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Trend Analysis of Groundwater Levels and Assessment of Regional Groundwater Drought: Ghataprabha River Basin, India

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Groundwater drought is a relatively new concept, particularly in the Indian subcontinent, where groundwater levels are declining rapidly. The present study focuses on understanding the trends in groundwater levels and evaluates regional groundwater drought characteristics in the drought-prone Ghataprabha river basin, India. Cluster analysis was performed on the long-term monthly groundwater levels to classify the wells, and the Mann–Kendall test was accomplished to investigate the annual and seasonal groundwater-level trends. Standardized Groundwater level Index (SGI) was used to evaluate groundwater drought. Significant decreasing trends were observed in more than 61% of the wells in the study area with average decline of 0.21 m. Results of the SGI analysis showed that the wells of clusters 1 and 2 experienced recurrent droughts, which can be attributed to diminishing rainfall and over-exploitation of groundwater resources. The outcome of this study provides valuable information about the long-term behavior of regional groundwater levels which, in turn, helps to establish an operative groundwater management strategy for upcoming droughts.

KEY WORDS: Cluster analysis, Groundwater trend, Mann–Kendall test, Groundwater drought, SGI.

INTRODUCTION

Groundwater is one of the vital sources of freshwater, and it plays a critical role in the sustainable development of agricultural, industrial and socioeconomic status of the area. Groundwater can also act as an alternative source of water for drought mitigation, and it provides resilience to drought at its initial stage (Hughes et al. 2012; Mussá et al. 2015). Due to uncertainty and uneven distribution of rainfall and decreased surface flow, the dependency on groundwater resources has increased enormously, particularly, in arid and semiarid regions.

Groundwater resource is declining significantly owing to the intense agricultural activity, increase in water demand by population and industrial growth. Along with anthropogenic activity, the occurrence of frequent droughts can hamper groundwater recharge and regulate groundwater pumping, which in turn, leads to reduction in groundwater levels (Goodarzi et al. 2016).

Drought is an extreme natural hazard and can be explained as a temporary deficit in water availability over a prolonged period of time. Based on the water availability in different sectors of water resources, drought has been classified into meteorological drought, hydrological drought, agricultural drought and socioeconomic drought (American Meteorological Society 2004). Among these types of droughts, groundwater drought is a distinct category of hydrological drought that deals with various

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characteristics of groundwater resources and can be quantified with the help of groundwater recharge, discharge, groundwater levels and volume. Groundwater drought can be defined as a ''lack of groundwater recharge or a lack of groundwater expressed in terms of storages or groundwater heads in a certain area and over a particular period of time'' (Van Lanen and Peters 2000). However, groundwater drought has also been defined by many authors by considering either recharge, storage or groundwater heads. (Marsh et al. 1994; Eltahir and Yeh 1999; Peters et al. 2001; Goodarzi et al. 2016). Groundwater drought initiates with the decrease in the recharge due to the lack of rainfall leading to the drop in water table and depleting total groundwater storage. However, excessive pumping (abstraction) also enhances the groundwater drought (Mishra and Singh 2010; Gleeson et al. 2012; Zakhem and Kattaa 2017; Le Brocque et al. 2018).

Several studies from different parts of the globe have attempted to quantify groundwater drought and studied its propagation from meteorological and hydrological droughts (Peters et al. 2005; Bhuiyan et al. 2006; Tallaksen et al. 2006; Shahid and Hazarika 2010; Van Lanen et al. 2013; Motlagh and Ghasemieh 2016). With the help of water balance, groundwater resources index was proposed by Mendicino et al. (2008) to monitor and forecast groundwater drought in the Mediterranean region and high autocorrelation for groundwater drought in summer along with its spatial variability was observed. Standardized Groundwater Index (SGI) was developed by Bloomfield and Marchant (2013), and they observed good positive correlation between developed groundwater index and meteorological drought, whereas the drawbacks of meteorological drought to identify groundwater drought were highlighted by Kumar et al. (2016). Recently, a few researchers have also attempted to understand groundwater drought, by assessing terrestrial water storage derived from Gravity Recovery and Climate Experiment (GRACE) data (Van Loon and Rohini Kumar 2017; Thomas et al. 2017).

Along with groundwater drought assessment and monitoring, investigation of trends in groundwater levels is an important aspect of groundwater management strategies. Further, it helps to understand the underlying pattern associated with groundwater hydrographs. Trends in groundwater levels provide better knowledge of long-term temporal behavior exhibited by time series of groundwater heads and can be either positive (increasing),

negative (decreasing) or zero (stable) (Le Brocque et al. 2018). However, significant decreasing groundwater trend could lead to frequent and severe groundwater droughts (Castle et al. 2014). Trend analysis characterized by long-term time series of groundwater levels consists of both dry and wet period, which, in turn, conveys implicit drought information of an area (Famiglietti and Rodell 2013).

Groundwater-level studies had been carried out by various researchers to estimate groundwater fluctuation trends (Panda et al. 2012; Patle et al. 2015). Annual, seasonal and monthly groundwater trends have been investigated by Tabari et al. (2012) in Iran, and they witnessed dominant positive trends in summer and spring seasons. Average declining trend of 4.51 m and 4.73 m was observed by Rahman et al. (2017) in Bangladesh during 1991–2010, and the reduction of groundwater was predicted to be 1.16–1.8 times greater during the period 2020–2050. The study conducted by Singh and Kasana (2017) on groundwater-level fluctuations in the rice and wheat ecosystem of Haryana state, India, revealed an average annual decrease of 32.2 cm. India, being an agronomic country, equipped with the highest groundwater-fed irrigation area in the world (Siebert et al. 2010), can establish enhanced groundwater management policies by assessing groundwater drought. In the Indian subcontinent, various studies have been carried out on groundwater levels (Rodell et al. 2009; Tiwari et al. 2009; Thakur and Thomas 2011). However, according to the author's best of knowledge, only a few studies (Mishra and Nagarajan 2013; Ganapuram et al. 2015) have been focused on groundwater drought. Therefore, the present study aims to evaluate annual and seasonal groundwater-level trends with respect to regional groundwater drought characteristics in the drought-prone sub-basin of Krishna river, in India.

STUDY AREA AND DATA USED

The Ghataprabha river basin is a sub-basin of the river Krishna and is positioned between 15°45′ and 16°25′N latitudes and 70°00′ and 75°55′E longitudes of (Fig. 1). It originates in the Western Ghats at an altitude of 884 m. The total length of the Ghataprabha River is about 260 km, and total catchment area of the basin is 8829 km^2. The study area is a semiarid region where rainfall is confined to
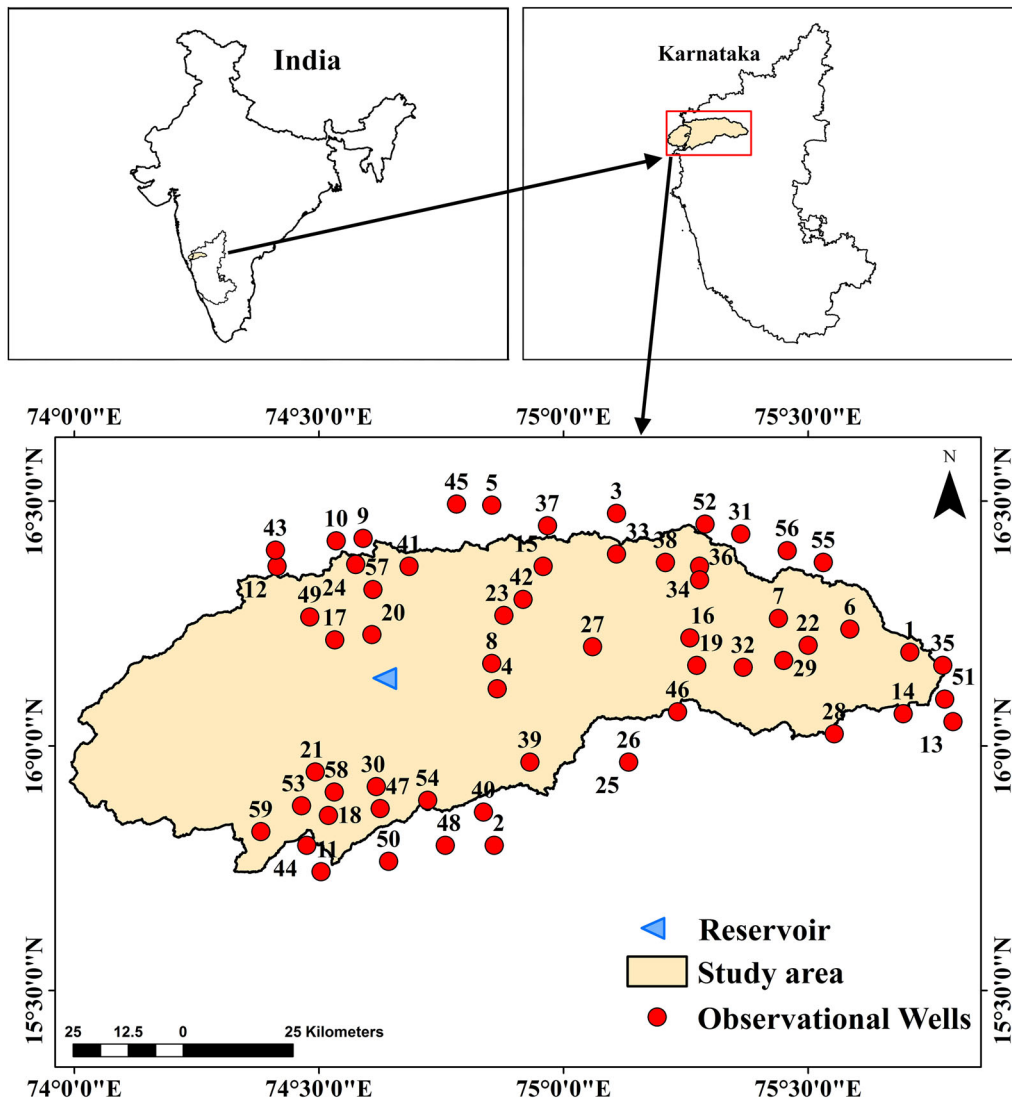
Figure 1. Location map of the Ghataprabha River Basin.

monsoon season from June to October, and normal rainfall varies from 5000 mm (in a small portion of Westside, which covers the Western Ghats) to less than 600 mm at the eastern part. The annual mean temperature of the basin varies from 25.1 to 26.6 °C, and soil found in the region comprises clay loam, sandy clay loam and clay. The main land use of the area is agriculture, and groundwater is one of the prime sources for irrigation. The study area covers three major aquifer systems, namely Basalt, Limestone and Schist (CGWB 2012); basalt covers most

of the area. The Ghataprabha river basin, being a drought-prone area, encompasses semi-critical or overexploited groundwater areas in the major portion of the basin (CGWB 2011). In the present study, monthly groundwater-level data of 70 wells situated in and around the study area were obtained from the Mines and Geology department Karnataka, India. The procured data were checked for sufficient volume of data availability with continuous observations. The wells with less than 25 years of data were excluded from the present study. Finally, ground-

water-level data from 59 wells (Fig. 1), spanning not less than 25 years, were considered for the analysis.

METHODOLOGY

Hierarchical Cluster Analysis

Groundwater levels considered for the drought assessment vary strongly from one well to another. As a consequence, it is impractical to present groundwater drought per well. Therefore, cluster analysis was employed to classify groups of wells according to their similarities in water-level fluctuation. Cluster analysis is a statistical method, which groups individuals based on similarity or dissimilarity associated with variables. In this study, the wells that exhibit similar groundwater fluctuations are clustered into different groups by considering long-term (more than 25 years) monthly groundwater levels as variables for clustering. Among the several clustering methods, hierarchical clustering is a basic method that is popularly applied for groundwater studies (Subbarao et al. 2013; Bloomfield et al. 2015). In this study, hierarchical clustering with Ward's linkage method (Ward 1963; Murtagh 2000; Murtagh and Legendre 2014) was performed to identify the homogeneous wells based on groundwater-level hydrographs. The measure of similarities between the wells was obtained by Square Euclidean Distance measure (Yerel and Ankara 2007; Shiau and Lin 2015). In hierarchical clustering the distance matrix, based on the groundwater levels, is calculated first and each well is considered as a separate group. Later, each group is merged with groups nearest to it based on the Ward's linkage method (Murtagh and Legendre 2014; Shiau and Lin 2015). The cluster analysis was performed in the ''RStudio'' statistical environment with the help of ''hclust'' package (R Core Team 2013).

Nonparametric Trend Test for Groundwater Levels and Groundwater Drought

To quantify the trend in a time series data, the Mann–Kendall (MK) test has been widely used in the field of water resources and climatic studies (Wu et al. 2008; Jain and Kumar 2012; Patle et al. 2015). The MK test, as initially formulated by Mann (1945) as a nonparametric test for trend detection and as a test statistic, was introduced by Kendall (1975). The

Z statistics of the MK test defines whether a variable has increasing trend ($Z > 0$), decreasing trend ($Z < 0$) and no trend ($Z = 0$). To assess the significance of the trend test, null hypothesis H_o (variable does not possess trend) is tested against the alternative hypothesis H_1 (variable is has trend). H_o is rejected if $|Z| > Z_{\alpha/2}$, which indicates the presence of a trend. The only caution to be taken before applying the MK test is that the data should not possess lag l autocorrelation at 95% confidence level. The present work uses the nonparametric MK test to identify trends in the annual and seasonal groundwater levels of the Ghataprabha river basin. The trend test was conducted for all the stations at 95% of confidence level, and the magnitude of trend was quantified by the Sen's slope (Sen 1968) method. Formulations and equations of the MK test and Sen's slope method can be found in many standard literature (e.g., Güner Bacanli 2017; Rahman et al. 2017).

In this study, groundwater drought was assessed with the help of the SGI. Bloomfield and Marchant (2013) proposed the SGI to analyze groundwater drought using groundwater levels. The SGI is a nonparametric method whereby normal scores of monthly groundwater data are transformed with inverse normal cumulative distribution function and values are arranged continuously, according to months, to get SGI time series. Because SGI considers inverse normal function, the classification using SGI was done similar to the Standardized Precipitation Index as presented by Rahman et al. (2017). Groundwater drought characteristics such as severity, duration and intensity can be defined by considering a threshold value (-1 in this study) for SGI. Drought event (episode) is the period when the magnitude of SGI falls below truncation level, and drought duration is the period in which the magnitude of drought index is below the threshold value. The severity is the sum of negative values during the drought duration, and intensity is defined as the ratio of the drought severity to drought duration.

RESULTS AND DISCUSSIONS

Classification of Wells Based on Cluster Analysis

Cluster analysis was carried out to classify the wells according to their similarities in water-level fluctuation. Hierarchical clustering with Ward's linkage method was employed, and the resulting

dendrogram is presented in Figure 2. To obtain different clusters, the dendrogram has to be cut at a particular level of linkage distance called threshold. Threshold selection is subjective, and it varies from user to user. For instance, threshold at 100 will give two clusters, whereas threshold of 50 will give four clusters. However, some researchers considered a threshold value less than or equal to linkage distance of 75 to obtain different clusters (Simon and Morris 2014; Nagaraju et al. 2016).

To avoid perplexity in a selection of the threshold, gap statistics was employed. The gap statistics was developed by Tibshirani et al. (2001) to identify optimum number of clusters. The gap statistics compares the variation of the total within sum of squares for different number of clusters with their expected values under null reference distribution of data. Variation of gap statistics is typically plotted for different number of clusters k (Fig. 3), and the appropriate number of clusters is selected. The optimum number of clusters is obtained based on the corresponding gap statistics in such a way that the rate of increment of the gap statistics from those clusters is insignificant. From Figure 3, it can be noticed that, after three clusters, there is not much change in the rate of increment of the gap statistics, which indicates that the wells can be grouped into three clusters optimally. From the spatial variation of the wells of different clusters (Fig. 4), it was observed that the group of 16 wells in the eastern
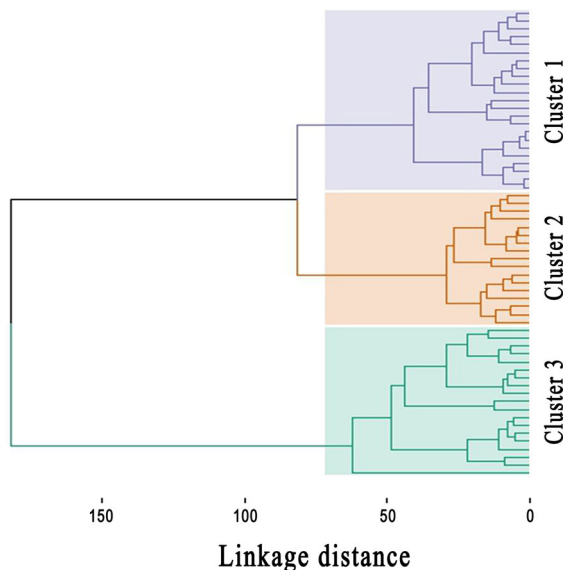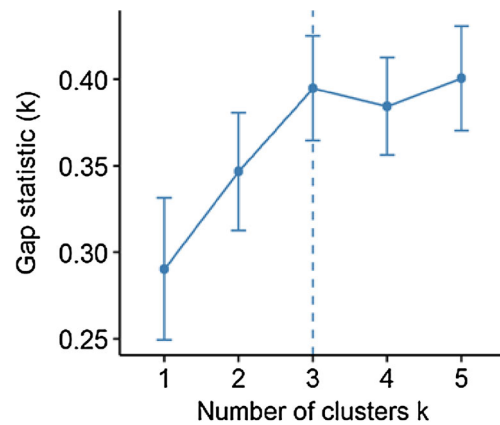

Figure 3. Gap statistics for hierarchical cluster analysis.

portion and 19 wells in the southwestern portion shows similar groundwater fluctuations and are termed as cluster 2 and cluster 3, respectively, whereas the remaining 24 wells are dispersed over the area and entitled as cluster 1.

The box plot portrayed in Figure 5 indicates average groundwater level of each cluster with the respective variations. The wells of cluster 1 have an average groundwater level of 600 m above mean sea level (amsl). Similarly, wells of clusters 2 and 3 have an average groundwater level of 533 m amsl and 720 m amsl, respectively. From Figure 5, it can be noted that the groundwater levels in the wells of cluster 1 (548–660 m amsl) and cluster 3 (660–800 m amsl) are more fluctuating as compared to the wells of cluster 2 (505–564 m amsl).

Annual and Seasonal Groundwater-Level Trends

The nonparametric MK test has been applied at a significance level of $\alpha = 0.05$, to evaluate monsoon (June to September), post-monsoon (October–December), winter (January–February), pre-monsoon (March–May) and annual (January to December) groundwater-level trends for all the wells of the study area. Prior to the MK trend test, serial correlation of the groundwater level for all the wells was calculated and significant lag 1 autocorrelation was observed for annual and seasonal groundwater levels for few wells. To incorporate the autocorrelation effects on trends of groundwater-level fluctuation, the modified Mann–Kendall (MMK) test (Hamed and Ramachandra Rao 1998) was em-
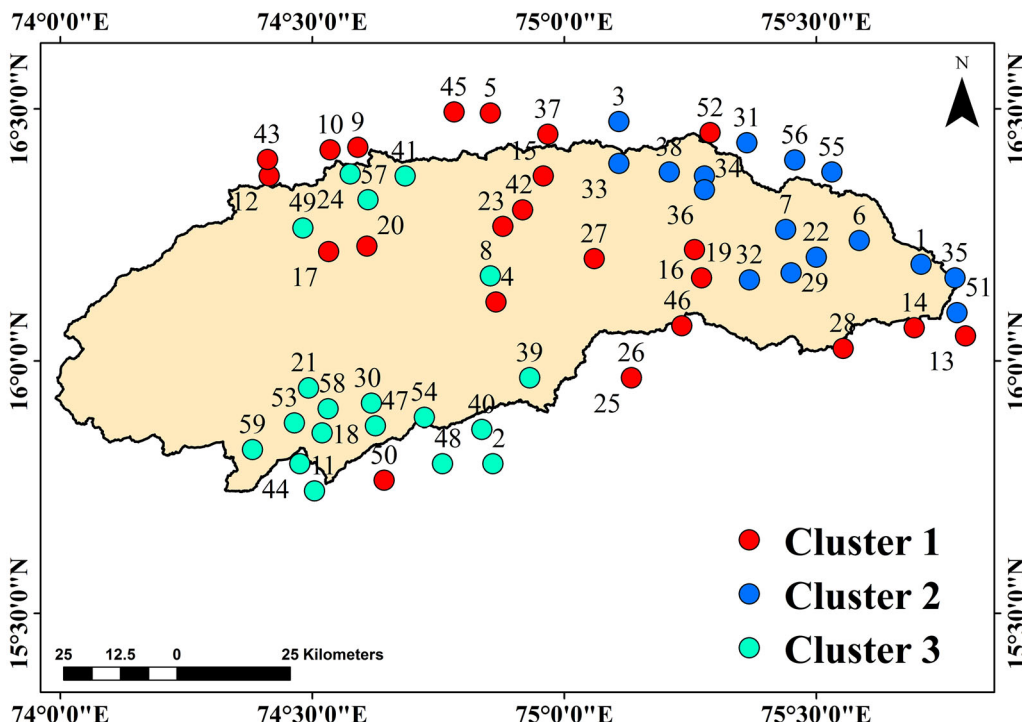

Figure 2. Dendrogram of hierarchical cluster analysis.

Figure 4. Spatial distribution of wells classified according to hierarchical cluster analysis.
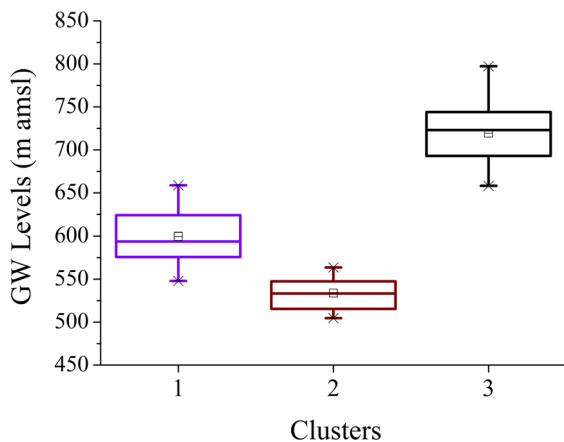

Figure 5. Groundwater variations in the wells of different clusters. The line and dot in the box plot indicate median and mean value, respectively.

ployed to identify the seasonal and annual trends in groundwater levels. Because the coefficients of variation of groundwater levels of the most of the wells are low (< 0.7) and the value of the Sen's slope is high (> 0.01), the results of the MMK do not alter the original decisions of the hypothesis of the MK test (Bayazit and Önöz 2007). Therefore, the MK

trend test was applied to the original time series of the groundwater levels of all the wells of each cluster.

The results of annual and seasonal groundwater-level trends are presented in Table 1 along with respective magnitudes of the trends calculated from the Sen's method. Significant trends were observed in both seasonal and annual groundwater levels. During the pre-monsoon season (Fig. 6a), 37 wells show a decreasing trend and 22 wells an increasing trend. Among these wells, eight wells belonging to cluster 1, thirteen wells belonging to cluster 2, and five wells belonging to cluster 3 show significant negative trend with average decrease in groundwater levels by 0.17 m, 0.24 m and 0.36 m per year, respectively. Similarly, 4, 1 and 6 wells belonging to cluster 1, 2 and 3, respectively, show a significant increasing trend with average increase in groundwater levels by 0.35 m, 0.1 m and 0.14 m per year, respectively.

Decreasing trend in groundwater level was observed in 36 wells, and increasing trend was noted for 23 wells during the monsoon season (Fig. 6b). Among these wells, 23 are depleting significantly with average reduction of 0.23 m per year, while in other 10 wells water level is increasing significantly

Table 1. Mann–Kendall statistics and Sen's slope values for annual and seasonal groundwater levels

ID	Pre-monsoon		Monsoon		Post-monsoon		Winter		Annual	
	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope
1	**− 3.28**	− 0.30	**− 2.65**	− 0.24	**− 2.67**	− 0.26	**− 2.98**	− 0.21	**− 2.77**	− 0.21
2	**2.48**	0.09	1.05	0.03	0.73	0.02	1.90	0.08	1.63	0.05
3	0.75	0.02	− 1.55	− 0.05	− 0.75	− 0.03	0.62	0.02	− 0.38	− 0.01
4	1.64	0.05	**2.36**	0.09	**2.36**	0.09	0.71	0.03	**2.74**	0.09
5	**− 4.01**	− 0.16	**− 3.65**	− 0.15	**− 2.22**	− 0.06	**− 2.60**	− 0.06	**− 4.46**	− 0.12
6	**− 1.97**	− 0.05	**− 3.03**	− 0.07	0.01	0.00	− 0.59	− 0.01	**− 2.78**	− 0.04
7	**4.35**	0.11	**4.08**	0.11	**2.92**	0.09	**3.45**	0.08	**4.83**	0.10
8	0.54	0.04	− 1.18	− 0.09	0.77	0.04	1.41	0.10	− 0.57	− 0.04
9	0.87	0.03	0.22	0.01	1.56	0.05	0.60	0.03	1.16	0.03
10	**− 4.55**	− 0.27	**− 5.10**	− 0.27	**− 3.50**	− 0.21	**− 3.73**	− 0.17	**− 5.17**	− 0.24
11	**4.35**	0.29	**2.79**	0.11	**2.40**	0.08	**3.86**	0.15	**4.16**	0.16
12	− 0.54	− 0.02	0.21	0.00	− 1.63	− 0.03	− 1.07	− 0.02	− 0.61	− 0.01
13	0.26	0.02	− 1.10	− 0.05	− 1.49	− 0.09	− 1.13	− 0.09	− 0.82	− 0.05
14	**− 5.14**	− 0.35	**− 5.55**	− 0.32	**− 5.60**	− 0.38	**− 5.50**	− 0.34	**− 5.72**	− 0.33
15	− 1.69	− 0.09	**− 2.09**	− 0.11	− 1.83	− 0.06	**− 2.12**	− 0.07	**− 3.15**	− 0.09
16	**− 3.49**	− 0.33	**− 4.28**	− 0.38	**− 2.79**	− 0.29	**− 3.40**	− 0.30	**− 3.71**	− 0.33
17	**3.78**	0.09	**3.63**	0.09	**2.55**	0.06	**3.17**	0.09	**4.15**	0.08
18	**− 2.58**	− 0.11	**− 3.54**	− 0.13	**− 3.11**	− 0.13	**− 2.01**	− 0.10	**− 3.88**	− 0.13
19	0.71	0.11	0.39	0.07	− 0.21	− 0.03	0.73	0.11	0.51	0.06
20	− 1.42	− 0.07	− 1.29	− 0.05	− 0.59	− 0.03	**− 2.14**	− 0.11	− 1.73	− 0.08
21	1.78	0.05	**2.08**	0.15	0.15	0.01	− 0.13	− 0.01	1.28	0.05
22	**− 6.40**	− 0.41	**− 5.80**	− 0.39	**− 3.86**	− 0.21	**− 6.16**	− 0.28	**− 6.48**	− 0.35
23	**3.01**	0.08	1.07	0.03	1.54	0.03	**3.18**	0.06	**2.33**	0.04
24	**2.15**	0.07	0.10	0.01	− 0.86	− 0.03	0.95	0.02	0.65	0.02
25	− 0.37	− 0.03	1.59	0.08	1.48	0.10	− 0.17	− 0.02	0.48	0.02
26	− 0.64	− 0.05	1.50	0.07	1.45	0.10	− 0.33	− 0.02	0.40	0.01
27	0.60	0.06	0.83	0.05	0.01	0.00	0.68	0.07	0.80	0.04
28	**− 2.52**	− 0.06	**− 2.70**	− 0.05	− 1.92	− 0.03	**− 2.37**	− 0.04	**− 3.10**	− 0.04
29	**− 3.62**	− 0.23	**− 3.60**	− 0.23	**− 2.38**	− 0.17	**− 3.71**	− 0.20	**− 4.40**	− 0.20
30	**2.37**	0.08	**3.63**	0.12	1.88	0.06	1.69	0.06	**2.71**	0.07
31	**− 4.14**	− 0.12	**− 6.11**	− 0.16	**− 3.91**	− 0.14	**− 3.63**	− 0.13	**− 6.01**	− 0.15
32	**− 4.45**	− 0.14	**− 5.92**	− 0.22	**− 6.06**	− 0.39	**− 5.78**	− 0.26	**− 6.28**	− 0.22
33	1.26	0.03	− 0.93	− 0.04	− 0.39	− 0.01	0.80	0.02	0.01	0.00
34	**− 3.18**	− 0.07	0.51	0.01	**− 4.00**	− 0.03	**− 2.93**	− 0.05	**− 3.09**	− 0.04
35	**− 3.76**	− 0.20	**− 3.18**	− 0.17	**− 3.32**	− 0.19	**− 3.35**	− 0.21	**− 3.86**	− 0.20
36	**− 4.82**	− 0.10	**− 4.88**	− 0.08	**− 4.24**	− 0.07	**− 5.48**	− 0.09	**− 5.93**	− 0.08
37	**− 2.00**	− 0.10	**− 2.73**	− 0.06	**− 3.35**	− 0.05	**− 3.25**	− 0.06	**− 4.03**	− 0.09
38	− 0.21	0.00	− 1.87	− 0.03	− 1.30	− 0.02	− 0.80	− 0.01	− 1.34	− 0.03
39	**− 3.38**	− 0.47	**− 2.95**	− 0.37	**− 2.61**	− 0.31	**− 3.28**	− 0.41	**− 3.52**	− 0.43
40	**− 3.86**	− 0.96	**− 2.91**	− 0.65	**− 3.05**	− 0.74	**− 3.69**	− 0.88	**− 3.69**	− 0.83
41	1.90	0.17	**3.00**	0.20	1.75	0.14	**2.55**	0.23	**2.87**	0.18
42	− 0.81	− 0.01	**− 1.96**	− 0.05	− 1.44	− 0.02	**− 2.25**	− 0.04	**− 2.82**	− 0.04
43	**4.82**	1.03	**4.50**	0.46	**4.32**	0.30	**5.11**	0.32	**4.48**	0.57
44	− 0.37	− 0.01	− 0.31	− 0.01	− 1.42	− 0.02	− 0.98	− 0.02	− 1.22	− 0.02
45	**− 2.76**	− 0.08	**− 2.55**	− 0.10	**− 3.37**	− 0.11	**− 4.25**	− 0.09	**− 3.88**	− 0.09
46	**− 2.17**	− 0.07	− 1.66	− 0.06	− 1.28	− 0.07	**− 2.31**	− 0.09	**− 2.12**	− 0.07
47	0.53	0.02	1.02	0.05	− 0.33	− 0.02	− 0.10	− 0.01	0.23	0.01
48	− 0.37	− 0.01	0.35	0.01	0.54	0.04	1.32	0.08	0.09	0.01
49	**4.52**	0.23	**3.70**	0.20	**3.70**	0.11	**3.66**	0.12	**4.19**	0.15
50	**3.41**	0.21	**3.55**	0.21	**2.59**	0.18	**2.07**	0.16	**2.65**	0.18
51	**− 2.39**	− 0.29	**− 2.72**	− 0.30	− 1.88	− 0.21	**− 2.30**	− 0.27	**− 3.22**	− 0.30
52	**− 5.95**	− 0.61	**− 5.58**	− 0.66	**− 5.35**	− 0.67	**− 4.95**	− 0.53	**− 6.21**	− 0.61
53	**2.66**	0.06	1.93	0.08	1.25	0.03	**2.07**	0.05	**2.10**	0.05
54	− 0.46	− 0.01	− 1.28	− 0.02	0.61	0.02	0.44	0.01	− 0.63	− 0.01
55	**− 2.63**	− 0.05	− 1.48	− 0.03	**− 2.88**	− 0.03	**− 2.68**	− 0.04	**− 3.04**	− 0.04
56	**− 2.69**	− 0.09	**− 4.09**	− 0.13	− 0.28	− 0.01	− 1.22	− 0.04	**− 2.58**	− 0.06

ID	Pre-monsoon		Monsoon		Post-monsoon		Winter		Annual	
	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope
57	− 1.50	− 0.06	− 1.52	− 0.08	− 0.89	− 0.08	− 1.21	− 0.07	− 1.19	− 0.09
58	**− 4.15**	**− 0.12**	− 1.17	− 0.03	**− 2.85**	**− 0.04**	**− 4.18**	**− 0.09**	**− 4.52**	**− 0.07**
59	**− 3.00**	**− 0.12**	− 1.10	− 0.03	− 1.22	− 0.04	**− 2.34**	**− 0.09**	**− 2.17**	**− 0.07**

*Bold values indicate significant trend at 95% confidence level

with average rise of 0.18 m per year. Similarly, groundwater-level trends are decreasing significantly in 20 and 27 wells in the post-monsoon (Fig. 6c) and in winter (Fig. 6d) with the average fall of 0.22 m and 0.19 m, respectively.

There is a minute difference in the trends of groundwater level observed while comparing post- and pre-monsoon trends. On the other hand, most of the wells that show a decreasing trend in the pre-monsoon season continued to be decreasing in the post-monsoon season also. This indicates that recharge of groundwater from monsoon rainfall is inadequate to replenish the drawdown that occurred during previous seasons. These observations convey the poor resilience of groundwater resources to rainfall variations (Le Brocque et al. 2018) and can also be interpreted as the consequence of diminished monsoon rainfall, which, in turn, leads to extensive groundwater abstraction during the monsoon and subsequent seasons.

Out of 59 wells, 38 show decreasing trends and 21 show increasing trends in the annual groundwater levels (Fig. 6e). Cluster 1 comprises 10 wells with annual groundwater levels decreasing significantly with average drop of 0.14 m annually. Similarly, clusters 2 and 3 comprise 13 and 5 wells that depict significant negative trends in annual groundwater level with average fall of 0.19 m and 0.31 m per annum, respectively. Similarly, significant rise in annual groundwater level was observed in 11 wells of the basin with average increase of 0.15 m per year. The results of the annual and seasonal trend analyses convey that most of the wells belonging to clusters 1 and 2 show decreasing trend as compared to the wells of cluster 3. Among all the wells, the 40th well of cluster 1 showed the highest decrease in groundwater level for all the seasons with an average fall of 0.81 m per season. Likewise, the 43rd well of cluster 1 has the highest increase in groundwater level for all the seasons with average rise of 0.54 m per annum.

The trend analysis of groundwater levels of different clusters (Fig. 6) revealed that the water level in the 81% of the wells of cluster 2 and 47% of the total wells of the study area are significantly declining annually and in all the seasons. The results obtained in this study are consistent with the observations made by various researchers at different parts of the country (e.g., Thakur and Thomas 2011; Dhar et al. 2014; Barik et al. 2017). For instance, Patle et al. (2015) reported decreasing groundwater trends during pre- and post-monsoon with the rate of 0.3 m/year in the Haryana state, India. Similarly, Panda et al. (2012) observed significant declining groundwater levels in the Gujarat state of western India.

Overall, groundwater levels of more than 61% of the wells in the study area are decreasing with average decline of 0.21 m during all the seasons, which can be attributed to either diminishing rainfall or severe groundwater exploitation or both (CGWB 2011). The water levels in few wells of clusters 1 and 3 are increasing may be due to recharge of aquifers from nearby reservoirs. The Ghataprabha river basin, being an agrarian region of river Krishna, is enriched with cash crops such as sugarcane and cotton (FAO 2008; KSAPCC 2011). The water requirement of these crops is high, and intensive irrigation practice using groundwater resources for these crops may be one of the key reasons for the significant depletion in groundwater levels in the area. Groundwater, being a dynamic and precious natural resource of Ghataprabha river basin, plays a crucial role in the overall socioeconomic development of the area, whereas these diminishing groundwater levels will certainly threaten the development of the region.

Groundwater Drought Characteristics

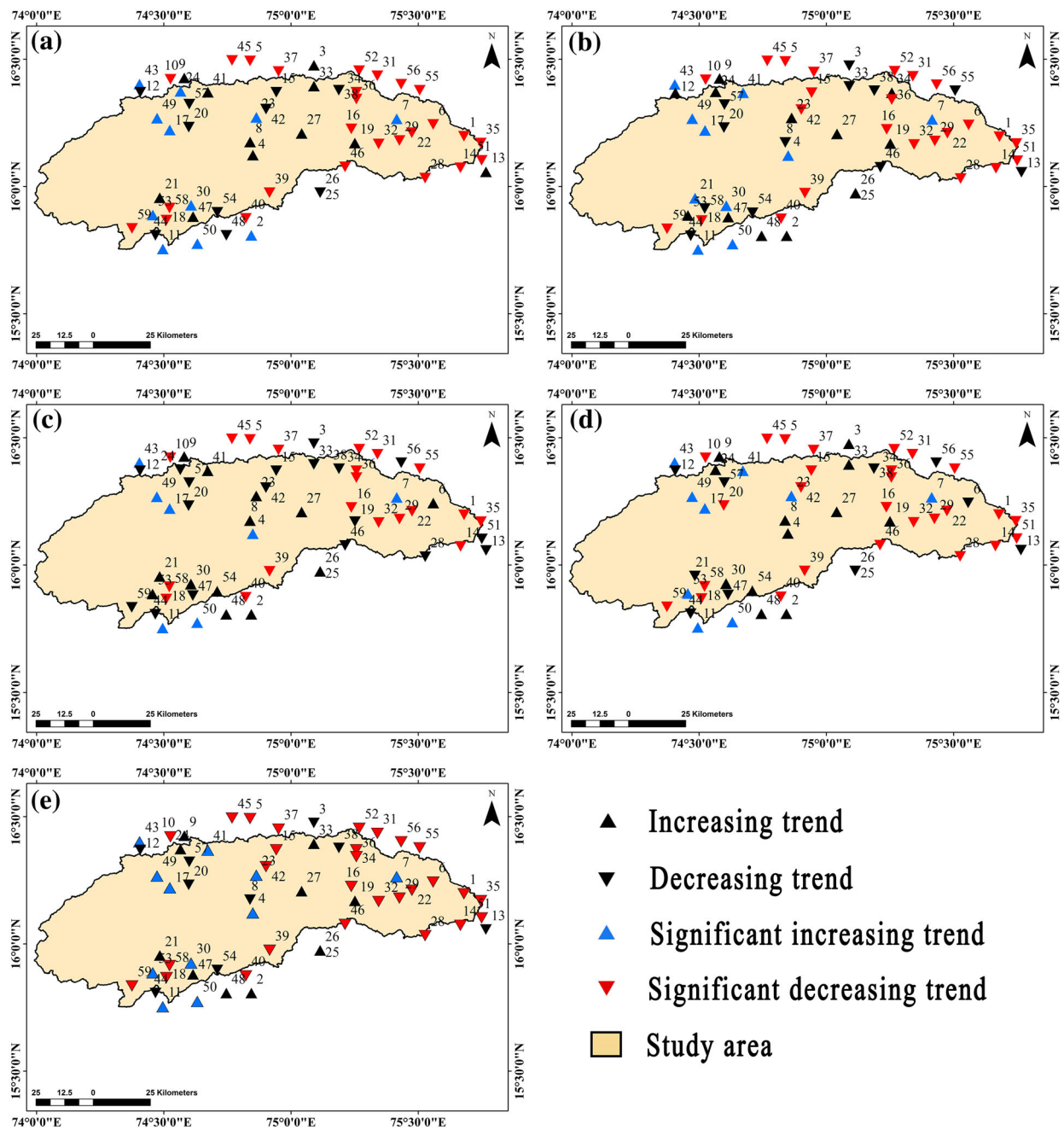Groundwater drought in the Ghataprabha river basin was assessed through SGI for all 59 wells. It

Figure 6. Groundwater-level trends for (**a**) pre-monsoon, (**b**) monsoon, (**c**) post-monsoon, (**d**) winter and (**e**) annual.

was difficult and unfeasible to present groundwater drought for all the wells of the basin within the manuscript. Since all the wells are grouped into three clusters based on similar water-level fluctua-

tion, a typical well from each cluster was selected as a representative well of a respective cluster. The wells with ID 15, 6, 47 are selected from clusters 1, 2,

3, respectively, and results of analysis of these wells are presented and discussed further.

Based on the results of SGI, a significant number of groundwater droughts are observed and the temporal variation of SGI of the representative wells of each cluster is depicted in Figure 7. Negative values of SGI are presented in red color indicating drought months, and the SGI values greater than zero are presented in blue color representing normal condition. The wells of clusters 1 and 3 each suffered 24 severe drought (SGI ≤ -1.5) events, and among these drought events, three drought events last for at least for 3 months. Similarly, 34 severe drought months were observed in the wells of cluster 2, with four events spanning 3 months or more. The wells of cluster 1 suffered extreme drought during 2008–2009 with an average magnitude of SGI 2.1. However, longer drought was noted during 2003–2005. Similarly, wells of clusters 2 and 3 experienced extreme drought during 2015–2016 and in 1987–1988 with average magnitude of SGI 2.23 and 1.98, respectively.

The results of SGI analysis clearly indicated that the wells of all the clusters experienced severe drought during 2000–2003, which is mainly due to the deficit of rainfall during these years, which were declared as drought years in the country (Ministry of Agriculture 2009; Ganguli and Reddy 2014; Ghosh and Srinivasan 2016). This observation draws attention toward the teleconnection between meteorological variables and groundwater drought. However, in the context of climate change, assessment of groundwater drought and its propagation by considering single meteorological variable could be highly uncertain. Therefore, studies that connect hydro-meteorological variables with groundwater drought by considering land-use and land-cover changes and aquifer properties are required to understand the complex nature of groundwater drought, which, in turn, helps to mitigate the consequences of groundwater drought risks of an area.

Drought characteristics such as severity, duration and intensity disclose that wells of cluster 2 faced the highest number of drought events in comparison with wells of clusters 1 and 3. However, the highest severity of 23 with duration of 12 months was observed in the wells of cluster 1 with average intensity of 2. From the results, it can be inferred that the wells of clusters 1 and 2 experienced frequent droughts with short duration, whereas severe droughts were seldom experienced by the wells of cluster 3. The detailed drought characteristics are presented in Table 2. The temporal variations of SGI for clusters 1 and 2 reveal that severe droughts were more frequent in the last two decades and, on the other hand, lower frequency of severe droughts affected the wells of cluster 3. Similar groundwater drought conditions were reported by Ganapuram et al. (2016) and Thomas et al. (2016) in the tributaries of river Krishna and in the Bundelkhand Region of Central India, respectively.

The groundwater droughts observed in the representative wells per cluster explain the future risks involved in the agricultural and groundwater sectors of the basin. Recurrent droughts that affected the wells of clusters 1 and 2 during the last two decades strongly convey the message that the underlying aquifer is getting deteriorated from year to year. In addition to frequent droughts, significant decreasing groundwater levels will magnify the drought intensity in the study area. However, the regression trend line through the time series of SGI of cluster 3 is increasing, suggesting the rise in water level of the respective wells. Similarly, the decreasing trends of SGI of clusters 1 and 2 substantiate the significant diminishing groundwater-level trends of the respective wells and provide a clear forewarning for upcoming severe groundwater droughts.

SUMMARY AND CONCLUSIONS

Long-term annual and seasonal groundwater-level trends were investigated for the 59 wells of the drought-prone Ghataprabha river basin. Along with the trend analysis, groundwater drought assessment was also carried out using SGI. Before evaluating the groundwater droughts, cluster analysis was performed to group the wells based on similarities in groundwater-level fluctuations. The results of gap statistics suggested that three clusters are adequate to explain groundwater-level fluctuations of the basin efficiently. Trend analysis of annual and seasonal groundwater levels of the basin conveyed annual decreasing trends in 64% of the wells, of which 28 wells show significantly decreasing trend with average fall of 0.21 m per year. Most of the wells of cluster 2 show significant depletion in groundwater levels during all the seasons, which can be attributed to over-exploitation coupled with diminishing rainfall and rainy days. The analysis of SGI showed a significant number of groundwater droughts in the study area. However, the wells of clusters 1 and 2 suffered frequent severe droughts. Because the
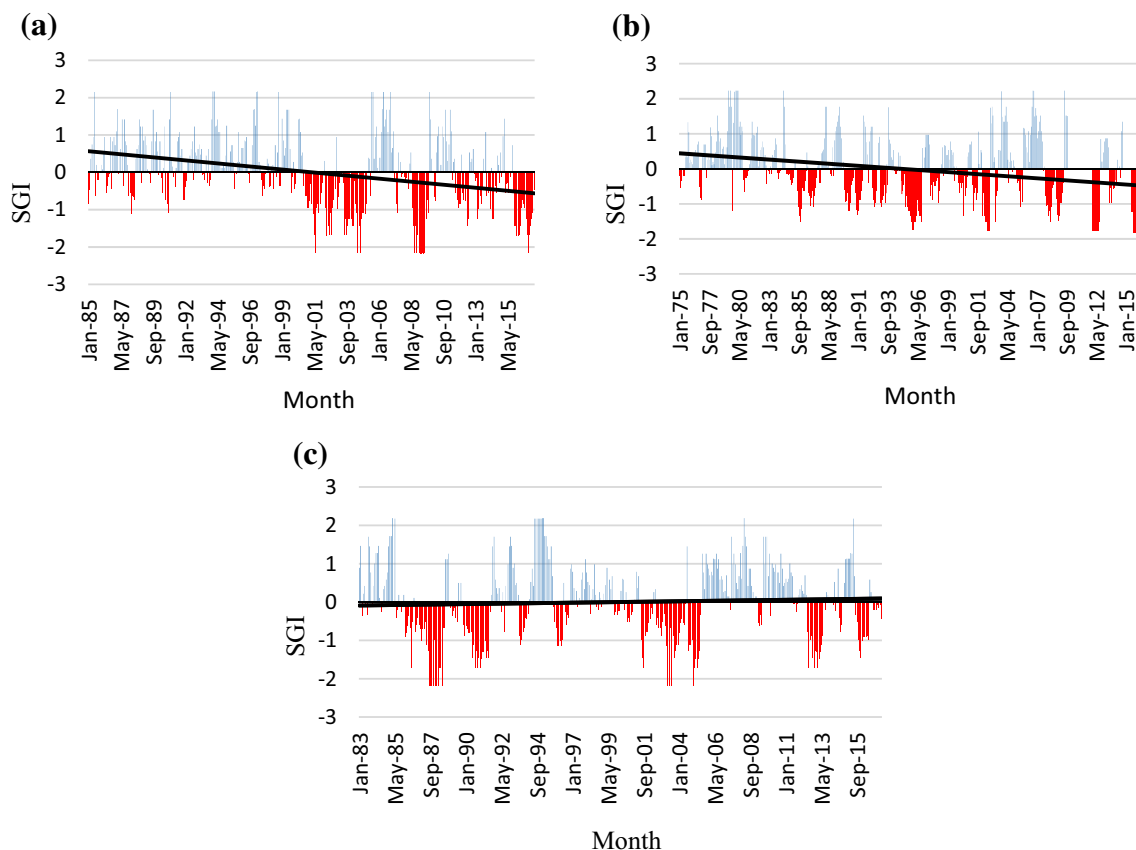
Figure 7. SGI time series for representative wells of (**a**) cluster 1, (**b**) cluster 2 and (**c**) cluster 3.

Table 2. Drought characteristics based on SGI value for representative wells

Well	Total duration (months)	No. of drought events	Average intensity	Maximum severity	Maximum duration (months)
Cluster 1	60	15	1.91	23.00	12
Cluster 2	71	22	1.90	20.94	11
Cluster 3	64	16	1.51	19.60	14

regression line of SGI is decreasing for the wells of clusters 1 and 2, the area is more vulnerable to upcoming extreme groundwater droughts. Because the eastern part of the basin is susceptible to recurrent severe groundwater droughts, serious attention is required in the planning and management of the groundwater resources of that area. This study recommends construction of artificial groundwater recharge structures and conjunctive use of surface water and groundwater to prevent further deterioration of precious groundwater resources. In addition, of which, cultivation of high-water demand cash crops such as cotton, sugarcane should be minimized in the areas where groundwater is the main source of irrigation and cropping pattern needs to be modified accordingly. The outcome of this study may help to develop regional groundwater policies for sustainable development of water resources in the Ghataprabha river basin.

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