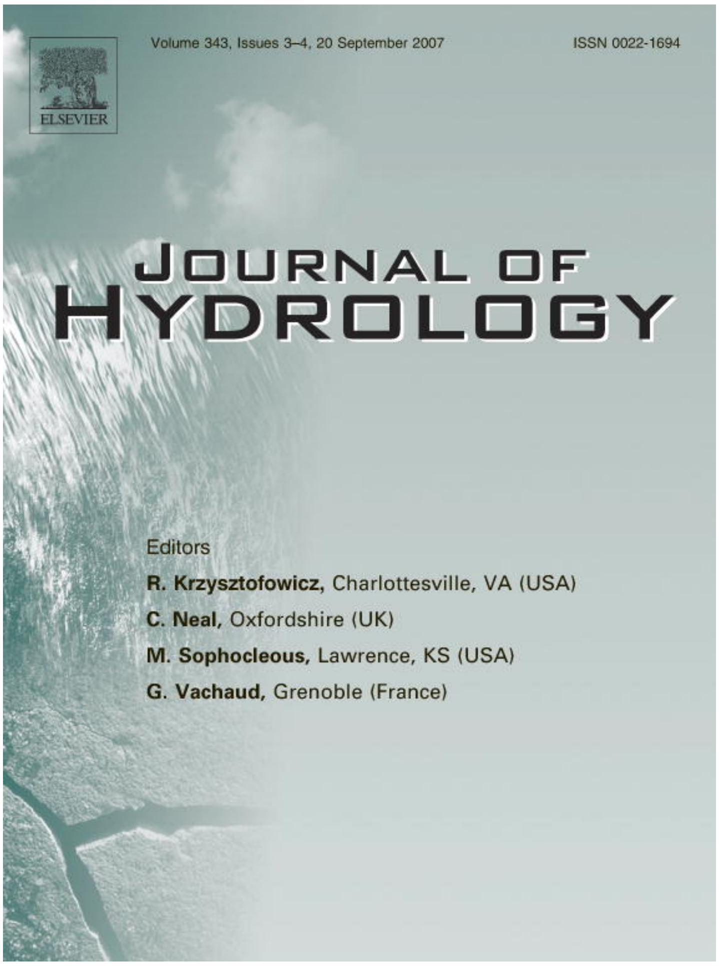
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# The influence of drought and anthropogenic effects on groundwater levels in Orissa, India

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$\chi^2$-test

**Summary** Investigating the response of groundwater levels to the extreme weather events provides essential information for sustainable planning and management of water resources. The aim of this study was to identify and quantify the groundwater level trend of the state Orissa (India) to understand the forcing mechanism of droughts in conjunction with the anthropogenic pressure using the non-parametric Mann–Kendall statistical procedure. The pre- and post-monsoon groundwater level records of 1002 monitoring stations during the period 1994–2003 were analyzed. The results show that the drawdowns due to deficient rainfall during dry years, high temperatures, and anthropogenic pressure have not been recovered through the recharge in wet years. However, this study does not determine whether drought, high temperatures or anthropogenic effects have had largest influence on the groundwater levels decline. The cases of significant water table declines are higher in number than those expected to occur by chance. In the pre-monsoon season, 59% of the monitoring stations experienced groundwater declines as against 51% in the post-monsoon season for the study area as a whole. This could be interpreted that the fluctuation is not a part of noise, but that a signal is being identified. Further, the trend result showed wide spatial and seasonal differences. Irrespective of seasons, the consolidated rock formation that covers 80% of the geographical area experienced significant water table decline. However, the semi-consolidated and unconsolidated formations experienced water table decline in the pre-monsoon (summer) season only. The vulnerable sites where the groundwater-level declined significantly were identified so that recharge measures could be taken up.

## Introduction

Any anomaly in the atmosphere will have impacts on every component of the whole hydrologic cycle (Loaiciga et al., 1996). The groundwater is the invisible and ultimate indicator

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of the atmospheric anomalies in the hydrologic cycle. The occurrence of drought and heavy precipitation are the most important climatic extremes having both short and long-term impacts on the groundwater availability. These impacts include changes in groundwater recharge resulting from the erratic behavior of the annual and seasonal distribution of precipitation and temperature; changes in evapotranspiration resulting from changes in vegetation; and possible increased demands for groundwater as a backup source of water supply (Alley, 2001). However, the link between climate variability and the groundwater response is more complicated than that with the surface water regime. Its dynamics is rather a stable system, and responds slowly with a time lag to climate variability. Further, the diverse aquifer characteristics respond differently to the surface stresses (Chen et al., 2004; Environment Canada, 2004).

During past few years, India has experienced extreme weather events such as droughts, floods and cyclones more frequently. However, the effect of drought is more pronounced given the quantum of economic and environmental losses. Drought in the year 2002 was one of the severest in the history of India which affected 56% of the geographical area and the livelihoods of 300 million people in 18 states (Samra, 2004). The groundwater level declined significantly, which will take years to recharge and recover in many parts of the country. In Orissa, repeated droughts in conjunction with the anthropogenic water demand have significantly affected the groundwater availability. The population of Orissa has increased 2.5 times during the last 50 years, reaching 36 million in the year 2001. Further, it is increasing with a decadal growth rate of above 15%. Nearly, 80% of the population depends on groundwater as a source for drinking water. About 3 million people in the western part of Orissa are facing acute drinking water crisis due to large-scale deforestation, unplanned use of irrigation water, and low participation by people in the management of natural resources (Rejani et al., 2003). Moreover, overdraft of groundwater in certain parts of the densely populated coastal basin has resulted in declining of groundwater levels and seawater intrusion. Anthropogenic activities have also caused high erosion and sedimentation in the major river basins of Orissa. Chakrapani and Subramanian (1993) noted the high sedimentation rate of 5.08–20.39 mm yr$^{-1}$ in the Mahanadi river basin, owing to local activities such as agriculture, deforestation, grazing, and intense construction work. Further, weathering of rocks and anthropogenic inputs are found to be the main source of trace elements such as Fe, Mn and Cr in the groundwater of the coastal sediment aquifer (Das, 2003). In the context of global climate change, the Intergovernmental Panel on Climate Change (IPCC, 2001) has reported that one of the anticipated effects of climate change is the possible increase in both frequency and intensity of extreme weather events. Further, due to global warming 1.1 °C rise in temperature would increase the water demand by 12% for agriculture alone (Yu et al., 2002). Hence, it is essential to understand the potential future changes in groundwater availability in the backdrop of repeated droughts and ever increasing anthropogenic thrust.

Several analytical techniques have been reported to investigate the sensitivity of aquifer water levels to climate variability. Using the crossing theory approach, Eltahir and Yeh (1999) assessed the asymmetric response of aquifer water level to floods and droughts. They reported that the drought left a significantly more persistent signature in the aquifer water level than the corresponding signature of the flood. Based on the projected climate change scenarios using general circulation models (GCM), a few authors have simulated the potential impacts on groundwater (Loaiciga et al., 2000; Allen et al., 2004). However, the GCMs projections have questionable accuracy due to the uncertainty of the model structure. Additionally, such climate models do not include adequate representations of the groundwater aquifer to simulate the change precisely; so hydrological models are necessary to transfer the climate changes to the groundwater system (Eltahir and Yeh, 1999). To examine the relative importance of climate on groundwater level variation, Chen et al. (2004) used cross-correlation analysis between historical climate records and groundwater levels. Their results showed that the annual precipitation explained the variations in groundwater levels significantly. Van der Kamp and Maathuis (1991) investigated the annual fluctuation of groundwater levels as a result of loading by surface moisture considering both the theoretical aspects of aquifer characteristics and empirical data. They observed that the relatively poor correlation between the climatic parameters and the groundwater levels was due to the distance of the observation wells from the climate stations. To link climate variables with groundwater levels, the weather station should exist in the recharge zone of the observation well (Van der Kamp and Maathuis, 1991; Chen et al., 2002). But, for a large-scale groundwater-monitoring network it may not be possible. However, the groundwater level data itself provide a direct means of measuring the overall impacts of both natural and anthropogenic changes to groundwater resources (Taylor and Alley, 2001). Although the groundwater monitoring networks have existed for several years, very little research has been carried out internationally to interpret the water table and quality trends. Broers and Grift (2004) studied the groundwater quality trends due to anthropogenic-induced changes in agricultural practices. They employed a combination of the Mann–Kendall non-parametric trend analysis of time series at specific depths and the time-averaged concentration–depth profiles. By plotting the median and other percentiles over years, Almasri and Kaluarachchi (2004) evaluated the nitrate pollution trend of groundwater in agriculture-dominated watersheds. They combined the concentration data of different wells having few observations to reduce the uncertainty of predictions and conclusions.

To date, most of the studies on non-parametric trend analysis have used climatic variables and surface water hydrologic parameters as response variables to assess the impacts of climate variability. As of our knowledge, no international reference is available to non-parametric trend analysis of groundwater levels, though references are available with respect to analysis of groundwater quality (e.g. Almasri and Kaluarachchi, 2004; Broers and Grift, 2004). In this study, the groundwater level is considered as the response variable, and is used for trend analysis, which can contribute to the understanding of the effect of extreme climate events on groundwater. We have made an attempt to identify and quantify the groundwater level trends, to know the type and amount of thrust of extreme climate events in conjunction with anthropogenic pressure on the groundwater resources of Orissa, using non-parametric statistical methods. The groundwater level data of the national hydrograph network stations during the period 1994–2003 was used for the analysis. The results of trend quantification can be used to predict the future groundwater levels. The groundwater levels show wide spatial variation, and the presence of seasonality in data further complicates the interpretation of trend results. To examine the overall groundwater level trend scenario, the test of homogeneity was carried out. The novelty of this test lies in the fact that the homogeneous vulnerable zones were delineated in both spatial and seasonal context. The results of the analysis can be used for policy developments related to drought proofing and sustainable management of groundwater resources to meet future water requirements. Additionally, the results can be used as a reference to address the issue of trend attribution, which establishes a linkage between the climate variables and the groundwater level. ''Methodology'' section of this paper describes the non-parametric test for trend detection, and the test of homogeneity. The general characteristics of the study area Orissa and the data source are presented in ''Study area and data set'' section. This is followed by a presentation of the results of trend analysis. The paper ends with a summary of the results and conclusions.

## Methodology

### Non-parametric test for trend detection

Recently, the Mann–Kendall non-parametric statistical procedure given by Mann (1945) and Kendall (1975) has been extensively used to assess the significance of monotone trends in hydro-meteorological time series such as precipitation, temperature and stream flow (Gan, 1998; Zhang et al., 2001; Burn and Elnur, 2002; Xu et al., 2003; Yang et al., 2004). The non-parametric statistical tests are flexible, and can handle the idiosyncrasies of data like presence of missing values, censored data, seasonality and highly skewed data. However, the Mann–Kendall test for trend detection assumes that the sample data are serially independent, even though few hydrological series show significant serial correlation. The presence of positive serial correlation increases the probability that Mann–Kendall test detects trend even though no such trend exists. One approach to handle serial correlation is to consider a subset of data that ensures the data independence (Gan, 1998). The other approach is to remove the serial correlation such as lag 1 auto regression (AR (1)) or higher order process from the time series before application of the test. This is called pre-whitening the time series (Zhang et al., 2001; Burn and Elnur, 2002). When seasonality is present in the time series data, then season-wise trend analysis is more efficient (Darken, 1999). Here, the season-wise subsets of the time series were analyzed.

Consider the time series data generated from the monitoring network for $s$ seasons in each of the $n$ years and at $t$ stations. Each observation may be denoted by $X_{igk}$, which represents the observation collected in year $i$ ($i = 1, 2, \ldots n$), season $g$ ($g = 1, 2, \ldots, s$) and from station $k$ ($k = 1, 2, \ldots, t$). The data can be displayed as follows:

| | | Station 1 | | | | … | Station $t$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Seasons | | $1$ | $2$ | … | $s$ | … | $1$ | $2$ | … | $s$ |
| | $1$ | $X_{111}$ | $X_{121}$ | … | $X_{1s1}$ | … | $X_{11t}$ | $X_{12t}$ | … | $X_{1st}$ |
| | $2$ | $X_{211}$ | $X_{221}$ | … | $X_{2s1}$ | | $X_{21t}$ | $X_{22t}$ | … | $X_{2st}$ |
| Years | . | . | | | . | | . | | | . |
| | . | . | | | . | | . | | | . |
| | . | . | | | . | | . | | | . |
| | $n$ | $X_{n11}$ | $X_{n21}$ | … | $X_{ns1}$ | … | $X_{n1t}$ | $X_{n2t}$ | … | $X_{nst}$ |

The series for the season $g$ at station $k$ may be expressed as $\{X_{1gk}, X_{2gk}, X_{3gk}, \ldots, X_{ngk}\}$. The Mann–Kendall test statistic for the series, $S_{gk}$, is the sum of all signs of consecutive observation differences defined as

$$S_{gk} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(X_{jgk} - X_{igk}) \quad \forall 1 \leqslant i < j \leqslant n. \tag{1}$$

Here

$$\operatorname{sgn}(\theta) = \begin{array}{ll} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{array}$$

Under the null hypothesis of no trend, $S_{gk}$ is asymptotically normally distributed with mean 0 and variance given as

$$(\sigma_{gg})_k = \frac{[n(n-1)(2n+5) - \sum d(d-1)(2d+5)]}{18}$$

Here, $d$ is the extent of any tie (i.e. length of tie), and the summation is over all the ties. The series having no repeat observations, $d$ becomes 0. For a time series of more than equal to 10 years, i.e. $n \geqslant 10$, the Mann–Kendall test statistics is nearly normally distributed.

Applying continuity correction, the test statistic becomes $S'_{gk} = S_{gk} - \operatorname{sgn}(S_{gk})$, which follows normal distribution. For testing the null hypothesis, the $Z$-value associated with the test statistic can be calculated as

$$Z_{gk} = \frac{S'_{gk}}{(\sigma_{gg})_k^{1/2}} \tag{2}$$

The null hypothesis is accepted if $-Z_{(1-\alpha/2)} \leqslant Z_{gk} \leqslant Z_{(1-\alpha/2)}$, where $\pm Z_{(1-\alpha/2)}$ are the $1 - \alpha/2$ quantiles of the standard normal distribution at the $\alpha$ level of significance.

The unified trend test over seasons can be derived using the Hirsch–Slack test (Hirsch and Slack, 1984; Stalnacke et al., 2003) as the sum of the Mann–Kendall statistics for all seasons (Eq. (3)).

$$S_k = \sum_g S_{gk}, \quad g = 1, 2, \ldots, s \tag{3}$$

which is asymptotically normally distributed with mean zero and variance

$$\mathrm{Var}(S_k) = \sum_{g} (\sigma_{gg})_k + \sum_{\substack{g,h\\ g\neq h}} (\sigma_{gh})_k, \quad g,h = 1,2,\ldots,s$$

where $\sigma_{gh}$ denotes the covariance between the test statistics for seasons $g$ and $h$. In case of independent assumption of seasons, $\sigma_{gh}$ becomes zero.

The unified trend test by summing the Mann–Kendall statistics for all seasons is misleading when they are highly heterogeneous. In case of absolutely negatively correlated seasonal observations, the overall trend gives zero value although there is presence of distinct trends (Van Belle and Hughes, 1984). Then, it is required to have a preliminary test of homogeneity for the trends.

Another very useful index to quantify the monotone trend is Kendall slope ($\beta$), initially proposed by Sen (1968), and later extended by Hirsch et al. (1982). It is defined as

$$\beta_{gk} = \mathrm{Median}\left(\frac{X_{igk} - X_{jgk}}{i - j}\right), \quad \forall 1 \leqslant i < j \leqslant n. \tag{4}$$

The estimator $\beta$ is the median over all combination of record pairs for the whole data set, and is resistant to the extreme observations. A positive value of $\beta$ indicates an upward trend, and the negative value indicates a downward trend with time.

## Trend homogeneity test

The homogeneity test is based on partitioning the sum of square that uses the chi-square ($\chi^2$) test to determine the trend homogeneity between seasons, sites and season-site interactions (Van Belle and Hughes, 1984; Gan, 1998). The normalized Mann–Kendall trend statistics $Z_{gk}$ associated with season $g$ and site $k$ is presented in a two-way format as

| | | Sites | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | … | $t$ | $Z_{g.}$ |
| Seasons | 1 | $Z_{11}$ | $Z_{12}$ | … | $Z_{1t}$ | $Z_{1.}$ |
| | 2 | $Z_{21}$ | $Z_{22}$ | … | $Z_{2t}$ | $Z_{2.}$ |
| | . | | | | | . |
| | . | | | | | . |
| | . | | | | | . |
| | $s$ | $Z_{s1}$ | $Z_{s2}$ | … | $Z_{st}$ | $Z_{s.}$ |
| | $Z_{.k}$ | $Z_{.1}$ | $Z_{.2}$ | … | $Z_{.t}$ | $Z_{..}$ |

where $Z_{g.} = t^{-1}\sum_{k=1}^{t} Z_{gk}$ denotes the average $Z$ value over $t$ sites for season $g$; $Z_{.k} = s^{-1}\sum_{g=1}^{s} Z_{gk}$ denotes the average $Z$-value over $s$ seasons for site $k$; $Z_{..} = (st)^{-1}\sum_{g=1}^{s}\sum_{k=1}^{t} Z_{gk}$ denotes the overall average $Z$-value. Without loss of generality, we define the hypotheses of interest in terms of $\tau_{gk}$ as

(I) $H_0$: $\tau_{1.} = \tau_{2.} = \cdots = \tau_{s.}$ (i.e. is there trend homogeneity among seasons?)
(II) $H_0$: $\tau_{.1} = \tau_{.2} = \cdots = \tau_{.t}$ (i.e. is there trend homogeneity among sites?)
(III) $H_0$: $(\tau_{gk} - \tau_{g.} - \tau_{.k} - \tau_{..})$ = constant (i.e. is there presence of site-season interaction?)
(VI) $H_0$: $\tau_{..} = 0$ (i.e. is there presence of overall trend given the above conditions?)

Under the null hypothesis that there is no trend for a particular season in a given station, i.e. $H_0$: $\tau_{gk} = 0$, $\sum_g\sum_k Z^2_{gk}$ has a $\chi^2$ (total) distribution with $st$ degrees of freedom. Subsequently, the total $\chi^2$ is partitioned into respective sources of variations as

(I) $\chi^2_{\text{total},st} = \sum_{g=1}^{s}\sum_{k=1}^{t} Z^2_{gk}$, i.e. the total $\chi^2$ with $st$ degrees of freedom (d.f.)
(II) $\chi^2_{\text{homogeneity},st-1} = \sum_{g=1}^{s}\sum_{k=1}^{t}(Z_{gk} - Z_{..})^2$, i.e. the homogeneity $\chi^2$ with ($st - 1$) d.f.
(III) $\chi^2_{\text{season},s-1} = t\sum_{g=1}^{s}(Z_{g.} - Z_{..})^2$, i.e. the $\chi^2$ due to season with ($s - 1$) d.f.
(IV) $\chi^2_{\text{site},t-1} = s\sum_{k=1}^{t}(Z_{.k} - Z_{..})^2$, i.e. the $\chi^2$ due to site with ($t - 1$) d.f.
(V) $\chi^2_{\text{site-season},(t-1)(s-1)} = \sum_{g=1}^{s}\sum_{k=1}^{t}(Z_{gk} - Z_{.k} - Z_{g.} - Z_{..})^2$, i.e. the $\chi^2$ due to site-season interaction with ($t - 1$)($s - 1$) d.f.
(VI) $\chi^2_{\text{trend},1} = st Z_{..}^{\,2}$, i.e. the $\chi^2$ due to trend with 1 d.f.

The following steps are used for testing the null hypothesis:

(1) Under the null hypotheses, the $\chi^2$ statistics presented above are used for testing site homogeneity ($\chi^2_{\text{site}}$), season homogeneity ($\chi^2_{\text{season}}$), and site-season homogeneity ($\chi^2_{\text{site–season}}$).
(2) If site, season and site-season homogeneity are not found to be significant, then the test for overall trend is carried out using the $\chi^2_{\text{trend}}$.
(3) If sites are heterogeneous but not seasons then the trend test for individual site is obtained from $sZ^2_{.k}$ ($k = 1, 2, \ldots, t$), which is distributed as $\chi^2$ variate under the null hypothesis $H_0$: $\tau_{.k} = 0$.
(4) If seasons are heterogeneous but not sites, then trend test for individual season is obtained from $tZ_{g.}^{\,2}$ ($g = 1, 2, \ldots, s$), which is distributed as $\chi^2$ variate under the null hypothesis $H_0$: $\tau_{g.} = 0$.
(5) If both sites and seasons are heterogeneous or there is significant site-season interaction, then the individual entries in the site-season two way table, i.e. $Z_{gk}$, ($g = 1, 2, \ldots, s$; $k = 1, 2, \ldots, t$) are tested for significance of trends. The null hypothesis of no trend is accepted if $-Z_{\alpha/2} < Z_{gk} < Z_{\alpha/2}$, where $\pm Z_{\alpha/2}$ is the standard normal deviate at the significance level $\alpha$.

## Study area and data set

The study area Orissa is situated on the eastern coast of India. It has been the regular host to natural disasters of varying degree and nature due to its geographical location (Fig. 1) and physical features. It is quite natural that adjoining regions to seashores are more vulnerable to erratic

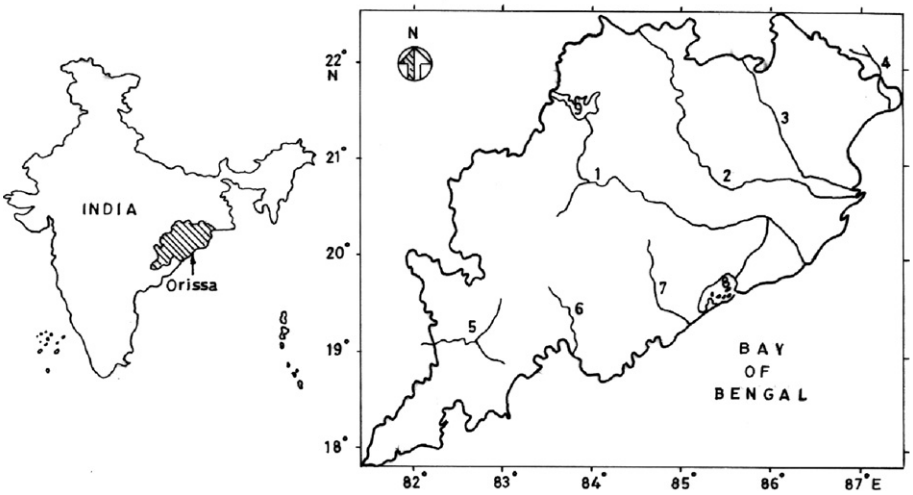

**Figure 1** Location map of study area, Orissa (India). The rivers and lakes are: (1) Mahanadi, (2) Brahmani, (3) Baitarani, (4) Subarnrekha, (5) Indravati, (6) Vanshadhara, (7) Rushikulya, (8) Chilka lake, and (9) Hirakud dam reservoir.

behavior of the climate than the inlands. As cyclones normally hit the Bay of Bengal between 5° and 21°N latitude, Orissa bears the grunt of natural climate extremes due to its geographical location between 17°47′–22°33′N latitude and 81°31′–87°30′E longitude. Five droughts, four floods, and a super cyclone have ravaged the state since the 1990s.

The total geographical area of the state is 1,55,707 km$^2$, of which around 1,18,800 km$^2$ area is suitable for groundwater exploration. The gross annual draft for all uses (including industrial use) is only 14.79% of the total assessed groundwater resource of 20,99,000 ha m (1 ha m = $10^4$ m$^3$) (CGWB, 2000). Based on the geological setting and the occurrence and distribution of aquifers, the state is divided into three major hydrogeological units (CGWB, 2000): (1) the consolidated rock formation is the predominant hydrogeological class covering 80% of the geographical area of the state. It contains hard crystalline and compact sedimentary formations of pre-Cambrian age; (2) the semi-consolidated formation covers 2% of the study area. This formation contains Gondwana sandstones, shales, coal and loosely cemented Tertiary sandstones; (3) the unconsolidated formation is the alluvial deposit of the coastal tract, and forms narrow patches in the inland river basins. Roughly, it covers 18% of the area. Other hydrogeological characteristics are presented in Table 1.

In India, the Central Ground Water Board (CGWB) has been carrying out the groundwater monitoring activities through a network of observation wells called ''national hydrograph network stations''. The monitoring network is a surveillance system of the water storage and quality status of the groundwater reservoirs. In order to get unbiased readings, the monitoring wells are ideally located away from pumping and irrigation areas. The location of the monitoring wells depends on the aquifer characteristics so that they can capture the variability of the groundwater system. Given the diverse aquifer characteristics of Orissa, more than one thousand observation wells have been set up. Normally, the groundwater levels are recorded four times in a year such as the pre-monsoon (April), monsoon (August), post-monsoon (November), and irrigation (January) periods. The unit of the groundwater level records is meter below ground level (m.b.g.l.). In some years, the monitoring during the monsoon and irrigation periods is skipped due to financial crisis. Further, the recording of groundwater levels during these times is prone to possible unpredictable rain and pumping effects. However, the pre- and post-monsoon monitoring occasions are more important as they reflect the influence of both natural and anthropogenic intervention more accurately. The groundwater levels trend of Orissa was studied using the pre- and post-monsoon monitoring records of 1002 observation wells (consolidated formation 726 wells; semi-consolidated formation 60 wells; unconsolidated formation 216 wells) during the period 1994–2003.

**Table 1** Characteristics of different soil formations of Orissa

| Characteristics | Consolidated | Semi-consolidated | Unconsolidated |
|---|---|---|---|
| Area (000 ha) | 12,579 | 924 | 2056 |
| Assessed groundwater (000 ha m) | 1348 | 176 | 575 |
| Utilizable resource (000 ha m) | 1275 | 164 | 549 |
| Annual draft for agriculture (000 ha m) | 118 | 13 | 103 |
| Moderate water yielding capacity (l/s) | 3–10 | <15 | 15–40 |

## Results and discussions

### Rainfall variability and groundwater-level fluctuation

The south-west monsoon contributes the major portion of the annual rainfall, which arrives in Orissa by the 10th June, and withdraws by the 10th October. Out of the normal annual rainfall of 1482 mm, the monsoon rain from June to September accounts around 1300 mm. The normal annual rainfall is calculated taking the average of annual rainfall from 314 administrative blocks (stations) representing the state during the period 1951–1990. In recent years, however, the annual rainfall is more erratic in comparison to the normal annual rainfall causing both drought and flood to occur even in the same year. During the period 1994–2003, Orissa experienced six deficits and four excess rainfall years with an average annual rainfall of 1367.85 mm and standard deviation of 279.41 mm (Fig. 2). The low annual rainfall less than (mean – standard deviation) in 1996, 2000 and 2002 resulted in wide-spread drought. The erratic distribution of rainfall caused localized drought in 1997, 1998 and 1999 even though the average annual rainfall was little below the normal. The excess rainfall more than the annual normal rainfall in 1994, 1995, 2001 and 2003 resulted in floods to occur. The smoothed curve of rainfall was obtained using the LOWESS (locally weighted scatter-plot smooth) technique, which is a non-parametric tool for exploratory data analysis (Cleveland and Devlin, 1988). This technique is often used for water resources data because of its robustness and insensitivity to outliers (Burn and Elnur, 2002; Broers and Grift, 2004). The smoothed curve of annual rainfall in Fig. 2 indicates a decreasing trend below the normal rainfall line during the first half of the study period (till 1998), and then shows a slightly increasing trend. However, the available rainfall data suggests that the observed trends could be a part of a natural variability.

The rainfall during the wet period from June to September (i.e. the monsoon rainfall) constitutes more than 80% of the total annual rainfall, and contributes significantly to the groundwater recharge. The average monsoon rainfall during the study period, however, was 1077 mm (standard deviation 241.57 mm) in comparison to the normal monsoon rainfall of 1300 mm. The smoothed curve of erratic monsoon rainfall in Fig. 3 is similar to the smoothed curve of annual rainfall in Fig. 2, and could be a part of natural variability. To examine the relationship between the monsoon rainfall and the groundwater levels fluctuation, the time series of the average water table of 1002 observation wells in pre- and post-monsoon seasons during the period 1994–2003 was analyzed. Fig. 3 shows that there is a direct correspondence between the monsoon rainfall and the post-monsoon groundwater levels. The influence of droughts and floods was reflected more prominently during the later years of the study period. The reason could be the high intensity and persistence of extreme weather events in recent years. Negative correlation coefficient ($r = -0.38$, $p = 0.28$) indicates the increase in decline of water table in post-monsoon in response to the monsoon rainfall during the study period. The non-significance of the correlation coefficient could be due to the erratic distribution of rainfall and spatial diversity of groundwater levels in some years. A better correlation coefficient ($r = -0.52$, $p = 0.15$) was observed by taking the average of the two consecutive rainfall points and correlating with the lag-1 post-monsoon water table. This implies that the water table responds to the recharge with a time delay, and some of the high frequency noise in the rainfall curve is also removed.

The groundwater-level drawdown takes place during the cooler period from October to January and the dryer period from February to May. The dry summer period is associated with high air temperatures. During the study period, the average of the annual maximum temperature (Fig. 4) was found to be 43.13 °C (standard deviation 3.05 °C) in comparison to the normal annual maximum temperature of 38.52 °C (average of 314 administrative blocks during the period 1951–1990). Although, the smoothed curve indicates a slightly decreasing trend, very high temperature in some years must have increased the overall water demands.

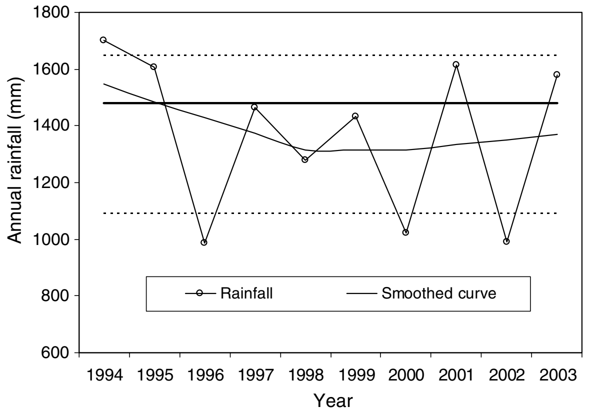

**Figure 2** Average annual rainfall of Orissa fitted by a smoothed curve indicating a downward trend in the first half of the study period (till 1998) and then starts to increase slightly. Solid line is the annual normal rainfall of 1482 mm. Upper and lower dotted lines show the mean (1367.85 mm) ± standard deviation (279.41 mm) of rainfall.

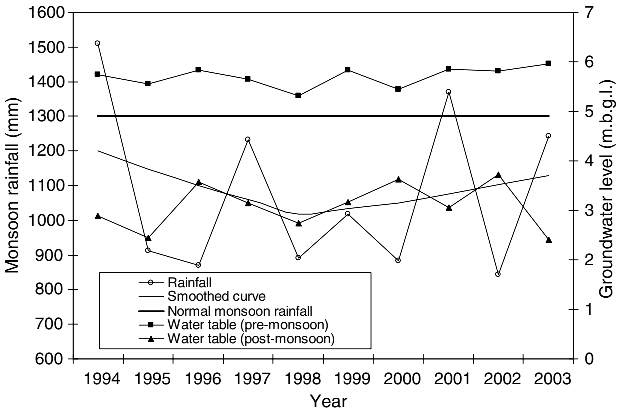

**Figure 3** Average monsoon rainfall fitted by a smoothed curve indicating downward trend in the first half of the study period (till 1998) and then starts to increase. The normal annual monsoon rainfall is 1300 mm.

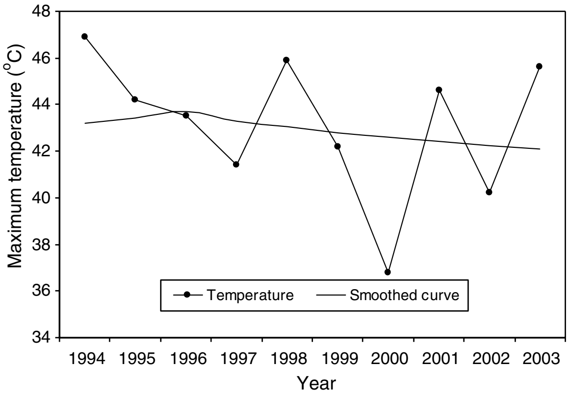

**Figure 4** Maximum annual temperature during the study period in comparison to the long-term normal annual maximum temperature of 38.52 °C.

Drought affects the groundwater table because it reduces the water availability to recharge. Temperature is also an important factor impacting the groundwater table through human stress and high evapotranspiration. The pre- and post-monsoon season groundwater tables (Fig. 3) behave differently, which may indicate the controlling factors for these two are different. For the pre-monsoon groundwater table, the variation mostly reflects the stress side, i.e. the human impact and air temperature. In contrast, the predominant control of the post-monsoon water table could be the recharge side, that is, the availability of recharge and the capacity of different aquifers to respond to the recharge during and after the rainy season; and the human effect could be secondary in this period. Despite the human stress and temperature impacts, the pre-monsoon water table may better reflect the impact of rainfalls in the previous rainy seasons through lagged recharge than the post-monsoon water table because it contains less random noise of high frequency from surface water infiltrations. However, it is difficult to separate the human stress and temperature impacts from the time lagged recharge effects in the pre-monsoon water table. Comparison of Figs. 3 and 4 indicates that all anomalous hot years with maximum annual temperature, 1994, 1998, 2001 and 2003 show large difference between pre- and post-monsoon water tables. In other words, the difference between the pre- and post-monsoon water tables shows a good correlation with annual maximum temperature. To model precisely the effect of assignable factors on water table fluctuation, the response of observation wells monitored in short time intervals are required.

Due to the skewed spatial and seasonal distribution of rainfall accompanied with diverse geological and hydraulical characteristics, the average groundwater levels partially reflect the influence of rainfall variability. The typical hydrographs from the consolidated, semi-consolidated and unconsolidated formations in Fig. 5a–c show the spatial and seasonal variability of groundwater levels. The influence of the rainfall is reflected even in the typical hydrographs, and the drawdown in the pre-monsoon season is recovered through the recharge from the monsoon rain. Table 2 shows the wide diversity of groundwater levels at the regional scale during the period 1994–2003. Besides the mean and trimmed mean (2% of observations trimmed), other location parameters such as $Q_1$ (25th percentile), $Q_2$ (median) and $Q_3$ (75th percentile) showed both regional and seasonal variations of groundwater level. To understand the response of the groundwater levels to the weather extremes, the effect of the 2002 drought on the groundwater levels of Orissa was examined as a case study.

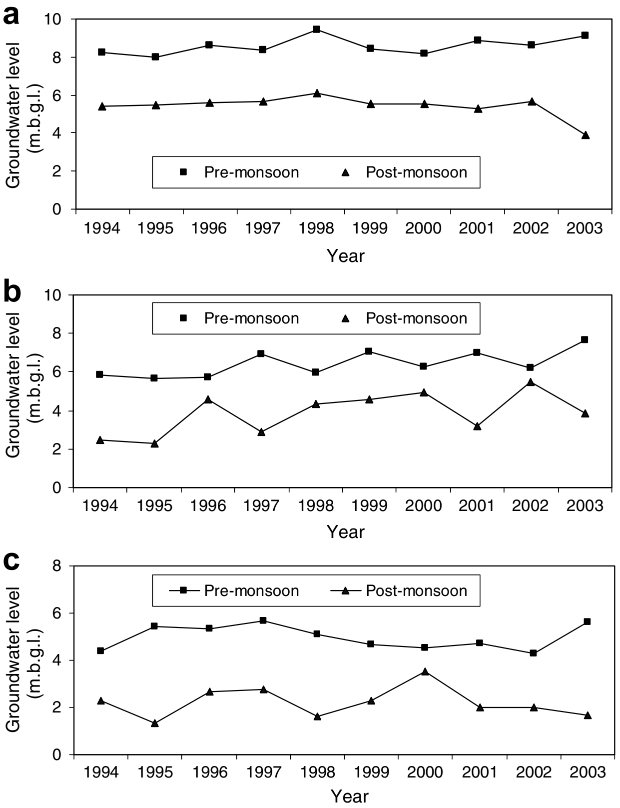

**Figure 5** Typical hydrographs showing the spatial and seasonal variability of groundwater levels in (a) consolidated (well 65J-1B2), (b) semi-consolidated (well 73H-2A2), and (c) unconsolidated (well 73L-2C5) formations.

## Effect of the 2002 drought on groundwater levels

Although the monsoon arrived on time during 2002, the state received a deficit rainfall of 167.8 mm (−21.28%) in June, 140.14 mm (−60.14%) in July and 195.2 mm (−17.46%) in September compared to the normal rainfall. The July rainfall was the lowest in the last 40 years. Inadequate rainfall affected the rain-fed ecosystem and also the irrigated command of irrigation projects. Consequently, the agricultural operations experienced a serious setback, and around 68% of crop loss was estimated in the same drought year. To study the effect of the 2002 drought on the groundwater levels the observation wells monitored during the post-monsoon (November) period were analyzed. The frequency distribution of the monitoring wells pertaining to different water table ranges for the year 2002 was compared to the corresponding distribution of the average water table during the period 1994–2001. The result indicates that a considerable number of wells in the average

**Table 2** Descriptive statistics of groundwater levels during the study period (1994–2003)

| Water table (m.b.g.l.) | Consolidated | | Semi-consolidated | | Unconsolidated | |
|---|---|---|---|---|---|---|
| | Pre-monsoon | Post-monsoon | Pre-monsoon | Post-monsoon | Pre-monsoon | Post-monsoon |
| Mean | 6.17 | 3.34 | 6.06 | 3.38 | 3.81 | 1.98 |
| Observations | 7260 | 7260 | 600 | 600 | 2160 | 2160 |
| Standard deviation | 2.64 | 2.09 | 2.75 | 2.26 | 1.97 | 1.42 |
| Trimmed mean | 6.16 | 3.33 | 6.05 | 3.35 | 3.80 | 1.97 |
| Minimum | −0.04 | −0.73 | 0.73 | −0.25 | −0.24 | −0.94 |
| $Q_1$ | 4.49 | 1.78 | 4.08 | 1.81 | 2.49 | 0.91 |
| Median | 6.07 | 2.94 | 6.02 | 2.94 | 3.50 | 1.65 |
| $Q_3$ | 7.65 | 4.47 | 7.68 | 4.55 | 4.77 | 2.66 |
| Maximum | 18.30 | 15.96 | 14.95 | 14.27 | 14.56 | 7.93 |

Trimmed mean: 2% of observations trimmed; $Q_1$: 25th percentile; $Q_3$: 75th percentile.

groundwater levels range of 0–3 m shifted to the range of 3–<7.5 m categories in the drought year. Further, the effect of drought propagated to all the water level zones in the categories below 10 m. The groundwater table deviation for the drought year compared to the average indicates that 77% of the monitoring wells exhibited −1% to −100% deviations, and the remaining 23% of the wells exhibited water levels improvements, represented by a positive deviation. The groundwater table improvements could be due to the lagged recharge from the previous wet year and the influence of localized rainfall.

The significant difference between the post-monsoon groundwater levels in 2002 was tested against the corresponding average years (1994–2001) water table using the commonly followed two-sample *t*-test. The monitoring wells showing absolute groundwater level deviation greater than 100% in the drought year in comparison to the average year figure were not considered for the analysis to avoid bias due to erroneously recorded data or data recorded on rainy days. In the consolidated region, the spatio-temporal average groundwater level of 3.51 m decreased to 3.96 m in 2002, and the difference is significant at the 1% ($\alpha = 0.01$) level. In the semi-consolidated region, the spatio-temporal average water table was found to be 3.33 m, and in the drought year it dropped significantly ($\alpha = 0.05$) to 4.12 m. In the unconsolidated region, however, no significant change in groundwater-level was observed. The spatio-temporal average water table of 2.05 m dropped to 2.26 m in the drought year. The reason is that the unconsolidated formation contains prolific and extensive aquifers. The moderate yielding areas yields 15–40 l/s (Table 1), while the coastal tract yield generally more than 40 l/s. Further, the network of rivers flowing through the region, and the seawater ingression in certain belts of the coastal region may have partially contributed to the water table rise. In general, the 2002 drought had significant influence on the groundwater levels of the consolidated and semi-consolidated formations, which cover over 82% of the geographical area of the state. But, the state has experienced five severe droughts and four floods during the study period 1994–2003. In the following sections, the groundwater level trends over years are presented which provide an insight into the cumulative influence of the recurrent extreme weather events.

## Non-parametric test results

The application of Mann–Kendall test statistics using Eqs. (1) and (2) has resulted in the identification of trend direction of the groundwater levels in three predominant hydrogeological units of Orissa. As the groundwater levels are recorded in m.b.g.l. (i.e. meters below ground level), positive observational values indicate a drop in the water table. Hence, a positive trend indicates the decline of water level, and a negative trend indicates the rise of water levels over years. As each monitoring well reflects the groundwater dynamics of the surrounding area, each trend value gives an idea about the water table fluctuation of that area over years. Fig. 6 shows the percentage of stations having positive, negative and neutral trends for the pre- and post-monsoon seasons of different formations. Table 3 presents the number of stations having significant trends at the significance levels $\alpha = 0.05$, 0.1 and 0.2, respectively. Unless technological interventions are made in coming years, it is expected that more stations will become significant at the 0.05 level of significance. In the following Sub-sections, the trend results for each formation are presented.

### Trends in the consolidated formation

In the pre-monsoon (April) season, the positive trend indicating the groundwater-level decline was observed in 414 (57%) stations of the total of 726 monitoring stations. Out of these positive trends, 83 (20%), 107 (26%) and 169 (41%) stations experienced significant water table decline at the significance levels $\alpha = 0.05$, 0.1 and 0.2, respectively. In contrast, out of 256 (35%) stations where water table improved in the dry season in terms of negative trends, 47 (18%), 60 (23%) and 96 (37%) stations exhibited significant improvement at the significance levels $\alpha = 0.05$, 0.1 and 0.2, respectively. In recent years, the average maximum summer temperature has been much higher than the normal (average for the period 1951–1990), which means that the water table should decline gradually. But, the contrast result necessitates further research to see whether the summer rainfall has also increased over years, or whether this traditionally flood-proof region has become prone to floods. In the post-monsoon (November) season, 54% of 726 stations experienced water level decline, and 32% of the stations were found to have experienced an improvement of water

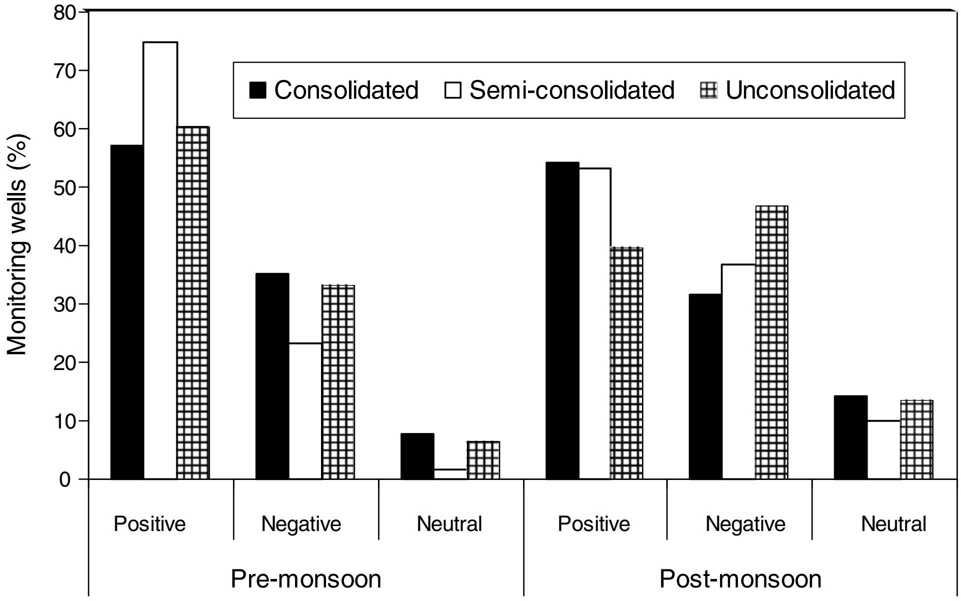

**Figure 6** Percentage of positive, negative, and neutral trends in consolidated (total number of wells 726), semi-consolidated (total number of wells 60), and unconsolidated (total number of wells 216) formations. A high percentage of positive trends show more cases of groundwater declines.

**Table 3** Cases of significant Mann–Kendall trends for different formations

| Formation | | Consolidated | | | Semi-consolidated | | | Unconsolidated | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Season | Significant level ($\alpha$) | 0.05 | 0.1 | 0.2 | 0.05 | 0.1 | 0.2 | 0.05 | 0.1 | 0.2 |
| Pre-monsoon | Positive | 83 | 107 | 169 | 5 | 8 | 18 | 20 | 31 | 47 |
| | Negative | 47 | 60 | 96 | 2 | 2 | 3 | 14 | 19 | 29 |
| Post-monsoon | Positive | 44 | 66 | 104 | 0 | 0 | 5 | 15 | 21 | 29 |
| | Negative | 20 | 29 | 46 | 0 | 0 | 2 | 5 | 5 | 11 |

level. However, the significant water table decline was observed in 11%, 17% and 26% of the stations having positive trends as against the significant water table improvements in 9%, 12% and 20% of stations at the levels $\alpha = 0.05$, 0.1 and 0.2, respectively. According to the null hypothesis, the groundwater level trends over years should be neutral. But, the small percentage of neutral trends (i.e. 8% in the pre-monsoon and 14% in the post-monsoon) indicates that the groundwater level trends have moved in a positive or negative direction. However, the water table decline cases are observed to be more in number than that are expected to occur by chance. This gives enough evidence that the groundwater level trends are the signals of a systematic change, not the result of random natural variability.

### Trends in the semi-consolidated formation

In April, the water table decline was observed in 45 (75%) stations of the total 60 monitoring stations in this region. However, the significant decline took place in 5 (11%), 8 (18%) and 18 (40%) sites at the levels $\alpha = 0.05$, 0.1 and 0.2, respectively. Around 23% of the monitoring sites have experienced water table improvements. In November, the water table fluctuation reflected a downward trend in 32 (53%) sites of which only 5 (15%) sites were significant at the level $\alpha = 0.2$. Further, 22 (36%) sites experienced improved water table during the study period from which only 2 (9%) site were significant at the $\alpha = 0.2$ level. The semi-consolidated formation covers 2% of the geographical area. Only, 2% and 11% of the monitoring stations exhibited neutral trends in the pre- and post-monsoon seasons, respectively. Further, the large number of decline cases suggests that the groundwater is vulnerable to the deficient rainfall over years.

### Trends in the unconsolidated formation

In the pre-monsoon season, 130 (60%) monitoring stations experienced water table decline in terms of positive Mann–Kendall trend statistics. The significant decline was observed in 20 (15%), 31 (24%) and 47 (36%) sites at the level of significance $\alpha = 0.05$, 0.1 and 0.2, respectively. Further, significant water table improvement was observed in 14 (19%), 19 (26%) and 29 (40%) sites of the total 72 cases at the levels $\alpha = 0.05$, 0.1 and 0.2, respectively. In the post-monsoon season, out of 86 (40%) positive trends 15 (17%), 21 (24%) and 29 (34%) sites were identified to have experienced significant water table decline at the levels $\alpha = 0.05$, 0.1 and 0.2, respectively. On the contrary, water table improvement over years was observed in 101 (47%) sites. Significant water table improvement was observed in 5 (5%) and 11 (10%) sites only at the levels $\alpha = 0.05$ and 0.2, which may well lie in the data error margin. This indicates that the groundwater level is not sensitive to the rainfall variation at the current level. As long as the rainfall is sufficient to recharge the aquifer, groundwater level will remain relatively stable in the post-monsoon season.

The systematic forcing mechanism of drought and high temperature is prominently reflected in the groundwater levels of Orissa. The drawdown due to deficient rainfall and anthropogenic pressure has not been recovered through the recharge in wet years. This inference is similar to the findings of Eltahir and Yeh (1999) who reported that the droughts leave a more persistent signature than that of floods. The monitoring stations showing significant water table fluctuation at the level $\alpha = 0.05$ for both the pre- and post-monsoon seasons of the study area are displayed in Figs. 7–10. The figures reveal a spatial pattern of the location of the stations that exhibit a significant water table fluctuation in different seasons. In the pre-monsoon season, the significant groundwater table declining trends are more concentrated in the northwestern part of the study area. In the post-monsoon season, however, the noticeable spatial groupings of significant decline trends are seen in the southwestern and the eastern parts of the state (Fig. 8). Distinct groups of significant upward trends of groundwater levels occur in the extreme southwestern and the eastern parts of the study area (Figs. 9 and 10). Spatial diversity of significant trend results could be due to the spatial differences of the topography of the soil and the hydraulic properties of the aquifer, through which the meteorological inputs propagate.

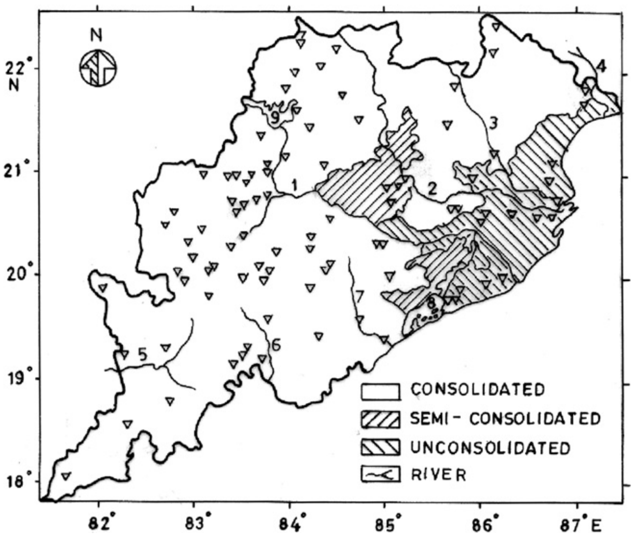

**Figure 7** Stations showing significant ($\alpha = 0.05$) decline trends of groundwater level in the pre-monsoon season (April). The rivers and lakes are: (1) Mahanadi, (2) Brahmani, (3) Baitarani, (4) Subarnrekha, (5) Indravati, (6) Vanshadhara, (7) Rushikulya, (8) Chilka lake, and (9) Hirakud dam reservoir.

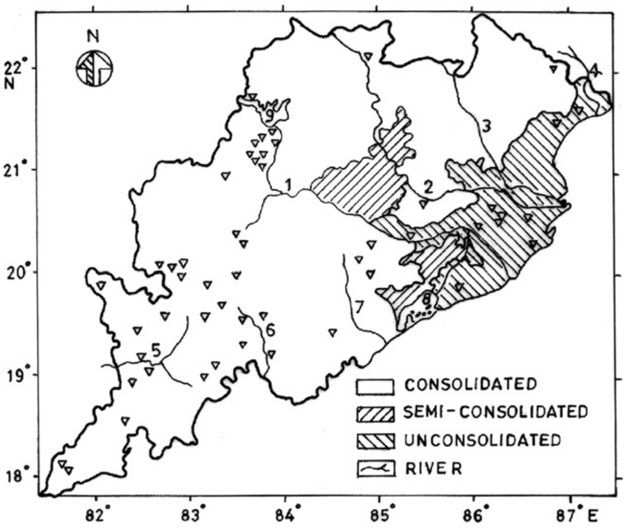

**Figure 8** Stations showing significant ($\alpha = 0.05$) decline trends of groundwater level in the post-monsoon season (November). The rivers and lakes are: (1) Mahanadi, (2) Brahmani, (3) Baitarani, (4) Subarnrekha, (5) Indravati, (6) Vanshadhara, (7) Rushikulya, (8) Chilka lake, and (9) Hirakud dam reservoir.

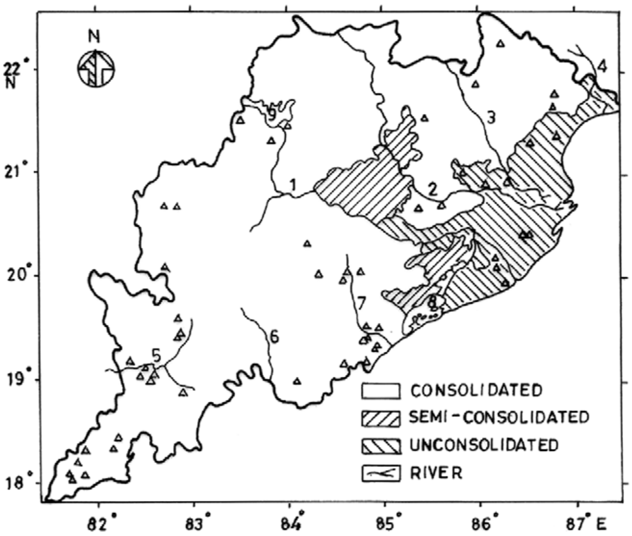

**Figure 9** Stations showing significant ($\alpha = 0.05$) improvement trends of groundwater level in the pre-monsoon season (April). The rivers and lakes are: (1) Mahanadi, (2) Brahmani, (3) Baitarani, (4) Subarnrekha, (5) Indravati, (6) Vanshadhara, (7) Rushikulya, (8) Chilka lake, and (9) Hirakud dam reservoir.

The Mahanadi, Brahmani, Baitarani, Subarnarekha, Indravati, Vansadhara, Rushikulya rivers, Chilika lake, and their tributaries drain about 95% (1,48,104 km$^2$) of the geographical area of the state (Lenka, 2001). The total annual runoff from the rivers and streams is around $132 \times 10^9$ m$^3$ (Mahanadi $66.88 \times 10^9$ m$^3$), out of which the catchments lying in the territory of the state contribute $95 \times 10^9$ m$^3$. The major portion of the rainfall is lost through runoff due to the natural sloping topography, and the anthropogenic activities such as agriculture, mining and construction works (Chakrapani and Subramanian, 1993). Figs. 7 and 8 shows that the significant water table declining trends are more concentrated in the upstream catchments and tributaries of the river system in the northwestern and southwestern parts of the study area. This indicates that the

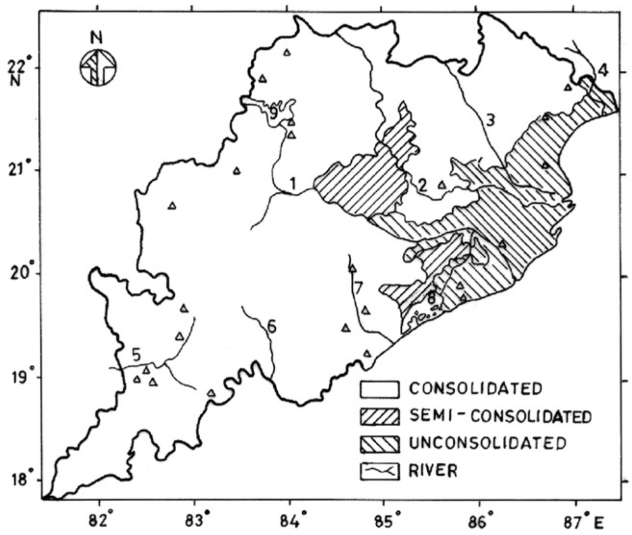

**Figure 10** Stations showing significant ($\alpha = 0.05$) improvement trends of groundwater level in the post-monsoon season (November). The rivers and lakes are: (1) Mahanadi, (2) Brahmani, (3) Baitarani, (4) Subarnrekha, (5) Indravati, (6) Vanshadhara, (7) Rushikulya, (8) Chilka lake, and (9) Hirakud dam reservoir.

upstream catchments drain a significant portion of the rainfall directly to the rivers. Further, the significant water table improvement trends are more oriented in the downstream eastern region, where the major rivers get segregated into small rivers and flood zones before meeting the sea (Figs. 9 and 10). Additionally, the spatial and seasonal differences of the rainfall and temperature pattern, and the seasonal anthropogenic water demands could have influenced the trend results. The urbanization is more concentrated in the semi-consolidated and unconsolidated formations having the population density (people per km$^2$) 365 and 400, respectively. The drinking water demand in these densely populated regions increases in the summer season, and the dry and warm climate further aggravate the situation. Although, the population density in the consolidated formation is 235, the low water yielding capacity of the aquifer, the high runoff, and anthropogenic factors lead to drinking water crisis (Rejani et al., 2003). However, it is difficult to separate the factors that influence the groundwater table precisely from the existing trend results due to local variation of the climate, recharge pattern, and anthropogenic influence.

Summary statistics of the Mann—Kendall test results in Table 4 illustrate the overall trend direction along with the variability of groundwater-level trends for different formations. The average trend was found to be positive for both the pre and post-monsoon seasons indicating an overall drop in groundwater levels for all the three formations. However, the average trend values were associated with very high standard deviation for all the spatial and temporal domains under study. Hence, there was a need to study the spatial, temporal and spatio-temporal variation of water table trends, and thus the test of homogeneity was conducted.

## Trend homogeneity results

The trend results of the pre- and post-monsoon seasons are so contrasting that the seasonal trend test of Hirsch et al. (1982) could not be carried out by just adding the trend statistics over seasons to get the unified trend for a formation as in Eq. (3). Further, the spatial variability of trend results needs to be studied for testing the homogeneity aspects of it. Accordingly, the $\chi^2_{\text{total}}$ i.e. $\sum_g \sum_k Z^2_{gk}$ was partitioned into two major sources of variations such as $\chi^2_{\text{homogeneity}}$ and $\chi^2_{\text{trend}}$ with $(st - 1)$ and 1 degrees of freedoms. Again, the $\chi^2_{\text{homogeneity}}$ was partitioned into assignable sources such as $\chi^2_{(\text{site},t-1)}, \chi^2_{(\text{season},s-1)}$ and $\chi^2_{(\text{site-season},(t-1)(s-1))}$ for the consolidated, semi-consolidated and unconsolidated formations, respectively. The results are presented in Table 5.

In the consolidated rock formation, none of the site, season and site-season interaction components exhibited significant trend heterogeneity since $\chi^2_{\text{site},725} < \chi^2_{0.975,725}$, $\chi^2_{\text{season},1} < \chi^2_{0.975,1,}$ and $\chi^2_{(\text{site-season},(t-1)(s-1))} < \chi^2_{0.975,725}$, respectively. But, the overall trend heterogeneity was found to be significant since $\chi^2_{\text{trend}} > \chi^2_{0.975,1}$ (=5.02). The average of Mann—Kendall test statistics $Z_{gk}$ over seasons ($g = 1,2$) and sites ($k = 1,2,\ldots,726$) was found to be positive ($Z_{..} = 0.275$) indicating the drop in groundwater level. In the semi-consolidated and unconsolidated formations, the seasons only exhibited groundwater level trend heterogeneity since $\chi^2_{\text{season},1} > \chi^2_{0.975,1}$. But, the sites were found to have homogeneous trends for both the formations. Hence, the test of significance of trend homogeneity for each season was conducted using the average Mann—Kendall test statistics for each season ($Z_{g.}$). Here, $tZ^2_{g.}$ was obtained to test the overall seasonal trend homogeneity, which under the null hypothesis follows a $\chi^2$ distribution with 1 degree of freedom. As Table 6 reveals, the overall groundwater levels declined significantly in the pre-monsoon season for the semi-consolidated and unconsolidated formations since

**Table 4** Summary statistics of the Mann—Kendall trend results

| Formation | Season | Observations | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|
| Consolidated | Pre-monsoon | 726 | 0.28 | 1.30 | −3.40 | 3.22 |
| | Post-monsoon | 726 | 0.27 | 1.03 | −3.40 | 3.40 |
| Semi-consolidated | Pre-monsoon | 60 | 0.57 | 1.06 | −2.24 | 2.86 |
| | Post-monsoon | 60 | 0.12 | 0.75 | −1.61 | 1.61 |
| Unconsolidated | Pre-monsoon | 216 | 0.32 | 1.28 | −3.40 | 2.68 |
| | Post-monsoon | 216 | 0.08 | 1.01 | −2.86 | 2.68 |

**Table 5** Significance test of trend homogeneity for different formations

| Sources | Consolidated | | | Semi-consolidated | | | Unconsolidated | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\chi^2$-value | d.f. | Sig. | $\chi^2$-value | d.f. | Sig. | $\chi^2$-value | d.f. | Sig. |
| Total | 2113.85 | 1452 | – | 119.56 | 120 | – | 597.09 | 432 | – |
| Homogeneity | 2004.10 | 1451 | – | 105.02 | 119 | – | 580.37 | 431 | – |
| Site | 1325.29 | 725 | NS | 63.37 | 59 | NS | 316.93 | 215 | NS |
| Season | 0.08 | 1 | NS | 5.96 | 1 | S | 6.27 | 1 | S |
| Site-Season | 678.73 | 725 | NS | 35.69 | 59 | NS | 257.17 | 215 | NS |
| Trend | 109.74 | 1 | S | 14.54 | 1 | Not used | 16.71 | 1 | Not used |
| Average (Z..) | 0.275 | | | 0.348 | | | 0.196 | | |

NS: not significant; S: significant; d.f.: degrees of freedom; Sig.: significance.

**Table 6** Seasonal trend test results for the semi-consolidated and unconsolidated formations

| Formation | Season | $Z._k$ | $t(Z._k)^2$ | Sig. |
|---|---|---|---|---|
| Semi-consolidated | Pre-monsoon | 0.57 | 19.56 | S |
| | Post-monsoon | 0.12 | 0.98 | NS |
| Unconsolidated | Pre-monsoon | 0.32 | 21.70 | S |
| | Post-monsoon | 0.08 | 1.25 | NS |

NS: not significant; S: significant; Sig.: significance.

$tZ^2_{g.} > \chi^2_{0.975,1}$. In the post-monsoon season, however, the water table did not decline significantly for both the formations. The reason may be the porous nature of soil having high water yielding capacity in these deltaic regions, where the major rivers pass through, and get flooded by the monsoon rain. Further, water logging is a major problem in the coastal unconsolidated formation due to urbanization, sedimentation, and other anthropogenic factors.

It could be inferred that the overall groundwater-level scenario in the consolidated formation that covers 80% of the geographical area of the state has experienced significant water table decline irrespective of seasons. The consolidated formation is basically a hard rock region having a sloping topography. Heavy rainfall is associated with high runoff, thus reducing the opportunity time for groundwater recharge. Additionally, prolonged dry periods may have affected the aquifer characteristic such as transmissivity, which ultimately alter the recharge rate. Earlier, Larocque et al. (1998) and Chen et al. (2004) also made similar observations pointing out that during prolonged dry periods the aquifer gets desaturated as some conductive channels become desaturated during low-flow periods. The hard rock areas occupy nearly 65% of the geographical area of India. Specifically, the groundwater of the hard rock area is reeling under stress due to overdraft, as the natural recharge is not favourable. If the dryer weather of recent years continues to prevail in coming decades then the gap between the net discharge and recharge will widen. The groundwater levels could be significantly improved if a fraction of the total annual runoff loss of 1150 km$^3$ is stored underground through recharge (Shah et al., 2003). Further, the population of India is increasing continuously, and is expected to reach 1.4 billion by 2025. It is projected that the present per capita per annum water availability of 2001 m$^2$ will reduce to the stress level of 1700 m$^2$ by that period (Singh, 2004). To meet the food and potable water demand of the ever growing population, the groundwater resources are to be managed efficiently. The present methodology could be used to identify the vulnerable zones with significant groundwater level decline, and thus provide critical inputs to the policy makers and water managers for sustainable management of groundwater resources.

## Trend quantification results

The monotone trends of groundwater levels in the pre- and post-monsoon seasons were quantified using the Kendall slope in Eq. (4) for all the three formations. The box plots of trend magnitudes are shown in Fig. 11. The horizontal line within the box represents the median value, length of the box represents the interquartile range, and whiskers at upper and lower extremities are located at 1.5 times of the interquartile range. The solid circles within the box represent means, and squares represent outliers. The mean and median of the estimated trend magnitudes are above zero

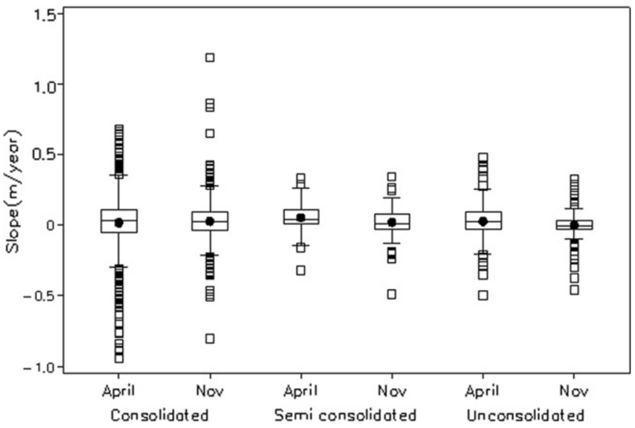

**Figure 11** Box plots showing the Kendall slopes for trend quantification in the pre- and post-monsoon seasons of different formations. The horizontal line within the box represents the median value, length of the box represents the interquartile range, and whiskers at upper and lower extremities are located at 1.5 times of the interquartile range. The solid circles within the box represent means, and squares represent outliers.

(except for the unconsolidated formation in post-monsoon) indicating the groundwater level decline (Fig. 11). In April, the groundwater level depleted at an average rate of 0.018, 0.053 and 0.028 m yr$^{-1}$ for the consolidated, semi- and unconsolidated formations, respectively. In November, the trend declines at an average rate of 0.028 and 0.02 m yr$^{-1}$ were observed in the consolidated and semi-consolidated formations, respectively. However, the groundwater levels improved marginally at an average rate of 0.0002 m yr$^{-1}$ for the unconsolidated formation.

In terms of variability, the box plots show that the slopes at the 25th and 75th percentiles do not differ much between the seasons for the consolidated and semi-consolidated formations. However, the presence of quite a comfortable number of positive and negative outliers in all formations irrespective of seasons indicates heterogeneity of trend magnitudes. Hence, the trend magnitude at a particular site is more informative than the average value of a formation. The average rates of groundwater level fluctuation were estimated for the monitoring stations having significant ($\alpha = 0.05$) trend presented in Figs. 7–10. The water table depleted at an average rate of 0.23 m yr$^{-1}$ and 0.17 m yr$^{-1}$ for the pre-and post-monsoon seasons, respectively. Unless technological interventions are made, the water table decline at this rate may lead to major environmental problems in future. Further, the water table improvements at an average rate of 0.30 and 0.19 m yr$^{-1}$ for the pre- and post-monsoons in few stations, mostly located in the unconsolidated formation, may be due to the flooding effect.

## Summary and conclusions

The present study was aimed at studying the influence of repeated droughts and increased anthropogenic pressure on the groundwater levels of the state Orissa during the period 1994–2003. Preliminary study showed that the groundwater levels of the network observation wells are very sensitive to the monsoon rainfall, and any irregularity in rainfall directly influences the groundwater levels. Due to drought in 2002, the groundwater level dropped significantly in the consolidated formation that covers 80% of the geographical area of the state Orissa. The fitted curves of both the annual and monsoon rainfall indicated a downward trend although four wet years were experienced during the study period. The effect of droughts and high temperature on groundwater levels should be counterbalanced by the effect of flood, and over years it should remain stable. However, this study revealed that the recharge is not significant enough to balance the groundwater discharge due to the anthropogenic and natural processes. The groundwater level trends have moved in a positive or negative direction against the null hypothesis of neutral trend direction. The monitoring stations showing groundwater level decline in terms of positive trends were considerably more in number than the stations showing negative trends for all the formations. Further, the cases of significant water table declines were almost double the number of stations having significant water table improvement. This gives enough evidence that the groundwater level trends are not the part of random natural variability, rather the result of a systematic forcing mechanism namely drought in conjunction with human stress and high temperatures. The trend results showed wide spatial and seasonal differences both in the occurrence and the direction of trends. Spatial differences of the trends in a particular season can be related to the differences in the topography and the hydraulic properties of the aquifer. Seasonal differences of the trends, however, reflect more the seasonal differences of the meteorological variables, and the increased water demands during the pre-monsoon season. Future research on the issue of trend attribution is needed to establish relationships between the hydraulic parameters of the areas having a similar spatial pattern of significant trends and the weather variables. The homogeneity test of the groundwater level trends indicated that the consolidated formation experienced an overall significant decline of groundwater level during the study period irrespective of the seasons. The semi-consolidated and unconsolidated formations, however, experienced significant water table decline in the pre-monsoon summer season only. This result may be of practical implication for formulating long-term policy measures for sustainable management of groundwater resources to meet the future water requirements. Finally, for an optimal groundwater management, it is essential to know, whether the water table fluctuation is due to systematic variation or the part of random fluctuation. The method described in this paper is a step forward in this direction, and can be applied to the groundwater level monitoring networks in other settings.

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