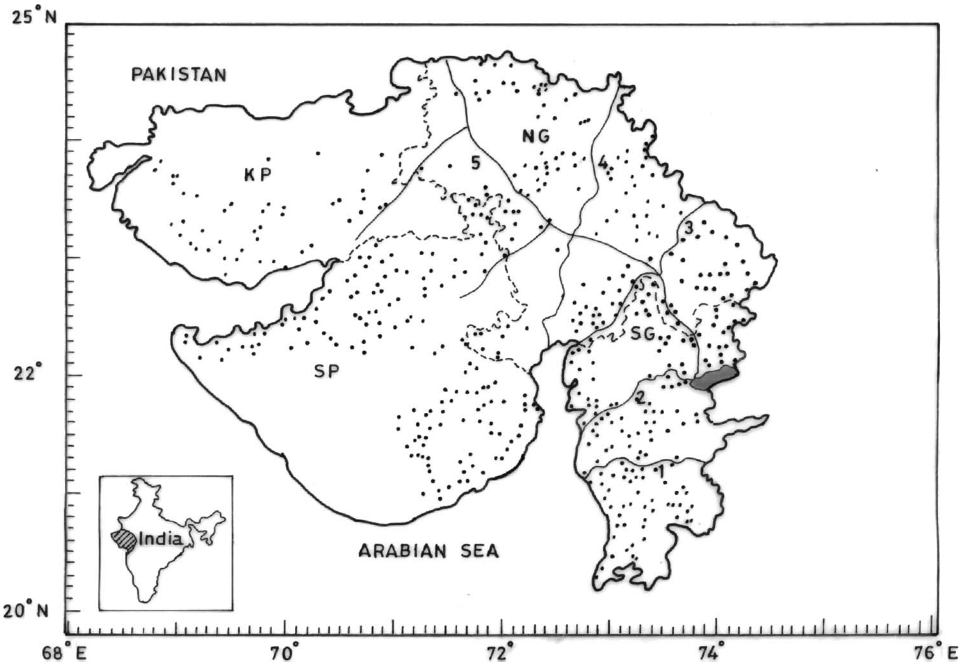

Fig. 1 Inset map: location of the study area Gujarat (dark shading) in western India. Main map: location of the 555 monitoring wells (points) analysed in this study. The physiographic regions are bounded with dotted lines: NG: north Gujarat; SG: south Gujarat; SP: Sourashtra Peninsula; and KP: Kachchh Peninsula. The major rivers that drain to the Arabian Sea include: 1: Tapi; 2: Normada; 3: Mahi; 4: Sabarmati; and 5: the Normada main canal system originating from the reservoir on the Normada River.

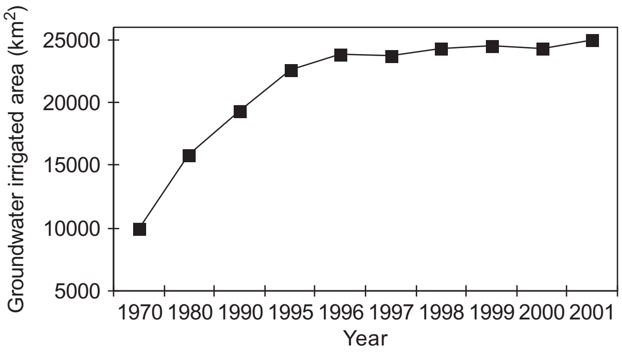

Fig. 2 Decadal growth in groundwater irrigation, from the 1970s to 2000s, in Gujarat; this was accompanied by a nearly two-fold growth in population, from 26.7 million in 1971.

Similarly, the aquifer of the arid Kachchh Peninsula is highly stressed, as 86% of the annual recharge of 0.63 km^3 is extracted to meet anthropogenic demands. The pronounced groundwater-level decline in Gujarat has led to social divide, as only wealthy farmers can afford the increased drilling and pumping costs (Dubash 2002). Moreover, over-abstraction has also resulted in the occurrence of high fluoride in the groundwater of the north Gujarat aquifer and salinity ingression in the coastal Sourashtra Peninsula (Gupta *et al.* 2005, Pujari and Soni 2009). Although southern Gujarat is a high-rainfall region, the net cropped area is only 13 090 km^2, due to the unsuitable aquifer characteristics and the hilly terrain. Around 40% of the annual groundwater recharge of 2.88 km^3 is extracted. Similarly, a variety of hard and fissured formations with discontinuous aquifers and moderate yield (5–15 L s^{-1}) characterize the undulating landscape of the Sourashtra Peninsula. However, strips of alluvial formations in the coastal and deltaic region, with a net cropped area of 39 000 km^2, facilitate groundwater withdrawal of 69% of the annual recharge of 5.67 km^3.

Analyses were performed on the groundwater-level monitoring data of Gujarat state, which were compiled by the CGWB, India. Currently, a network of 995 observation wells has been set up under the National Hydrograph Network Stations (NHNS) for proper hydrogeological representation in the state. The recording of groundwater levels in metres below ground level (m b.g.l.) is carried out four times per year in the following periods: 20–30 May (pre-monsoon season); 20–30 August (monsoon season); 1–10 November (post-monsoon season); and 1–10 January (recession stage of water table). The pre- and post-monsoon season groundwater-level data are relatively complete and also capture both rainfall variability and anthropogenic stresses. However, the water-table records for August and January contain numerous data gaps and missing values, due to a lack of monitoring dictated by financial restrictions. The piezometer records representing the water table of the confined aquifer were excluded from this study for uniform comparison of the trends and variability. Moreover, monitoring wells that had been created recently, and wells with less than 10 years of observations for both the pre- and post-monsoon seasons, were excluded. Finally, the groundwater-level records of 555 monitoring wells for the period 1995–2005 were selected for the analysis. The selected monitoring wells adequately represent the four physiographic regions (Fig. 1): 180 wells in north Gujarat (NG), 171 in south Gujarat (SG), 159 in the Sourashtra Peninsula (SP), and 45 in the Kachchh Peninsula (KP). Each well represents the local water table of the aquifer with minimal pumping and artificial recharge effects.

The updated high-resolution gridded daily rainfall (Rajeevan and Bhate 2008) and temperature (Srivastava *et al.* 2008) data sets of the Indian Meteorological Department (IMD) for the period 1995–2005 were analysed. The extreme rainfall frequency and intensity (described in the next section) were calculated for each of a grid of 84 cells (each of 0.5° latitude × 0.5° longitude) over the study area. Goswami *et al*. (2006) and Krishnamurthy *et al*. (2009) investigated trends in rainfall extremes using the earlier gridded rainfall data set at 1° latitude × 1° longitude. Furthermore, the percentiles of daily maximum temperature were calculated for 34 grid cells each at 1° latitude × 1° longitude. This can better depict the impacts of extreme temperatures than the percentiles of daily minimum and average temperatures.

3 METHODS

3.1 Statistics of extremes

As the locations of the monitoring stations and the timing of groundwater-level recording were different from those of the rainfall and temperature, we could not find the station-level correspondence among them. To explore the spatial and temporal variability, we averaged seasonal groundwater level and annual rainfall over the physiographic regions and computed the linear correlation. However, station-level trends were assessed for all three hydroclimatic variables using the non-parametric Kendall slope. In general, increases in extreme rainfall events influence the recharge rates, which differ based on the frequency and intensity of extreme rainfall. In order to explain the groundwater-level trends, we calculated percentile-based exceedence frequency and intensity of rainfall, as defined by Krishnamurthy *et al*. (2009). This will clarify whether the recent groundwater declines (Rodell *et al.* 2009, Tiwari *et al.* 2009) can possibly be linked to the extreme climatic events in conjunction with the anthropogenic irrigation factor. The frequency of extreme rainfall is defined as the number of days in each year having rainfall events exceeding a threshold, while the intensity is defined as the average daily rainfall in each year only for those days on which rainfall exceeds the specific threshold. For each grid cell, we computed the 95th and 99th percentiles of the daily rainfall series for each year, and the median value of these percentiles across the study period was treated as the threshold value for calculating the extremes. The resultant thresholds, which differ from grid to grid, can represent better the high spatial variability of rainfall in comparison to that of the fixed threshold value across grids. The frequency of exceedence f_{jt} for grid j and year t is calculated as:

$$f_{jt} = \sum_{i=1}^{365} F_{R_{itj} > R_j *} \tag{1}$$

and the intensity of exceedence s_{jt} for grid j and year t is calculated as:

$$s_{jt} = \left(\frac{\sum_{i=1}^{365} F_{R_{itj} > R_j *} R_{ijt}}{f_{jt}} \right) F_{f_{jt>0}} \tag{2}$$

where R_{itj} is the rainfall on day i in year t at grid j, R_j^* is the threshold rainfall for grid j, F takes the value 1 if $R_{itj} > R_j^*$ and 0 otherwise. For the temperature time series, the 25th, 50th and 75th percentiles and the annual maximum value of daily maximum temperatures for each year and for each grid were computed for the trend analysis.

3.2 Kendall slope analysis

The robust Kendall slope (β) was used to assess the magnitude of the trend (Sen 1968, Hirsch *et al.* 1982). The paucity of long time series of groundwater-level data necessitated the use of the non-parametric Kendall slope, which has been widely adopted in climate and hydrological time series analysis. This procedure does not require distributional assumptions, and it minimizes the effects of outliers on the estimated trend by taking the median of all slopes calculated from all possible pairs of data in the time series (Zhang *et al.* 2001). The test statistic is given by:

$$\beta = \text{median}\left(\frac{X_j - X_i}{j - i}\right) \tag{3}$$

where X_i and X_j are the sequential data values from the sample of n independently and identically-distributed random variables. A positive and a negative β, indicate water-table level fall (decline) and rise (improvement), respectively. In order to allow a better interpretation of the spatial behaviour of the trends, the inverse distance weighted (IDW) method of interpolation was used. This is a widely-employed spatial interpolation tool, which estimates the value at the unsampled location using the values of nearby sampled points, weighting inversely by their distance to the location (Ruelland *et al.* 2008). The spatial tools of ArcGIS 9 software were used to obtain the maps.

4 RESULTS

4.1 Rainfall and groundwater-level variability

Figure 3 shows the spatially-averaged annual rainfall and groundwater level in the pre- and post-monsoon seasons for the physiographic regions of Gujarat. In general, a direct correspondence between rainfall and groundwater level was observed, although the spatial and seasonal differences were more pronounced (Fig. 3). In the post-monsoon season, groundwater level corresponds well with the rainfall variability, as is evident from the high correlation coefficients (r). However, the pre-monsoon groundwater level of a particular year is mainly influenced by the monsoon rainfall of the previous year, and the anthropogenic factor in terms of groundwater extraction for agriculture and drinking water requirements. In addition, the rising extreme temperatures (Fig. 4), which influence the irrigation and drinking water requirements, are likely to affect the pre-monsoon groundwater level. Therefore, the correspondence between the rainfall and the pre-monsoon groundwater level of the succeeding year (r_1) was found to be comparatively weak for different physiographic regions (Fig. 3).

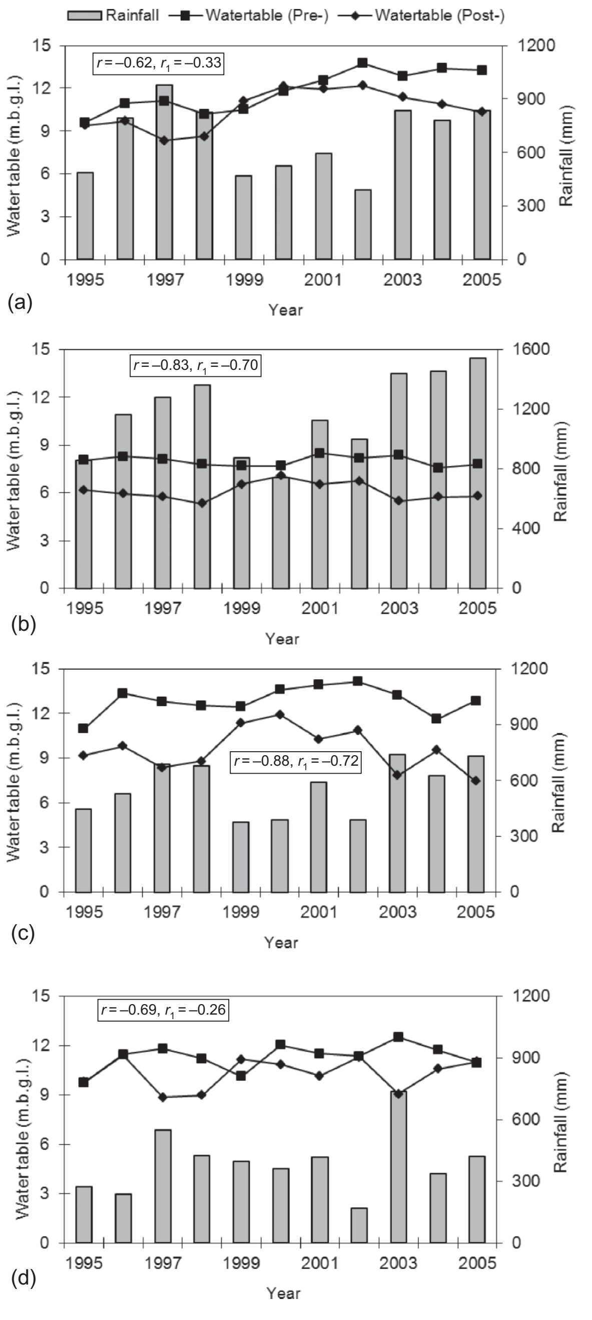

Fig. 3 Correlation between the spatially-averaged annual rainfall (mm) and groundwater-table fluctuation (m b.g.l.) in the pre- (r_1) and post-monsoon (r) seasons for: (a) north Gujarat, (b) south Gujarat, (c) Sourashtra Peninsula, and (d) Kachchh Peninsula during the study period 1995–2005. The correlation r_1 is calculated using the rainfall and pre-monsoon water table of the succeeding year.

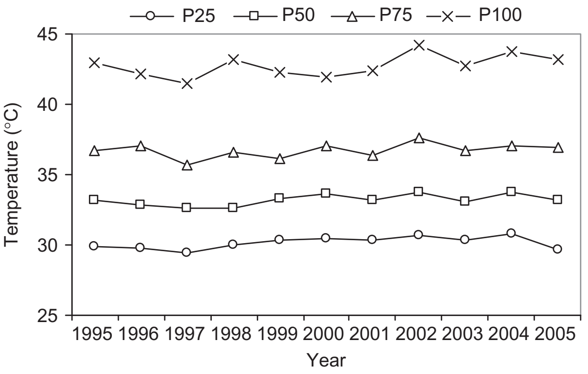

Fig. 4 Spatially-averaged percentiles (P) of daily maximum temperatures indicate a subtle increasing pattern, particularly for the 25th (P25) percentile and the annual maximum temperature (P100).

As the study region is characterized by a great variation in topography, hydrogeology and climate, averaging the time series has the chance of masking the existing variability (Lettenmaier *et al.* 1994), and thus confounding the regional influencing factors. For example, the correlation between the rainfall and the pre- and post-monsoon groundwater levels was comparatively high, with $r_1 = –0.65$ and $r = –0.81$, respectively, for the state as a whole. However, this result does not reflect the different degrees of correspondence among the physiographic regions. Furthermore, significant correlations were observed for the four physiographic regions between rainfall and average groundwater level (i.e. the average of the post-monsoon groundwater level and the pre-monsoon groundwater level of the succeeding year), although the seasonal groundwater level responded differently to the rainfall variability. Therefore, analysis of time series from individual monitoring wells that contain information of both climatic and anthropogenic stresses, could properly explain the signal of groundwater-level changes in both the spatial and seasonal contexts.

4.2 Trends in groundwater level

In the pre-monsoon season, declines in groundwater level in terms of positive trends were observed in 58% of 555 monitoring wells, in comparison to rises in 39% of the wells; the overall rate of decline was 0.11 m year^{-1} (Table 1). In the post-monsoon season, however, the groundwater level declined in 50% and improved in 39% of the wells, with an overall declining rate of 0.05 m year^{-1}. Spatial interpolation of trends indicates a generally coherent occurrence (i.e. declining and rising trends tend to occur in clusters) for the state as a whole (Fig. 4). Although groundwater-level fluctuation is more of a location-specific response to recharge and discharge at the initial stage, the persistent tendency progressively spreads to the whole system by inter-aquifer leakage. The distinct spatial patterns of the trends also suggest that the aquifers are hydraulically connected and that the trends are interdependent.

Table 1 Regional and seasonal variations of the descriptive statistics of the Kendall slope.

Region	Stations	Season	Trends		Kendall slope (β)	
			Positive (decline)	Negative (improvement)	Mean	Std Dev.
North Gujarat	180	Pre-monsoon	128	46	0.30	0.60
		Post-monsoon	129	35	0.19	0.47
South Gujarat	171	Pre-monsoon	83	84	−0.03	0.54
		Post-monsoon	70	87	−0.01	0.14
Sourashtra	159	Pre-monsoon	85	69	0.04	0.74
Peninsula		Post-monsoon	49	85	−0.05	0.32
Kachchh	45	Pre-monsoon	24	18	0.14	0.72
Peninsula		Post-monsoon	32	11	0.06	0.22

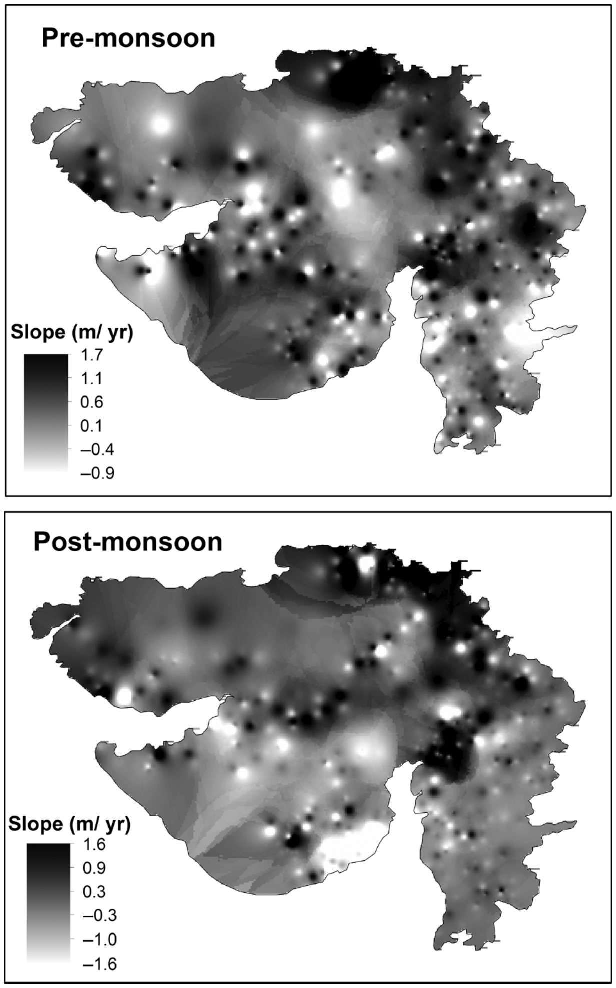

Fig. 5 Spatial distribution of the pre- and post-monsoon season groundwater-table trend. Scales are shown to the left, indicating the trend magnitudes. Note that the marked decline occurred in most parts of the state during the pre-monsoon summer season. In the post-monsoon season, the rising water tables are concentrated in the south and south-eastern regions, while declining trends are concentrated in the northeastern region.

The observed declining groundwater-level trends are widespread across the state in the pre-monsoon season (Fig. 4). More striking is the high congregation of declining groundwater-level trends in north Gujarat and in the northwestern Kachchh Peninsula irrespective of season. Table 1 also indicates that the pre- and post-monsoon declining trends outnumber the corresponding rising trends by substantial proportions for both the northern physiographic regions. In general, the declining trends are more concentrated in the northeast and south-central parts of the state in the pre-monsoon season, in contrast to the concentration of rising groundwater-level trends in the southeast portion. Descriptive statistics of Kendall slope also indicate that north Gujarat experienced the largest water-table decline of 0.3 and 0.19 m year^{-1} in the pre- and post-monsoon seasons, respectively. In contrast, the overall water tables have improved marginally in south Gujarat, although location-specific declines are observed.

4.3 Trends in rainfall and temperature extremes

Increases in rainfall exceedence frequency of the 99th percentile were observed in 54% of 89 grid cells in comparison to decreases in 12% of the grid cells. However, the exceedence intensity of the 99th percentile increased in 57% and decreased in 42% of the total grids. For the exceedence of the 95th percentile, the increases in both frequency and intensity of rainfall outnumbered the corresponding decreases in high proportions. Figures 6 and 7 illustrate the spatial interpolation of the trend magnitudes in exceedence frequency and intensity of rainfall, respectively. It is interesting to note that the frequency and intensity of rainfall differ spatially at different exceedence percentiles. The increasing trends in frequency of the 95th percentile threshold are predominant in the north-central and sub-humid southern region, while most of the southern parts experienced increases for the 99th percentile threshold.

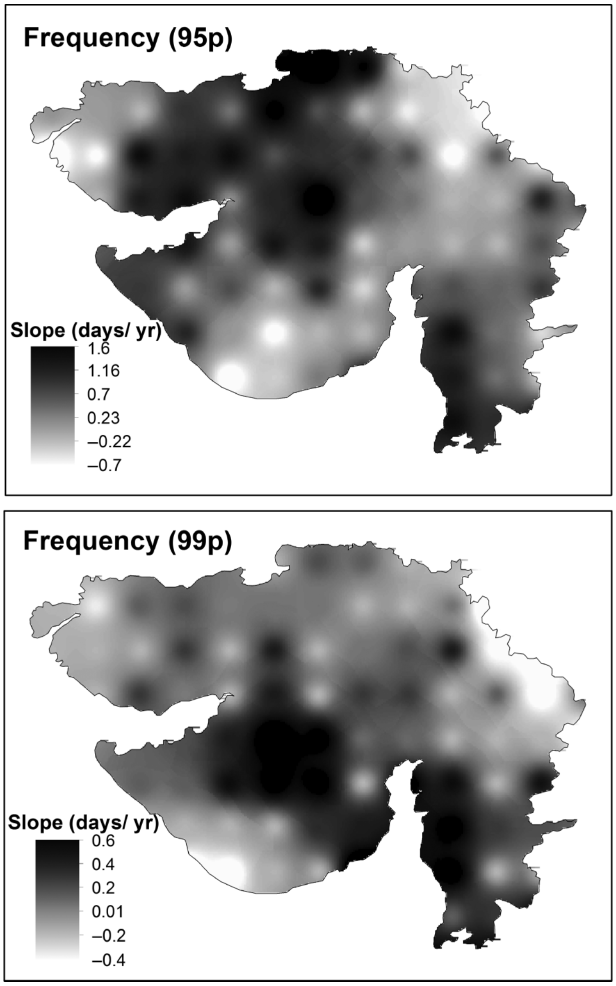

Fig. 6 Spatial distribution of trend magnitudes in rainfall exceedence frequency of the 95th and 99th percentile thresholds. Note that the increasing trends in frequency of the 95th percentile threshold are predominant in the north-central and sub-humid southern region, while most of the southern parts have experienced increases for the 99th percentile threshold.

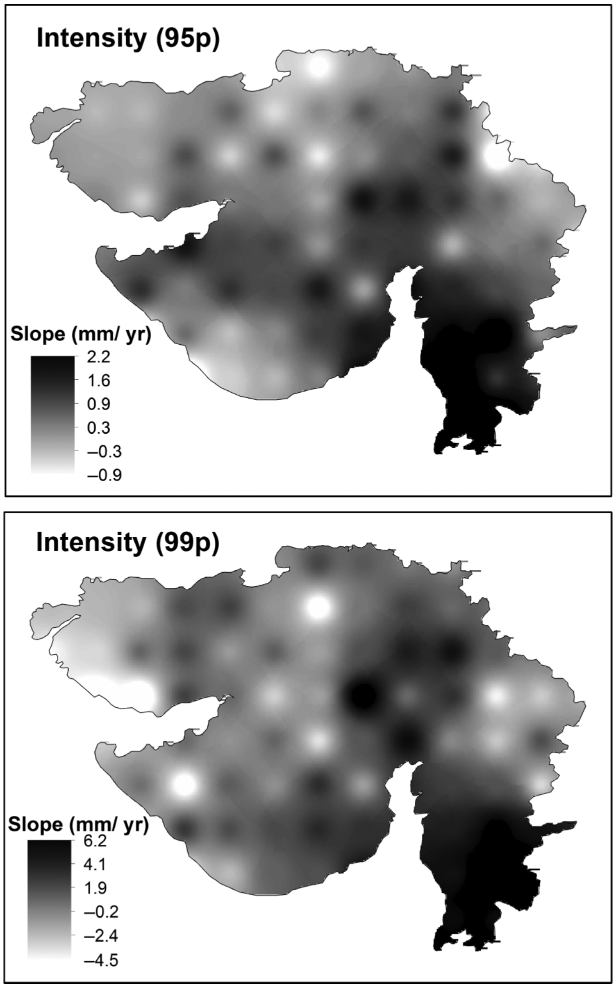

Fig. 7 Spatial distribution of trend magnitudes in rainfall exceedence intensity of the 95th and 99th percentile thresholds. Predominant increasing trends in intensity for both the thresholds are observed in the humid and sub-humid southern region.

In south Gujarat, both the exceedence frequency and intensity of the 99th percentile showed increases of 0.27 d year^{-1} and 2.1 mm year^{-1}, respectively. North Gujarat also experienced increases in both frequency and intensity. However, the intensity showed decreases in the Sourashtra and Kachchh Peninsulas. Generally, the increases in the exceedence frequency of the 95th percentile have more spatial dominance in comparison to that of the 99th percentile. In general, the humid and sub-humid climates of south Gujarat and the Sourashtra Peninsula, adjacent to the Arabian Sea, experienced increases in both frequency and intensity of extreme rainfall irrespective of the percentile thresholds. However, the decreasing trends in intensity of rainfall were more prevalent over the dry and desert regions of Kachchh Peninsula. It can be presumed that the observed significant increases in annual rainfall could be due to the increases in the exceedence frequency and intensity. As trends in frequency and intensity have different connotations, it is worthwhile to note that the increases in extreme rainfall frequency have not always led to corresponding increases in intensity for the 99th percentile. In contrast, the increases in extreme rainfall intensity outnumbered the corresponding increases in frequency for the 95th percentile.

The annual maximum temperature increased in 19 of 20 grids at an average rate of 0.12°C year^{-1}. However, the 75th, 50th and 25th percentile of the daily maximum temperatures increased in all the grids at an average rate of 0.04, 0.06 and 0.09°C year^{-1},

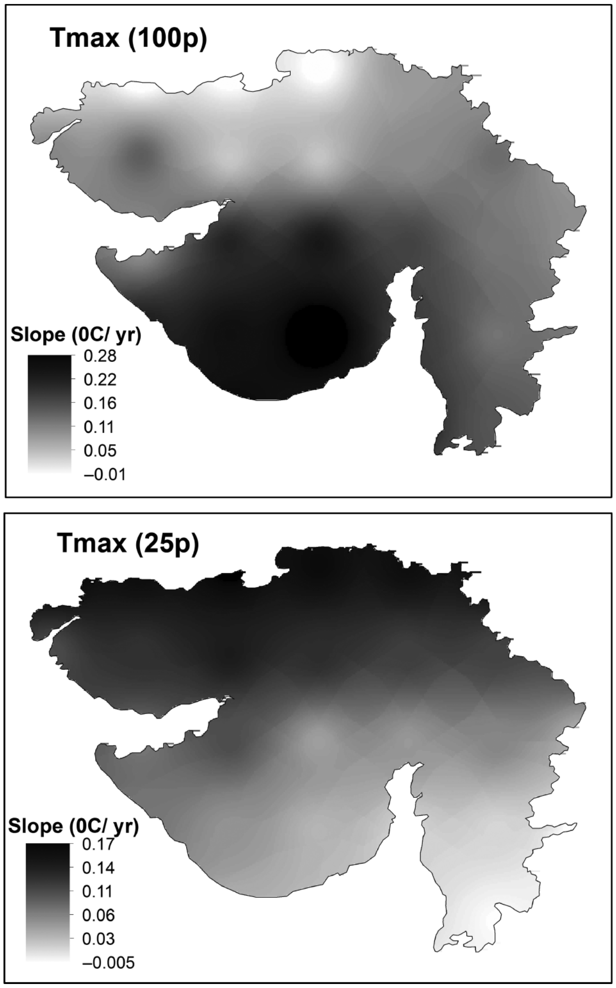

Fig. 8 Spatial distribution of trends in the annual maximum (100p) and 25th percentile of daily maximum temperature. Note that the increases in annual maximum temperature are observed in the southern region of the state, while increasing trends in the 25th percentile temperatures spread over the northern and central region.

respectively. Figure 8 illustrates the spatial interpolation of the trends in the annual maximum and 25th percentile of daily maximum temperatures, indicating a general state-wide increasing pattern. However, it is important to note a distinct increase in the annual maximum temperature in the southern parts of the state. In contrast, the increasing trends in the 25th percentile maximum temperatures showed a large increasing trend uniformly spread across the northern regions. Noticeable increases in the 50th percentile temperatures were also observed (not shown) in north Gujarat and Kachchh Peninsula. Although the time series is of 11 years only, this analysis shows a general increasing pattern in the extreme rainfall frequency and intensity, which is consistent with the findings of Krishnamurthy *et al*. (2009) and Goswami *et al*. (2006). However, it is interesting to note the distinct spatial features of the trends, even for a small region, that may be due to the use of the densely-gridded, fine-resolution data sets. In addition, all the indices of daily maximum temperature have increased for almost all the grids, with a high proportion of increasing trends for lower and middle percentiles. Thus, it can be inferred that the observed extreme rainfalls may have led to high rainfall variability in terms of droughts and floods during the study period (Fig. 3).

5 DISCUSSION

In consistence with the reported large-scale groundwater depletion in northwest India (Rodell *et al*. 2009), the current analysis also showed a general decline in groundwater level in the state of Gujarat. Rodell *et al*. (2009) attributed the severe groundwater depletion to irrigation and other human consumption, as no unusual trends in annual rainfall were observed during the period 2002–2008. However, that study period includes a severe drought year in 2002 and also flood years in 2003 and 2008. Our results also provide no evidence of patterns in annual rainfall. The annual and extreme rainfalls may not have yielded a systematic trend because of high inter-annual variability in terms of droughts and floods (Matalas 1997). It should also be noted that the rainfall, temperature and groundwater level averaged over the physiographic regions, as well as over the state, exhibited no perceptible trends. However, perceptible changes were observed in the rainfall frequency and intensity, and also in the temperature percentiles for the station-scale data sets. Therefore, we reason that the combined effect of the climatic extremes and the anthropogenic forcing mechanism of over-abstraction could be one of the major causes of the observed water-table decline in the state. However, it is difficult to quantify these separately, as both the mechanisms coincide on an annual to inter-annual scale. It must be noted that the 11-year data set analysed in this study is too small to ensure the statistical properties for differentiating the systematic pattern *versus* natural climate variability (Koutsoyiannis 2006). However, individual extreme years, which are a part of natural variability, can also have long-term hydrological impacts for a populous country like India.

The extremes in rainfall were observed in terms of drought and flood years during the study period (Fig. 3(a) and (d)). It is suggested that the amount and duration of effective rainfall, which facilitates the groundwater recharge in a given topographic and hydrogeological setting, are likely to have decreased primarily because of the rainfall extremes. This is clear, as the post-monsoon season groundwater levels have coincided or exceeded that of the pre-monsoon season for some years (Fig. 3(a) and (d)). Matching of the seasonal groundwater levels in a particular year suggests that the post-monsoon recharge is not sufficient to counteract the drawdown in the pre-monsoon season. This is observed in a dry year as the scanty rainfall is just sufficient to compensate the further drawdown due to the increased reliance on groundwater for irrigation and drinking water requirements during the monsoon season.

Overlapping of the post-monsoon groundwater level with that of the pre-monsoon suggests that the greater reliance on groundwater has reduced groundwater storage with little or no replenishment from recharge. This situation is further exacerbated when the drawdowns cumulate due to successive occurrences of drought, as observed during 1999 and 2000 in this study. In addition, the widespread increase in temperature is likely to have stressed the groundwater resources due to increases in crop water and drinking water requirements. Based on the findings of artificial recharge studies (UNDP 1986, Rushton and Phadtare 1989), the Narmada main canal system (Fig. 1) was set up to recharge the over-exploited aquifer of north Gujarat (GoG 1989). Although groundwater levels do not show improvements along the canal system, declines are also not observed in the large, middle portion of the canal (Fig. 5). This suggests that the canal system may have partially replenished the declining groundwater level in the region. Occurrence of a few rising trends, particularly in the Kachchh Peninsula and north Gujarat (Fig. 5), in the pre-monsoon summer season could be due to the location of specific interventions that require analysis of the hydroclimatic and water-table data records at shorter intervals for explanation.

Although the rainfall extremes in terms of both frequency and intensity seem to have increased in the humid and sub-humid region of south Gujarat and Sourashtra Peninsula, the post-monsoon groundwater level trend remains stable without showing any improvements (Table 1 and Fig. 3). First, the hard rocks and other aquifer properties of these regions are not conducive to deep percolation of the large amounts of water. In addition, the sloping terrain and the exceedence of infiltration capacity of the soil might have resulted in more runoff losses. For example, the 2005 wet year in Gujarat was due to the week-long downpour beginning on the 24 June, with some parts of the state having received more than the mean annual rainfall. Such an extreme rainfall shortens the recharge process relative to what would have been realized had the rainfall been distributed over a month or so. Moreover, a small amount of water from occasional rainfalls rarely penetrates the hard rocks. In the post-monsoon season, the surface water is sufficient to meet both the evaporative and anthropogenic demands. Few decreasing water-table trends (Fig. 5) could be due to location-specific abstraction, because the tracts of land near rivers and the coast are agriculture-dominated. However, it is interesting to note the simultaneous groundwater-level declines and improvements in the pre-monsoon summer season. The increasing trends in temperature and drought are likely to have caused the groundwater level to decline in the southeast and northeast of south Gujarat as the human stress (due to groundwater pumping) is comparatively less there. The groundwater-level improvements in the pre-monsoon summer season reflect the recent increases in the baseflow, as several major rivers flow through the southern region (Gupta and Chakrapani 2007).

6 CONCLUSIONS

This study quantified the trends in groundwater levels for the state of Gujarat using the pre- and post-monsoon water-table records for the period 1995–2005. In addition, the study analysed rainfall and temperature extremes based on high-resolution gridded daily rainfall and maximum temperature data sets for the same period. The trend results show that groundwater-table levels have decreased in most parts of the state of Gujarat, while the rainfall and temperature extremes have increased. The declining groundwater-level trends outnumbered the rising trends by substantial proportions, particularly in north Gujarat and Kachchh Peninsula. Although a widespread fall in water table was observed across the state with an overall rate of decline of 0.11 m year^{-1} in the pre-monsoon season, groundwater-level improvements were noted in south Gujarat and Sourashtra Peninsula. In the post-monsoon season, a marked groundwater decline was observed in north Gujarat only. In spite of increases in the frequency and intensity of rainfall events, particularly in south Gujarat and Sourashtra Peninsula, the post-monsoon water-table levels showed no large-scale improvements, as is evident from a few localized increasing and decreasing trends.

If these observed patterns in climatic variables continue into the future decades, there will likely be a shortage of groundwater availability due to the probable increases in the human stresses on groundwater. A recent White Paper on water scenarios for Gujarat State projects a widespread water crisis with an annual deficit of around 12 km^3 by the year 2025 (GEC 2005). Moreover, the model-based simulation studies have predicted a warming-induced intensification of the Indian monsoon rainfall, leading to the occurrence of more extremes along with a large inter-annual variability in rainfall (May 2004, Rupa Kumar *et al.* 2006). As the coarse spatial resolutions of the models are unable to depict the regional-scale changes, it is necessary to detect and attribute the trends at the regional scale to ensure sustainable management of water resources. Future research needs to accurately characterize the trends in groundwater level and climatic extremes, and this requires integration of the long-term, high-resolution geophysical and geological data sets along with flow and transport measurements.

Acknowledgements We greatly appreciate the help of the reviewers, the associate editor and the editor for their constructive comments and suggestions that contributed to an improved version of the paper. We are also thankful to the Central Groundwater Board (CGWB), Government of India, for providing the data sets for this research.

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