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Analysis of Trend in Groundwater-Quality Parameters: A Case Study

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Abstract: In the 21st century, groundwater has a pivotal role in ensuring water, food, and environmental securities worldwide. Systematic observation, protection and restoration are essential for sustainable management of water resources. Regular monitoring is key to investigate temporal changes in groundwater quality, and statistical trend tests define whether these changes are significant or not. This study focuses on investigating trend in seasonal groundwater quality in an alluvial coastal basin of West Bengal, India. The seasonal groundwater-quality data (pH, TH, TDS, Fe^{2+} and HCO_3^-) of pre-monsoon and post-monsoon seasons were collected for 2011–2018 period and analyzed using three non-parametric statistical trend detection tests, namely: (i) Original Mann-Kendall (M-K) test, (ii) Modified Mann-Kendall (mM-K) test, and (iii) Spearman Rank Order Correlation (SROC) test. The trend magnitudes were estimated by using the Sen's slope estimation test. Statistical analyses revealed that seasonal concentrations of all five groundwater-quality parameters have large spatial (block-wise) variation within the study area. The results of trend analyses indicated that seasonal TH and TDS concentrations mainly have significant decreasing trends (α = 5% or 1%), whereas seasonal HCO_3^- and Fe^{2+} concentrations mostly show significant increasing trends (α = 5% or 1%) in different blocks. However, seasonal pH concentrations exhibited no trend. The mM-K test was found to be over-sensitive in finding trends than M-K and SROC tests. The SROC test was found to be less sensitive in detecting trends than M-K and mM-K tests. Trend magnitudes of seasonal pH, TH, TDS, HCO_3^- and Fe^{2+} concentrations varied from –0.03/year to 0.23/year, –57.44 mg/L/year to 25.88 mg/L/year, –172.98 mg/L/year to 92.58 mg/L/year, –15.81 mg/L/year to 27.88 mg/L/year, and –0.05 mg/L/year to 0.61 mg/L/year, respectively. Continuous and proper groundwater-quality monitoring is critically required in all aquifer systems. The outcomes of this study will aid policy-makers in appropriately monitoring and managing groundwater quality.

Keywords: Alluvial coastal aquifer, Trend analysis, Original Mann-Kendall test, Sen's slope, Modified Mann-Kendall test, Spearman Rank Order Correlation test.

1. Introduction

In the last few decades, rapid rise in freshwater demand in various fields, changing climatic and socio-economic circumstances, and improper human-induced activities have resulted in its quantitative and qualitative deterioration worldwide [1, 2], as well as in India [3, 4]. Planning and efficient management of groundwater resources requires knowledge of the regional distribution and temporal fluctuation of groundwater quality [5, 6]. However, generating an accurate groundwater distribution over an area needs an extensive groundwater monitoring network, which is highly expensive. Trend analysis of meteorological, hydrological and climatological variables provides useful information for water resources management [7]. The aim of trend analysis is to detect whether a time series data is increasing, decreasing, or stationary over a certain period. However, the detection of trend is complex because of the characteristics of data [7]. In the recent past, researchers have applied various techniques for investigating trends in groundwater levels [9, 10] and groundwater quality [8, 11, 12]. Although several parametric and non-parametric statistical tests are used to check the existence or absence of trend in time series data, non-parametric methods are more robust in dealing with a time series that have a significant skew and cannot be fitted with statistical distributions [13].

The inter-basin area of Haldi, Kansabati and Subarnarekha rivers in southern coastal region of West Bengal state has been selected as the study area for this research, where groundwater from dug wells, shallow tubewells and deep tubewells is the major source of freshwater for drinking and irrigation. In the study area, geogenic processes as well as anthropogenic activities such as salt farming, aquacultural activities, excessive use of fertilizers and groundwater pumping are possible causes of freshwater contamination [14]. The goal of this study is to analyze trends in selected groundwater-quality parameters of unconfined, leaky-confined and confined aquifers measured in pre-monsoon and post-monsoon seasons during 2011–2018 period.

2. Materials and Method

2.1 Study area description

The inter-basin area of the Haldi, Kansabati, and Subarnarekha rivers in the southern coastal section of West Bengal state along the Bay of Bengal is the study area chosen for this research. Its area is about 6358.70 km^2, and it is located between the latitudes 21º32′45″N–22º29′33″N and the longitudes 87º00′58″E–88º02′55″E. It is surrounded by Kansabati River in the north, Haldi River in the northeast, Subarnarekha River in the west, and Bay of Bengal in the south (Figure 1). The study area consists of 32 blocks (administrative units). The climate of the region is 'Humid-Sub-Tropical' type. This region experiences on average 1758 mm of rainfall in a year, of which the 'southwest monsoon' contributes about

73% during the 'monsoon season' (June to September). Pre-monsoon season is defined as the time period between March and May, while the post-monsoon season is defined as the time period between October and November.

The study area is distinguished by lateritic soil/terrain underlain by older Pleistocene alluvium (a thick sequence of brownish clay, fine to medium sand, kankar, and gravel up to a depth of 250 m bgl) in the northwest, and gently sloping unconsolidated Quaternary sediments of newer alluvium (clay, silt, and grey fine sand) and flat coastal alluvium terrain (with saline, saline-alkali and degraded-alkali soils) in the northeast, east and south that gradually merges with the deltaic plain towards the Bay of Bengal. The whole alluvial and coastal plains are underlain by semi-consolidated tertiary deposits. 'Agriculture' covers 58.4% of the total area, followed by 'built-up regions' (21.4%), 'forest and barren lands' (11.5%), and 'rivers and wetlands' (8.7%). *Kharif* (July-October) and *Rabi* (October-March) are the key farming seasons in the research region. Over 70% of the total cropped acreage in *Kharif* and *Rabi* seasons is under paddy. Moreover, jute, lentils, mustard, oilseeds, potatoes, sugarcane, wheat, etc. are also grown here.

2.2 Data Acquisition

In this study, seasonal groundwater-quality data of both pre-monsoon (April) and post-monsoon (November) seasons were obtained from 21 dug wells (0–20 m bgl), 90 shallow tubewells (20–120 m bgl), and 118 deep tubewells (120–300 m bgl) for the 2011–2018 period. In the study area, the unconfined aquifers are being tapped by dug wells, while leaky-confined and confined aquifers are being tapped by shallow and deep tubewells, respectively. The groundwater-quality parameters used in this study are pH, Total Hardness (TH), Total Dissolved Solids (TDS), Bicarbonate (HCO_3^-), and Iron (Fe^{2+}). The data used in this study were collected from: (i) State Water Investigation Directorate (SWID), Govt. of West Bengal, Kolkata, and (ii) Ground Water Survey and Investigation (GWS&I), Govt. of Odisha, Bhubaneswar.

2.3 Statistical Analysis of Groundwater Quality

In this study, descriptive statistical estimates (e.g., 'minimum', 'maximum', 'mean' and 'standard deviation') of the five seasonal groundwater-quality parameters (pH, TH, TDS, HCO_3^- and Fe^{2+}) were calculated for the unconfined, leaky-confined and confined aquifers in MS-Excel (v2016) software.

2.4 Trend Analysis of Groundwater-Quality Parameters

In this study, three non-parametric statistical trend tests were used to identify trend in seasonal (both pre-monsoon and post-monsoon seasons) groundwater-quality time series (pH, TH, TDS, HCO_3^- and Fe^{2+}) of 2011–2018 period for the unconfined, leaky-confined and confined aquifers.

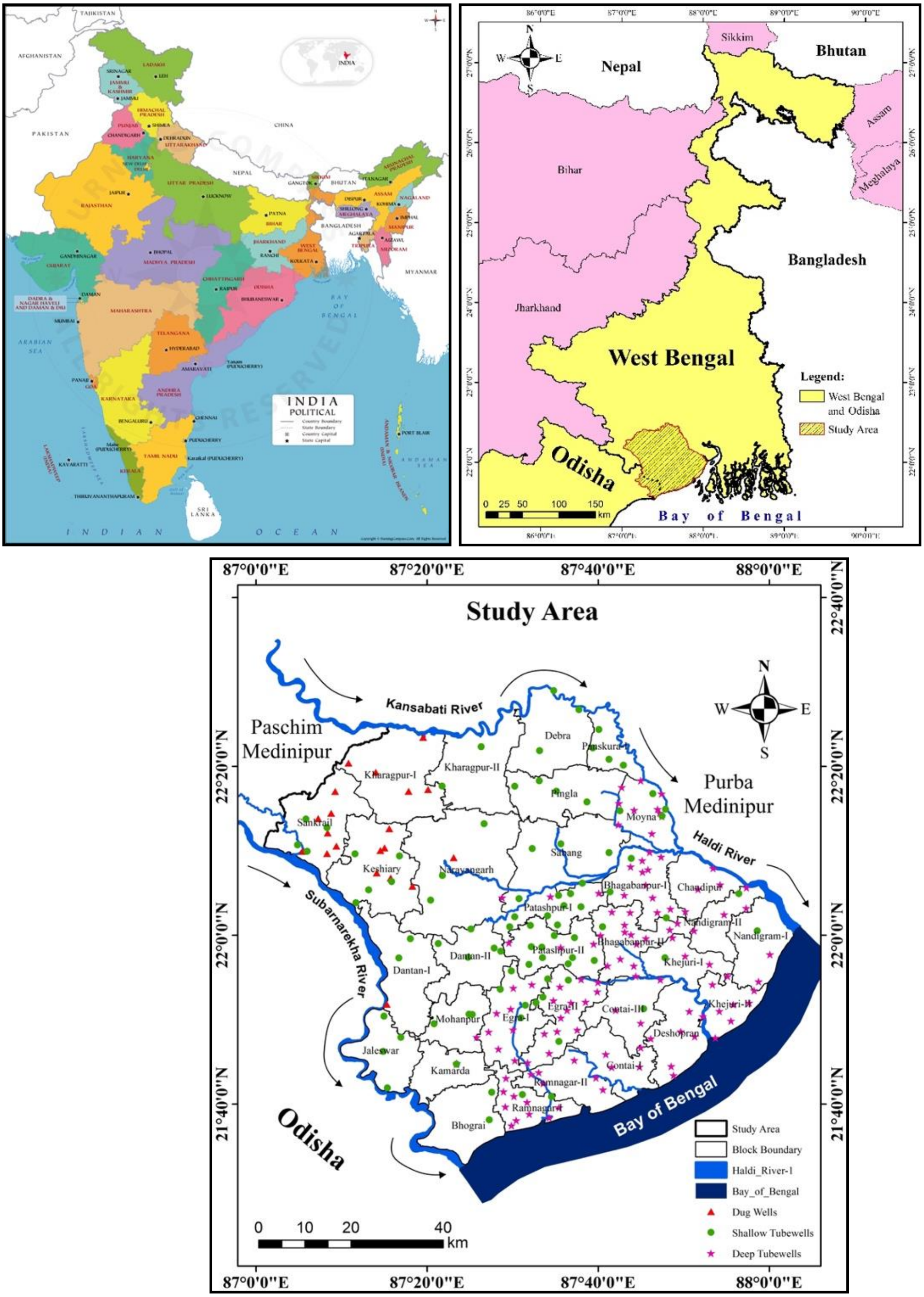

Figure 1. Location map of the study area.

The three trend detection tests used in this study are: (i) Original Mann-Kendall (M-K) test, (ii) Modified Mann-Kendall (mM-K) test, and (iii) Spearman Rank Order Correlation (SROC) test. Therefore, whenever at least two tests indicate the presence of a trend (increasing or decreasing) in a certain groundwater-quality parameter within a block, it can be inferred that the parameter most certainly has a trend (increasing or decreasing) in that block. For this analysis, block-wise average values of seasonal groundwater-quality parameters were computed for all three aquifer systems. The trend magnitudes were quantified by using the Sen's slope estimation test. All these analyses were carried out in R (v3.5.2) statistical programming software. A brief description about the above-mentioned trend tests is given below.

2.4.1 Original Mann Kendall (M-K) Test

The M-K test can withstand the jarring variations and shifts introduced by an inhomogeneous series [15]. This test was originally introduced by Mann (1945) which was modified thereafter by Kendall (1962). This test requires your data to be independent, identically distributed, and ordered randomly. The M-K test is valid for non-normal data that can accommodate a large number of observations per time series [16, 17]. This test has been reported to be robust, and hence, it has been widely applied during the last three decades for detecting trends in several environmental, atmospheric, hydrologic, climatologic, and agricultural time series [18]. It is a rank-based method which looks at the relative magnitudes of a given variable in its time series. The test is performed by calculating 3 different metrics, namely: (i) statistic 'S', (ii) 'variance of S', and (iii) statistic 'Z' (M-K test-statistic). The M-K test-statistic 'S' is computed using Equation 1 [19] as:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \operatorname{sgn}\left(x_j - x_i\right) \quad (1)$$

$$\operatorname{sgn}\left(x_j - x_i\right) = \begin{cases} -1, & \text{if } \left(x_j - x_i\right) < 0 \\ 0, & \text{if } \left(x_j - x_i\right) = 0 \\ +1, & \text{if } \left(x_j - x_i\right) > 0 \end{cases} \quad (2)$$

According to Mann (1945) and Kendall (1962), for $N \geq 8$, the statistic 'S' is approximately normally distributed with its mean [E(S)] and variance [var(S)] as given below:

$$E(S) = 0 \quad (3)$$

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

where, x_i and x_j = sequential data values in i^{th} and j^{th} years, respectively; N = length of the data record; g = number of tied groups; and t_p = number of data points in p^{th} group. A tied group is a set of data having the same value. In situation, where the data points N > 10, then the standard normal M-K test-statistic 'Z' for the normal distribution at 95% and 99% confidence levels, are computed using Equation 5 as:

$$Z=\begin{cases}\frac{S-1}{\sqrt{\mathrm{var}(S)}} & \text{if} \quad S>0\\ 0 & \text{if} \quad S=0\\ \frac{S+1}{\sqrt{\mathrm{var}(S)}} & \text{if} \quad S>0\end{cases} \qquad (5)$$

Positive values of M-K test-statistic 'Z' indicate increasing trends and negative values indicate decreasing trends. When $Z > Z_{crit,\,(1-\alpha/2)}$ (increasing) or $Z < -Z_{crit,\,\alpha/2}$ (decreasing), the *null hypothesis* (H_0) of '*no trend exists*' is rejected, and *alternate hypothesis* (H_1) of '*significant trend exists*' is accepted. This test was performed at both α = 5% and α = 1% *significance levels*, and the Z_{crit} values are the areas under the standard Normal curve for *2-tailed* tests.

Furthermore, the strength/magnitude of a trend is calculated using non-parametric Sen's slope estimation test [20]. It is a robust method against extreme outliers, and has been broadly used in identifying the slope of the trend in hydrological time series [21, 22]. This method computes the slopes for all the pairs of ordinal time points using the median slope as an estimate of the overall slope [20]. The Sen's slope 'β', is estimated using Equation 6 as:

$$\beta=\mathrm{median}\left[\frac{x_i-x_j}{i-j}\right] \qquad \forall \quad i>j \qquad (6)$$

where, x_i and x_j = sequential data values in i^{th} and j^{th} years, respectively. The positive (or negative) value of 'β' indicates the increasing (or decreasing) trends in the time series data.

2.4.2 Modified Mann-Kendall (mM-K) Test

Serial correlation (auto-correlation) in a time series data alters the variance of the original M-K test-statistic. Therefore, by modifying the variance through a *pre-whitening* process we may be able to limit the effect of serial correlation. That modified variance can be calculated using Equation 7 [23, 24] as:

$$\mathrm{var}(S)^* = \left[\mathrm{var}(S) \times \frac{n}{n_e} \right] \quad (7)$$

where, var(S) = variance of original M-K test; $\mathrm{var}(S)^*$ = modified variance after incorporating variance-correction approach; n = actual sample size/actual number of observations; n_e = equivalent sample size/effective number of observations to account for the serial correlation; and (n/n_e) = variance correction factor.

Accordingly, the 'variance-correction factor' is calculated using Equation 8 [5] as:

$$\frac{n}{n_e} = \left[1 + \left\{ \frac{2}{n(n-1)(n-2)} \times \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2) r_k \right\} \right] \quad (8)$$

where, r_k = auto-correlation function of the ranks of the observations obtained after subtracting Sen's slope value from the data; and k = number of lags in the autoregressive process. The remaining steps in mM-K test are similar to that of original M-K test.

2.4.3 Spearman Rank Order Correlation (SROC) Test

To overcome the problem associated with the linear model for trend detection, the Spearman Rank Order Correlation (SROC) non-parametric test [25] is used to check the existence of long-term non-linear trend.

The coefficient of trend (r_s) is computed using Equation 9 as:

$$r_s = \left[1 - \frac{6 \sum_{t=1}^{n} d_t^2}{n(n^2-1)} \right] \quad (9)$$

and

$$d_t = (R_{xt} - t) \quad (10)$$

where, R_{xt} = rank assigned to data series (x_t) observed in time 't' such that the largest 'x_t' has R_{xt} = 1, and the least 'x_t' has R_{xt} = n. Under the *null hypothesis* (H_0), the SROC test-statistic

't_s' has a *two-tailed* Student's t-distribution with (n–2) *degrees of freedom*, and is defined using Equation 11 as:

$$t_s = r_s \times \sqrt{\frac{n-2}{1-r_s^2}} \quad (11)$$

The calculated value of 't_s' is compared with the critical value (t_{crit}) of the *two-tailed* t-distribution $t_{s\,(\alpha,\,n-2)}$ for the chosen *significance level* (α = 5% or 1%) and (n–2) *degrees of freedom*. The *null hypothesis* (H_0) of '*no trend exists*' can be rejected, and the *alternate hypothesis* (H_1) of '*significant trend exists*' is accepted if $|t_s| > t_{s\,(\alpha,\,n-2)}$.

3. Results and Discussion

3.1 Statistical Analysis of Groundwater Quality

The results obtained from the descriptive statistical analysis [i.e., minimum, maximum, mean, and standard deviation (S.D.)] of five seasonal (pre-monsoon and post-monsoon seasons) groundwater-quality parameters (pH, TH, TDS, HCO_3^- and Fe^{2+}) of 2011–2018 period for the unconfined, leaky-confined and confined aquifers, have been presented and discussed in this section.

3.1.1 Unconfined Aquifer

The pH concentration values in the unconfined aquifers of the study area during pre-monsoon season ranges 5.30–9.48 with a mean±S.D. of 7.60±0.80, whereas it ranges 5.08–8.51 with a mean±S.D. of 7.75±0.59 during post-monsoon season. The TH values in the unconfined aquifers of the study area during pre-monsoon season ranges 10–450 mg/L with a mean±S.D. of 113.36±78.89 mg/L, whereas it ranges 10–560 mg/L with a mean±S.D. of 109.69±82.95 mg/L during post-monsoon season. The TDS values in the unconfined aquifers of the study area during pre-monsoon season ranges 26–902 mg/L with a mean±S.D. of 233.55±177.36 mg/L, whereas it ranges 26–1230 mg/L with a mean±S.D. of 216.16±212.84 mg/L during post-monsoon season. The HCO_3^- values in the unconfined aquifers of the study area during pre-monsoon season ranges 18–455 mg/L with a mean±S.D. of 109.19±74.97 mg/L, whereas it ranges 10–485 mg/L with a mean±S.D. of 107.62±77.91 mg/L during post-monsoon season. The Fe^{2+} values in the unconfined aquifers of the study area during pre-monsoon season ranges 0–6.92 mg/L with a mean±S.D. of 0.58±1.41 mg/L, whereas it ranges 0–6 mg/L with a mean±S.D. of 0.47±1.1 mg/L during post-monsoon season. Results indicate that all five seasonal groundwater-quality parameters have considerable spatial (block-wise) variation in the unconfined aquifers of the study area.

3.1.2 Leaky-Confined Aquifer

The pH concentration values in the leaky-confined aquifers of the study area during pre-monsoon season ranges 5.72–9.94 with a mean±S.D. of 7.89±0.67, whereas it ranges 5.88–9.02 with a mean±S.D. of 8.01±0.55 during post-monsoon season. The TH values in the leaky-confined aquifers of the study area during pre-monsoon season ranges 10–660 mg/L with a mean±S.D. of 146.28±62.55 mg/L, whereas it ranges 10–660 mg/L with a mean±S.D. of 149.52±67.19 mg/L during post-monsoon season. The TDS values in the leaky-confined aquifers of the study area during pre-monsoon season ranges 26–1714 mg/L with a mean±S.D. of 313.76±175.82 mg/L, whereas it ranges 26–2560 mg/L with a mean±S.D. of 314.13±220.50 mg/L during post-monsoon season. The HCO_3^- values in the leaky-confined aquifers of the study area during pre-monsoon season ranges 15–580 mg/L with a mean±S.D. of 214.66±79.17 mg/L, whereas it ranges 20–480 mg/L with a mean±S.D. of 223.71±83.04 mg/L during post-monsoon season. The Fe^{2+} values in the leaky-confined aquifers of the study area during pre-monsoon season ranges 0–8.95 mg/L with a mean±S.D. of 0.79±1.48 mg/L, whereas it ranges 0–10.40 mg/L with a mean±S.D. of 0.82±1.46 mg/L during post-monsoon season. Results reveal that all five seasonal groundwater-quality parameters have high spatial (block-wise) variability in the leaky-confined aquifers of the study area.

3.1.3 Confined Aquifer

The pH concentration values in the confined aquifers of the study area during pre-monsoon season ranges 6.16–8.93 with a mean±S.D. of 7.88±0.68, whereas it ranges 6.16–9.13 with a mean±S.D. of 8.05±0.59 during post-monsoon season. The TH values in the confined aquifers of the study area during pre-monsoon season ranges 6–3400 mg/L with a mean±S.D. of 194.70±208.97 mg/L, whereas it ranges 6–2240 mg/L with a mean±S.D. of 187.97±166.03 mg/L during post-monsoon season. The TDS values in the confined aquifers of the study area during pre-monsoon season ranges 96–6464 mg/L with a mean±S.D. of 501.61±514.22 mg/L, whereas it ranges 134–6464 mg/L with a mean±S.D. of 494.44±437.13 mg/L during post-monsoon season. The HCO_3^- values in the confined aquifers of the study area during pre-monsoon season ranges 40–495 mg/L with a mean±S.D. of 261.43±75 mg/L, whereas it ranges 50–590 mg/L with a mean±S.D. of 266.04±91.12 mg/L during post-monsoon season. The Fe^{2+} values in the confined aquifers of the study area during pre-monsoon season ranges 0–8.28 mg/L with a mean±S.D. of 0.91±1.46 mg/L, whereas it ranges 0–8.44 mg/L with a mean±S.D. of 0.96±1.52 mg/L during post-monsoon season. Results show that all five seasonal groundwater-quality parameters exhibit large spatial (block-wise) variability in the confined aquifers of the study area.

3.2 Results of Trend Analysis

The results obtained from the trend analysis of five seasonal (pre-monsoon and post-monsoon seasons) groundwater-quality parameters (pH, TH, TDS, HCO_3^- and Fe^{2+}) of 2011–2018 period for the unconfined, leaky-confined and confined aquifers performed using three non-parametric statistical trend detection tests, namely (i) Original Mann-Kendall (M-K), (ii) Modified Mann-Kendall (mM-K) and (iii) Spearman Rank Order Correlation (SROC) tests, have been presented and discussed in this section. A trend with a negative slope specifies that the concentration of parameter is declining, and positive slope indicates that the concentration is increasing. Both positive and negative trends were identified by the original M-K, mM-K, SROC, and Sen's slope estimation tests for the data.

3.2.1 Unconfined Aquifer

The test-statistic 'Z' values obtained from the trend analysis of five seasonal groundwater-quality parameters from unconfined aquifers using three above-mentioned trend tests have been presented in Tables 1(a–e). The critical test-statistic 'Z_{crit}' values of both original Mann-Kendall (M-K) test and modified Mann-Kendall (mM-K) tests were ±1.960 (at α = 5%), and ±2.575 (at α = 1%). On the other hand, critical test-statistic 't_{crit}' values of the SROC test were ±2.447 (for n−2 = 6, and at α = 5%), and ±3.707 (for n−2 = 6, and at α = 1%). The calculated test-statistics 'Z' and 't_s' values were compared with the critical test-statistics 'Z_{crit}' and 't_{crit}' values, respectively. It is evident from Tables 1(a–e) that the pre-monsoon pH concentrations in unconfined aquifers showed no trend, whereas post-monsoon pH concentrations exhibited significant increasing trends in Sankrail (α = 5%) and Keshiary (α = 5%) blocks. The pre-monsoon TH concentrations in unconfined aquifers had significant increasing trend in Dantan-I (α = 5%) block, whereas post-monsoon TH concentrations indicated significant decreasing trends in Kharagpur-I (α = 1%) and Narayangarh (α = 5%) blocks. The pre-monsoon TDS concentrations in unconfined aquifers showed significant decreasing trend in Kharagpur-II (α = 5%) block, whereas post-monsoon TDS concentrations exhibited significant decreasing trend in Kharagpur-I (α = 5%) block. The pre-monsoon HCO_3^- concentrations in unconfined aquifers had no trend, whereas post-monsoon HCO_3^- concentrations indicated significant increasing trends in Keshiary (α = 5%) block, and significant decreasing trend in Kharagpur-I (α = 5%) block. The pre-monsoon Fe^{2+} concentrations in unconfined aquifers showed significant increasing trend in Keshiary (α = 5%) block, whereas post-monsoon Fe^{2+} concentrations exhibited no trend. It was observed that mM-K test detects trend even though M-K and SROC tests are failed to detect it, which indicates over-sensitiveness of the mM-K test in assessing significance of the trends. It is also apparent that the trends identified by the mM-K test are generally more significant than those detected by the M-K and SROC tests for all the parameters. On the other hand, the SROC test was proved to be less sensitive than both M-K and mM-K tests as it fails to capture hidden trends.

Table 1(a). Results of the trend analysis of seasonal pH concentrations in Unconfined Aquifers during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Kharagpur-I	0.619	0.852	1.071	0.126	No	-0.124	-0.210	0.000	-0.010	No
Kharagpur-II	1.496	**2.099 ****	1.623	0.135	No	0.124	0.303	0.189	0.048	No
Narayangarh	1.247	1.407	1.446	0.084	No	1.361	**3.930 ***	1.638	0.111	No
Dantan-I	1.496	**2.356 ****	1.564	0.115	No	0.866	**2.283 ****	0.945	0.098	No
Sankrail	-0.124	-0.203	0.126	-0.016	No	**2.351 ****	**4.746 ***	2.268	0.148	**Increasing ****
Keshiary	0.000	0.188	0.567	-0.021	No	**2.120 ****	**2.890 ***	1.953	0.148	**Increasing ****

Note: * = Significant at α = 1%; ** = Significant at α = 5%; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 1(b). Results of the trend analysis of seasonal TH concentrations in Unconfined Aquifers during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Kharagpur-I	-1.496	**-2.704 ***	-1.623	-15.417	No	**-3.093 ***	**-4.389 ***	**-2.583 ****	-18.688	**Decreasing ***
Kharagpur-II	-1.131	**-2.970 ***	-1.584	-5.833	No	-1.746	**-3.114 ***	-1.778	-14.643	No
Narayangarh	-0.764	-1.489	-0.904	-12.500	No	**-2.136 ****	**-4.735 ***	-2.179	-31.500	**Decreasing ****
Dantan-I	**2.071 ****	**3.750 ***	2.144	5.000	**Increasing ****	-0.499	-0.737	-0.633	-2.708	No
Sankrail	0.619	1.832	0.882	3.393	No	0.866	**2.288 ****	0.819	4.042	No
Keshiary	0.124	0.292	0.567	3.063	No	1.361	**2.988 ***	1.575	11.667	No

Note: * = Significant at α = 1%; ** = Significant at α = 5%; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 1(c). Results of the trend analysis of seasonal *TDS* concentrations in *Unconfined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Kharagpur-I	-1.856	**-3.139 ***	-1.827	-30.792	No	**-2.103 ****	**-3.309 ***	-2.205	-31.000	**Decreasing ****
Kharagpur-II	**-2.244 ****	**-6.030 ***	-2.147	-14.500	**Decreasing ****	-0.880	-1.537	-0.867	-9.057	No
Narayangarh	-1.273	**-2.562 ****	-1.291	-33.667	No	-1.361	**-2.596 ***	-1.764	-40.750	No
Dantan-I	0.997	**2.325 ****	1.175	3.850	No	0.394	1.075	0.464	0.000	No
Sankrail	0.866	1.762	1.008	10.306	No	1.361	**4.074 ***	1.197	16.459	No
Keshiary	0.866	**2.369 ****	1.323	14.751	No	1.608	**4.009 ***	1.512	36.083	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 1(d). Results of the trend analysis of seasonal HCO_3^- concentrations in *Unconfined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Kharagpur-I	-0.371	-0.694	-0.819	-3.438	No	**-2.103 ****	**-4.262 ***	-2.079	-15.781	**Decreasing ****
Kharagpur-II	-1.773	**-5.451 ***	-1.714	-5.417	No	-1.247	**-2.247 ****	-1.658	-9.286	No
Narayangarh	0.000	0.000	-0.452	0.000	No	-0.371	-1.080	-0.567	-4.583	No
Dantan-I	0.748	1.694	1.263	5.500	No	0.249	0.525	0.347	2.024	No
Sankrail	1.361	**3.695 ***	1.386	8.208	No	0.866	1.605	0.693	5.750	No
Keshiary	0.866	1.590	0.945	7.083	No	**1.995 ****	**5.013 ***	2.090	10.292	**Increasing ****

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 1(e). Results of the trend analysis of seasonal *Fe^{2+}* concentrations in *Unconfined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Kharagpur-I	0.255	0.458	0.452	0.004	No	1.247	**2.578 ***	1.505	0.063	No
Kharagpur-II	1.196	**1.976 ****	1.210	0.056	No	0.748	1.334	1.092	0.008	No
Narayangarh	0.399	0.665	0.242	0.000	No	0.499	0.907	0.915	0.027	No
Dantan-I	0.000	0.000	0.258	0.000	No	0.249	0.521	0.856	0.011	No
Sankrail	0.249	0.549	0.915	0.011	No	1.783	**3.520 ***	1.291	0.133	No
Keshiary	**2.244 ****	**4.155 ***	2.154	0.071	**Increasing ****	0.664	1.126	0.968	0.005	No

Note: * = Significant at α = 1%; ** = Significant at α = 5%; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

From the Sen's slope estimation test, it was observed that trend magnitudes (rate of increase or decrease per year) of pre-monsoon pH, TH, TDS, HCO_3^- and Fe^{2+} concentrations in the unconfined aquifers of the study area varied from –0.02 (Keshiary) to 0.14 (Kharagpur-II), –15.42 mg/L (Kharagpur-I) to 5.00 mg/L (Dantan-I), –33.67 mg/L (Narayangarh) to 14.75 mg/L (Keshiary), –5.42 mg/L (Kharagpur-II) to 8.21 mg/L (Sankrail), and 0.00 mg/L (Dantan-I) to 0.07 mg/L (Keshiary), respectively. On the other hand, the trend magnitudes of post-monsoon pH, TH, TDS, HCO_3^- and Fe^{2+} concentrations in the unconfined aquifers of the study area varied from –0.01 (Kharagpur-I) to 0.15 (Keshiary), –31.50 mg/L (Narayangarh) to 11.67 mg/L (Keshiary), –40.75 mg/L (Narayangarh) to 36.08 mg/L (Keshiary), –15.78 mg/L (Kharagpur-I) to 10.29 mg/L (Keshiary), and 0.01 mg/L (Keshiary) to 0.13 mg/L (Sankrail), respectively.

3.2.2 Leaky-Confined Aquifer

The test-statistic 'Z' values obtained from the trend analysis of five seasonal groundwater-quality parameters from leaky-confined aquifers have been presented in Tables 2(a–e). The critical test-statistic 'Z_{crit}' values of both original Mann-Kendall (M-K) test and modified Mann-Kendall (mM-K) tests were ±1.960 (at α = 5%), and ±2.575 (at α = 1%). On the other hand, critical test-statistic 't_{crit}' values of the SROC test were ±2.447 (for n−2 = 6, and at α = 5%), and ±3.707 (for n−2 = 6, and at α = 1%). The calculated test-statistics 'Z' and 't_s' values were compared with the critical test-statistics 'Z_{crit}' and 't_{crit}' values, respectively.

It is evident from Tables 2(a–e) that both pre-monsoon and post-monsoon pH concentrations in leaky-confined aquifers exhibited no trend. The pre-monsoon TH concentrations in leaky-confined aquifers had significant increasing trend in Keshiary (α = 5%) block, whereas post-monsoon TH concentrations indicated significant decreasing trends in Ramnagar-I (α = 5%) and Pingla (α = 5%) blocks. The pre-monsoon TDS concentrations in leaky-confined aquifers showed significant decreasing trends in Nandigram-I (α = 5%), Nandigram-II (α = 5%), Ramnagar-I (α = 5%), Narayangarh (α = 5%), Pingla (α = 5%), Debra (α = 5%), Mohanpur (α = 5%) and Dantan-II (α = 1%) blocks, whereas post-monsoon TDS concentrations exhibited significant decreasing trends in Bhagabanpur-I (α = 1%), Nandigram-I (α = 5%), Nandigram-II (α = 1%) and Narayangarh (α = 5%) blocks. The pre-monsoon HCO_3^- concentrations in leaky-confined aquifers had significant decreasing trend in Debra (α = 5%) block, whereas post-monsoon HCO_3^- concentrations indicated no trend. The pre-monsoon Fe^{2+} concentrations in leaky-confined aquifers showed significant increasing trends in Egra-I (α = 5%), Egra-II (α = 5%), Nandigram-I (α = 5%), Khejuri-I (α = 5%) and Ramnagar-I (α = 5%) blocks, whereas post-monsoon Fe^{2+} concentrations exhibited significant increasing trend in Nandigram-I (α = 1%) block. In examining the significance of trends, it was found that the mM-K test is overly sensitive, since it finds a trend when the M-K and SROC tests failed to do so. It is also clear that the trends discovered by the mM-K test are more significant than those revealed by the M-K and SROC tests for all parameters. However, due to its inability to detect hidden patterns, the SROC test was found to be less sensitive than both M-K and mM-K tests.

Table 2(a). Results of the trend analysis of seasonal *pH* concentrations in *Leaky-Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	**mM-K**	**SROC**	**Trend Magnitude**	**Trend**	**M-K**	**mM-K**	**SROC**	**Trend Magnitude**	**Trend**
Jaleswar	0.249	0.627	0.814	0.010	No	-0.371	-0.710	-0.567	-0.023	No
Bhograi	0.997	**3.062 ***	1.196	0.022	No	-0.748	-1.700	-0.829	-0.020	No
Panskura-I	0.000	0.152	0.504	0.034	No	0.000	0.202	-0.126	-0.009	No
Moyna	0.124	0.169	0.630	0.030	No	0.124	0.232	0.252	0.067	No
Bhagabanpur-I	0.619	1.114	0.945	0.124	No	0.124	0.225	0.252	0.049	No
Bhagabanpur-II	0.371	0.729	0.693	0.110	No	0.000	0.224	-0.189	0.012	No
Patashpur-I	0.371	0.508	0.756	0.051	No	0.371	0.650	0.315	0.074	No
Patashpur-II	0.866	1.119	0.882	0.041	No	0.000	0.215	-0.126	0.016	No
Egra-I	-0.124	-0.133	0.441	-0.019	No	0.124	0.195	0.378	0.022	No
Egra-II	-0.371	-0.510	-0.315	-0.025	No	0.124	0.226	-0.063	0.064	No
Nandigram-I	0.866	1.562	0.882	0.145	No	0.866	1.467	0.882	0.063	No
Nandigram-II	0.866	1.609	1.197	0.208	No	0.249	0.416	0.485	0.055	No
Khejuri-I	0.748	1.410	0.974	0.119	No	-0.249	-0.416	-0.978	-0.006	No
Contai-III	1.746	**2.081 ****	1.602	0.118	No	1.496	**2.527 ****	1.534	0.145	No
Ramnagar-I	0.619	1.082	0.819	0.163	No	0.000	0.000	-0.277	0.060	No
Kharagpur-II	0.499	0.558	0.974	0.018	No	0.371	0.846	0.504	0.041	No
Narayangarh	0.997	1.458	1.328	0.133	No	0.371	0.585	0.567	0.018	No
Pingla	1.328	0.909	1.151	0.087	No	0.124	0.200	0.441	0.010	No
Sabang	0.997	1.548	1.446	0.174	No	0.371	0.724	0.504	0.045	No
Debra	1.247	1.940	1.505	0.175	No	0.124	0.259	0.378	0.031	No
Mohanpur	0.748	1.453	1.210	0.171	No	0.619	1.553	1.008	0.081	No
Dantan-I	1.247	**2.564 ****	1.505	0.218	No	0.866	1.726	0.819	0.050	No
Dantan-II	1.746	**2.699 ***	1.682	0.129	No	0.124	0.215	0.441	0.017	No
Sankrail	-0.124	-0.176	0.441	-0.013	No	1.856	**3.491 ***	1.890	0.125	No
Keshiary	0.124	0.192	0.630	0.043	No	1.361	1.906	1.512	0.168	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 2(b). Results of the trend analysis of seasonal *TH* concentrations in *Leaky-Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Jaleswar	0.499	1.365	0.995	7.730	No	1.114	**3.296 ***	1.260	10.476	No
Bhograi	0.997	**2.620 ***	1.140	11.042	No	-0.873	**-1.994 ****	-1.386	-4.000	No
Panskura-I	-0.619	-1.412	-1.071	-7.020	No	-0.371	-0.605	-0.567	-2.333	No
Moyna	-0.619	-1.185	-1.071	-5.208	No	-0.124	-0.229	0.063	-2.604	No
Bhagabanpur-I	-0.371	-1.276	-0.441	-2.458	No	-0.371	-0.609	-0.504	-3.875	No
Bhagabanpur-II	-0.748	-1.277	-0.797	-11.250	No	0.000	0.000	-0.065	0.000	No
Patashpur-I	0.000	0.369	0.189	0.240	No	-0.124	-0.212	0.063	-1.500	No
Patashpur-II	-1.856	**-4.414 ***	-1.890	-7.240	No	-0.619	-1.244	-0.693	-3.760	No
Egra-I	-0.619	-1.384	-0.756	-7.500	No	-0.124	-0.210	-0.378	-1.450	No
Egra-II	-0.124	-0.274	-0.126	-1.875	No	0.000	0.000	0.095	1.000	No
Nandigram-I	-1.746	**-2.515 ****	-1.972	-22.667	No	**-2.351 ****	**-3.218 ***	-2.205	-15.000	**Decreasing ****
Nandigram-II	0.000	0.000	0.410	1.667	No	1.382	**3.625 ***	1.400	4.875	No
Khejuri-I	0.000	0.000	-0.410	-4.000	No	0.126	0.274	0.242	2.500	No
Contai-III	-1.267	-1.812	-1.029	-43.333	No	-0.253	-0.577	-0.104	-10.000	No
Ramnagar-I	**-2.136 ****	**-3.628 ***	-2.118	-20.833	**Decreasing ****	-1.382	-1.946	-1.599	-5.000	No
Kharagpur-II	0.000	**2.452 ****	1.097	0.521	No	-0.249	-0.702	-0.462	-1.548	No
Narayangarh	-1.885	**-2.936 ***	-1.819	-7.917	No	-1.608	**-3.190 ***	-1.638	-6.458	No
Pingla	**-1.995 ****	**-4.991 ***	-2.011	-12.083	**Decreasing ****	-0.619	-1.325	-0.756	-5.313	No
Sabang	-0.748	-1.418	-1.325	-7.333	No	**-1.995 ****	**-6.299 ***	-1.972	-5.583	**Decreasing ****
Debra	-1.885	**-5.336 ***	-1.919	-11.944	No	-0.748	-1.454	-0.743	-2.167	No
Mohanpur	-1.156	-1.478	-1.228	-4.375	No	**-2.103 ****	**-4.438 ***	-1.890	-9.792	**Decreasing ****
Dantan-I	0.000	0.226	-0.151	0.000	No	-0.499	-1.093	-0.512	-2.750	No
Dantan-II	-1.496	**-2.879 ***	-1.534	-9.688	No	0.499	1.088	0.498	0.670	No
Sankrail	1.114	1.697	0.945	11.250	No	1.247	**2.255 ****	1.140	13.958	No
Keshiary	**2.103 ****	**5.832 ***	2.142	9.444	**Increasing ****	0.619	1.195	0.882	4.250	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 2(c). Results of the trend analysis of seasonal *TDS* concentrations in *Leaky-Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Jaleswar	1.496	**3.156 ***	1.859	13.978	No	1.361	**4.013 ***	1.512	25.300	No
Bhograi	0.997	**2.587 ***	1.296	9.333	No	0.371	0.863	0.756	6.857	No
Panskura-I	-0.866	-1.846	-1.197	-5.312	No	-0.866	-1.899	-0.945	-7.940	No
Moyna	-0.371	-1.133	-0.756	-13.533	No	0.000	0.237	0.126	0.833	No
Bhagabanpur-I	0.371	1.077	0.819	1.467	No	**-2.846 ***	**-6.342 ***	**-2.520 ****	-31.500	**Decreasing ***
Bhagabanpur-II	-1.131	-1.459	-1.277	-16.000	No	-0.997	**-3.346 ***	-1.263	-9.929	No
Patashpur-I	0.000	0.344	0.126	0.216	No	-0.866	-1.650	-1.197	-9.038	No
Patashpur-II	-0.124	-0.326	-0.252	-6.297	No	-0.619	**-2.024 ****	-1.134	-22.360	No
Egra-I	-0.866	-1.597	-0.693	-5.450	No	-1.361	**-2.055 ****	-1.323	-15.329	No
Egra-II	-1.496	**-4.280 ***	-1.293	-2.917	No	-1.361	**-2.299 ****	-1.323	-5.208	No
Nandigram-I	**-2.244 ****	**-7.452 ***	-2.147	-33.167	**Decreasing ****	**-2.351 ****	**-4.744 ***	-2.205	-25.500	**Decreasing ****
Nandigram-II	**-2.103 ****	**-3.848 ***	-2.079	-22.833	**Decreasing ****	**-2.846 ***	**-5.897 ***	**-2.520 ****	-26.067	**Decreasing ***
Khejuri-I	-1.746	**-4.769 ***	-1.692	-51.500	No	-0.748	-1.341	-0.614	-17.333	No
Contai-III	-0.997	-1.674	-0.797	-142.000	No	-1.247	**-2.624 ***	-0.814	-70.400	No
Ramnagar-I	**-2.351 ****	**-4.846 ***	-2.205	-21.857	**Decreasing ****	-1.856	**-3.889 ***	-1.890	-18.400	No
Kharagpur-II	-0.126	-0.299	-0.067	-0.500	No	-1.608	**-4.606 ***	-1.512	-11.667	No
Narayangarh	**-1.995 ****	**-3.740 ***	-2.079	-18.250	**Decreasing ****	**-2.103 ****	**-4.119 ***	-2.142	-8.917	**Decreasing ****
Pingla	**-2.494 ****	**-7.519 ***	-2.352	-22.036	**Decreasing ****	-0.371	-1.182	-0.567	-2.125	No
Sabang	-1.496	**-5.193 ***	-1.559	-18.076	No	-0.619	-1.654	-0.693	-11.100	No
Debra	**-2.494 ****	**-6.322 ***	-2.352	-26.762	**Decreasing ****	-1.114	**-3.467 ***	-1.386	-7.333	No
Mohanpur	**-2.494 ****	**-6.626 ***	-2.352	-15.500	**Decreasing ****	-1.496	**-3.378 ***	-1.861	-7.929	No
Dantan-I	-0.748	-1.787	-0.662	-3.000	No	-0.371	-0.975	-0.315	-2.550	No
Dantan-II	**-2.743 ***	**-5.520 ***	**-2.488 ****	-31.833	**Decreasing ***	-0.866	-1.737	-0.945	-3.542	No
Sankrail	0.866	1.951	1.197	24.264	No	0.866	1.826	1.008	11.971	No
Keshiary	1.608	**3.671 ***	1.512	17.792	No	1.114	**2.116 ****	1.512	12.659	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 2(d). Results of the trend analysis of seasonal HCO_3^- concentrations in *Leaky-Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Jaleswar	1.247	**3.012 ***	1.446	10.667	No	1.856	**4.959 ***	2.079	27.878	No
Bhograi	0.499	1.207	0.797	8.625	No	0.000	0.260	0.126	2.442	No
Panskura-I	0.000	0.209	0.252	0.833	No	-0.124	-0.178	0.063	-11.875	No
Moyna	0.249	0.457	0.291	1.292	No	0.124	0.194	0.252	8.490	No
Bhagabanpur-I	0.000	0.257	-0.126	-0.972	No	0.000	0.000	-0.032	1.000	No
Bhagabanpur-II	0.628	1.427	0.585	10.625	No	0.000	0.000	-0.100	0.625	No
Patashpur-I	0.124	0.213	0.189	3.872	No	-0.866	-1.578	-0.693	-7.159	No
Patashpur-II	0.000	0.207	0.252	1.317	No	0.000	0.221	0.189	-2.433	No
Egra-I	0.371	0.642	0.189	1.750	No	-0.124	-0.204	-0.126	-5.505	No
Egra-II	0.124	0.293	0.378	3.056	No	-0.124	-0.231	0.063	-4.375	No
Nandigram-I	0.000	0.000	0.339	3.750	No	0.000	0.212	0.189	6.667	No
Nandigram-II	-0.371	-0.618	-0.252	-4.167	No	0.249	0.372	0.401	5.000	No
Khejuri-I	-0.249	-0.538	0.226	-2.917	No	-0.249	-0.575	0.226	-3.500	No
Contai-III	-0.880	-1.510	-0.928	-9.583	No	-0.126	-0.237	-0.178	-5.417	No
Ramnagar-I	-0.499	-0.738	-0.814	-6.000	No	0.124	0.173	0.252	3.875	No
Kharagpur-II	1.496	**3.451 ***	1.880	5.063	No	-0.866	**-2.024 ****	-1.134	-3.750	No
Narayangarh	-1.247	**-2.790 ***	-1.193	-7.135	No	-0.124	-0.217	-0.567	-1.771	No
Pingla	-1.746	**-4.078 ***	-1.806	-15.813	No	0.499	1.190	0.511	1.927	No
Sabang	-1.634	**-3.141 ***	-1.850	-8.056	No	-0.866	**-2.108 ****	-1.008	-12.278	No
Debra	**-2.494 ****	**-7.068 ***	-2.352	-15.417	**Decreasing ****	-0.249	0.802	-0.277	-3.611	No
Mohanpur	-1.247	**-3.214 ***	-1.465	-8.813	No	-1.114	**-2.038 ****	-1.071	-5.625	No
Dantan-I	1.746	**3.912 ***	1.838	2.813	No	0.748	1.351	0.873	3.917	No
Dantan-II	-1.247	**-2.640 ***	-1.397	-9.375	No	-0.124	-0.259	-0.567	-0.335	No
Sankrail	0.371	0.856	0.504	8.361	No	1.746	**3.302 ***	1.758	16.458	No
Keshiary	1.608	**4.102 ***	1.638	11.667	No	1.114	**2.497 ****	1.197	2.361	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L

Table 2(e). Results of the trend analysis of seasonal Fe^{2+} concentrations in *Leaky-Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	**mM-K**	**SROC**	**Trend Magnitude**	**Trend**	**M-K**	**mM-K**	**SROC**	**Trend Magnitude**	**Trend**
Jaleswar	-1.309	-1.656	-1.528	0.000	No	N.A.	N.A.	N.A.	N.A.	N.A.
Bhograi	-1.309	-1.656	-1.528	0.000	No	-1.309	-1.656	-1.528	0.000	No
Panskura-I	1.247	**2.456 ****	1.387	0.232	No	0.748	1.728	1.210	0.051	No
Moyna	0.997	1.896	1.269	0.245	No	1.247	**2.895 ***	1.505	0.244	No
Bhagabanpur-I	0.997	**2.566 ****	1.387	0.096	No	0.499	1.077	0.974	0.014	No
Bhagabanpur-II	0.000	0.000	0.679	0.005	No	0.000	0.000	0.679	0.005	No
Patashpur-I	0.748	1.868	1.151	0.134	No	0.000	0.000	0.620	-0.030	No
Patashpur-II	1.496	**3.733 ***	1.682	0.179	No	1.247	**2.006 ****	1.210	0.112	No
Egra-I	**1.995 ****	**6.471 ***	2.213	0.328	**Increasing ****	1.746	**3.255 ***	1.859	0.611	No
Egra-II	**2.244 ****	**6.489 ***	2.331	0.394	**Increasing ****	0.000	0.000	0.679	0.023	No
Nandigram-I	**2.388 ****	**4.138 ***	2.310	0.137	**Increasing ****	**2.743 ***	**4.421 ***	**2.449 ****	0.140	**Increasing ***
Nandigram-II	1.247	**2.649 ***	1.505	0.045	No	1.247	**2.041 ****	1.387	0.070	No
Khejuri-I	**1.995 ****	**4.198 ***	1.977	0.118	**Increasing ****	-0.128	-0.248	0.102	0.000	No
Contai-III	0.628	1.223	0.870	0.084	No	0.899	1.520	1.115	0.146	No
Ramnagar-I	**2.244 ****	**6.417 ***	2.213	0.126	**Increasing ****	1.746	**4.296 ***	2.036	0.113	No
Kharagpur-II	0.255	0.453	0.452	0.021	No	0.000	0.000	0.620	-0.028	No
Narayangarh	0.509	0.964	0.581	0.057	No	0.000	0.000	0.620	-0.053	No
Pingla	0.255	0.415	0.452	0.005	No	0.000	0.000	0.679	0.005	No
Sabang	0.509	1.060	0.581	0.009	No	0.000	0.000	0.738	0.005	No
Debra	0.000	0.000	0.194	0.000	No	0.748	1.755	1.092	0.053	No
Mohanpur	0.000	0.000	0.194	0.000	No	0.748	1.449	0.974	0.009	No
Dantan-I	0.000	0.000	0.258	0.000	No	0.249	0.576	0.797	0.007	No
Dantan-II	1.273	**1.988 ****	1.097	0.038	No	0.997	**2.132 ****	1.151	0.046	No
Sankrail	0.499	1.006	0.915	0.041	No	0.255	0.512	0.452	0.018	No
Keshiary	1.496	**2.767 ***	1.682	0.070	No	0.509	1.104	0.645	0.153	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; N.A. = Data not available; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

From the Sen's slope estimation test, it was observed that trend magnitudes (rate of increase or decrease per year) of pre-monsoon pH, TH, TDS, HCO_3^- and Fe^{2+} concentrations in the leaky-confined aquifers of the study area varied from −0.03 (Egra-II) to 0.22 (Dantan-I), −43.33 mg/L (Contai-III) to 11.25 mg/L (Sankrail), −142.00 mg/L (Contai-III) to 24.26 mg/L (Sankrail), −15.81 mg/L (Pingla) to 11.67 mg/L (Keshiary), and 0.00 mg/L (Jaleswar) to 0.39 mg/L (Egra-II), respectively. On the other hand, the trend magnitudes of post-monsoon pH, TH, TDS, HCO_3^- and Fe^{2+} concentrations in the leaky-confined aquifers of the study area varied from −0.02 (Jaleswar) to 0.17 (Keshiary), −15.00 mg/L (Nandigram-I) to 13.96 mg/L (Sankrail), −70.40 mg/L (Contai-III) to 25.30 mg/L (Jaleswar), −12.28 mg/L (Sabang) to 27.88 mg/L (Jaleswar), and −0.05 mg/L (Narayangarh) to 0.61 mg/L (Egra-I), respectively.

3.2.3 Confined Aquifer

The test-statistic 'Z' values obtained from the trend analysis of five seasonal groundwater-quality parameters from confined aquifers have been presented in Tables 3(a–e). The critical test-statistic 'Z_{crit}' values of both original Mann-Kendall (M-K) test and modified Mann-Kendall (mM-K) tests were ±1.960 (at α = 5%), and ±2.575 (at α = 1%). On the other hand, critical test-statistic 't_{crit}' values of the SROC test were ±2.447 (for n−2 = 6, and at α = 5%), and ±3.707 (for n−2 = 6, and at α = 1%). The calculated test-statistics 'Z' and 't_s' values were compared with the critical test-statistics 'Z_{crit}' and 't_{crit}' values, respectively.

It is evident from Tables 3(a–e) that both pre-monsoon and post-monsoon pH concentrations in confined aquifers exhibited no trend. The pre-monsoon TH concentrations in confined aquifers had significant decreasing trends in Nandigram-II (α = 5%) and Contai-I (α = 1%) blocks, whereas post-monsoon TH concentrations indicated no trend. The pre-monsoon TDS concentrations in confined aquifers showed significant increasing trend in Bhograi (α = 5%) block, and significant decreasing trends in Bhagabanpur-I (α = 5%), Nandigram-I (α = 5%), Nandigram-II (α = 5%), Chandipur (α = 5%) and Contai-I (α = 1%) blocks, whereas post-monsoon TDS concentrations exhibited significant increasing trend in Bhograi (α = 5%) block and significant decreasing trend in Nandigram-II (α = 5%) block. Both pre-monsoon and post-monsoon HCO_3^- concentrations in confined aquifers had significant increasing trends in Bhograi (α = 1%) block. The pre-monsoon Fe^{2+} concentrations in confined aquifers showed significant increasing trends in Nandigram-II (α = 5%) and Khejuri-I (α = 5%) blocks, whereas post-monsoon Fe^{2+} concentrations exhibited no trend. The mM-K test detects trends even when the M-K and SROC tests are unable to do so points to the test's excessive sensitivity in determining the significance of trends. Additionally, it is clear that for all parameters, the trends observed by the mM-3K test are generally more significant than those found by the M-K and SROC tests. In contrast, the SROC test was less sensitive in identifying hidden trends than both M-K and mM-K tests.

Table 3(a). Results of the trend analysis of seasonal *pH* concentrations in *Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Bhograi	0.377	1.216	0.908	0.005	No	0.377	1.216	0.908	0.005	No
Moyna	0.124	0.204	0.630	0.093	No	0.124	0.217	0.252	0.027	No
Bhagabanpur-I	0.124	0.219	0.630	0.120	No	0.124	0.217	0.252	0.031	No
Bhagabanpur-II	0.371	0.658	0.756	0.120	No	0.371	0.682	0.315	0.045	No
Patashpur-I	0.371	0.649	0.756	0.105	No	0.000	0.203	0.126	0.006	No
Patashpur-II	0.619	1.130	0.819	0.119	No	0.124	0.221	0.252	0.034	No
Egra-I	0.000	0.142	0.567	-0.014	No	0.000	0.204	-0.126	-0.004	No
Egra-II	0.000	0.162	0.567	0.012	No	0.124	0.213	0.063	0.023	No
Nandigram-I	0.371	0.692	0.756	0.121	No	0.371	0.625	0.315	0.084	No
Nandigram-II	0.619	0.895	1.071	0.098	No	0.371	0.624	0.504	0.035	No
Chandipur	0.371	0.641	0.756	0.159	No	-0.124	-0.190	-0.252	-0.019	No
Khejuri-I	0.371	0.650	0.756	0.153	No	0.371	0.562	0.693	0.035	No
Khejuri-II	0.371	0.615	0.756	0.120	No	0.124	0.224	-0.063	0.038	No
Contai-I	1.114	1.955	1.386	0.233	No	0.124	0.214	0.189	0.040	No
Deshopran	1.856	**2.810 ***	2.016	0.188	No	0.619	0.997	0.882	0.066	No
Contai-III	0.866	1.431	0.882	0.141	No	0.124	0.220	-0.063	0.083	No
Ramnagar-I	0.124	0.169	0.630	0.067	No	-0.124	-0.171	-0.252	-0.027	No
Ramnagar-II	0.866	1.580	1.071	0.174	No	0.124	0.169	0.315	0.007	No

Note: * = Significant at α = 1%; ** = Significant at α = 5%; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L

Table 3(b). Results of the trend analysis of seasonal *TH* concentrations in *Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Bhograi	1.247	**4.372 ***	1.263	7.917	No	1.247	**4.372 ***	1.263	7.917	No
Moyna	-0.619	-0.988	-0.882	-9.944	No	0.000	0.238	0.126	-2.306	No
Bhagabanpur-I	-0.619	-1.607	-1.071	-4.708	No	0.371	0.527	0.378	2.723	No
Bhagabanpur-II	0.371	0.729	0.252	2.598	No	-1.114	**-3.633 ***	-1.386	-17.727	No
Patashpur-I	-1.361	**-2.754 ***	-1.323	-10.556	No	-0.124	-0.222	-0.315	-5.000	No
Patashpur-II	-0.619	-1.804	-0.756	-4.417	No	-0.619	-1.148	-0.630	-3.833	No
Egra-I	0.124	0.232	0.252	5.483	No	0.124	0.287	0.252	2.583	No
Egra-II	-0.371	-0.946	-0.567	-8.378	No	-0.371	-0.917	-0.252	-3.583	No
Nandigram-I	-1.634	**-2.725 ***	-1.695	-14.375	No	-0.619	-0.863	-0.819	-4.750	No
Nandigram-II	**-2.103 ****	**-4.183 ***	-1.890	-29.167	**Decreasing ****	-1.608	**-2.318 ****	-1.512	-10.000	No
Chandipur	-1.496	**-2.741 ***	-1.572	-15.000	No	-0.499	-0.833	-0.512	-1.750	No
Khejuri-I	0.000	0.000	-0.032	0.625	No	0.000	0.000	0.031	4.063	No
Khejuri-II	-0.619	-0.852	-0.756	-1.083	No	-0.866	-1.215	-0.756	-2.625	No
Contai-I	**-2.598 ***	**-3.678 ***	-2.394	-57.444	**Decreasing ***	-0.124	-0.205	-0.630	-3.583	No
Deshopran	-0.371	-0.921	-0.567	-5.458	No	-0.866	**-2.367 ****	-1.008	-2.083	No
Contai-III	0.124	0.259	0.378	4.889	No	1.361	**2.414 ****	1.575	25.875	No
Ramnagar-I	0.124	0.270	0.378	5.190	No	1.361	**2.235 ****	1.134	8.727	No
Ramnagar-II	-0.249	-0.622	-0.536	-1.083	No	0.000	0.000	-0.162	-0.313	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 3(c). Results of the trend analysis of seasonal *TDS* concentrations in *Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Bhograi	**2.494 ****	**4.890 ***	2.331	20.125	**Increasing ****	**2.494 ****	**4.890 ***	2.331	20.125	**Increasing ****
Moyna	-1.361	**-1.988 ****	-1.323	-20.444	No	0.619	1.346	0.819	11.095	No
Bhagabanpur-I	**-2.103 ****	**-5.083 ***	-2.079	-16.432	**Decreasing ****	-1.856	**-3.861 ***	-1.953	-18.815	No
Bhagabanpur-II	-0.371	-0.975	-0.504	-6.280	No	-0.124	-0.412	-0.252	-5.870	No
Patashpur-I	-0.371	-0.779	-0.630	-5.100	No	-1.114	-1.799	-1.071	-27.152	No
Patashpur-II	-0.866	**-2.613 ***	-1.008	-3.730	No	-0.124	-0.196	-0.189	-7.278	No
Egra-I	0.866	1.231	0.945	6.139	No	-0.371	-0.710	-0.504	-4.302	No
Egra-II	-0.371	-0.916	-0.504	-9.933	No	-0.866	-1.566	-0.882	-17.547	No
Nandigram-I	**-2.244 ****	**-4.055 ***	-2.079	-24.208	**Decreasing ****	-1.114	**-2.910 ***	-1.512	-17.417	No
Nandigram-II	**-2.351 ****	**-5.164 ***	-2.331	-52.800	**Decreasing ****	**-2.103 ****	**-3.789 ***	-2.079	-43.111	**Decreasing ****
Chandipur	**-2.351 ****	**-4.155 ***	-2.205	-49.250	**Decreasing ****	-1.856	**-3.073 ***	-1.890	-38.262	No
Khejuri-I	-1.361	**-3.049 ***	-1.449	-20.075	No	-0.124	-0.288	-0.378	-22.792	No
Khejuri-II	-1.856	**-2.885 ***	-2.016	-23.428	No	-1.608	**-3.214 ***	-1.638	-22.259	No
Contai-I	**-3.093 ***	**-4.903 ***	**-2.583 ****	-172.975	**Decreasing ***	-0.619	-1.342	-0.882	-55.600	No
Deshopran	-1.361	**-2.908 ***	-1.890	-22.900	No	-0.619	-1.498	-0.945	-7.550	No
Contai-III	0.619	1.570	0.756	64.467	No	1.361	**2.507 ****	1.575	92.583	No
Ramnagar-I	0.124	0.323	0.756	15.707	No	0.371	0.551	0.819	10.080	No
Ramnagar-II	-1.114	**-2.219 ****	-0.945	-14.307	No	-1.114	**-2.015 ****	-1.260	-23.133	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 3(d). Results of the trend analysis of seasonal HCO_3^- concentrations in *Confined Aquifers* during 2011–2018 period

Blocks	**Calculated Test-Statistics (Pre-Monsoon Season)**					**Calculated Test-Statistics (Post-Monsoon Season)**				
	M-K	**mM-K**	**SROC**	**Trend Magnitude**	**Trend**	**M-K**	**mM-K**	**SROC**	**Trend Magnitude**	**Trend**
Bhograi	**2.743 ***	**5.697 ***	2.441	21.565	**Increasing ***	**2.743 ***	**5.697 ***	2.441	21.565	**Increasing ***
Moyna	-0.371	-0.706	-0.567	-0.938	No	0.000	0.222	0.189	-0.750	No
Bhagabanpur-I	-0.619	-1.278	-0.882	-0.947	No	0.000	0.211	0.189	0.057	No
Bhagabanpur-II	0.866	1.780	1.008	3.215	No	-0.124	-0.219	-0.126	-1.125	No
Patashpur-I	0.619	1.222	0.693	7.222	No	-0.619	-1.123	-0.756	-5.083	No
Patashpur-II	0.249	0.426	0.384	1.944	No	0.371	0.555	0.315	7.083	No
Egra-I	-0.124	-0.217	0.189	-0.407	No	0.124	0.189	0.126	1.129	No
Egra-II	-0.371	-0.590	0.000	-3.792	No	-1.361	**-2.689 ***	-1.260	-11.020	No
Nandigram-I	-1.608	**-2.624 ***	-1.575	-13.988	No	0.371	0.711	0.252	7.292	No
Nandigram-II	0.000	0.189	0.000	1.167	No	0.124	0.200	0.189	4.333	No
Chandipur	0.000	0.193	-0.189	-0.083	No	0.255	0.388	-0.129	0.625	No
Khejuri-I	-0.124	-0.195	0.063	-4.444	No	-0.619	-1.544	-0.882	-5.625	No
Khejuri-II	-0.866	-1.392	-0.693	-10.833	No	-0.371	-0.624	-0.315	-4.926	No
Contai-I	0.371	0.637	0.315	3.033	No	0.371	0.623	0.504	3.210	No
Deshopran	1.361	**2.221 ****	1.449	19.708	No	1.114	**2.509 ****	1.512	18.161	No
Contai-III	-0.371	-1.053	-0.693	-3.611	No	0.000	0.287	0.252	0.556	No
Ramnagar-I	-0.371	-0.571	-0.315	-8.651	No	0.124	0.192	0.126	3.988	No
Ramnagar-II	-0.619	-1.189	-0.630	-14.104	No	0.124	0.196	0.252	5.656	No

Note: * = Significant at α = 1%; ** = Significant at α = 5%; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

Table 3(e). Results of the trend analysis of seasonal *Fe^{2+}* concentrations in *Confined Aquifers* during 2011–2018 period.

Blocks	Calculated Test-Statistics (Pre-Monsoon Season)					Calculated Test-Statistics (Post-Monsoon Season)				
	M-K	mM-K	SROC	Trend Magnitude	Trend	M-K	mM-K	SROC	Trend Magnitude	Trend
Bhograi	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Moyna	0.997	**2.165 ****	1.387	0.152	No	0.997	**2.166 ****	1.328	0.266	No
Bhagabanpur-I	1.247	**3.018 ***	1.328	0.161	No	0.748	1.622	1.092	0.121	No
Bhagabanpur-II	0.249	0.450	0.797	0.094	No	0.748	1.242	1.033	0.117	No
Patashpur-I	1.496	**4.359 ***	1.741	0.240	No	0.748	1.945	1.151	0.168	No
Patashpur-II	0.997	**2.942 ***	1.446	0.242	No	0.499	1.059	1.033	0.056	No
Egra-I	0.997	**2.670 ***	1.387	0.144	No	0.997	1.872	1.151	0.160	No
Egra-II	1.247	**2.577 ***	1.623	0.076	No	0.997	1.856	1.387	0.077	No
Nandigram-I	0.499	1.098	0.974	0.057	No	0.000	0.000	0.738	0.015	No
Nandigram-II	**1.995 ****	**4.873 ***	1.977	0.256	**Increasing ****	1.496	**3.028 ***	1.682	0.166	No
Chandipur	1.247	**2.884 ***	1.623	0.216	No	-0.255	-0.516	0.065	-0.005	No
Khejuri-I	**2.244 ****	**4.144 ***	2.213	0.245	**Increasing ****	0.764	1.522	0.968	0.140	No
Khejuri-II	0.000	0.000	0.738	0.033	No	0.000	0.000	0.387	0.000	No
Contai-I	0.000	0.000	0.620	-0.004	No	0.000	0.000	0.258	0.000	No
Deshopran	1.746	**3.686 ***	1.918	0.122	No	0.748	1.579	1.092	0.065	No
Contai-III	1.746	**4.387 ***	1.918	0.167	No	1.247	**3.392 ***	1.623	0.150	No
Ramnagar-I	0.997	**2.119 ****	1.328	0.094	No	0.997	**2.025 ****	1.387	0.121	No
Ramnagar-II	1.496	**3.200 ***	1.741	0.163	No	0.509	1.121	0.581	0.042	No

Note: * = Significant at $\alpha = 1\%$; ** = Significant at $\alpha = 5\%$; N.A. = Data not available; Units of TH, TDS, HCO_3^- and Fe^{2+} are in mg/L.

From the Sen's slope estimation test, it was observed that trend magnitudes (rate of increase or decrease per year) of pre-monsoon pH, TH, TDS, HCO_3^- and Fe^{2+} concentrations in the confined aquifers of the study area varied from –0.01 (Egra-I) to 0.23 (Contai-I), –57.44 mg/L (Contai-I) to 7.92 mg/L (Bhograi), –172.98 mg/L (Contai-I) to 64.47 mg/L (Contai-III), –14.10 mg/L (Ramnagar-II) to 21.57 mg/L (Bhograi), and 0.00 mg/L (Contai-I) to 0.26 mg/L (Nandigram-II), respectively. On the other hand, the trend magnitudes of post-monsoon pH, TH, TDS, HCO_3^- and Fe^{2+} concentrations in the confined aquifers of the study area varied from –0.03 (Ramnagar-I) to 0.08 (Nandigram-I), –17.73 mg/L (Bhagabanpur-II) to 25.88 mg/L (Contai-III), –55.60 mg/L (Contai-I) to 92.58 mg/L (Contai-III), –11.02 mg/L (Egra-II) to 21.57 mg/L (Bhograi), and –0.01 mg/L (Chandipur) to 0.27 mg/L (Moyna), respectively.

4. Conclusion

This study explores trends in five seasonal (pre-monsoon and post-monsoon seasons) groundwater-quality parameters (pH, TH, TDS, HCO_3^- and Fe^{2+}) of 2011–2018 period for the unconfined, leaky-confined and confined aquifers in a coastal alluvial basin of West Bengal, India. Performance evaluation of three non-parametric statistical trend detection tests, namely: (i) Original Mann-Kendall (M-K) test, (ii) Modified Mann-Kendall (mM-K) test, and (iii) Spearman Rank Order Correlation (SROC) test was carried out. The Sen's slope estimation test was used to find the magnitude (increasing or decreasing per year) of trend.

Statistical analyses indicated that seasonal concentrations of all five groundwater-quality parameters have high spatial (block-wise) variation over the study area. The results of trend analyses revealed that the seasonal pH concentrations mostly had no trend except in the unconfined aquifers of Sankrail (increasing at α = 5%) and Keshiary (increasing at α = 5%) blocks during post-monsoon season. The seasonal TH concentrations mainly showed decreasing trends except in the unconfined aquifers of Dantan-I (increasing at α = 5%) and leaky-confined aquifers of Keshiary (increasing at α = 5%) blocks during pre-monsoon season. The seasonal TDS concentrations majorly had decreasing trends except in the confined aquifers of Bhograi (increasing at α = 5%) block during both the seasons. The seasonal HCO_3^- concentrations mostly showed increasing trends except in the unconfined aquifers of Kharagpur-I (decreasing at α = 5%) and leaky-confined aquifers of Debra (decreasing at α = 5%) blocks during post-monsoon and pre-monsoon seasons, respectively. The seasonal Fe^{2+} concentrations mainly had increasing trends (α = 5% or 1%) over the study area. The fact that the mM-K test can identify hidden trends even when the M-K and SROC tests cannot demonstrates the test's over-sensitiveness in judging the significance of trends. Furthermore, it is obvious that trends detected by the mM-K test are typically more significant than those discovered by the M-K and SROC tests. However, the SROC test was found to be less sensitive in finding hidden trends than the M-K and mM-K tests. Results of the Sen's slope estimation test showed that trend magnitudes of seasonal pH, TH, TDS, HCO_3^- and Fe^{2+} concentrations varied from –0.03/year to 0.23/year, –57.44 mg/L/year to 25.88 mg/L/year, –172.98 mg/L/year to 92.58 mg/L/year, –15.81 mg/L/year to 27.88 mg/L/year, and –0.05 mg/L/year to 0.61 mg/L/year, respectively.

This study was conducted with limited groundwater-quality data of only 8 years (2011–2018) as there was absence of long-term hydrogeochemical data in this coastal inter-basin area. In addition, those data were not available for all the blocks. Lack of sufficient number of observation wells, proper monitoring network as well as regular monitoring of groundwater quality are the major causes of data scarcity particularly in unconfined aquifers. On the other hand, unconfined aquifers are primary and most feasible sources of freshwater in this coastal region for meeting human needs, which are tapped by dug wells. Therefore, proper and regular monitoring of groundwater quality is urgently required in all aquifer systems extensively for acquiring continuous data records to perform scientific studies, and accordingly adopt suitable management action plans for the sustainable utilization of this invaluable resource. The findings of this study will assist the decision makers to properly monitor and efficiently manage groundwater resources with respect to its quality.

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CRediT Authorship Contribution Statement

Subhankar Ghosh: Investigation, Review of literature, Data collection and processing, Data analysis, Software, Writing – Original draft; **Madan Kumar Jha:** Conceptualization, Methodology, Supervision, Resources, Writing – Review and Technical Editing.

Data Availability

The datasets used in this study are available from the corresponding author upon reasonable request.

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