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Analyzing Coastal Groundwater Variability in Sindhudurg, Maharashtra: A Spatio-temporal GIS Approach

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ABSTRACT

Due to a sharp increase in groundwater demands in coastal regions, groundwater levels are getting depleted day by day. The local groundwater table fluctuation eventually speeds up sea water intrusion. The present study investigates spatial and temporal groundwater level fluctuations to identify the area affected by sea water intrusion as well as for sustainable water resource management in coastal stretch of Sindhudurg district, Maharashtra, which is about 121 km. Using groundwater level data collected from Central Groundwater Board (CGWB), Sindhudurg for the period from 1991 to 2022, fluctuations of groundwater levels were examined. The collected levels were evaluated for monsoon, pre-monsoon & post-monsoon seasons and all levels were interpolated over the study area using the Inverse Distance Weighted Method as a spatial interpolation technique in QGIS 3.22.1, in order to obtain the actual differences in groundwater levels. According to the results, the groundwater level varies from 1.88m to 13.45 m below ground level (bgl) in the pre-monsoon season, from 0.1m to 7.05 m (bgl) in the post-monsoon season and from 1m to 10.6m (bgl) in the monsoon season. Using statistical tests like Mann-Kendall test & Sen's slope estimator, the pattern of variation of groundwater levels was anticipated. According to our findings, over 80% of the basin has a falling water table during the monsoon season. It was observed that the groundwater level in the pre-monsoon season was more as compared to those in the monsoon and the post-monsoon seasons in the entire study area. The overall outcome of the study demonstrates that the groundwater level fluctuations were non-uniform in the study area, which may cause an increase in the sea water intrusion, leading to a decrease in crop production.

Keywords: GIS, Groundwater level, Sea water intrusion, Mann Kendall test, Spatial interpolation, Sen’s slope estimator.

INTRODUCTION

Surface water supplies are scarce and evaporation rates are high in arid and semi-arid regions. That’s why groundwater is a crucial source of water for the agricultural, household and industrial sectors. Drinking water from groundwater resources is being used more and more as population rises (Mack et al., 2013). Growth in the population and economy puts further strain on groundwater supplies and poses a threat to water security for meeting various rising demands and the availability of fresh water (Gehrels et al., 1994; Tabari et al., 2012). Monitoring groundwater levels is one of the key strategies for sustainable growth and offers crucial data for water management (Mende et al., 2007).

One of a country's main development objectives should be the efficient management of groundwater resources when considering increasing demand for safe drinking water (Konikow & Kendy, 2005; Zektser et al., 2005). Worldwide, groundwater abstraction has been growing quickly and steadily (El Moujabber et al., 2006), and in many places, excessive groundwater abstraction has led to significant reductions in groundwater levels. There are several negative effects of declining groundwater levels on the ecosystem (Patle et al., 2015). The most obvious sign of groundwater depletion is a fall in groundwater level, which affects the sustainability of aquifer development (Ahmadi & Sedghamiz, 2008).

Other noticeable effects include groundwater contamination owing to extra recharge from leaking sewers and other sources of wastewater (Daneshvar Vousoughi et al., 2013) and land subsidence caused by compaction of aquifer materials (Naidu & Gupta, 2018). Similar to how lower groundwater flows have an impact on ecosystems, surface waterways are likewise impacted (Sorek et al., 2004).

Measurement and analysis of the groundwater level, variations, and geographic and temporal conditions constitute the first step in this direction. It is possible to apply geostatistic techniques, which have been shown to be successful for spatial analysis, and trend analysis and stationary tests for temporal analysis (Ahmadi & Sedghamiz, 2007). The analysis of the temporal variations of groundwater level has not received as much attention as the studies that have looked at the spatial patterns of groundwater level (Ravichandran et al., 2023). This is because groundwater level monitoring requires a lot of time and labour, and funding constraints have made it impossible to measure data regularly and often in upcoming years (Alipour et al., 2018).

Understanding the dynamic nature of coastal groundwater levels is crucial for effective management, as highlighted by the need for spatio-temporal analysis in regions like Sindhudurg (Daliakopoulos et al., 2005). The integration of GIS with AI-based models could potentially enhance the prediction and analysis of groundwater level fluctuations in coastal areas, such as Sindhudurg, building upon the foundational work of Tao et al. (2022).

To effectively address the complexities of coastal groundwater systems in regions like Sindhudurg, a comprehensive approach combining hydrological modeling, GIS, and AI techniques, as suggested by Rajaee et al. (2019), is necessary. The spatio-temporal analysis of groundwater levels in coastal regions -like Sindhudurg- can benefit from advancements in machine learning, as demonstrated by (Daliakopoulos et al., 2005; Tao et al., 2022), to improve prediction accuracy and inform decision-making.

A fall in groundwater levels would result in a decrease in water pressure, which might allow salty seawater to seep into the mainland. The border between freshwater and saltwater is referred to as the interface, and this phenomenon is known as sea water intrusion (SWI). One may argue that the SWI is a major issue in coastal cities, because it has the potential to modify the quality of groundwater, making it less usable as a drinking water source and for crop cultivation (Purnama, 2019). Potential issues including groundwater depletion, saline intrusion, and environmental impacts were reduced by doing groundwater management and reducing groundwater extraction.

STUDY AREA AND DATA USED

The study location chosen in this research work is the Sindhudurg district in Maharashtra, India, a coastal region with arid environment (Figure 1). The study area lies between latitudes of 15°40' and 16°44' North & longitudes of 73°19' and 74°13' East. With an average annual rainfall of 4234 mm, the overall geographic area is 1,750 km^2. Between 300 and 400 meters above mean sea level, the basin has a terrain. The average high temperature is 40°C in May, while the average low temperature is 11.5°C in December. For this study, groundwater levels from 16 observation wells are gathered from the Central Groundwater Board (CGWB) which periodically monitors National Hydrograph Network Stations (NHNS) in Sindhudurg district during pre-monsoon, monsoon, and post-monsoon seasons from 1991 to 2022 (Table 1).

Table 1. Location details of observation points with latitude and longitude

Sr. No.	Taluka	Latitude	Longitude	Distance from Shore (km)
1	Malvan	16.27750	73.55722	15.6
2	Malvan	16.21083	73.45833	1.51
3	Malvan	16.10722	73.48528	2.8
4	Malvan	16.05972	73.4925	3.91
5	Malvan	16.07556	73.53556	7.6
6	Vengurla	15.89528	73.67056	8
7	Vengurla	15.86222	73.63056	2.11
8	Vengurla	15.95389	73.57083	7.21
9	Vengurla	15.90833	73.66250	7.74
10	Devgad	16.48278	73.38361	4.5
11	Devgad	16.37639	73.57833	18.1
12	Devgad	16.46917	73.60639	25
13	Devgad	16.44389	73.39611	4.1
14	Devgad	16.32444	73.48806	9.91
15	Devgad	16.31333	73.45389	5.9
16	Devgad	16.37528	73.37833	0.74

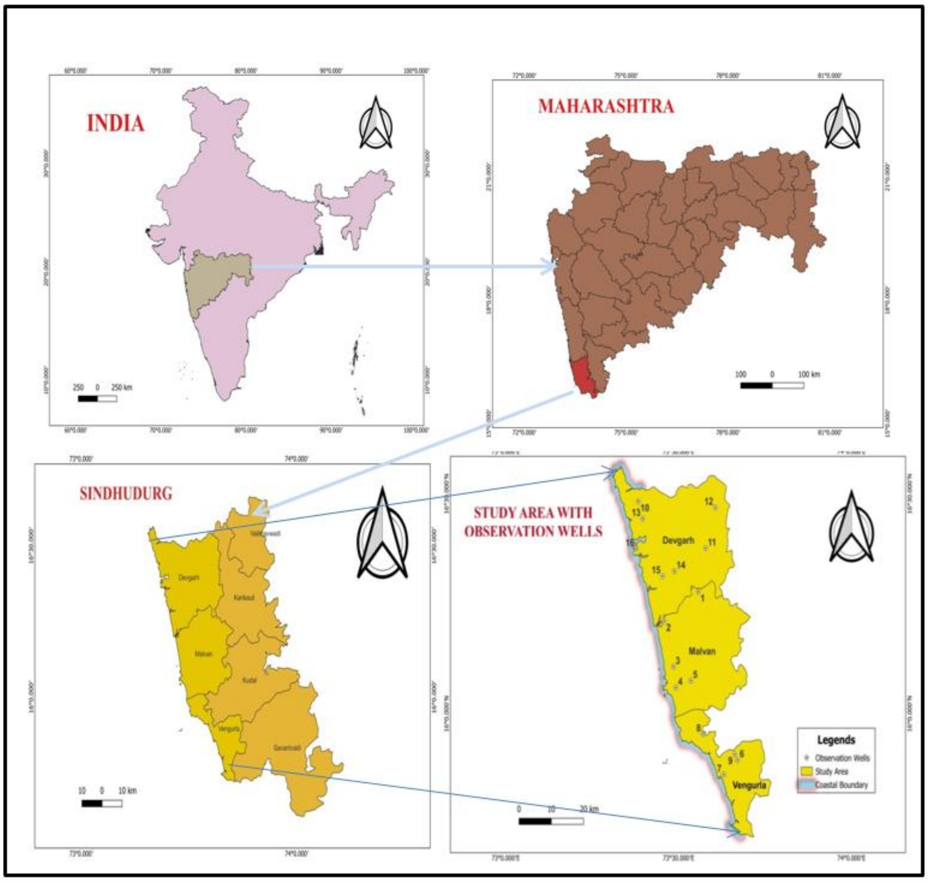

Figure (1): Study area location map

METHODS

Groundwater Level Analysis

Pre-monsoon (February-May), monsoon (June–September), and post-monsoon (October–January) groundwater level data for the study area was obtained from CGWB, Sindhudurg for the study period (1991-2022). The measurements were made during a time when water levels generally tended to be at their highest in May (pre-monsoon) and at their lowest in October (post-monsoon). The groundwater level data of 32 years (1991-2022), collected at several points representing the pre-monsoon, post-monsoon and monsoon seasons, was used to determine the average depth of water level. The data was examined in order to know the fluctuations & trend of the groundwater table. Furthermore, groundwater level's spatial variance in relation to the average depth was investigated (Figure 2).

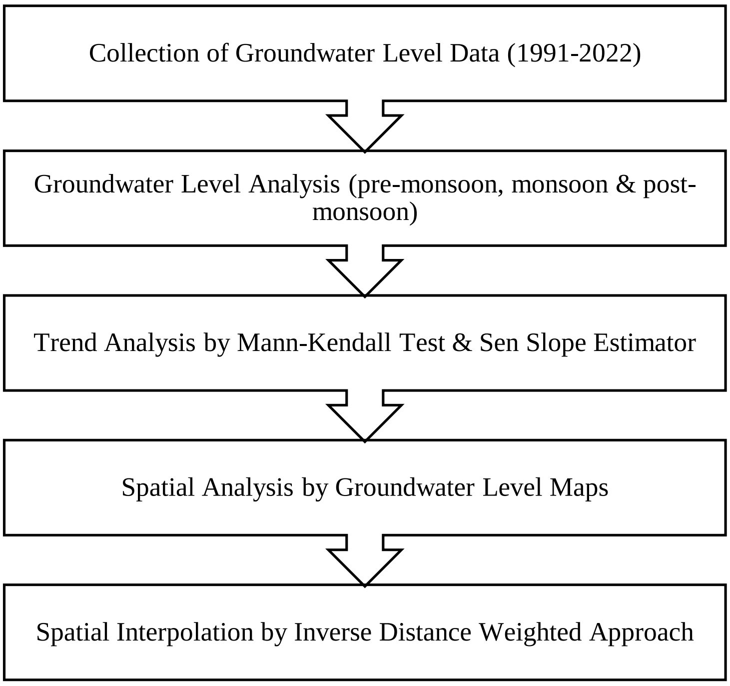

Figure (2): Methodology flowchart

Spatial-temporal Mapping

The inverse distance weighted (IDW) methodology, a method for deterministic multi-variate interpolation employing a known scattered collection of points for all 16 observation wells in the research region, was used to spatially interpolate the point-by-point data of groundwater level. Weighted average of values found at known sites is utilized in inverse distance weighted (IDW) strategy to ascertain values assigned to unknown points.

Cell values are created by adding linear weights to a series of sample points. These values are subsequently utilized in the precise and convex IDW interpolation method. The premise behind this is that a variable's influence diminishes as one gets farther away from the sample location. One important characteristic of the IDW interpolation is that all expected values lie between the maximum and minimum values of the known locations. Equation (1) represents a general IDW method:

$$\text{Zo} = \frac{\sum_{i=0}^{s} Zi\left(1/d_{i}^{k}\right)}{\sum_{i=0}^{s}\left(1/d_{i}^{k}\right)} \quad (1)$$

Zi is the Z value at a known point i and d_i is the distance between a known point i and a known point o, and Zo is the estimated value at point o. Here, k is the suggested power and s is the number of known points utilized in the estimation. Power k determines how big the local influence is. In a linear interpolation to power of 1, value changes between points happen steadily. The rate of change in the data increases at a certain point and levels out away from it, according to power of 2 or higher. The known number of points included in the estimation has an impact on the local effect as well.

Statistical Test for Trend Analysis

A well-known rank-based opposition distribution, without test for analysis of movements in time series data, is the Mann-Kendall (MK) test. When evaluating the importance of non-continuous fluctuations in climatological uses of various temporal data, such as water levels, rainfall, temperatures, and stream action, the routine Mann–Kendall test is applied. For various reasons, including the following: (1) facts don't have to be normally distributed; (2) data reinforces unified explanations for certain intervals; (3) non-parametric MK test allows for eradicated and amended essential observances in the temporal data sequence; and (4) time series is non-homogeneous, which ends in weakly responsive disparities. The supreme virtue of the MK test is in its assimilation from numerical delivery, which is essential for the parametric practice. Grounded on the application, the null hypothesis (Ho) clarifies the n amount of data points & inspects depersonalized data (x1, x2, x3, x4... xn), whereby x_j represents data dots at a point j.

Thus, MK statistic (S) in Equations (2, 3 & 4) is as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \quad (2)$$

$$sign(x_j - x_i) = \begin{Bmatrix} 1, & if\ x_j - x_i > 0 \\ 0, & if\ x_j - x_i = 0 \\ -1, & if\ x_j - x_i < 0 \end{Bmatrix} \quad (3)$$

$$VAR(S) = \frac{1}{18}\left[\mathrm{n(n-1)(2n+5)} + \sum_{p=1}^{g} t_p(t_p - 1)(2t_p + 5)\right] \quad (4)$$

Here, "t" stands for the range of any sample point tie that may be expected. It is the total of all the ties expressed as ∑t. Consequently, n > 10 is the sample size, and Equation (5) calculates the standard input 'Z' value.

$$Z = \begin{Bmatrix} \frac{S-1}{[VAR\ (S)]^{1/2}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \frac{S-1}{[VAR\ (S)]^{1/2}}, & if\ S < 0 \end{Bmatrix} \quad (5)$$

As a result, upward trends (growths) are displayed by positive "Z" values; conversely, downward trends (decreasings) are displayed by negative "Z" values. Whenever the approximate value of Z is smaller than the level (α = 0.05) and if there exist upwad or downward monotonic trends at the significance limit α, the alternative hypothesis (Ha) is accepted, while the null hypothesis (Ho) is ignored. One cannot ignore the null hypothesis (Ho) if the value of Z exceeds the significance level. The current investigation used a significance level of α = 0.05, with a 95% confidence level. As a result, data on groundwater levels has been used to identify any upward or downward trends.

Sen's Slope Estimator Test

When dealing with unbiased estimator of trends in cases when data is highly skewed, Sen's slope estimator is a reliable technique. This study used this approach to determine the trend line slope based on water level decline rate (m/year). A Sen's slope's positive value represents an increase in groundwater level and an on-going upward trend, whereas a negative slope value denotes a declining tendency. Over the course of 32 years, there have been variations in the groundwater level in the research region. Slope measurement requires a time series dataset with an equal design arrangement. A minimal non-parametric technique was used to estimate the calculated slope variation of the measurement per time if the trend was linear; see Equation (6).

$$\mathrm{Q} = \frac{x_j - x_i}{\mathrm{j - i}} \quad (6)$$

where the slope of data points between x_j and x_i is determined by Q. As a result, x_i indicates the data amount at time intervals of i, j, and after time i, x_j indicates the data dimension at a given time period of j.

RESULTS

The groundwater level analysis was carried out for each season (pre-monsoon, post-monsoon, and monsoon seasons) by conducting trend analysis and spatial analysis, for the study period (1991-2022), as mentioned in the methodology section.

Annual Groundwater Level Fluctuations

The lowest groundwater level was recorded in the year 2006 (4.26 m bgl), while the highest level was recorded in the year 2000 (5.76 m bgl), based on an annual review of post-monsoon groundwater level data. Indeed, according to pre-monsoon statistics, the lowest groundwater level was documented in the year 2000 (5.69 m bgl), while the highest groundwater level was noted in the year 2016 (6.96 m bgl).

The average yearly groundwater level depth in relation to the below-groundwater level throughout the various monsoon seasons was shown during 32 years (1991–2022) in order to predict sea water incursion (Figure (3)). According to the monsoon data, the plot shows that the average yearly groundwater level has decreased after 2004 by more than 3.5 m (bgl). The post-monsoon map in Figure (3) shows that the water level fell below 5 m (bgl) between 2002 and 2012.

Figure (4) shows the average groundwater level at the well location as well as the variations in groundwater level during the pre-monsoon, monsoon, and post-monsoon seasons. It demonstrates that in contrast to the monsoon and post-monsoon seasons, the groundwater level was higher during the pre-monsoon season. The greatest below-groundwater levels in the pre-monsoon, monsoon, and post-monsoon seasons are shown by well location 16, while the minimum below-groundwater levels are shown by well locations 5 and 11.

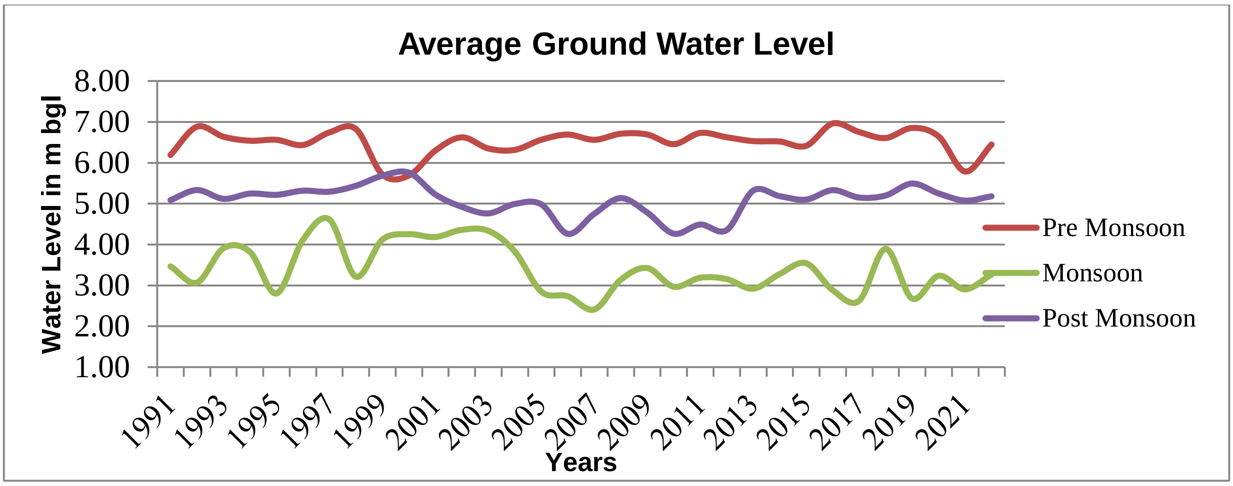

Figure (3): Average yearly water level depth for monsoon, pre-monsoon, and post-monsoon seasons

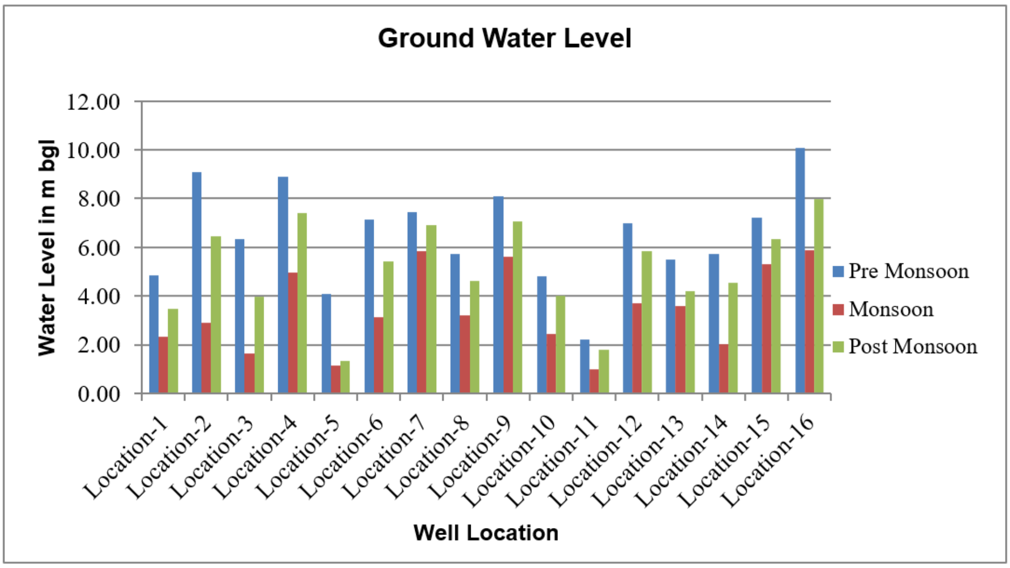

Figure (4): Average depth of yearly water level at well locations

Groundwater Level Trend Analysis

The findings of the testing statistics have led to conclusions about the trend of water level in Sindhudurg district study area. MK test was used to calculate the Z-statistic findings for groundwater level analysis. The 95% confidence threshold was used to identify the trend. Using the slope-estimator technique, the groundwater level trend line slope, and monsoon season's outcome were calculated. Pre-monsoon season (from -0.151 to 0.094 m/year), monsoon season (from -0.109 to 0.008 m/year) and post-monsoon season (from -0.021 to 0.124 m/year) were the slope values for the different seasons. Table 2 presents the statistical results. Of the sixteen observation wells, wells 1, 2, 6, 7, 8, and 9 showed a declining tendency in long-term water level (1991-2022) in all seasons. But, throughout the duration of the three seasons, a rising tendency appeared in wells 4 and 16. A constant groundwater table is evident in such locations, because, according to 32-year analysis of groundwater level data, well 3 showed no trend throughout the post-monsoon season.

According to trend analysis results in Table 2 during the pre-monsoon season, a falling nature was seen in 50% of the wells and an increasing nature in 50% of the wells. In a similar vein, 81% of the wells during the monsoon season showed a falling tendency, while 19% showed a growing trend. According to the post-monsoon water-level data, 63% of the wells showed a decreasing tendency, 31% showed an increasing tendency, and 6% showed no change at all.

Table 2. Mann-Kendall & Sen’s slope values for trend analysis (1991-2022)

Well No.	Well Location	Pre-monsoon		Monsoon		Post-monsoon	
		MK-value	Sen's Slope	MK-value	Sen's Slope	MK-value	Sen's Slope
1	Malvan	-0.234	-0.008	-0.320	-0.031	-0.338	-0.015
2	Malvan	-0.124	-0.009	-0.347	-0.109	-0.067	-0.004
3	Malvan	-0.173	-0.020	-0.319	-0.033	0.006	0.000
4	Malvan	0.320	0.037	0.081	0.008	0.178	0.020
5	Malvan	0.147	0.004	-0.408	-0.013	-0.381	-0.005
6	Vengurla	-0.288	-0.016	-0.100	-0.020	-0.322	-0.021
7	Vengurla	-0.394	-0.009	-0.115	-0.018	-0.506	-0.018
8	Vengurla	-0.498	-0.151	-0.432	-0.081	-0.648	-0.080
9	Vengurla	-0.256	-0.036	-0.206	-0.021	-0.351	-0.020
10	Devgad	0.033	0.002	-0.403	-0.052	-0.105	-0.004
11	Devgad	0.361	0.015	-0.180	-0.006	0.043	0.001
12	Devgad	0.402	0.028	-0.094	-0.007	-0.062	-0.001
13	Devgad	0.275	0.017	-0.153	-0.013	-0.090	-0.003
14	Devgad	0.494	0.078	-0.188	-0.029	0.430	0.055
15	Devgad	-0.171	-0.011	0.026	0.004	0.289	0.008
16	Devgad	0.172	0.094	0.053	0.003	0.469	0.124

Groundwater level Variation in the Pre-monsoon Season

To assess groundwater conditions, we calculated the average depth of the groundwater table during the pre-monsoon season over a 32-year period. This data was used to create maps illustrating the average groundwater depth across the study area, which ranged from 6.187 to 6.443 meters.

However, groundwater levels can fluctuate significantly. In 2022, for example, the pre-monsoon water level varied dramatically, reaching a maximum of 11.00 meters and a minimum of 2.25 meters (Table 3).

Figure (5) provides a visual representation of groundwater level patterns over the entire study period, while Table 3 summarizes key statistical measures of pre-monsoon water levels.

Figure (5) illustrates a progressive rise in the size and intensity of groundwater depletion, with 300 km^2 of territory under 4-7 m(bgl) in 2006 compared to a smaller area under the same in 2000. With the exception of 2013, about 80% of the studied area was found to have groundwater depths more than 4 m(bgl) between 2006 and 2022.

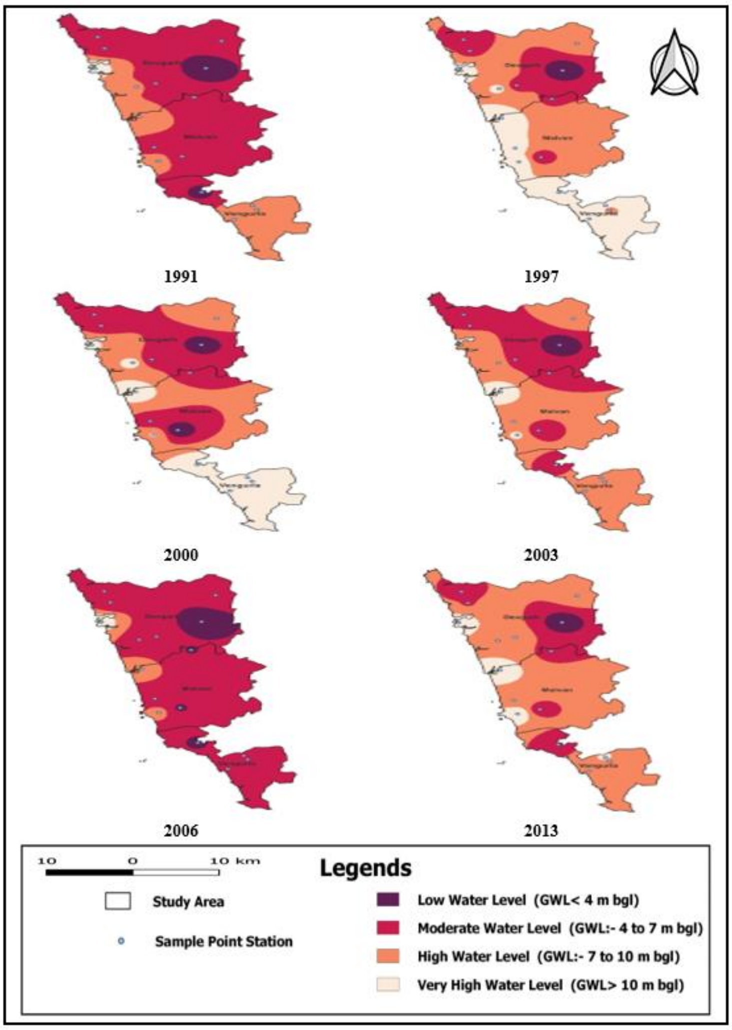

Figure (5): Variation in pre-monsoon groundwater level in the study area

Table 3. Groundwater level statistics for 16 wells in the pre-monsoon season

Statistics	**Annual Groundwater Levels**	
	1991	**2022**
Mean	6.187	6.443
Median	6.185	6.500
Standard Deviation	2.247	2.249
Maximum	11.08	11.00
Minimum	1.96	2.25
Skewness	0.2648	0.1810

Groundwater level Variation in the Monsoon Season

The average depth of groundwater level was computed for the period under observation for the monsoon season. By averaging the groundwater level values for 32 years, the average depth for groundwater level maps of the monsoon season was created. The study area's mean groundwater level depth at the monsoon season varies from 3.468m to 3.269 m. Figure (6) depicts the spatial patterns of monsoon groundwater levels throughout the research period at different most fluctuating years. For the monsoon season, the spatio-temporal maps show that nearly 300 km^2 area was beyond 10 m(bgl) in the year 1997.

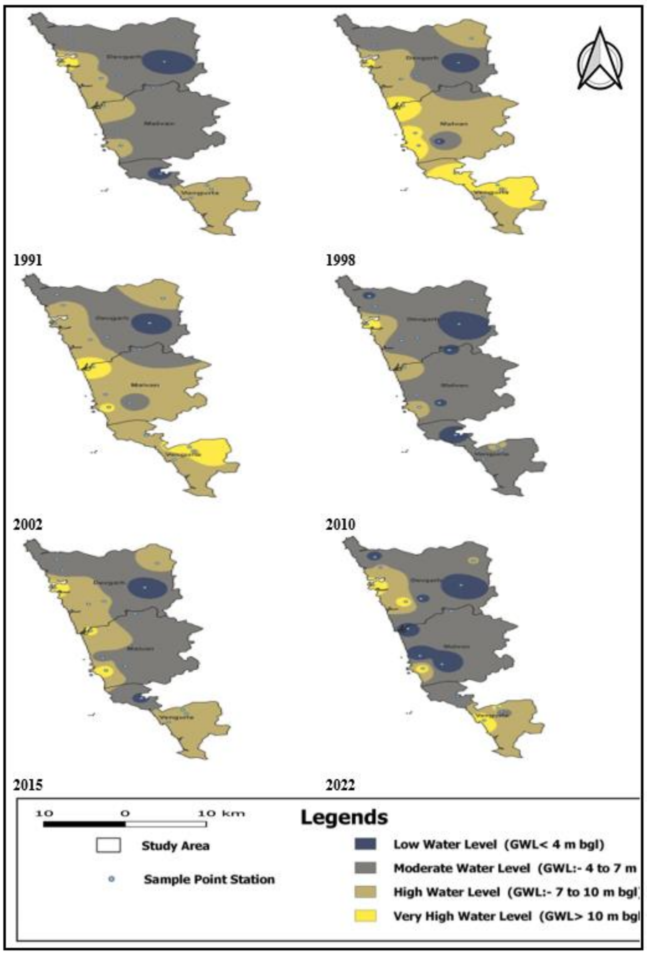

Figure (6): Variation in monsoon groundwater level in the study area

Groundwater Level Variation in the Post Monsoon Season

For the post-monsoon season, the average depth of groundwater level was calculated. The average groundwater depth for groundwater level maps at the post-monsoon season was determined by averaging the groundwater levels over the duration of 32 years. The post-monsoon season mean water level in the study area ranges from 5.088 to 5.181 meters. In 2022, the maximum and minimum fluctuations in the water level throughout the post-monsoon season were 1.30 m and 9.30 m, respectively (Table 4). Figure 7 depicts the spatial patterns of post-monsoon groundwater levels throughout the research period at some more affected years. Table 4 provides the mean, median, minimum, and maximum annual post-monsoon water levels for the study area. A gradual decrease of groundwater level is observed from Figure (7) from the year 2006 in the post-monsoon season.

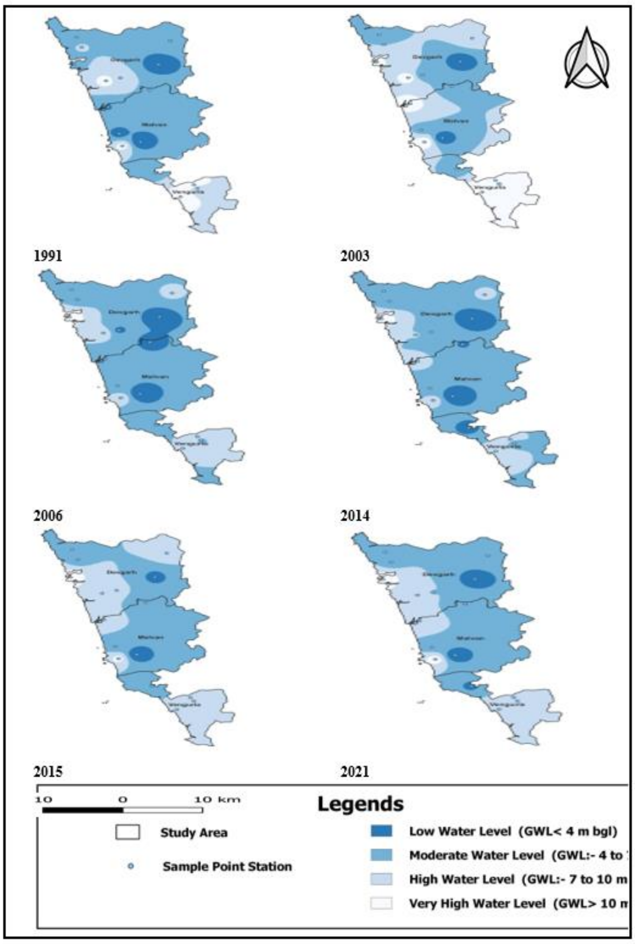

Figure (7): Variation in post-monsoon groundwater level in the study area

Table 4. Groundwater level statistics for 16 wells in the post monsoon season

Statistics	**Annual Groundwater Levels**	
	1991	**2022**
Mean	5.088	5.181
Median	4.810	5.250
Standard Deviation	1.883	2.223
Maximum	8.20	9.30
Minimum	1.35	1.30
Skewness	-0.5021	-0.0516

DISCUSSION

This paper presents an examination of groundwater level variations, revealing some interesting features of the groundwater level patterns in the studied region. The less pronounced seasonal differences and lower yearly cycle amplitudes obtained suggest that rainfall and groundwater levels have less of an impact. In some wells, the 32-year average of the changes between dry and wet seasons was found to have negative values at the lowest measurements. This suggests that groundwater levels were higher during the dry season than during the rainy season. The trend analysis shows that the monsoon season is when dropping water tables are most common. The slower rate of precipitation infiltration into the aquifers that are deeper could be the cause of this phenomenon.

Sea level rises anticipated due to climate change will hasten the infiltration of salt water, compromising the quality of groundwater, like harming the sustainable development of coastal aquifers. The local government's decision to stop pumping groundwater from those areas' top-most aquifer was a major factor in less than 0.1 cm/year rising trend in groundwater levels that was seen from 1991 to 2022. As a result, groundwater levels have gradually returned to normal values.

Other research has shown that when sea levels rise, the location of the freshwater-seawater interface generally rises, which in turn elevates the shallow groundwater in coastal regions. It is crucial to remember that a rise in groundwater levels results in seawater intrusion, which lowers agricultural output.

CONCLUSION

In the coastal region of Sindhudurg district in Maharashtra, a groundwater level database made up of 16 monitoring wells has been developed, and spatio-temporal patterns of recent (1991–2022) changes in groundwater levels have been created. At 16 monitoring stations, estimated trends in seasonal groundwater level data are provided. The results of the spatio-temporal maps revealed lowering patterns in almost 60% of the wells for every season of the year. Analysis has shown that the coastline zone is mostly experiencing substantial dropping trends, at a rate of about 0.10 m/year. In general, the neighboring coastal regions exhibited bigger drops in groundwater levels than other places. Due to saltwater intrusion, rapidly dropping groundwater levels in coastal locations particularly endanger sustainable aquifer development.

The trend analysis shows that over the course of 32 years, the water level has decreased in 50% of the wells during the pre-monsoon season, in 63% of the wells during the post-monsoon season, and in 81% of the wells during the monsoon season. The areas in Vengurla Taluka are primarily impacted by the groundwater level's downward tendency. The findings also show that the Vengurla Taluka's overuse of groundwater for irrigation causes more groundwater variation during the pre-monsoon season, stressing the aquifer. The human populations are deeply affected by these variations in groundwater levels regarding time, space and depth. Therefore, by constructing the appropriate structures, it is crucial to increase groundwater resources in the impacted areas *via* artificial recharge methods.

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