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An Integrated Approach for Delineating and Characterizing Groundwater Depletion Hotspots in a Coastal State of India

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ABSTRACT

Visualization of present state of aquifers and identification of groundwater depletion hotspots are important tools in preparing an effective groundwater management plan. Therefore, this study developed an integrated framework by bridging a number of relevant factors to characterize and visualize groundwater depletion hotspots in Andhra Pradesh, India. Firstly, the groundwater status was assessed by detecting spatio-temporal trends in groundwater levels of 429 dug well sites from 2004 to 2018 using Mann-Kendall (MK)/modified Mann-Kendal (mMK), Spearman's Rho test, and the magnitude of the slope was determined by Sen's slope estimator. Subsequently, multiple decision factors were considered in the analytical hierarchy process (AHP) method for producing the groundwater stress zone map. A multicollinearity test was performed prior to the incorporation of these factors in order to improve the decision-making power of the AHP method. The results of the groundwater stress zoning map showed that 19.99%, 16.93%, 24.63%, 18.86% and 19.59 % of areas were classified as low, moderate, high and very high stress zones, respectively. Results also identified the south-western parts as groundwater depletion hotspots. Furthermore, validation results using Sen's slope map, evaluation metrics of ROC (receiver operating characteristics) and AUC (area under curve) showed that AHP method had exhibited a reliable performance with an accuracy of 76.7%. Thus, the applied integrated approach can be used to explicitly characterize groundwater status by integrating different factors. The findings of our study also would be helpful for water resources managers and planners who need to design proper and sustainable management of groundwater resources.

INTRODUCTION

Groundwater is a precious natural resource (Rahman et al., 2020) and a reliable source of fresh water for a country (Das and Pal, 2020). It is generally used in industrial, agricultural, mining, and residential applications (Jhariya et al., 2019). Economic development, agricultural productivity, and food security in a country are largely dependent on groundwater availability (Bhanja and Mukherjee, 2019). In the recent past, groundwater levels have been declining rapidly in various parts of the world due to overexploitation, overuse in irrigation, industry and other sectors (Machiwal et al., 2019). Higher intensive developments (>100%) of groundwater are found in different parts of Delhi, Punjab, Rajasthan, Gujrat, Haryana, Tamil Nadu, Karnataka, and Andhra Pradesh of India. Therefore, rapid declination of groundwater is found in these states (CGWB, 2012). In this connection, a variety of negative impacts are remarkably noticed in the environment (Bui et al., 2012). Aquifer threats (Akther et al., 2009), land subsidence (Othman and Abotalib, 2019), groundwater pollution (Jhariya, 2019) are the major adverse effects of the declining groundwater level. Accordingly, several studies showed that the time-based trend detection and the study of groundwater fluctuation are essential for proper management of groundwater resource (Patle et al., 2015; Das et al., 2020a). Due to the lack of detailed information on all relevant control factors for groundwater dynamics, it is not possible to infer the underlying mechanisms, therefore, one cannot take effective action to combat groundwater depletion. The integration of time series data patterns with spatio-temporal information on the various controlling factors of groundwater fluctuation would be helpful for water resource planners in preparation of an efficient groundwater management plan.

Time series analysis is the most appropriate technique for depicting trends, nature and causes of groundwater fluctuations (Patle et al., 2015). In this context, different types of parametric and non-parametric methods are generally used (Das et al., 2021). The Mann-Kendall (MK) and Modified Mann-Kendall (mMK) tests are the most usable non-parametric tests for identifying significant trends (Das and Bhattacharya, 2018). Moreover, the Spearman Rho (SR) test is also a useful non-parametric method (Das et al., 2020b), but it has not received much attention as MK or mMK (Yue et al., 2002). However, its applications can supplement or conform to the detected trend by other approaches such as MK/mMK.

Groundwater risk and vulnerability assessment have recently become a crucial tool for designing effective aquifer management systems (Ouedraogo et al., 2016). The primary goal of this evaluation is to identify the groundwater depletion hotspots, where the groundwater levels have dropped dramatically. Generally, a variety of qualitative and quantitative factors are responsible for groundwater depletion and therefore, the assessment requires lots of data that are mostly unavailable in the rural areas of many developing countries. Additionally, generating such data are also expensive (Olivares et al., 2020). Hence, a simple method is needed, which can provide substantial information on risk assessment using the relevant data. Over time, various effective techniques for delineating vulnerable or stress zone have emerged, of which the Analytical Hierarchy Process (AHP) is a simple, powerful, and structured multi-criteria decision-making method (Ghezelayagh et al., 2020). Interestingly, for comparative analysis, various criteria are used in the AHP method (Das et al., 2017). The AHP method assesses the relative weights of various criteria and sub-criteria according to their relative significance (Nahayo et al., 2019). Several studies have also been conducted on groundwater vulnerability assessment using the AHP method. Murmu et al. (2019) delineated potential zones of groundwater by using geographical information systems (GIS) and the AHP method in the Dumka district of Jharkhand. They concluded that 11 %, 38%, 44%, and 7% of areas were classified as very good, good, moderate, and poor zones of groundwater,

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respectively. Olivares et al. (2020) also used the AHP and GIS method to assess the groundwater vulnerability in the Central Valleys of Mexico. They summarized that pollution, abstraction and recharge rate were the main reasons for groundwater vulnerability. Another study by Sahoo et al. (2016) showed the groundwater vulnerability zone in Hirakud command area using AHP, DRASTIC, and modified AHP methods. In the study, they applied quantitative parameters to determine the vulnerability and also concluded that northern parts were more vulnerable as compared to other parts.

Andhra Pradesh is the most agrarian state. Approximately 70 % of the state's population is engaged in the agricultural sector and providing 25% of the state's total GDP (Amarasinghe et al., 2008). Groundwater is the main source of irrigation in this state and it contributes to about 49% of the total irrigation of the state (Kumar et al., 2011). Excessive reliance and growing fresh water demand of various sectors create heavy pressures on the aquifer system. Therefore, an assessment of the potential groundwater stress zone and the delineation of groundwater hotspots is required. However, the validity and accuracy of the groundwater stress zone calculated using the AHP method mainly depended on the precise selection of the different factors responsible for groundwater fluctuation. Therefore, a proper selection of sufficient criteria and their perfect combination should be included in the study to provide reliable information on the groundwater stress zone. However, a comprehensive study that combines hydrological, climatological, geological and anthropogenic factors for the assessment of the potential groundwater depletion stress zone is rare in literature. Moreover, most of the studies (Janipella et al., 2020; Venkatesan et al., 2019) investigated the groundwater vulnerability in terms of groundwater quality and hence, quantitative analysis is lacking. Therefore, the present study was conducted to identify the trend of groundwater depth using Mann-Kendall (MK) or modified Mann-Kendall (mMK), Spearman's Rho test, and Sen's slope estimator determined its slope. The study also analyzed the associated factors for fluctuations in groundwater levels. Moreover, a multi-criterion (hydrological, climatological, geological and anthropogenic factors) based groundwater stress zoning was assessed using the AHP method. Although a multi-collinearity test was carried out prior to the integration of these criteria into the AHP method to eliminate statistical disturbances in the dataset and also to improve the decision-making capacity of the AHP method. The specific objectives of the study are to (1) find out the trend and its magnitude of groundwater depth, (2) examine the role of associated driven forces on groundwater level fluctuation, (3) assess the spatial groundwater stress zone through the AHP method to characterize and identify the groundwater depletion hotspots in Andhra Pradesh and also to evaluate the performance level of the AHP method.

MATERIALS AND METHODS

Study Area

Andhra Pradesh is a south-eastern state of India. It covers a geographical area of 160,205 km^2 and lies between 12°37'N to 19°10'N latitude and 76°45'E to 84°48' E longitude (Fig. 1). The state has Chhattisgarh and Odisha state in northeast, Telangana in northwest, Karnataka in the west, and Tamil Nadu in south and Bay of Bengal to the eastern part of this state. Godavari and Krishna are the major rivers that flow through the state and fall into the Bay of Bengal. The state experiences a tropical monsoon climate, and the climatic condition is influenced by topographical variation and coastal effects. The average temperature during May and June (summer months) is about 40°C, and in December and January (winter months), the temperature reaches 28°C. The mean annual temperature is 31.5°C. The mean annual rainfall is 952 mm, and south-west monsoon contributes 58% of the total annual rainfall (CGWB, 2016).

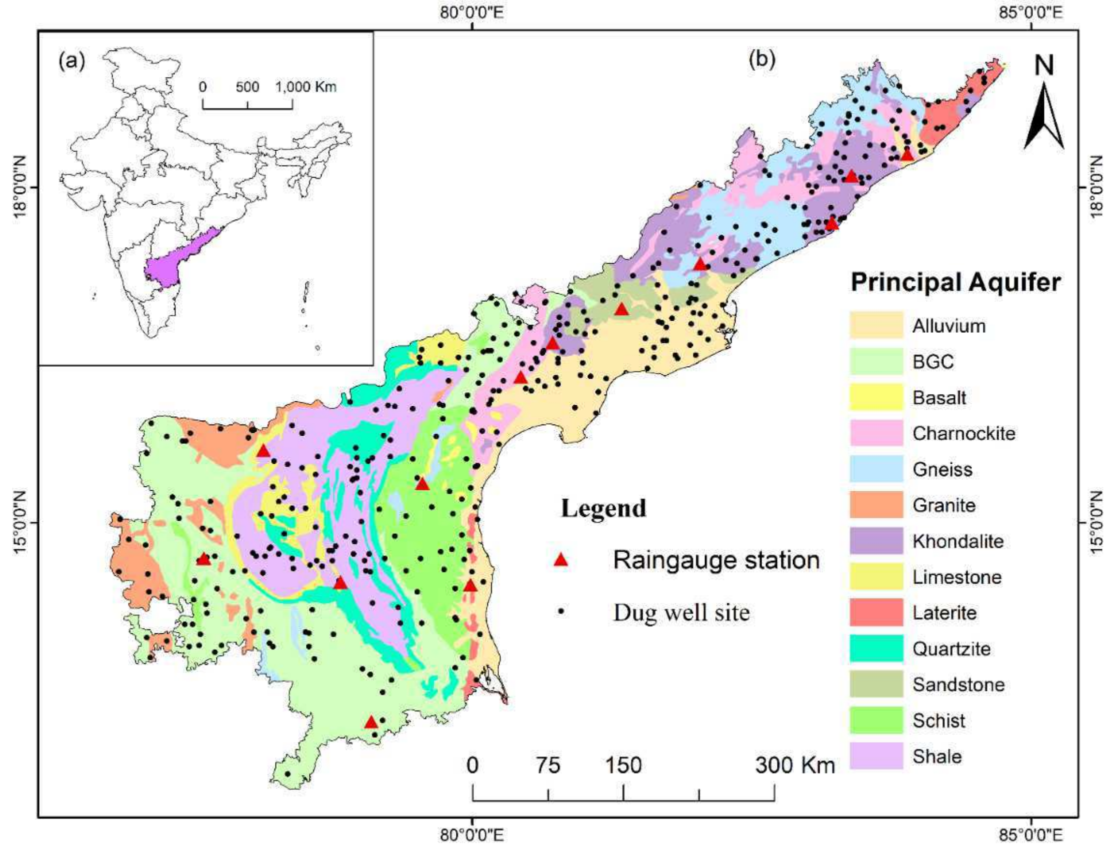

Fig.1. Location of study area **(a)** India and **(b)** Principal aquifer system of Andhra Pradesh with the location of rain gauge stations and dug well sites

Aquifer Characteristics

There is a great variety in physiography in Andhra Pradesh, ranging from hills and plains to deltaic plain. The state belongs to hard rock aquifer underlain by Archean to recent ages with various rock types (Reddy and Reddy, 2010). The hard rocks (igneous, volcanic, and metamorphic rocks) underlines about 85% and 15% of the total area is underlined by soft rock (sandstone, shale, and alluvium), respectively. Fractures in rocks play a significant role in the storage and movement of groundwater (Karunanidhi et al., 2014). In hard rocks, the yield of wells ranges between 10-35 m^3/hr, while in soft rocks yield of wells varies from 12-220 m^3/hr. The yield of wells ranges between 15-60 m^3/hr in the recent alluvial formation of the delta region (CGWB, 2020). The state has 36.50 billion cubic meters (BCM) of replenishable groundwater resources (annual) (CGWB, 2020). Generally, the entire state has been divided into 13 major aquifers. Alluvium covering the eastern and south-eastern coastal parts of the state. By contrast, southern and south-western parts are dominated by BGC, shale and granite aquifer. Likewise, khondolite, shale and gneiss cover the northern and north-eastern parts (Fig. 1). The availability of net annual groundwater resource is 32.95 BCM, out of which the annual groundwater draft is 14.90 BCM, and the exploitation rate of groundwater is 45% (CGWB, 2020). The depth of deep-water level (>20m) is found in Guntur, Prakasham, west Godavari, and Kurnool districts. In contrast, the moderate depth of groundwater level (8-20 m) is observed in east Godavari, Anantapur districts and shallow groundwater depth (<3m) are found in all coastal regions and Nellore district of the state (CGWB, 2016). About 219 Mandals overexploit the groundwater, and 77 Mandals are critical in terms of groundwater consumption.

Database

Recent monthly groundwater data (2004-2018) of Andhra Pradesh were collected from the website of Central Ground Water Board (CGWB) (http://cgwb.gov.in/GW-data-access.html). However, many stations have missing records of groundwater data. Therefore, the study has discarded these stations that had missing values. We collected the seasonal time series data of 429 stations of the groundwater level. The annual time series data of groundwater were aggregated from the seasonal time series. Irrigational and rainfall data as the driven forces of groundwater level fluctuation. Irrigational data (1997-2014) were collected from https://data.gov.in/ portal, while rainfall data was also used (1997-2018) were obtained from India Water Portal (IWP) website (https://www.indiawaterportal.org/) and Customized Rainfall Information System, Hydromet division, IMD (http://hydro.imd.gov.in/hydrometweb/(S(d2ezft3ehkd1dqypzhkr3c45))/landing.aspx). The data for computing cropping intensity (2016-2017) were downloaded from http://www.ap.gov.in/ portal.

Trend Analysis

The study used a non-parametric MK test to hydro-meteorological data (i.e., groundwater depth and rainfall) as well as in irrigational data to explore the significant trends (Mann, 1945; Kendall, 1975) and the magnitude of the slope was determined by Sen's Slope estimator (Sen, 1968). Though, the MK test is not capable of estimating the trend of auto correlated series (Rahman et al., 2018). Therefore, Modified Mann-Kendall (mMK) is applied to identify the trend in an autocorrelated data series (Hamed and Rao, 1998). The present study used the mMK test for the detection of the trend at lag-1 autocorrelated time series. On the other hand, the Spearman's rho (ρ) test measurement R and the standardized test statistic Z_{SR} are calculated. Further details of mathematical background can be found in Das et al., (2020c) and Das et al., (2019).

Multicollinearity

Generally, in multiple regression, multicollinearity occurs when two or more input variables are highly correlated with other input variables. The multicollinearity can lead to misleading results when the impact of every independent variable on the dependent variable is assessed (Mukherjee and Singh, 2020). It also determines whether an input variable is linearly predicted from other input variables, which led to a non-trivial degree of accuracy in the result. This is why it is inevitable to validate multicollinearity among these input variables before applying the regression model. An analysis of the linear regression method is performed for assessing this validation where an input variable is treated as the dependent variable and the rest of the input variable is considered as independent parameters. Afterwards, the value of R^2 is computed and after that, the value is again applied to compute tolerance and VIF (variance inflation factor) of input variable using to equations 10 and 11:

$$\text{Tolerance of the i}^{\text{th}}\text{ predictor variable } (T_i) = 1 - R_{\text{i}}^2 \tag{1}$$

$$\text{VIF of the i}^{\text{th}}\text{ predictor variable } (VIF_i) = 1/T_i \tag{2}$$

For every single input variable, the steps have been repeated and VIF, as well as tolerance, are computed for specific input variables. The VIF value of ≥ 10 and the tolerance value of <0.10 present multicollinearity problems (Saha, 2017). Decision factors with the VIF value of and the tolerance value of <0.10 are excluded from this evaluation.

Ten major decision factors were considered in the present study for the multicollinearity test and the study also selected 500 points among these decision factors. The data was collected randomly for these 500 selected points and checked and assessed the multicollinearity in R environment. The result of the multicollinearity test is presented in Table 1. The result obtained from the multicollinearity test showed that the tolerance value of >0.10 and VIF value <10 for every decision factor (p<0.01, p<0.05), which indicated that there is no collinearity among these decision factors (input variables). It also showed that no uncertainties are introduced in the model for multicollinearity conditions.

The Analytical Hierarchy Process (AHP)

AHP is the most powerful multi-criteria decision-making method, which is first introduced by Saaty in 1980. Generally, it is used for ranking the attributes to select the optimal attribute based on the hierarchical structure of goal at the top level, criteria at the second level and alternative at third level. The AHP model is used to quantify ten decision criteria applied in the present study and thereby assessed the performance of alternatives.

Table 1 Multicollinearity statistics

Evaluation Matrix	Groundwater depth	Groundwater trend	Magnitude of groundwater trend	Aquifer	Annual rainfall	Annual rainfall trend	Magnitude of annual rainfall	Irrigated area	Cropping intensity	Population Density
R²	0.418	0.389	0.502	0.188	0.554	0.627	0.703	0.162	0.684	0.653
Tolerance	0.582	0.611	0.498	0.812	0.446	0.373	0.297	0.838	0.316	0.347
VIF	1.718	1.636	2.008	1.231	2.242	2.68	3.373	1.193	3.162	2.884

At first, we built a tree-like hierarchical structure with a goal at the top. Second, we created a pairwise comparison matrix to give the relative importance of ten attributes concerning the goal of this model. Eventually, the third step was to compute the Consistency Ratio (CR) value to test whether we gave the correct importance to the different factors.

Pairwise Comparison Matrix

The study considered 10 decision factors and sub-factors in the AHP method. Based on the factors, a pairwise comparison matrix table was created. Then, priorities were given to each factor concerning the other factor. This relative importance was given with the help of scale relative importance, as shown in Table 2. The length of the pairwise matrix is equivalent to the attribute used in the decision-making process.

In the pairwise comparison matrix, weights of attributes, class weight, and CR value were calculated, as shown in Table 7. CR was computed by the following formula (Saaty, 1980, 2000):

$$CR = CI / RI \tag{3}$$

Consistency Index (CI)

The rule of transitivity was considered in the pairwise comparison matrix for the consistent result.

$$\lambda_{max} = \Sigma^{n}_{j=1} a_{ij} (w_j / w_i) = n \tag{4}$$

The value of CR determines the consistency of the matrix. If CR=0, a matrix is consistent, and the value >0 reveals the inconsistency of the matrix. Saaty (1980) proposed the consistency of the matrix (CR ≥ 0.10) to eliminate type II error. In our study, the value of CR was 0.0594.

In most of the cases, λ_{max} is not equal to n. Hence, we computed CI to portray whether the rule of transitivity was violated or not. CI was determined by the following equation:

$$CI = (\lambda_{max} - 1) / (n - 1) \tag{5}$$

The Priority Weights within the Hierarchy

The relative importance between the attribute (sub-attribute) was achieved by computing the eigenvector. The pairwise wise comparison matrix (A) was multiplied with priority weight (W) equivalent to (n.W)

$$A.w = n.\,W \tag{6}$$

From the above equation we can say that:

$$(A - n)\,W = 0 \tag{7}$$

The relative importance of attributes and sub-attributes achieved by the pairwise comparison matrix is shown in Table 7.

RESULTS AND DISCUSSION

Trend in groundwater depth

The recent trend of groundwater depth of 429 dug wells during 2004-2018 was calculated using the Mann-Kendall (MK) or Modified Mann-Kendall (mMK) test, and Sen's slope estimator determined its magnitudes in Andhra Pradesh. An increasing trend of Z statistic indicates that the groundwater level is declining while the decreasing trend of Z statistic shows the rising trend of groundwater level.

Table 2. Fundamental 9-point intensity scale for measuring relative importance between two parameters

Scale of relative importance

Intensity of Relative Importance	Definition	Explanation
1	Equal importance	Two activities contribute Equally to 1
3	Moderate importance	Experience and judge slightly favor one activity over another activity
5	Strong or essential importance	Experience and judge strongly favor one activity over another activity
7	Very strong importance	An activity is strongly favored and its dominance is exhibited in practice
9	Extreme importance	The evidence of favoring one activity over another is of highest possible order of affirmation
2,4,6,8	Intermediate	Applied when comparison is required
Reciprocals	Inverse comparison	Applied in inverse comparison

Trend in Groundwater Depth in the Wet Season

The trend of groundwater depth in the wet season is presented in Table 3, and its spatial variations are shown in Fig. 2a. The results of Z statistics showed that 62.47 % stations of the study area experienced an increasing trend in this season, of which 6.53% (α = 0.01) and 7.69% (α = 0.05) stations witnessed the significant increasing trend of groundwater depth. The significant increasing trend was mostly observed in the south-western part of the state (Fig. 2a). The result of the Rho test also showed a similar result and portrayed that 6.99 % (α = 0.01) and 6.99 % (α = 0.05) stations of the state exhibited increasing groundwater trends, as presented in Table 4. The significant positive slope in the wet season was varied from 0.06 cm/year to 1.57 cm/year (α = 0.01). On the contrary, the slope was varied from 0.06 cm/year to 1.99 cm/year (α = 0.05) in this season. Fig. 3a showed that positive slope was found in the Kurnool, Anantapur, Kadapa, West Godavari and Krishna districts in the wet season.

On the other hand, during the wet season, 3.50 % (α = 0.01) and 1.86% (α = 0.05) stations showed significant decreasing groundwater depth (Table 3). By contrast, the results of the Rho test (Table 4) depicted that the decreasing groundwater trend was observed in 3.96% (α = 0.01) and 3.26% (α = 0.05) stations. Fig. 2d indicated that decreasing groundwater trends were found in southern, eastern, and north-eastern parts of the state. The significant negative slope at (α = 0.01) was varied from -0.02 cm/year to -3.24 cm/year in wet season, while at (α = 0.05) the significant slope was ranged between and -0.87 cm/year and - 0.05 cm/year in this season.

Trend in Groundwater Depth in the Dry Season

The results of Z statistics (Table 3) showed that the increasing trend of groundwater was detected in 74.83 % stations in the dry season. However, significant increasing trend was detected in 13.05% (α = 0.01) and 11.19% (α = 0.05) stations in dry season. This rising trend was found in the south-western and eastern parts of the state (Fig. 2b). The results of the Rho test are presented in Table 4 and showed that 73.19 % of stations experienced an increasing trend in the dry season. Though, the significant increasing trend was detected in 12.59 % (α = 0.01) and 14.92 % (α = 0.05) stations of the state. The significant positive slope at (α = 0.01) was varied from 0.06 to 3.68 cm/year,

Table 3. Trend detection using MK and mMK methods at different confidence levels

	Minimum		Maximum		Average	
	Number of Observation Wells	% of Wells	Number of Observation Wells	% of Wells	Number of Observation Wells	% of Wells
Increasing Trends in Groundwater Depth						
99% Confidence Level	28	6.53	56	13.05	60	13.99
95% Confidence Level	33	7.69	48	11.19	44	10.26
Insignificant	207	48.25	217	50.58	201	46.85
Total	**268**	**62.47**	**321**	**74.83**	**305**	**71.10**
Decreasing Trends in Groundwater Depth						
99% Confidence Level	15	3.50	5	1.17	11	2.56
95% Confidence Level	8	1.86	9	2.10	11	2.56
Insignificant	138	32.17	94	21.91	102	23.78
Total	**161**	**37.53**	**108**	**25.17**	**124**	**28.90**

Table 4. Trend detection using Spearman Rho test at different confidence levels

	Minimum		Maximum		Average	
	Number of Observation Wells	% of Wells	Number of Observation Wells	% of Wells	Number of Observation Wells	% of Wells
Increasing Trends in Groundwater Depth						
99% Confidence Level	30	6.99	54	12.59	70	16.32
95% Confidence Level	30	6.99	64	14.92	56	13.05
Insignificant	189	44.06	196	45.69	173	40.33
Total	**249**	**58.04**	**314**	**73.19**	**299**	**69.70**
Decreasing Trends in Groundwater Depth						
99% Confidence Level	17	3.96	8	1.86	16	3.73
95% Confidence Level	14	3.26	10	2.33	12	2.80
Insignificant	149	34.73	97	22.61	102	23.78
Total	**180**	**41.96**	**115**	**26.81**	**130**	**30.30**

while at (α = 0.05) the value ranged from 0.08 cm/year to 3.97 cm/year. Most of the stations of Anantapur and Kadapa districts delineated the positive slope of groundwater depth in the dry season (Fig. 3b).

It was evident from the Z statistics that 1.17% (α = 0.01) and 2.10 % (α = 0.05) stations showed significant decreasing groundwater depth. On the other hand, the results of the Rho test showed that the significant decreasing trend was noted in 1.86 % (α = 0.01) and 2.33 % (α = 0.05) stations of the state. Similar trends were identified in spatial trend analysis of Z statistics and rho test. The results of Sen Slope showed that decreasing slope varied from -1.55 cm/year to - 0.01 cm/year in the dry season.

The seasonal trend analysis showed that the groundwater depth was increased in a relatively large number of stations in the dry season compared to the monsoon season and the magnitude of the slope was also steep in the dry season. This is due to the lower amount of recharge of groundwater dynamics through rainfall and increased consumption of groundwater by different sectors. Another interesting fact of seasonal groundwater trend is that south-western districts are more prone to groundwater depletion regarding increasing trend of groundwater depth.

Annual Trend in Groundwater Depth

The results of annual Z statistics are presented in Table 3 and showed that most of the stations (71.10%) of the study area experienced increasing groundwater depth. Approximately 13.99 % (α = 0.01) and 10.26 % (α = 0.05) stations witnessed a significant increasing trend. Fig. 2c depicted that most of the annual significant increasing trend was found in the south-western and eastern parts of the state. The Spearman Rho test also portrayed similar results. Table 4 indicated that significant increasing groundwater depth was detected in 69.70% stations. Approximately 16.32 % (α = 0.01) and 13.05% (α = 0.05) stations of the study area experienced significant increasing trend. The significant positive slope was varied from 0.06 cm/year to 2.86 cm/year at (α = 0.01) and 0.06 cm/year to 1.29 cm/year at (α = 0.05). Fig. 3c showed that the annual positive slope was mostly observed in the Anantapur, Kadapa, Chittoor, and Prakasham districts.

On the contrary, Z statistics showed 2.56 % (á = 0.01) and 2.56 % (α = 0.05) of stations witnessed significant decreasing groundwater depth. The result of Rho test (Table 4) depicted 3.73 % (α = 0.01) and 2.80% (α = 0.05) of stations witnessed significant decreasing groundwater depth. The annual negative slope was varied from -0.07 cm/year to -2.86 cm/year (α = 0.01) and -0.08 cm/year to - 0.78 cm/year (α = 0.05). Overall results of annual and seasonal groundwater trends showed that most of the stations had experienced an increasing trend of groundwater depth, which ultimately indicated a decline in the groundwater levels. Similar results were achieved by many researchers (Dhar et al., 2014; Thakur and Thomas, 2011). In addition, the spatial analysis showed that significant groundwater depletion was mainly recorded in the south-western part of the state. These findings show the steady groundwater depletion in this part and hence, some strategies and policies need to be adopted to meet the water needs of different sectors in the future.

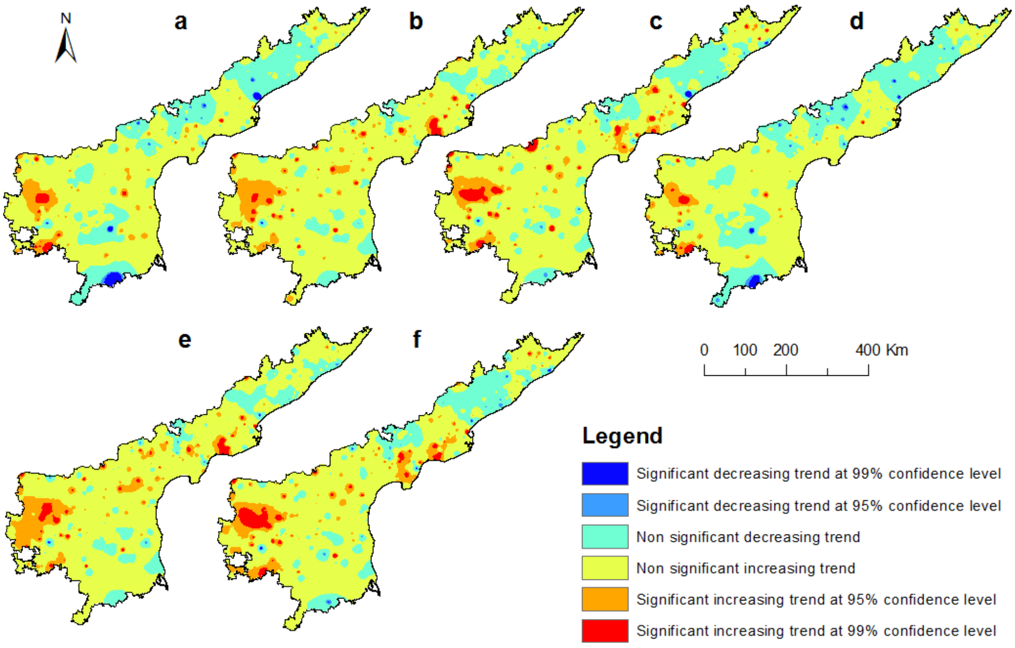

Fig. 2. The trend of groundwater depth **(a)** Z statistic of wettest month, **(b)** Z statistic of driest month **(c)** Z statistic of annual average, **(d)** Spearman's Rho of wettest month, **(e)** Spearman's Rho of driest month and **(f)** Spearman's Rho of the annual average.

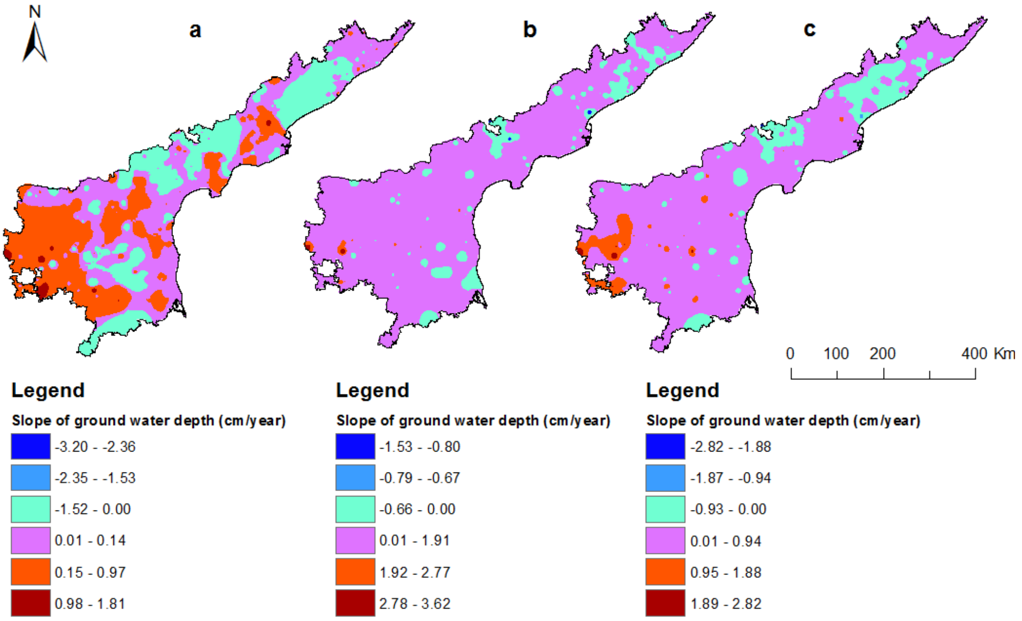

Fig. 3. The magnitude of trend of groundwater depth **(a)** wettest month, **(b)** driest month and **(c)** annual average.

Driving Forces of Groundwater Fluctuations

Rainfall

Rainfall is the most effective climatic variable and the driving force of groundwater storage. In general, the infiltration process increases with the increase in rainfall, which ultimately results in higher groundwater storage. Fig. 4 graphically summarized the seasonal and annual rainfall trends in Andhra Pradesh. Fig. 4a depicted that seven districts of the state displayed a decreasing trend of rainfall in Pre-monsoon season. Anantapur ($\alpha = 0.05$) and Krishna ($\alpha = 0.01$) districts exhibited a significant decreasing trend. Nevertheless, the significant increasing trend (α = 0.01, α =0.05) was detected in Srikakulam, Vizianagaram and Vishakhapatnam in the pre-monsoon season. Fig. 4b represented that only the Anantapur district experienced a significant decreasing trend (α = 0.01) of rainfall in the monsoon period. However, most districts displayed an insignificant trend of rainfall. In the post-monsoon season, Fig. 4c demonstrated that only Kadapa district experienced a significant increasing trend ($\alpha = 0.05$). Throughout this season the rainfall ranged from -8.88 mm/year to 2.13mm /year in this season. In the winter season, the districts of Guntur, Kurnool, Prakasham, Anantapur and West Godavari experienced a significant decreasing trend (α = 0.01, α =0.05), as shown in Fig. 4d. Other districts did not exhibit any significant trend of rainfall during this season.

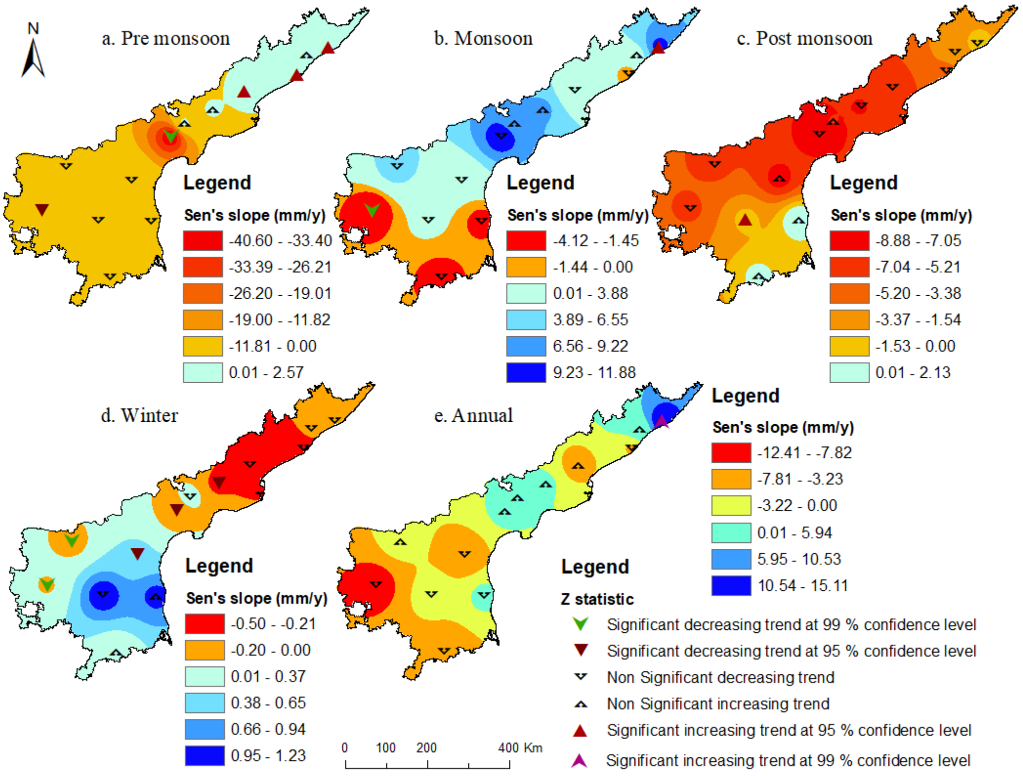

Fig. 4. Trend of rainfall **(a)** Pre-monsoon season, **(b)** monsoon season, **(c)** Post-monsoon season, (d) Winter season and (e) Annual.

Fig. 4e displayed the annual trend of rainfall in Andhra Pradesh. Table 6 showed that annual rainfall had both increasing and decreasing trends. However, a significant increasing trend ($\alpha = 0.01$) was detected only in the Srikakulam district of the state (Table 6). The slope of annual rainfall varied from -12.41 to 15.11 mm/year, as shown in Fig. 4e. The decreasing trend of rainfall was detected in Anantapur, Chittoor, Prakasham, Kadapa, Nellore, and East Godavari districts. Of these, the decreasing rate was very steep only in Anantapur district, as shown in Fig .4e. Likewise, an increasing rate of groundwater depth was observed in Anantapur district and some parts of Kadapa, Chittoor and Prakasham districts, as shown in Fig. 3c. The trends of rainfall and groundwater depth exhibited that rainfall had an inverse relationship with the groundwater depth and a proportional relationship concerning groundwater level. The comparison results between the trends of rainfall and groundwater depth showed that a steep decreasing rate of rainfall could lead to increase groundwater depth. Several researchers also established the relationship between rainfall and groundwater level. Kotchoni et al. (2019) reported that higher annual groundwater recharge was observed during the high annual rainfall time period. Abdullahi and Garba (2015) also showed a strong positive relation between rainfall and groundwater recharge.

Irrigation

Figure 5 showed the district-wise distribution of irrigated areas in Andhra Pradesh during rabi cultivation, while Fig. SM1 demonstrated the graphical representation of irrigated areas. During Rabi cultivation (1997), higher irrigated areas were noticed in the districts of Kurnool, East Godavari, Nellore, West Godavari, and Krishna, as shown in Fig. 5a. On the other hand, higher irrigated areas in 2014 were found in Kurnool, Prakasham, West Godavari, Nellore, Krishna and Guntur districts. The comparative discussion between 1997 and 2014 showed

Table 5. Trend of rainfall by MK &mMK Test at different confidence levels in the study area (1997-2018)

District	Pre-monsoon		Monsoon		Post-monsoon		Winter		Annual	
	Z	Q	Z	Q	Z	Q	Z	Q	Z	Q
Anantapur	-1.96*	-1.84	-1.64	-4.13	-2.80**	-5.58	-0.25	-0.03	-3.29	-12.41
Chittoor	-1.46	-1.23	-1.21	-2.68	0.22	0.46	0.12	0.05	-1.33	-7.18
East Godavari	-0.65	-0.70	-0.19	0.33	-0.42	-0.98	2.23*	1.23	-0.57	-0.73
Guntur	2.06*	2.20	0.23	0.35	-1.86	-6.57	-0.74	-0.42	-1.07	-5.71
Kadapa	-3.05**	-40.63	1.64	11.89	-2.75**	-8.89	-0.20	-0.22	-0.22	0.82
Krishna	1.27	1.64	1.12	7.74	-1.86	-7.00	0.52	0.10	0.12	2.15
Kurnool	-1.71	-0.86	1.92	6.12	-2.90**	-5.72	-1.27	-0.16	-0.52	-0.94
Prakasham	-0.57	-0.36	-1.21	-2.48	0.17	2.13	0.57	1.07	-0.27	1.27
Nellore	-0.47	-0.25	-0.28	0.39	-2.11*	-8.01	0.52	0.42	-1.66	-7.29
Srikakulam	2.06*	1.94	2.80**	10.16	-0.57	-0.96	-0.20	-0.08	2.16	15.12
Visakhapatanam	2.11*	2.57	-0.47	-1.25	-1.31	-3.82	-0.60	-0.50	-0.97	-3.73
Vizianagaram	1.46	1.51	1.07	3.02	-1.17	-2.52	-0.35	-0.12	0.22	2.16
West Godavari	1.31	0.89	1.21	7.17	-2.01*	-7.14	-0.55	-0.27	0.02	0.61

Z= MM/mMK Test, Q= Sen slope (mm/y), * Significant at 95% confidence level ** Significant at 99% confidence level that the irrigated area tremendously increased in Kurnool, Prakasham and Kadapa districts in 2014. On the contrary, Fig. 5c displayed that the irrigated areas were dramatically decreased in Chittoor, Vizianagaram and East Godavari districts in 2014. Table 5 also showed a decreasing trend in these three districts from 1997-2014. Of these, Chittoor (α = 0.01) and East Godavari (experienced a significant decreasing trend. However, only East Godavari district showed a steep decreasing rate of irrigated areas. Table 5 also showed that a significant increasing trend (α = 0.01, α =0.05) was found in these districts of Anantapur, Kadapa, Kurnool, Prakasham, Nellore, Srikakulam and West Godavari during rabi cultivation. However, the rate was very steep in Prakasham, Kadapa, West Godavari, and Nellore districts. Likewise, increasing rate of groundwater depth was also very steep in Anantapur and some parts of Kadapa, Chittoor and Prakasham districts, as shown in Fig. 3c. Therefore, it can be said that an increasing trend of irrigated areas in these districts, as mentioned earlier. This might be one of the principal reasons for increasing groundwater depth. Hence, it can be stated that an uncontrolled pumping system for irrigation withdrawals huge amounts of groundwater and ultimately causes severe groundwater depletion. Several researchers also focused on the impacts of irrigation on groundwater level fluctuations. Prasuna et al. (2018) showed that Andhra Pradesh is characterized by the hard rocks of the aquifer and poor groundwater storage. Most of the agricultural areas were not favorable for intensive irrigation. Though, the state accounts for 7.3 % of total irrigated areas in India. This finding depicts enormous pressure caused by intense irrigation on the aquifer system. Ozel et al. (2019) showed that uncontrolled irrigation ushered the severe groundwater depletion. Madhnure and Lavanya (2021) studied the challenges of groundwater-based irrigation. Their findings exposed that salinization was the major adverse impact of irrigation in terms of water quality.

Criteria Assessment for Groundwater Stress Zoning Map

The present study considered 10 major factors (i.e., groundwater depth, groundwater trend, the magnitude of groundwater trend, aquifer, annual rainfall, the trend of annual rainfall, magnitude of annual rainfall, irrigated area, cropping intensity and population density) and 43 sub-factors to generate the groundwater stress zonation map. The study also created a matrix table for the comparison of these criteria and sub-criteria in pairs. In relation, the relative importance of each criterion was determined using this pairwise comparison matrix table. Afterwards, the CR value was calculated after the computation of relative weight. This comparison between the factors showed that the measured CR value was less than 0.10. Therefore, such factors and sub-factors can be reasonably considered for AHP analysis. Table 7 depicted the relative weights of decision factors and showed that the trend in groundwater and its magnitude were both the most important attributes for evaluating groundwater stress zone as compared to other factors. The relative weights of the groundwater trend and magnitude of trend were 0.174. In general, the areas with an increasing trend of groundwater depth are more vulnerable with regard to groundwater levels, as the increasing trend of groundwater depth denotes the depletion of groundwater levels. Similarly, the steepest increasing rate of groundwater depth also exhibits the depletion of groundwater level. The annual and seasonal increasing trends of groundwater depth were observed in Anantapur, Kurnool, Kadapa, Chittoor, Krishna and West Godavari districts (Figs. 2a, 2b and 2c). Likewise, the steepest increasing rate was also observed in these districts. Fig. SM2a also depicted the average groundwater depth and showed that the districts of Anantapur, Kurnool, Prakasham, Krishna, West Godavari and East Godavari had relatively greater groundwater depth. Therefore, from the above discussion and pairwise comparison matrix table (Table 7), it can be concluded that these districts which are mostly located in the south-western parts which are more vulnerable in terms of decline groundwater levels.

Annual trend of rainfall, the magnitude of rainfall trend and amount of annual rainfall were other important factors for groundwater vulnerability assessment. The relative weights of the annual trend of rainfall, magnitude of rainfall trend, and the amount of annual rainfall were 0.125, 0.123 and 0.12, respectively. The depth of groundwater usually decreases with the increase of rainfall. Fig. SM2b graphically represented the average annual rainfall and showed that south-western part of Andhra Pradesh, particularly Anantapur, Kurnool, Kadapa, and Prakasham districts had the lowest average annual rainfall. On the contrary, the comparatively higher amount of annual rainfall was observed in West Godavari, East Godavari, Krishna, Vishakhapatnam, Vizianagaram and Srikakulam districts. So, it can be said that the districts that showed the lowest rainfall and decreasing trend were more vulnerable. By contrast, the population density was the least

Table 6. Trend of Rabi crop irrigated area by MK & mMK Test at different confidence level in the study area (1997-2014)

Sl. No.	District	Z	Sen's Slope
1	Anantapur	2.8**	3215.6
2	Chittoor	-2.35*	-1024.25
3	East Godavari	-2.65**	-4646.38
4	Guntur	1.89	3088.6
5	Kadapa	4.39**	6109.73
6	Krishna	0.83	1005.91
7	Kurnool	2.81**	8024
8	Prakasham	4.17**	8629.89
9	Nellore	7.85**	3460.53
10	Srikakulam	1.97*	963.57
11	Visakhapatanam	0.63	422.67
12	Vizianagaram	-1.67	-1136.67
13	West Godavari	3.71**	3644.67

* Significant at 95% confidence level. ** Significant at 99% confidence level

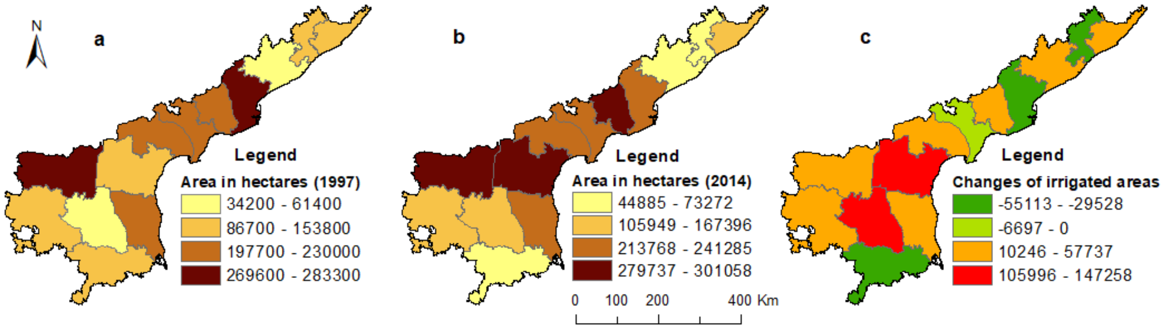

Fig. 5. District-wise distribution of Rabicrops irrigated area of **(a)** 1997, **(b)** 2014 and **(c)** Changes between two periods.

Table 7. Pair-wise priority rating of different data layers based on the AHP method

Decision factors	Weight of each factor	Decision Sub factors	Rating
Ground water depth	0.091	Low	0.072
		Medium	0.279
		High	0.649
Ground water trend	0.174	Significant decreasing trend at 99% Confidence level	0.028
		Significant decreasing trend at 95% Confidence level	0.036
		Non-Significant decreasing trend	0.053
		Non-Significant increasing trend	0.111
		Significant increasing trend at 95% Confidence level	0.282
		Significant increasing trend at 99% Confidence level	0.49
Magnitude of Ground water trend	0.174	- 2.82 to -1.88	0.027
		- 1.87 to -0.94	0.034
		- 0.93 to 0	0.054
		0.01 to 0.99	0.135
		0.95 to 1.88	0.235
		1.89 to 2.82	0.515
Aquifer	0.075	Alluvium	0.028
		Sandstone	0.04
		Limestone	0.1
		BGC, Shale	0.179
		Charnockite, Gneiss,Schist	0.264
		Granite, Khondalite, Laterite, Basalt, Quartzite	0.389
Annual rainfall	0.12	Low	0.731
		Medium	0.188
		High	0.081
Annual rainfall trend	0.125	Significant decreasing trend at 99% Confidence level	0.594
		Non-significant decreasing trend	0.253
		Non-significant increasing trend	0.114
		Significant increasing trend at 95% Confidence level	0.039
Magnitude of annual rainfall	0.123	- 12.41 to -7.81	0.445
		- 7.81 to -3.23	0.258
		- 3.22 to 0	0.169
		0.01 to 5.94	0.066
		5.95 to 10.53	0.039
		10.54 to 15.11	0.023
Irrigated area	0.075	Low	0.07
		Medium	0.223
		High	0.707
Cropping intensity	0.028	Low	0.143
		Medium	0.286
		High	0.571
Population Density	0.015	Low	0.088
		Medium	0.249
		High	0.669

important criteria for the evaluation of groundwater stress zones (Table 7). The relative weight of population density was only about 0.015. Population density and cropping intensity were higher in the districts of Srikakulam, Vizianagaram, Krishna, West Godavari and East Godavari (Figs. 7c and 7d). Therefore, the depth of groundwater was expected to be higher in these districts. Although the average depth of groundwater was lower in these districts. This finding indicates that population density and cropping intensity may be the least important factors for the groundwater stress zonation assessment in the state, as shown in Table 7.

Groundwater Stress Zone and Delineation of Groundwater Depletion Hotspots

The AHP method was used to prepare the groundwater stress zonation map in terms of groundwater depletion. A total of 10 major decision factors and 43 sub-factors were incorporated to develop this assessment. These decision factors were assessed by assigning the relative weight of each factor (Table 7). Afterwards, the groundwater stress zonation map was generated based on the relative importance of each decision factor. The principal factors for this assessment were groundwater depth, groundwater trend and trend of rainfall, as shown in Table 7.

The map of the groundwater stress zone classified the entire state into five categories, namely very low, low, moderate, high and very high-stress zones (Fig. 6). As indicated in Fig. 6, about 19.59 % of areas were identified as the very high-stress zone in terms of groundwater depletion. In this high-stress zone, the trend of groundwater depth and irrigated areas were steadily increasing and the trend of rainfall was declining continuously over time. The map further revealed that 18.86 % of areas were classified as the high-stress zone. Nevertheless, 24.63 %, 16.93 % and 19.99 % of areas were categorized as moderate, low and very low-stress zones,

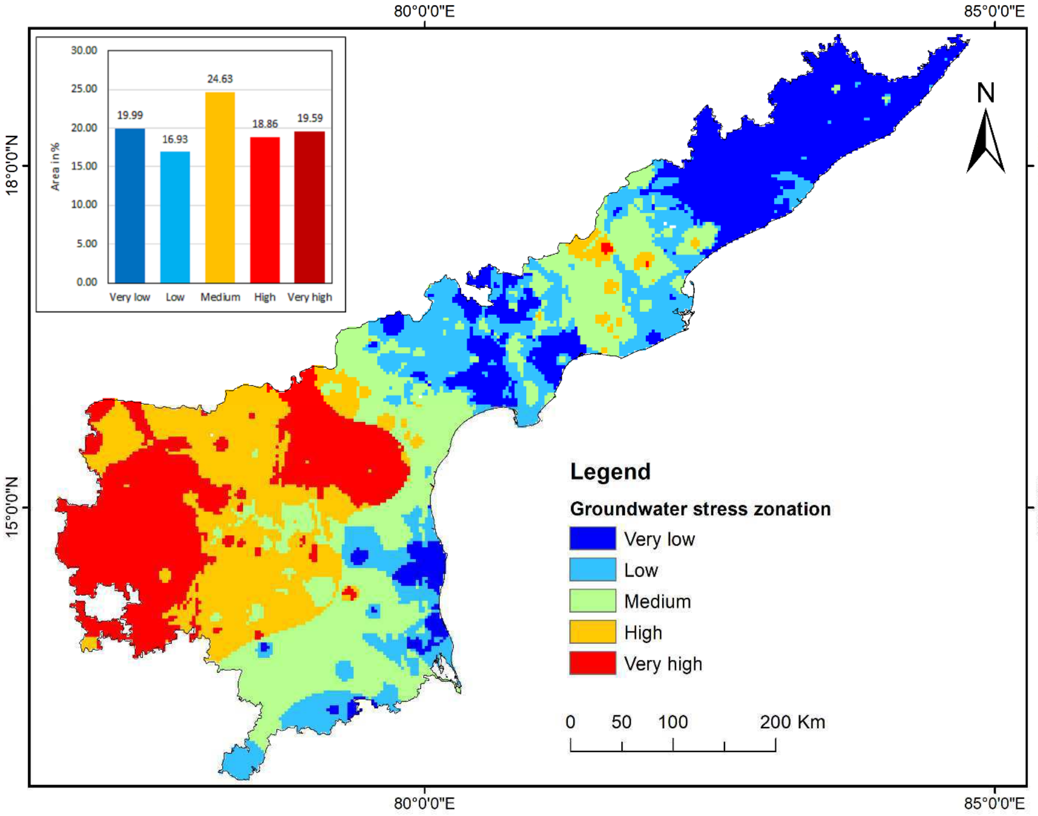

Fig. 6. Potential Groundwater stress zone of Andhra Pradesh

respectively (Fig. 6). The map also revealed that the aquifer system was under intense pressure in 38.45 % of the two high-stress zones combined (i.e., high and very high-stress zones). Significant higher stress on present aquifer was found in south-western districts like Anantapur, Kurnool, Prakasham, Kadapa and East Godavari. It may be due to lower rainfall and higher pressure caused by anthropogenic activities. Contrarily, comparatively low-stress zone was identified on the aquifer of Srikakulam, Vizianagaram, Vishakhapatnam, Krishna, Guntur and Nellore districts.

Groundwater levels were decreasing over time in south-western districts, making these districts more vulnerable to groundwater depletion. Therefore, these districts were identified as groundwater hotspots with reference to the trend of groundwater level and stress zonation map. The appropriate planning for the efficient management of current aquifer systems in these districts should be developed.

Validation of Groundwater Stress Zoning Map

Validation is an important procedure in modeling hydro-climatic variables as the scientific value of these models cannot be approved without the validation. In the present study, the assessment of the groundwater stress zonation map was validated with the magnitude of Sen's slope in Andhra Pradesh. Hence, the Sen's slope values (groundwater depth) of total of 429 dug wells, covering different geological settings of Andhra Pradesh, were analyzed to evaluate this validation. The computed values of Sen's slope were usually in the positive and negative forms. The positive values of Sen's slope

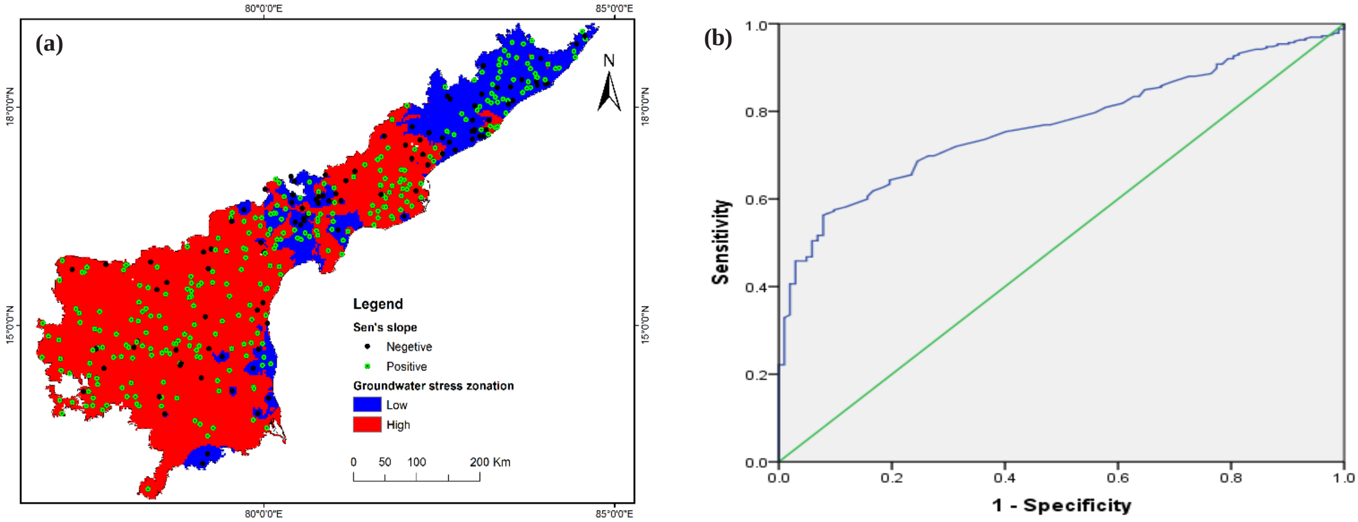

Fig. 7. Validation ofpotential Groundwater stress zone of Andhra Pradesh using **(a)** Sen's slope map of groundwater stress zone and (b) ROC curve

indicated gradual groundwater depletion in the study area and it also portrayed that the region was located in the more vulnerable areas with reference to groundwater depletion. In contrast, the negative values of groundwater depth signified opposite condition of the aquifer. The present aquifer of the state was categorized into two basic classes of groundwater stress zones, based on the magnitude of slope and these two classes were high-stress zone (positive values) and low-stress zone (negative values). In the present study, the validation map was obtained from Sen's slope values which indicated that south-western districts namely Anantapur, Kurnool, Kadapa, Chittoor, Nellore, Prakasham and eastern district such as East Godavari were more stressful to groundwater depletion. This is because positive Sen's slope values were observed in most of dug wells in these areas (Fig. 7a). On the other hand, the negative magnitude of Sen's slope indicated that the groundwater level had been increased in Srikakulam, Vizianagaram, Vishakhapatnam, Krishna and West Godavari districts. So, these districts were less vulnerable to groundwater depletion (Fig. 7a). This validation map proved that the groundwater stress zonation map which was obtained from Sen's slope having closely matched result with the stress zonation map acquired from the AHP model.

The present study further evaluated the results of the groundwater stress zone obtained through the AHP method using the evaluation metrics of ROC (receiver operating characteristics) and AUC (area under curve) analysis. This ROC curve plots True Positive Rate (TPR) against False Positive Rate (FPR). The AUC value is a measure of separability and its value generally ranges from 0 to 1. A higher value of AUC represents the better performance of the model. Fig. 7b showed the ROC predicting curve. The prediction curve assessment results exhibited that the AUC value was 0.767 in groundwater stress zonation map. Therefore, the validation of groundwater stress zonation map revealed reliable performance of AHP method, as the method has achieved higher AUC value. Therefore, satisfactory results were obtained through AHP method by determining the sufficient and relevant decision factors of groundwater stress zone.

CONCLUSIONS

A conceptual framework for visualizing the present aquifer, groundwater stress zone and groundwater depletion hotspots, which is essential for systematic management of groundwater resources. In the present study, seasonal and annual trends of groundwater depth were analyzed using Mann-Kendall (MK) or modified Mann-Kendall (mMK) test and Spearman's Rho test for 429 dug wells in Andhra Pradesh. In addition, an integrated framework based on multi-criteria was developed through the AHP method for groundwater stress zonation map. The results of seasonal and annual Z statistics showed that groundwater depth had been increased in most of the stations. However, an increasing trend and its magnitude were comparatively higher than the monsoon season as well as annual scale due to lower recharge and excessive uses of groundwater during the dry season. Results also analyzed the fact that the groundwater level had decreased in districts where low rainfall and high groundwater consumption were found. In addition, the spatial analysis showed that most of the significant increasing trend in groundwater depth was found mainly in the south-western parts. Consequently, different types of environmental and ecological problems may occur which ultimately restrict socio-economic progress in the south-western parts. Therefore, appropriate strategies need to be adopted for the effective management of groundwater resources.

For groundwater stress zone assessment, a total of 10 criteria and 43 sub-criteria that are responsible for groundwater fluctuation were applied in the AHP method. The results obtained from the AHP analysis showed that groundwater depth, groundwater trend and rainfall trend were the principal factors for the groundwater stress zone assessment. The AHP method provided satisfactory results (AUC = 0.767) since the groundwater stress zonation map was obtained by integrating the thematic map of different criteria and the map of Sen's slope perfectly matched each other. Besides, both generated maps indicated that southwestern districts such as Anantapur, Kurnool, Chittoor and Prakasham were identified as groundwater depletion hotspots regarding the stress zonation map and trend of groundwater depth. Hence, the AHP method proved to be a robust method for depicting groundwater stress zone by incorporating multi-criteria. This method can also be adopted in a variety of climatic environments with suitable modification in criteria selection. The findings of the current study can be a guideline for the visualization and demarcation of the groundwater depletion hotspots. Hence, the study will assist groundwater resource managers and practitioners in proper groundwater management and development.

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