



Impacts of climate change on groundwater quality in Coimbatore smart city areas of Tamil Nadu, India

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Received: 20 June 2022 / Accepted: 6 September 2023 / Published online: 26 September 2023
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Abstract

The impact of climate change is ubiquitous on all earth systems, including groundwater resources. The present study investigated the impact of climatic factors such as temperature and rainfall on groundwater resources in the Coimbatore smart city areas of Tamil Nadu, India, for 30 years (1990–2019). The study results revealed that the mean annual temperature (MAT) and mean minimum temperature (MMinT) in Coimbatore smart city areas had a significant annual increase in temperature by 0.24 °C and 0.48 °C per decade, respectively, which was evident during the northeast monsoon than the summer season. The region's annual total rainfall (TRF) declined by about 22 mm/decade. In contrast, the depth of the water table increased by 3 m in both the northeast monsoon and summer seasons might be due to the development of artificial recharge structures. The groundwater in the study area predominantly contained Ca–Cl (49%), Ca–HCO₃ (35%), and mixed Ca–Mg–Cl (17%) might attribute due to the lower groundwater table. It was found that the groundwater quality index during the recent decade was poor. The levels of groundwater quality parameters were significantly increased over a decade during the northeast monsoon: EC, TDS, Cl⁻, HCO₃⁻, total hardness, Na⁺, SO₄²⁻, NO₃⁻, K⁺ and CO₃²⁻ and summer season: EC, TDS, Cl, K⁺ and NO₃⁻, respectively. An increase of 1 °C MMinT has increased the groundwater concentrations of EC (176 μS/cm), TDS (105 mg/l), Cl⁻ (43 mg/l), Na⁺ (24 mg/l), K⁺ (7 mg/l) and CO₃²⁻ (-2.7 mg/l) during northeast monsoon season; and Cl⁻ (65 mg/l), K⁺ (7 mg/l), NO₃⁻ (10 mg/l) and CO₃²⁻ (-4 mg/l) during the summer season. Temperature attributed to the change in the groundwater quality parameters by 20% (TDS), 22% (EC), 31% (Na⁺), 30% (K⁺), 29% (Cl⁻), 33% (CO₃²⁻) in northeast monsoon and 54% (K⁺), 40% (Cl⁻), 95% (CO₃²⁻), 111% (NO₃⁻). The impact of summer temperature is higher compared to the northeast monsoon season. Even though the impact rate of 1 °C MMinT on groundwater quality was numerically low, the average concentrations of NO₃⁻ and EC exceeded the permissible limit of drinking water standards, and Cl⁻ exceeded the acceptable limit. As the trend increases, these impact rates will further increase. This trend will make groundwater unsuitable for drinking as the change in groundwater quality with respect to the temperature increases by 13–332%. Thus, sustainable groundwater management practices should be adopted. Groundwater policy should emphasise any pre-emptive actions to make groundwater resilient to thrive under uncertain future climatic scenarios.

Keywords Climate change · Temperature · Rainfall · Groundwater quality · Groundwater level · Groundwater recharge

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Introduction

Rapid industrialisation has led humankind to release enormous amounts of greenhouse gases, especially CO₂, into the atmosphere resulting in global climate change. The Intergovernmental Panel on Climate Change (IPCC) has recorded and indicated a drastic global increase in temperature of 0.85 °C from 1880 to 2012 (IPCC 2014). Specific over space and time, India has encountered an increase in temperature of 0.7 °C from 1901 to 2018 (Dhara et al. 2020). The entire earth system and its components are affected by climate change impacts. Even though several studies have reported

climate change's effects, many are still yet to be explored. Likewise, the impact of climate change on groundwater resources is still at its early (Green et al. 2011). Groundwater provides the global population with fifty per cent of drinking water access (FAO 2010). However, in recent decades, robust urbanisation and climate change have placed high demand and have exacerbated a frightful impact on groundwater resources in terms of quantity and quality (Reidel 2019; Saito et al. 2016; Khazaei et al. 2004; Kundzewicz and Doell 2009; Urama et al. 2016). A significant percentage of the world's population (68%) is expected to move toward urban areas by 2050, threatening global water security Hannah Ritchie and Max Roser 2018). Moreover, the global population will confront a shortfall of 40% in water supply if the existing groundwater management practices are left unchecked or changed (Urama et al. 2016). This scenario urges more research and well-designed pre-emptive policies and actions on groundwater resources.

Groundwater quality is defined by its physical, chemical, and biological characteristics. The effect of climate change on groundwater quality is identified either by its direct (temperature, precipitation, evapotranspiration, humidity, wind velocity, lithology of the aquifer, groundwater availability/recharge) or by indirect effect (land cover pattern, effluents/discharges from anthropogenic activities) (Bouraoui et al. 1999; Green et al. 2011; Kumar 2012; Reidel and Weber 2020). The wide variety of hydrochemical and geostatistical analysis techniques provide information on the multidimensional aspect of groundwater to understand the complex geochemical processes and find the principal factor influencing the incidence of physicochemical parameters. More often, studies typically focused on the climate change effect on groundwater recharge (Smerdon 2017), leaving behind a significant knowledge gap in understanding the implications on groundwater quality (Green et al. 2011). Complying with groundwater quality standards is as important as building a groundwater recharge structure for accomplishing water security at all levels. Groundwater quality exceeding the drinking water quality standards poses serious health problems, especially to the vulnerable community, and it is a significant challenge in the existing groundwater management practices (Kumar 2012). Sustainably managed groundwater resources will facilitate access to abstraction even during drought and prolonged dry spell conditions (Kundzewicz and Doell 2009).

After publishing IPCC's fourth report (2007), many scientists began their quest with a renaissance in reviewing and identifying the impact of climate change on groundwater quality (Green et al. 2011; Hollman et al. 2011; Taylor et al. 2013). The significant impacts observed were the sea-level rise and seawater intrusion (Mall et al. 2006) in the coastal aquifer, followed by the changing climatic pattern affecting groundwater recharge (Reidel and Weber 2020). It

reduces groundwater recharge in semi-arid and arid regions (Green et al. 2011). Sometimes, the thawing of mountain areas can increase the groundwater recharge (Jyrkama and Sykes 2007; Klöve et al. 2014; Kovalevskii 2007), and proper groundwater recharge in aquifers dilutes the ions. The groundwater recharge during dry summer can elevate TDS and salt concentration (Dragoni and Sukhija 2008). Apart from groundwater recharge, the linear trend in atmospheric, surface, and sub-surface (groundwater) temperature affects groundwater quality. Few studies explored and verified that warm surface air temperature increases the groundwater temperature (Beltrami and Mareschal 1995; Čermák et al. 1992; Taylor and Stefan 2009) in the range of 1.8–2.8 °C (Tanguichi et al. 2007), 2 to 4 °C (Taylor and Stefan 2009) and occasionally predicted to increase up to 5 °C in world's major metropolitan cities. In due course, the increasing groundwater temperature consequently affects the groundwater quality. Studies in Southwestern Germany indicated that the difference of +1 K gave a rising trend in K^+ , Mn^+ , Si^+ , F^- , DOC, and pCO_2 and a decreasing trend in pH and oxygen saturation (Reidel 2019). It was due to the release of ions from accelerated mineral weathering and accumulated carbon dioxide in the groundwater. Furthermore, an in-situ experiment in Japan with dual-well analysis (DWA) confirms that the warm trend in groundwater temperature of 7 °C provides a linear relationship in groundwater quality parameters of B, Si, Li, DOC, Na^+ , Mg^{2+} , NH_4^+ and K^+ (Saito et al. 2016). Even though it was highly area-specific, it confirms the effect of surface air temperature and subsurface temperature in determining and influencing groundwater quality and subsequently altering the biogeochemical reactions (Knorr et al. 2005; Tanguichi et al. 2007).

The effect of temperature change in groundwater is identified by infiltration or thermal diffusivity (Taylor and Stefan 2009). The infiltration occurs through percolation (unsaturated flow); seepage of warm waters from surface waters (saturated flow). The soil pore spaces explain the thermal diffusivity. Groundwater in low permeability, i.e., small grain size, has low flow velocities that allow thermal diffusivity through air replacement in pore spaces. In the high permeability region, i.e., large grain size and high flow velocity, the heat transport occurs at a high rate due to hydrodynamics. Temperature is the central component directly associated with the density and viscosity of water. The solubility of gases further affects the geochemical processes (dissolution and precipitation of minerals), and biological processes, consequently acting on the biotic and abiotic factors within the aquifer (Bonte et al. 2013). Temperature influences the system's absorption/desorption and cation/anion exchange. Notably, increased temperature accelerates and promotes these processes indefinitely. The high groundwater temperature collapses, breaks the equilibrium of any geochemical process, and alters the chemical

composition in the groundwater of the aquifer system. Temperature is essential in regulating the geochemical process (Klöve et al. 2014).

Assessing spatial trends of groundwater quality for several statutory reasons, mainly to evaluate its compliance with the standards of its intended use (Narshima et al. 2020; Shanmugasundharam et al. 2017); assess the impact of any particular anthropogenic activity (Mukate and Wagh 2020; Vijay et al. 2011); analyse any groundwater-induced health threat (Liu et al. 2003); or, evaluate after any natural disaster incidences (Malakootian and Nouri 2010) are common. The water quality indices do not account for temporal variations of the groundwater quality within the aquifer system (Machiwal et al. 2019). Only a few studies have focused on temporal trends (i.e., statistical time series analysis) for groundwater quality in Iran (Daneshvar Vousoughi et al. 2013; Pashaeifar et al. 2021), New Zealand (Daughney and Reeves 2006), South Korea (Lee et al. 2006), Afghanistan (Houben et al. 2009), Rajasthan (Machiwal et al. 2019) and Netherland (Broers and Grift 2004) by statistically interpreting and evaluating its trends. Finding the temporal trends in groundwater quality, rather than the spatial trend, provides aid in understanding changes in groundwater quality patterns over a period of time (Loftis 1996). The common groundwater quality trend analysis method used is Mann–Kendal (MK) test, Sen's Slope (or Slope Estimator of Sen) (Machiwal et al. 2019).

In recent times, the government of India developed a smart city mission in 2015 to revamp the 100 urban cities in India under the Atal Mission for Rejuvenation and Urban Transformation (AMRUT). With smart water management (SWM), these smart cities deploy to muddle through the existing groundwater management practices with the emerging climate change and urbanisation challenges. Coimbatore district, one of the districts selected for smart city mission, also known as the Manchester of South India, is the most industrialized district in Tamil Nadu. The district population has increased by 18% from 2001 to 2011 (Census 2011), which is higher than the state average growth of 15%. This robust urbanization has put a huge demand on the groundwater resources in Coimbatore. The government has constructed more than 181 check dams to artificially improve the groundwater level. Studies have focused on analysing the improving quality and level of groundwater and spatially mapping to examine its compliance with the Indian drinking water quality standards (BIS10500:2012). No study has attempted to analyse the temporal groundwater quality trends in Coimbatore District or any Tamil Nadu districts. Thus, this study attempts to study the variations of groundwater resources over space and time in the smart city areas (the municipal boundary) of the Coimbatore district. Thus, this study attempts to (i) analyse the trends in climatic parameters and groundwater resources in the study area of

Coimbatore, India, (ii) evaluate the relationship between the existing climatic parameters and groundwater resources, and (iii) predict the future groundwater resources scenarios for the study area.

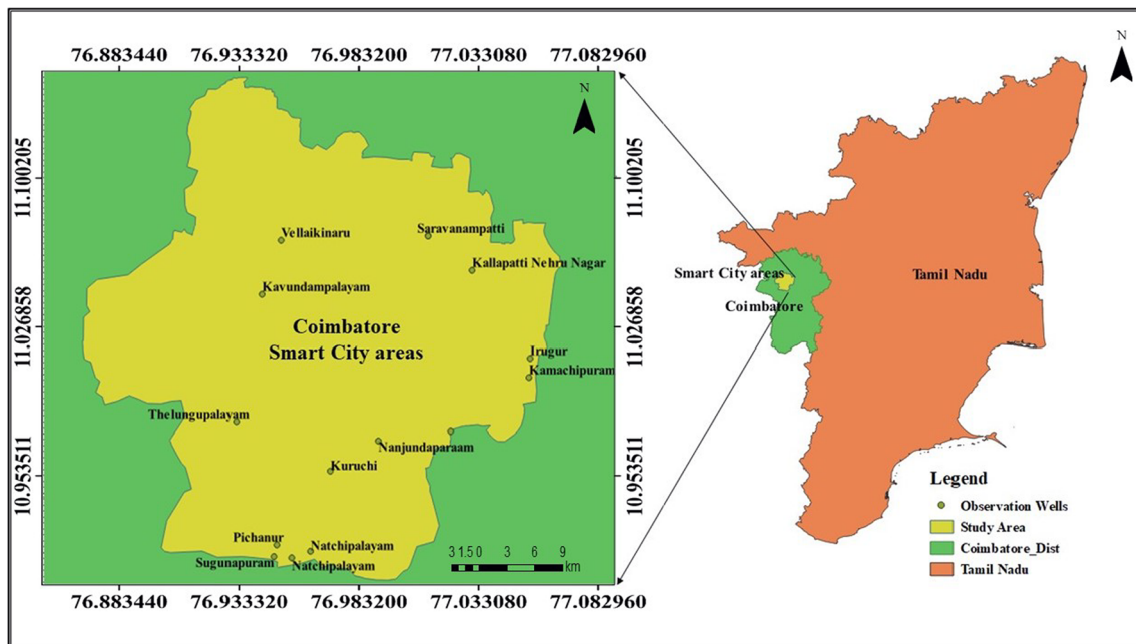
Materials and methods

Study area

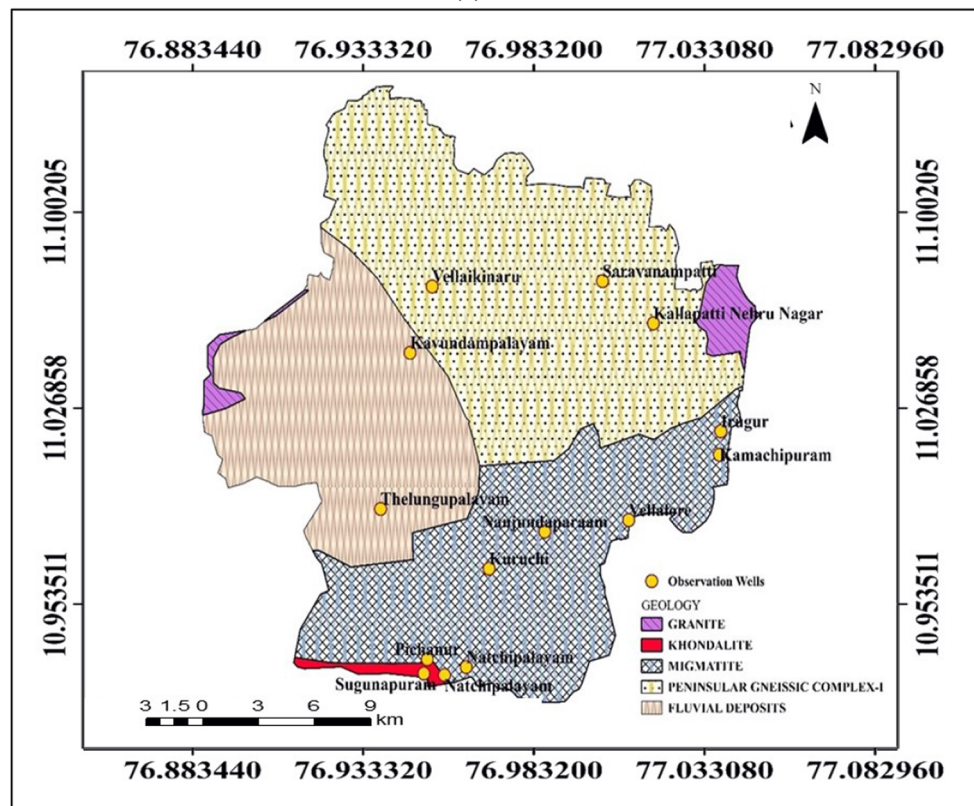
The smart city areas of the Coimbatore district in Tamil Nadu, state of India (Fig. 1a), extend from 10° 55' to 11° 10' N and 77° 05' to 76° 02' E and enclose an area of 319 km². The northwest and western regions of the district are a part of the Western Ghats and are located above 399 m MSL (average). The district experiences rainfall from the southwest and northeast monsoon, but the latter contributes higher. As a result, the district receives a good amount of rainfall annually (600–900 mm). According to the Central Ground Water Board (CGWB) assessment in 2008, most of the district encountered high concentrations of F⁻ (> 1.5 mg/l), NO₃⁻ (> 45 mg/l), EC (> 3000 µS/cm at 25 °C), SO₄²⁻ and total hardness that marked for industrial clusters causing groundwater pollution. Since 2015, the district has completed 25 smart city projects and has 11 ongoing projects. The smart city projects mainly include retrofitting urban development activities, such as a solar-powered ambient environmental monitoring system, a solar power plant of 1 MW and the erection of an 11 kV breaker with bay extension (in Kavundampalayam and Ukkadam), underground drainage schemes and solid waste management (in Vellalore and Kavundampalayam) (Coimbatore Smart City 2021). The sampling locations of the study area are given in Fig. 1a.

Geology and hydrogeology

The geology of the present study area is shown in Fig. 1b, and its data were obtained from Bhukosh and mapped in QGIS 3.0. The weathered and fractured crystalline rock formations in the Coimbatore district, India, study area associated with the Archean age consists of peninsular gneissic complex, granite, and Khondalite, respectively, fluvial deposits and migmatite (CGWB 2008). These rocks encompass granite, biotite, limestones and quartzite predominantly. Red calcareous soil is dominant in the study area, followed by black soil. The aquifers are discontinuous, typically unconfined to semiconfined. The transmissivity of the aquifer measures from 1.49 and 164.18 m²/day; permeability from 0.25 to 26.75 m/day. The groundwater flow direction goes along the southeastern path within the study area.



(a)



(b)

Fig. 1 Study area and locations of observation wells (a), Geology (b) and Land-Use Land-cover (c) of Coimbatore district, Tamil Nadu, India

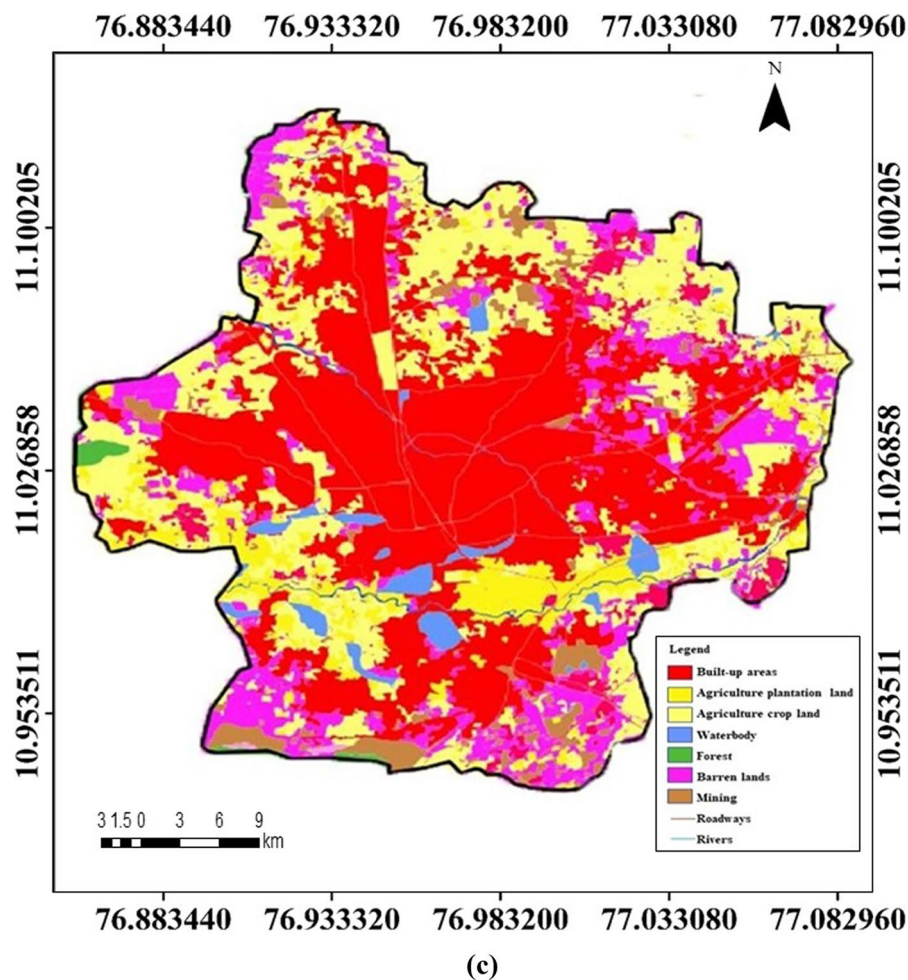


Fig. 1 (continued)

Land-Use and Land-Cover

The study area's Land-Use Land-Cover (LULC) pattern is shown in Fig. 1c, and its data were obtained from Bhuvan and mapped in QGIS 3.0. The Coimbatore district encountered rapid urbanisation: marking a higher decadal growth rate of 18.56% than the state average growth rate (Census of India 2011). Robust urbanisation has led to severe urban encroachment on agricultural lands and amplified its developmental activities. Urbanisation areas have increased from 18.07% in 2003 to 54.32% in 2013 (Prabu and Dar 2018). The study area represents moderate agricultural lands and fewer barren lands. Mining activities for granite and limestone were carried out in the study area's southern part.

Data analysis

Regarding envisaging climate change, the trend analysis for the study period was determined for 30 years from 1990 to 2019. The groundwater quality and quantity (depth to the

water table) data of the study period were collected from the Tamil Nadu state ground and surface water resources data centre under the Public Works Department (PWD), Government of Tamil Nadu. PWD conducts groundwater sampling analysis twice a year, i.e., January and July. The observation wells are shown in Fig. 1a. The groundwater sample collected in January implies the groundwater quality aftermath of the northeast monsoon season (October to December), while the July month implies the groundwater quality of the summer season (March to May). The samples were analysed for seventeen physicochemical parameters, and the analysis was according to the standard methods of APHA (APHA 2017). Only eleven physicochemical parameters were used in this study, including TDS, EC, pH, total hardness, cations (Na^+ , K^+) and anions (CO_3^{2-} , HCO_3^- , Cl^- , SO_4^{2-} , NO_3^-). The groundwater quality sample data were discrete and intermittent over space and time throughout the study period. The total number of groundwater quality samples was 1372 nos. 2016 records the most significant number of groundwater quality samples of 198, where the first half of the study years

(1990–2004) had the least groundwater quality samples, and the years 1994, 1998, 2000, 2001, 2002, 2003 and 2004 had fewer samples. Compared to other parameters, the Ca^{2+} and Mg^{2+} data were inconsistently available. The Ca^{2+} and Mg^{2+} were unavailable for five consecutive years (2000–2004) and 1994, 1997, and 2012–2015. Hence, these ions were not used for the time series analysis. However, Ca^{2+} and Mg^{2+} were available for the years 2016–2019. These data are used for hydrochemical analysis. For better understanding, primary groundwater sample analysis was conducted in January and March 2021. Only TDS, EC, pH, total hardness, Cl^- , and SO_4^{2-} were analysed. As per the APHA guidelines for water quality analysis, TDS was analysed by gravimetric method, EC by conductivity meter, pH by pH meter (model: EQUIPTRONICS EQ 660B), total hardness by EDTA titration, Cl^- by Mohr's method, and SO_4^{2-} by turbidity method (model: INFRADIGI IR 513C) (APHA 2017). The accuracy of the conductivity meter was ± 2 ; the pH meter was 0.01 to 14; the spectrophotometer was 0.0046 dL/mg at 420 nm. Temperature and rainfall are the two climatic factors, data obtained from IMD, Pune. The temperature data were determined as mean minimum temperature (MMinT) and mean maximum temperature (MMaxT), indicating the minimum and maximum temperature ($^{\circ}\text{C}$) for a given unit of time, respectively. Calculating the average of MMinT and MMaxT represents the mean annual temperature for a given unit of time, expressed as MAT. The rainfall is measured as total rainfall (TRF) for a given unit of time. Groundwater recharge for the district was only recorded in 2004, 2009, 2011, 2013, and 2017, and the data retrieved from the reports of dynamic groundwater resources of India, CGWB (CGWB 2004, 2009, 2011, 2013, 2017). Certain groundwater quality parameters were spatially mapped in QGIS 3.0. The quality parameters were interpolated by the inverse distance weight (IDW) method and spatially mapped.

Hydrochemical analysis

The groundwater type was identified by plotting the water quality parameters in Piper trilinear diagram. This Piper trilinear diagram or Piper plot also helps identify the dominant anion and cation in groundwater samples (Chenini et al. 2010; Pillai et al. 2020; Sajil Kumar and James 2016; Selvakumar et al. 2017). The total concentration of anions and cations was converted into one equivalent weight (meq), where one equivalent weight of cation equals one equivalent anion (Todd and Mays 2005). The Gibbs diagram helps identify the evolution of complex geochemical processes occurring in the groundwater. Furthermore, geo-statistical evaluation analyses such as Pearson's correlation

and Principal Component Analysis (PCA) were computed to gain insight into the individual groundwater quality parameters. Pearson's correlation analyses the significant relationship between the groundwater quality parameters and PCA distinguishes the significant factors determining the groundwater quality parameters in the study area (Eldaw et al. 2021; Jebastina and Arulraj 2016; Pillai et al. 2020; Selvakumar et al. 2017). The Pearson coefficient values range from -1 to 1 , where ≥ 0.5 expresses the strong correlation and ≤ 0.5 indicates the weak correlation between the groundwater quality parameters. PCA differentiates the impact between groundwater pollution and the dominant geochemical process. As a result of PCA analysis, the PCA matrix and scree plot were obtained. The principal component matrix consists of 10 main components. Eigenvalue was calculated for each component. The eigenvalue of each principal component matrix was plotted in the scree plot. The principal component with eigenvalue < 1 is not considered in further analysis. The PC1 defines the groundwater quality data's maximum variance (and correlation) and gently to the PC2, PC3, and PC4.

Water quality index (WQI)

The water quality index is better than analysing the compliance of each quality parameter to drinking water standards [BIS 2012 (10,500:2012)]. It is a beneficial tool that provides a numerical value, describing groundwater quality in the study area by assigning weights to each quality parameter (Ncibi et al. 2020). The WQI allows flexibility in assigning weights to the quality parameters. The high-important groundwater quality parameter is designated with the weight (w_i) of 5, which discretely descends to 1 for the low-important quality parameter. After assigning weights, the relative weights (W_i) are calculated by dividing the weights (w_i) by the average weight (Σw_i):

$$W_i = w_i / \sum_{i=1}^n w_i. \quad (1)$$

In the second step, the quality ratings (q_i) were evaluated by the following formula:

$$q_i = (C_i/S_i) \times 100, \quad (2)$$

where C_i is the i th groundwater quality parameter concentration in mg/l, and S_i is the i th permissible limit from the drinking water standard (BIS 10500: 2012).

Finally, the summation of sub-indices (SI_i) of the selected groundwater quality parameter produces the WQI of the specific well:

$$SI_i = W_i \times q_i, \quad (3)$$

$$WQI = \sum_{i=1}^n SI_i / n. \quad (4)$$

The WQI range from 0 to > 300, where < 50 represents the excellent quality of groundwater; 50–100 represents good; 101–200 represents poor; 201–300 represents very poor; and > 300 represents unfit for drinking (Chakraborty et al. 2016; Vaiphei et al. 2020; Vasanthavigar et al. 2010).

Time series and regression analysis

The selected climatic and groundwater factors with their respective parameters were reviewed for a summary of values (mean, minimum, and maximum). The climatic and groundwater parameters were evaluated with a time series analysis to understand the changing pattern over 30 years. The parameters were subjected to three non-parametric tests of time series analysis, namely, the Mann–Kendall test, the Slope estimator of Sen (or Sen's Slope) and the Pettit test. The Mann–Kendall test helps mark the significant change in the given data set (Helsel and Hirsch 2002). The statistical hypothesis does not show any difference in the data set but indicates whether the difference is significant enough to cause a rejection of the null hypothesis (Loftis 1996). Hence, Sen's slope helps find the magnitude of the change, and the Pettit test spots the abrupt change (time) in the data series. These non-parametric tests effectively analyse the environmental factors and are widely used in hydro-climatic data analysis (Broers and Grift 2004; Daughney and Reeves 2006; Ghasemi 2015; Jeganathan et al. 2019; Lee et al. 2006). After the time series analysis, temperature and rainfall (climatic factors) on groundwater quality, levels and recharge were examined by fitting the data set into the linear regression model in XLSTAT with a significance of 95%. The results of groundwater quality trend analysis are spatially plotted in QGIS 3.0. The points are spatially interpolated throughout the study area through the interpolation tool IDW. Later, the regression between climatic and groundwater quality parameters was executed seasonally. For instance, the summer season groundwater quality was analysed analogously to the summer climatic factors (temperature and rainfall). The significant climatic factor (temperature or rainfall) that determines the groundwater quality parameters was identified through regression analysis. Eventually, with reference to the past conditions, the future scenario of groundwater resources with the significant climatic factor was statistically predicted with the RCP 4.5 projections.

Results and discussion

The study results from the analysis of hydro-geochemical, geostatistical physicochemical, and time-series of groundwater quality and level in the study area with the future projections and adaptation strategies for groundwater resource management are detailed below.

Hydro-geochemical analysis of groundwater quality in Coimbatore

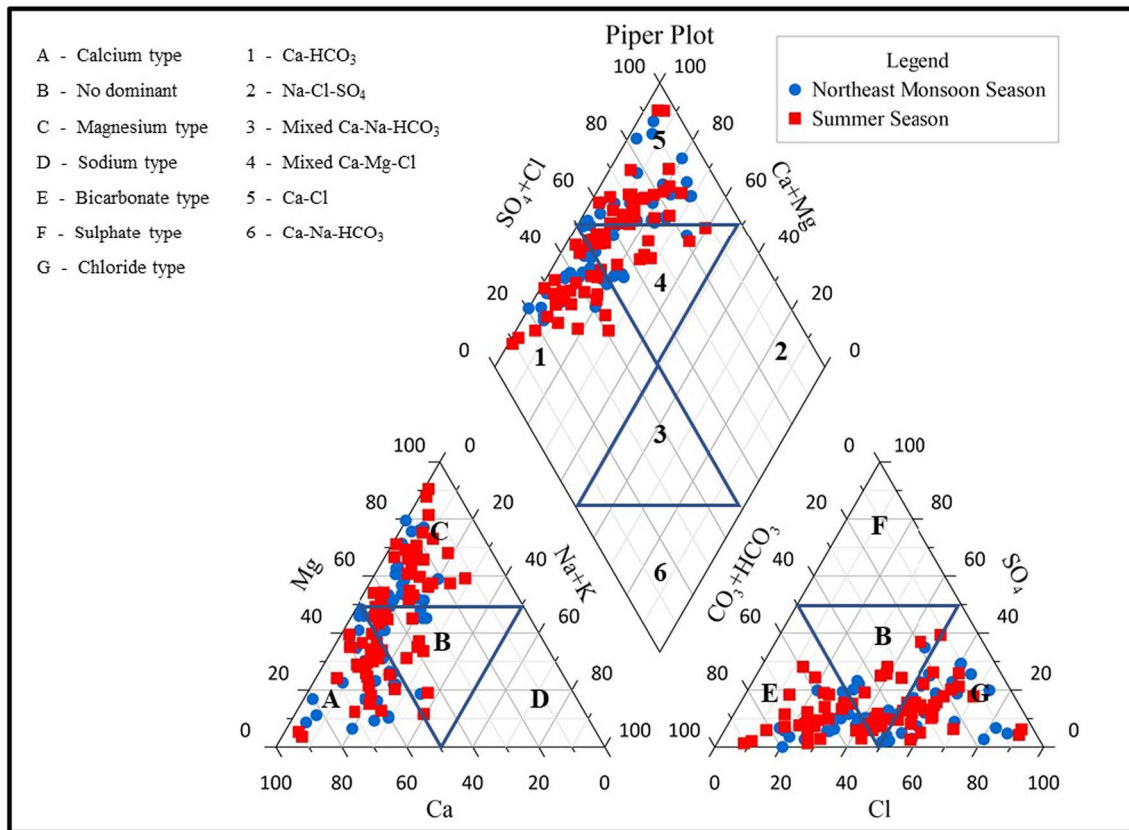
The hydrochemical analysis of groundwater represents the type of water and its classification (Piper 1944; Vaiphei et al. 2020). The anions (Cl^- , SO_4^{2-} , CO_3^{2-} , HCO_3^-) and cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) of groundwater quality parameters are plotted in the piper trilinear diagram (Fig. 2a) for both northeast and summer seasons. The groundwater of the study area predominantly contained Ca–Cl (49%) > Ca– HCO_3 (35%) > mixed Ca–Mg–Cl (17%) type, where Cl^- (45%) marks the major anion followed by HCO_3^- (36%); Ca^{2+} (43%) and Mg^{2+} (45%) fairly dominates the cation triangle. Besides, few samples were evident, with no dominance in the cation and anion triangle. It indicates the abundance of anions (Cl^- , HCO_3^-) and cations (Ca^{2+} , Mg^{2+}) availability in groundwater, probably due to the mineral dissolution of halite, calcite or dolomite. The dominant type of cation or anion varied within the district (Sajil Kumar and James 2016; Selvakumar et al. 2017) and adjacent districts (Vasanthavigar et al. 2010). As shown in the Gibbs plot, Fig. 2b, major samples spread in the evaporation region in both seasons (Sajil Kumar and James 2016).

Some samples fall out of the line, indicating the impact of anthropogenic activities due to fertilisers, industrial effluents and urban discharges (Pillai et al. 2020). Ascertain in the semi-arid region, the evaporation process dominates the geochemical process, and the results were similar to the findings of Selvakumar et al. (2017). They also indicated that the major samples from Singanallur fall within evaporation than rock dominance. However, in the southern part of the Coimbatore district, the groundwater was influenced by rock–water interaction together with the process of ion exchange, silicate weathering (halite), reverse ion exchange (with clay) and dissolution of deposition (calcite, dolomite) (Sajil Kumar and James 2016).

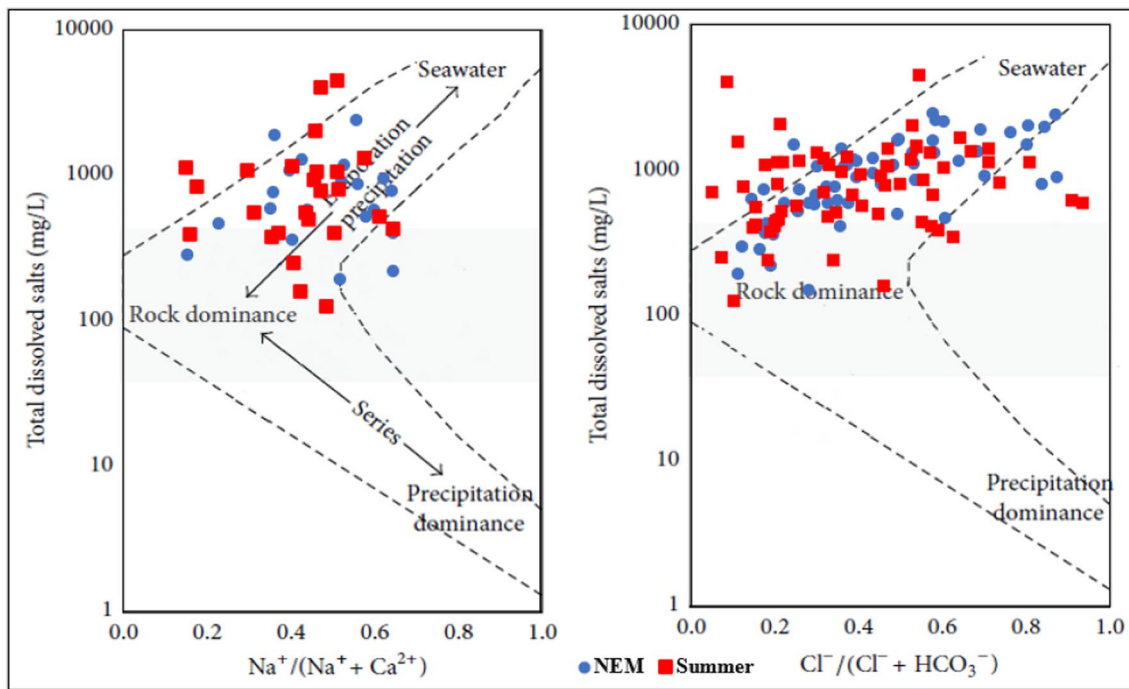
Geostatistical analysis of groundwater quality in Coimbatore

Pearson correlation results

The Pearson correlation matrix between the groundwater quality parameters for both seasons is summarised in Table 1



(a)



(b)

Fig. 2 Piper plot of hydro-chemical facies of groundwater (a) and Gibb's plot of the geochemical process in the groundwater (b)

Table 1 Pearson Correlation between the groundwater quality parameters after northeast monsoon (a) and summer season (b)

	TDS	EC	pH	TH	Na ⁺	K ⁺	NO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	CO ₃ ²⁻	HCO ₃ ⁻	
(a) Northeast monsoon season												
TDS	1											
EC	0.979*	1.00										
pH	-0.29	-0.23	1.00									
TH	0.708*	0.713*	-0.39	1.00								
Na ⁺	0.814*	0.817*	-0.03	0.32	1.00							
K ⁺	0.26	0.27	0.22	0.11	0.05	1.00						
NO ₃ ⁻	0.663*	0.651*	-0.20	0.36	0.43	0.36	1.00					
Cl ⁻	0.904*	0.928*	-0.19	0.691*	0.754*	0.22	0.48	1.00				
SO ₄ ²⁻	0.795*	0.786*	-0.16	0.66*	0.644*	0.07	0.41	0.694*	1.00			
CO ₃ ²⁻	-0.21	-0.19	0.672*	-0.30	0.02	0.01	-0.25	-0.14	-0.18	1.00		
HCO ₃ ⁻	0.25	0.31	-0.13	0.02	0.24	0.34	0.37	0.09	-0.05	-0.21	1.00	
(b) Summer season												
TDS	1											
EC	0.977*	1										
pH	-0.064	-0.098	1									
TH	0.597*	0.616*	-0.434	1								
Na ⁺	0.853*	0.834*	0.012	0.319	1							
K ⁺	0.27	0.219	0.205	-0.181	0.127	1						
NO ₃ ⁻	0.474*	0.455*	0.294	-0.083	0.334	0.276	1					
Cl ⁻	0.916*	0.894*	-0.024	0.509*	0.803*	0.235	0.472*	1				
SO ₄ ²⁻	0.745*	0.725*	-0.106	0.522*	0.589*	0.031	0.251	0.577*	1			
CO ₃ ²⁻	0.036	0.021	0.653*	-0.196	0.004	0.12	0.233	-0.03	0.075	1		
HCO ₃ ⁻	0.211	0.147	-0.245	0.174	0.34	-0.021	-0.157	0.116	0.01	-0.155	1	

*At 95%significance level

[(a) northeast monsoon; (b) summer]. During the northeast monsoon season, the TDS and EC were highly correlated with Cl⁻ ($r=0.9$ and 0.93), SO₄²⁻ ($r=0.8$ for both), Na⁺ ($r=0.8$ for both), total hardness ($r=0.7$ and 0.71), and moderately with NO₃⁻ ($r=6.6$ and 6.5), respectively, indicating the various source of infiltration or dissolution due to northeast monsoon rainfall. pH was moderately positively correlated with CO₃²⁻ ($r=0.67$), where CO₃²⁻ is the primary ion determining the pH of the groundwater. The CO₃²⁻ retained a negative correlation with total hardness ($r=-0.30$) due to CaCO₃ precipitation and release of dissolved CO₂ under favourable conditions of lower pressure and higher temperature (Todd and Mays 2005). The total hardness had a moderate correlation with Cl⁻ ($r=0.69$) and SO₄²⁻ ($r=0.66$) caused by permanent hardness, mainly by the dissolution of calcite and dolomite (Eldaw et al. 2021; Ncibi et al. 2020).

The Na⁺ ions maintained a higher correlation with Cl⁻ ($r=0.75$), commonly due to the equal dissolution rate from halite (Sajil Kumar and James 2016) and moderate correlation with SO₄²⁻ ($r=0.64$), respectively. The Cl⁻ also strongly correlates with SO₄²⁻ ($r=0.7$) due to anthropogenic activities, such as chemical fertilisers, industrial effluents, domestic discharges, etc. (Kura et al. 2013). The presence of

Na⁺, Cl⁻ and SO₄²⁻ in the groundwater is due to the chemical weathering of silicates or deposits of the evaporates (Vaiphei et al. 2020). K⁺ and HCO₃⁻ poorly correlate with any groundwater quality parameters considered (Pillai et al. 2020). Except for Na⁺ and Cl⁻, the correlation between other variables was low in the summer season. Na⁺ and Cl⁻ correlated with TDS ($r=0.85$ and 0.92), EC ($r=0.83$ and 0.89) and within ($r=0.8$) due to the dissolution of halite and silicate weathering at high temperatures (Pillai et al. 2020; Sajil Kumar and James 2016).

Principal component analysis results

The results of PCA analysis for the northeast monsoon and summer season are summarised in Table 2, and the scree plot representing the eigenvalue for each component is depicted in Fig. 3a. In both seasons, three significant components were considered for analysis. In the northeast monsoon season, the PCA1 first component contributed 49% of the total variance with significant positive loadings in TDS, EC, Cl⁻, SO₄²⁻, and moderate loadings in total hardness, Na⁺ and Na+NO₃⁻, respectively. The abundant natural availability of ions such as Cl⁻, SO₄²⁻, Na⁺, TDS and EC emphasise the

Table 2 Principal component analysis of groundwater quality parameters after Northeast Monsoon Season, and Summer Season

Parameters	Northeast Monsoon Season				Summer Season			
	PC1	PC2	PC3	Communalities	PC1	PC2	PC3	Communalities
TDS	0.986	0.07	-0.03	0.978	0.994	0.044	0.029	0.991
EC	0.987	0.118	-0.002	0.987	0.98	0.016	-0.036	0.961
pH	-0.332	0.858	-0.014	0.847	-0.102	0.856	-0.065	0.747
TH	0.751	-0.231	-0.223	0.668	0.613	-0.524	-0.344	0.768
Na ⁺	0.779	0.311	-0.129	0.72	0.864	0.037	0.186	0.782
K ⁺	0.261	0.377	0.639	0.619	0.215	0.452	0.575	0.581
NO ₃ ⁻	0.683	0.017	0.409	0.634	0.465	0.576	0.044	0.55
Cl ⁻	0.906	0.133	-0.178	0.87	0.922	0.069	0.048	0.858
SO ₄ ²⁻	0.811	0.059	-0.348	0.782	0.77	-0.039	-0.351	0.717
CO ₃ ²⁻	-0.301	0.81	-0.234	0.802	0.001	0.732	-0.263	0.605
HCO ₃ ⁻	0.281	-0.016	0.789	0.702	0.213	-0.389	0.62	0.582
Eigenvalues	5.409	1.726	1.474		4.831	2.239	1.071	
% Of variance	49.171	15.695	13.396		43.92	20.359	9.737	
% Of cumulative	49.171	64.865	78.261		43.92	64.279	74.016	

lithogenic process controlling the groundwater chemistry. The results followed the hydrochemical study conducted in Coimbatore during 2015–2016 (Selvakumar et al. 2017) and 2013 (Jebastina and Arulraj 2016). The PCA2 second component contributed to a total variance of 15%, in accordance with the highly positive CO₃²⁻ and pH loadings. It exhibits the presence of CO₂⁻ and its reaction with the groundwater (Riedel and Weber 2020). The third component, PCA3, contributed to a total variance of 13% revealing higher loadings in K⁺ and HCO₃⁻ and lower loadings in NO₃⁻. In the summer season, the chemical loadings in the PCA1 first component with 43% of total variance have higher loadings in TDS, EC, Cl⁻ and Na⁺ than the northeast monsoon, except for total hardness, SO₄²⁻ and NO₃⁻. In addition, the pH, CO₃²⁻, NO₃⁻ and total hardness have shown higher loadings in PCA2 (second component) with 20% of the total variance. The PCA3 third component had the least variance of 9% and showed maximum K⁺ and HCO₃⁻ loadings. The K⁺ and HCO₃⁻ indicate the mineral dissolution of gypsum or clay (Chenini et al. 2010; Pillai et al. 2020).

Physico-chemical analysis of groundwater quality in Coimbatore

The physical and chemical characteristics of groundwater depend upon the season, i.e., cold wet monsoon and hot dry summer season. The seasonal statistical summary (mean, minimum and maximum) of groundwater quality parameters is shown as a box plot in Fig. 3b, which indicates a lower concentration of TDS, EC, Na⁺, K⁺, Cl⁻, SO₄²⁻, and HCO₃⁻ in northeast monsoon season and higher concentration during the summer season. It is inverse in the case of pH, total hardness, NO₃⁻ and CO₃²⁻. In summer,

higher ionic concentration and carbon dioxide accumulation increase the groundwater's acidity (low pH) (Reidel 2019). The northeast monsoon, the primary source of groundwater recharge in the study region (CGWB 2008), dilutes the ions within and reduces the significant ionic concentrations in the groundwater. Similar seasonal variations in groundwater quality parameters were observed from the samples collected during January and March across the study area, whereas the concentrations were within the permissible standard limits. This seasonal variation is in accordance with the other studies reported in Texas (Kampbell et al. 2003), Western Turkey (Elçi and Polat 2011), Rajasthan (Machiwal et al. 2019) and Coimbatore district (Jebastina and Arulraj 2017).

The groundwater quality in the study area was mostly within the Indian standards for drinking water purposes, except 6–14% of the samples from 1990 to 2019 exceeded the permissible limits. The total hardness of CaCO₃ exceeds the permissible limit of 600 mg/l by 27% in the northeast monsoon and 16% in the summer. In the primary sample analysis, the EC was higher in summer (910 to 2610 μS/cm) than in northeast monsoon (1180 to 1788 μS/cm). Similarly, TDS and EC were typically higher in summer than in the northeast monsoon season due to the dissolution effect of monsoon rainfall and high temperature-associated weathering during the summer. Nevertheless, certain ionic concentrations recorded higher concentrations in summer and lower concentrations in the northeast monsoon season. The Na⁺ in groundwater may originate from the halite dissolution, silicate weathering of feldspar minerals (albite), dissolution of evaporate minerals, sewage leakage or discharges of effluents from industrial activities (Handa 1975; Vaiphei et al. 2020). The peninsular gneissic complex in the study area is the fundamental source of Na⁺ in groundwater (Sajil

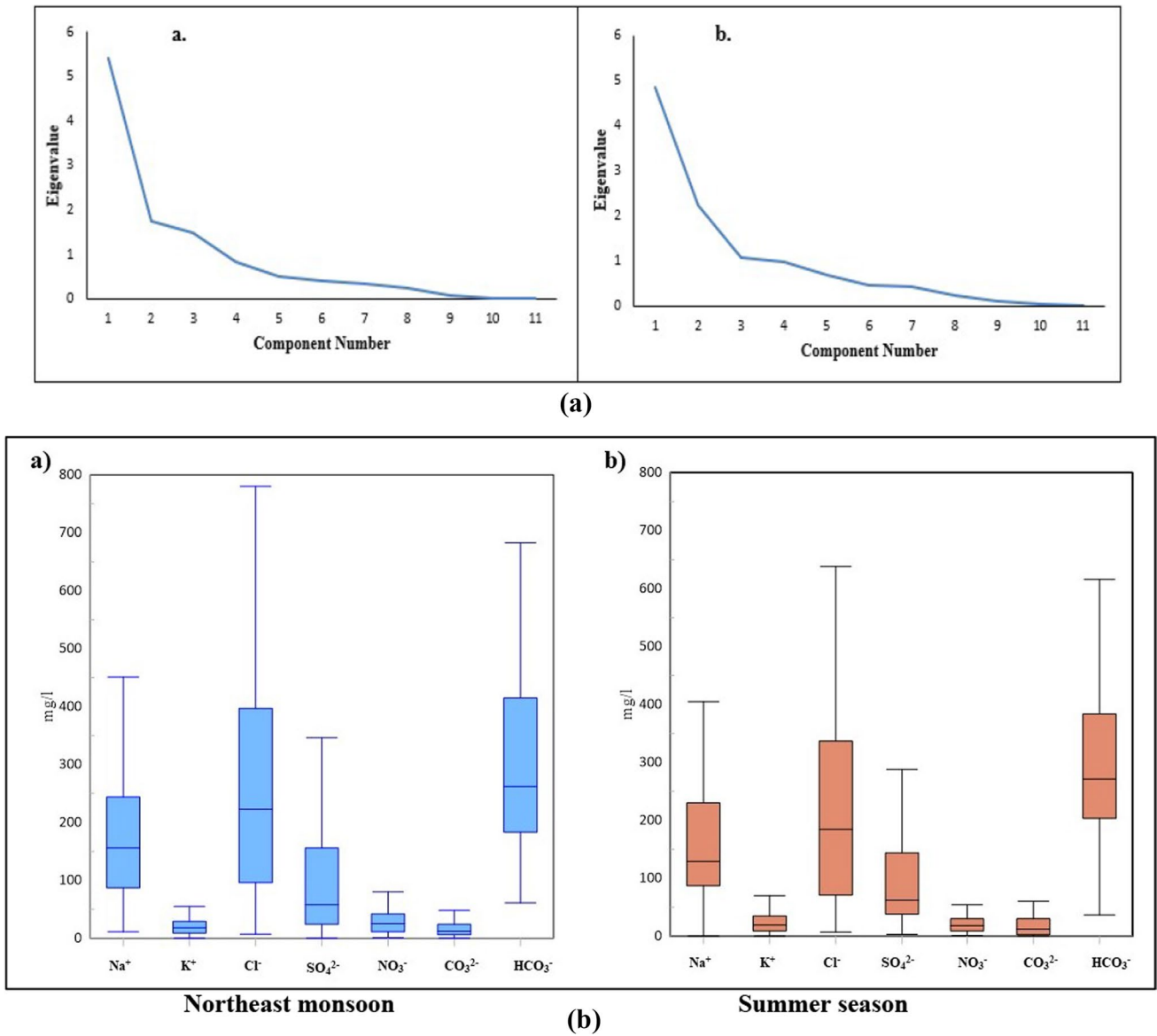


Fig. 3 Scree plot representing eigenvalue for each component (a) and Box plot for groundwater quality parameters (b) in northeast monsoon and summer season, respectively. Units: Na⁺, K⁺, Cl⁻, SO₄²⁻, NO₃⁻, CO₃²⁻, HCO₃⁻—mg/l

Kumar and James 2016). When comparing the seasonal variations, Na⁺ concentration was higher during summer (37–516 mg/L) than during the northeast monsoon season (25–286 mg/L), mainly due to the dissolution process occurring in the summer season. In addition, there are no specific guidelines for Na⁺ in the Indian drinking water standards (BIS 2012). WHO mentioned the high intake or prolonged exposure to excess Na⁺ in drinking water is significantly associated with hypertension and increases the risks of total cardiovascular diseases and stroke. Individuals under medical supervision are vulnerable to high concentrations of Na⁺ in drinking water.

Furthermore, halite dissolution also releases a similar amount of Na⁺ and Cl⁻ ions in groundwater (Sajilkumar and James 2016). Figure 4a shows the Na⁺ plot against Cl⁻, where most of the sample points in both seasons are alongside the 1:1 line. The Cl⁻ was the dominant anion higher during summer (18–638 mg/L) than during the northeast monsoon season (7–605 mg/l). Similarly, Cl⁻ in the primary sample analysis exhibited a lower concentration (93–144 mg/l) during the northeast monsoon season. Many samples have exceeded the acceptable limit of Cl⁻ (250 mg/L) in both seasons (42% in northeast monsoon and 50% in summer), whereas they abide within the permissible limits (1000 mg/L) of BIS drinking water standards. In

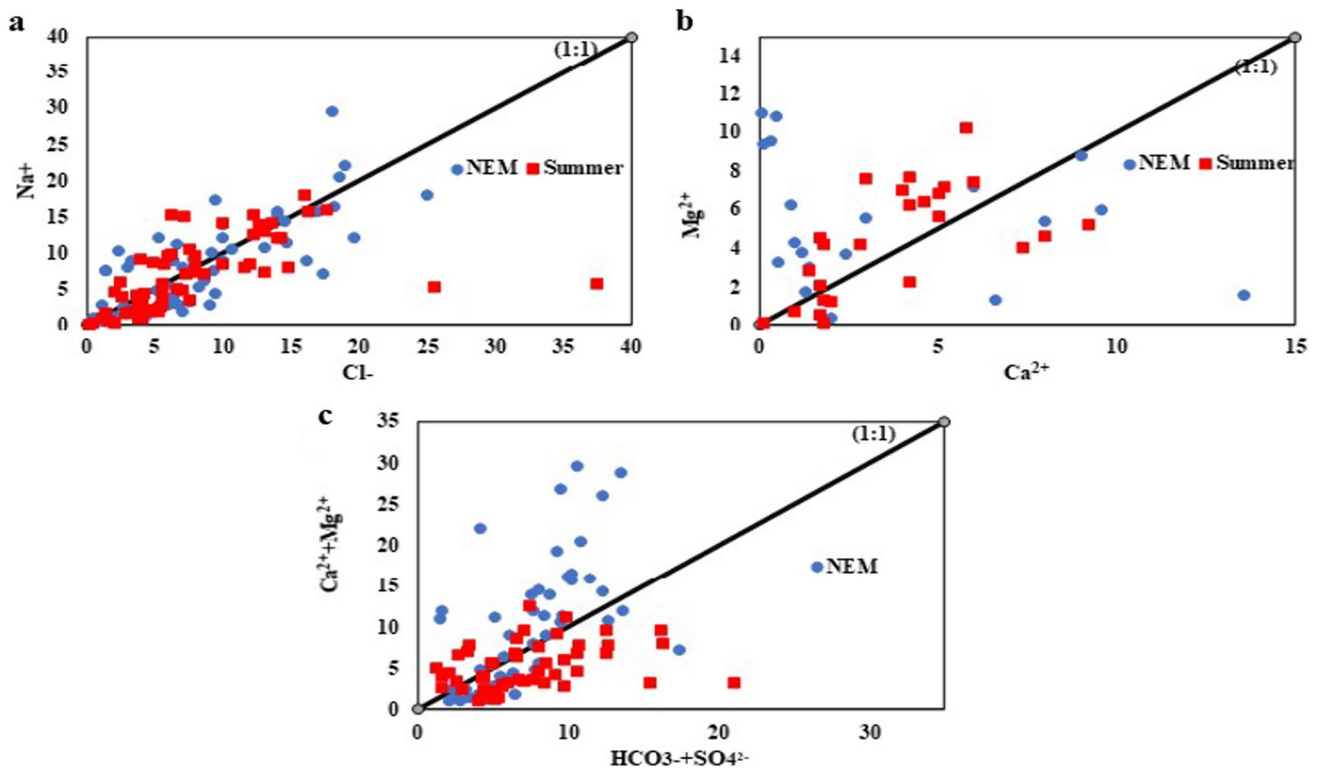


Fig. 4 Correlation diagrams between Na^+ and Cl^- (a); Ca^{2+} and Mg^{2+} (b); $\text{HCO}_3^- + \text{SO}_4^{2-}$ and $\text{Ca}^{2+} + \text{Mg}^{2+}$; All units are in meq; 1:1—unit ratio line

general, a significant increase in NO_3^- , Cl^- and SO_4^{2-} are noticed after the short-term drought (Kampbell et al. 2003). The results of groundwater quality parameters—TDS, Cl^- , and total hardness exceeding the acceptable limits of BIS drinking water purposes were similar to those of Sivakumar et al. (2023).

The study area is enriched with the genesis granite, increasing the Na^+ , K^+ , Ca^{2+} and HCO_3^- concentration in the groundwater. Other sources include the mafic and ultramafic igneous rocks or clay, the typical by-products of their weathering (Sajil Kumar and James 2016). In the summer, K^+ concentrations were around 0 to 156 mg/l; in the northeast monsoon, it was 0 to 293 mg/L. This concentration might be due to potassic minerals available for weathering and its ion exchange process with clay (Vaiphei et al. 2020). K^+ was also linked with hypertension in individuals susceptible to high-risk groups, and occasionally, they reach an adverse concentration in groundwater that has health-based effects (WHO 2017). The concentration of NO_3^- was a little higher during the northeast monsoon season (average of 33 mg/l) than in the summer season (25 mg/l) (Sangeetha et al. 2017). The NO_3^- is mainly due to fertilisers in agricultural practices or sewage contamination (Todd and Mays 2005). However, higher levels of NO_3^- were observed in the recent decade, where 21% of samples in northeast monsoon

and 11% in the summer season have exceeded the permissible limit of 45 mg/L in the study area. The occurrence of limestone and its dissolution (either calcite/dolomite) increases the concentration of Ca^{2+} and Mg^{2+} in groundwater. The plot with Ca^{2+} versus Mg^{2+} is depicted in Fig. 4b. Most points fall above the 1:1 line, indicating the dominance of Mg^{2+} compared to Ca^{2+} . Furthermore, the plot between $\text{HCO}_3^- - \text{SO}_4^{2-}$ versus $\text{Ca}^{2+} - \text{Mg}^{2+}$ is depicted in Fig. 4c, proves the existence of carbonate weathering and dissolution of calcite/dolomite/gypsum that predominantly increases the occurrences of Ca^{2+} , Mg^{2+} , HCO_3^- and SO_4^{2-} in groundwater (Chenini et al. 2010; Sajil Kumar and James 2016). The HCO_3^- , the second most dominating anion after Cl^- , increased during summer (118–574 mg/l) than during the northeast monsoon season (103–590 mg/l). The primary sample analysis gave HCO_3^- in the range of 93–186 mg/L during the northeast monsoon season.

Water Quality Index (WQI)

The weights and relative weights are calculated for the ten groundwater quality parameters. The parameters were compared with the limits of BIS drinking water standards. The calculated WQI is tabulated in Table 3. The WQI in the study area was dynamic over space and time. Between 1990

Table 3 Water Quality Index

Quality Parameters	BIS 10500:2015 Drinking water standards		Weight w_i	Relative Weight W_i
	Acceptable Limit	Permissible Limit		
TDS	500	2000	5	0.14
EC	–	2000	5	0.14
pH	6.5–8.5	No relaxation	4	0.12
Total Hardness	200	600	3	0.09
Cl ⁻	250	1000	5	0.14
SO ₄ ²⁻	200	400	5	0.14
NO ₃ ⁻	45	No relaxation	5	0.14
Total Alkalinity	200	600	3	0.09
			$\sum_{i=1}^n \omega_i = 35$	1

and 2000, the groundwater quality was markedly excellent in Kavundampalayam and Therampalayam. After massive urbanisation from 2001 to 2010, the WQI increased above 50. However, in 2005, 2006, and 2007, Natchipalayam and Nilambur recorded poor WQI. During the last 10 years (2011–2019), the groundwater quality has been marked as poor in almost many areas. During the northeast monsoon season, 44% of samples were within the WQI of less than 50 (excellent), 35% of samples were under the range of 50–100 (good water quality), and 21% of samples in the range of 100–200 (poor water quality). Similarly, 46% of samples had excellent water quality (WQI < 50), 41% indicated good water quality, and only 13% showed poor water quality. The groundwater quality has deteriorated over the years. In 2019, groundwater in Kamachipuram, Saravanampatti, Kuruchi, and Vellalore displayed poor water quality (WQI > 100). WQI in the summer season was poor when compared to Northeast Monsoon season. The results were also in accordance with the water quality of adjacent districts of Salem and Namakkal during the year 2008 (Vasanthaviagar et al. 2010) and the hard terrain regions of the Telangana district (Vaiphei et al. 2020).

Time series analysis of climatic data

The Mann–Kendall, Sen's Slope and Pettit test results for the climatic parameters are tabulated in Table 4a and groundwater characteristics in Table 4b, respectively. The temperature anomaly in the study area recorded a higher temperature range, where similar temperature trends were observed in many parts of India (Sanjay et al. 2020), Bangladesh (Shahid 2010), South Korea (Jung et al. 2002), Vietnam (Nguyen et al. 2014) and across the globe (IPCC 2007). During the study period, 2016 was recorded as the warmest year, with 0.9 °C (above the average value of 1990–2019). It has also been the official warmest year (2016) since 1880 recorded by NOAA, owing to the strong El-Nino effect (NOAA 2021). The 2019 (0.8 °C) and 2017 (0.6 °C) were recorded as the two warmest years between 1990 and 2019. The Coimbatore

district experienced many warm years after the year 2011. On the contrary, the year 1994 (–0.6 °C) was recorded as the coolest year, followed by 2006 (–0.5 °C) and 2008 (–0.4 °C), respectively (Jeganathan et al. 2019).

The annual time series analysis for the temperature parameters of MMinT and MAT revealed a statistically significant warming trend at the rate of 0.48 °C and 0.24 °C per decade, respectively. Seasonally, MMinT in summer and northeast monsoon displayed an increasing rate of 0.5 °C and 0.6 °C per decade, respectively. MMinT showed higher variation in monsoon than in summer. The MMinT exhibited a sudden increase from 2008 that ultimately affected MAT in the year 2011. Unlike MMinT or MAT, the MMaxT showed a dissimilar non-significant change over annual and seasonal time series analysis. The MMaxT displayed a higher value in the northeast monsoon than in summer, whereas it annually increased non-significantly at a low decadal rate of 0.01 °C. According to Kothawale and Kumar (2002), India's mean annual temperature warms at a significant rate of 0.18 °C per decade (1971–2000), more pronounced during the winter season (December to February) and perceived more vibrations in MMinT than MMaxT (Mondal et al. 2015; Shahid 2010; Nguyen et al. 2014; Kumar et al. 2017). During the period from 1969 to 2016, the inland regions of Tamil Nadu experienced a high increase in MMinT than the coastal regions, while coastal areas exaggerated a high rise in MMaxT (Jeganathan et al. 2019). Besides, Coimbatore being an inland station, gave a significant yearly decadal increase in MAT (0.20 °C) (Jeganathan et al. 2019) and MMinT (0.31 °C), which is analogous to the yearly decadal linear trends (MMinT-0.48 °C; MAT-0.24 °C) of this study.

The rainfall anomaly showed a decreasing trend at 22 mm/decade. On the contrary to temperature, TRF indicated no significant trend in both annual and seasonal time series analyses. At the same time, it depicted a drop in the northeast monsoon season and an increase in the summer season at –42 mm/decade and 8.5 mm/decade, respectively. However, the Coimbatore district's annual average and northeast monsoon rainfall during 1907–2012 have a

Table 4 Time series analysis (1990–2019) of Climatic parameters (a) and groundwater quality (b)

(a) Climatic parameters (Temperature—MMinT, MMaxT, MAT and TRF)									
Seasons	Factors	Mann–Kendall test					Sen's slope		Pettit test
		Std dev	Mean	Min	Max	Kendall tau	Years	Decade	Shift Break
Annual	MAT	0.4	27	26.7 (1994)	28 (2016)	0.373*	0.024	0.24	2011
	MMaxT	0.4	33	31.9 (2006)	33.5 (2016)	0.007	0.001	0.01	–
	MMinT	0.5	22	21 (1999)	23 (2016)	0.611*	0.048	0.48	2008
	TRF	198	596	240 (2012)	994 (1997)	–0.076	–2.25	–22	–
Summer	MMaxT	0.8	36	34 (2008)	37 (1998, 2019)	–0.147	–0.011	–0.11	–
	MMinT	0.6	23	22.5 (1999)	25 (2016)	0.503*	0.050	0.5	2008
	TRF	68	128	34 (2007)	263 (2018)	0.057	0.850	8.5	–
Northeast monsoon	MMaxT	0.6	30	29 (2016)	32 (1993)	0.250	0.023	0.23	–
	MMinT	0.6	21	20 (2000)	22 (2015)	0.548*	0.057	0.6	2008
	TRF	162	318	102 (1991)	812 (1997)	–0.154	–4.17	–42	–

(b) Groundwater quality parameters								
Parameters	Monsoon Season				Summer Season			
	Mean	Kendall's tau	Sen's Slope (Per decade)	Pettit test	Mean	Kendall's tau	Sen's Slope (Per decade)	Pettit test
TDS	873	0.565*	310	1997	879	0.348*	190	–
EC	1373	0.51*	470	2004	1482	0.327*	320	–
pH	8.2	–0.005	–	–	8.1	–0.172	–	–
Total hardness	340	0.281*	60	1997	367	0.003	–	–
Na ⁺	165	0.336*	47	1996	152	0.24	–	–
K ⁺	31	0.533*	14	1997	42	0.416*	13	–
Cl [–]	215	0.379*	90	2004	196	0.440*	77	1996
SO ₄ ^{2–}	76	0.274*	20	1997	99	0.12	–	–
NO ₃ [–]	33	0.455*	15	2004	25	0.288*	4.42	–
CO ₃ ^{2–}	16	–0.308*	–7	1999	10	–0.233	–1.4	–
HCO ₃ [–]	278	0.385*	80	1999	305	0.22	–	–

Units: MAT, MMinT, MMaxT—°C; TRF—mm; * at 95% significance level

Unit: TDS, pH, Total hardness, Na⁺, K⁺, Cl[–], SO₄^{2–}, NO₃[–], CO₃^{2–}, HCO₃[–]—mg/l; EC—μS/cm; * at 95% significance level

non-significant increasing trend (Arthi et al. 2014). This might be due to the disparity in data and time. The rainfall trend analysis in Tamil Nadu during 1877–1976 was non-significant, indicating the non-uniform and unprecedented state of rainfall over space and time (Dhar et al. 1982).

Time series analysis of groundwater quality and level

During the study period of 30 years in the Coimbatore smart city areas, the groundwater level in the summer season was found at higher depths than during the monsoon season. The mean groundwater level (i.e., below ground level, bgl) in summer and monsoon season was measured at 21 m (maximum—27 m; minimum—13 m) and 19 m (maximum—26 m; minimum—11 m), respectively. This intra-seasonal variation might be due to the implementation of

numerous groundwater recharge structures across the study area, and the whole district comprises 363 recharge structures (TWAD 2020). The time series analysis of groundwater level revealed that the depth to the water table has significantly decreased (i.e., improved) over the study period by approximately 3 m, which was remarkably observed after 2007 (monsoon) and 2009 (summer). Despite the decreasing trend in rainfall, the increased groundwater level endorses the occurrence of artificial recharge in the study area.

On the contrary, the trend analysis of groundwater levels for the Coimbatore district measured by the Tamil Nadu Water Supply and Drainage Board (TWAD) revealed a non-significant increasing trend (TWAD 2020). Whereas the CGWB report pointed out both rise (0.09 m/yr) and fall (0.2 m/yr) in groundwater levels over different parts of the district during the period 1998–2007 (CGWB 2008). This temporal variation in the groundwater level between CGWB

and TWAD results indicates that climatic and demographic conditions affect the dynamic nature of groundwater. The observed spatial disparity might be due to the nature of the monitoring wells (shallow/deep aquifer) and the location of the monitoring wells from artificial and natural recharge sites (Srinivasan 2014).

The time series analysis of groundwater quality parameters in both seasons is depicted in Fig. 5a. Inter-seasonal time series analysis over the study period revealed that most groundwater quality parameters significantly changed during the northeast monsoon rather than the summer season, except for pH, total hardness, Na^+ , SO_4^{2-} , CO_3^{2-} , and HCO_3^- . Throughout the northeast monsoon season, the groundwater quality parameters of TDS, EC, total hardness, Na^+ , K^+ , SO_4^{2-} , Cl^- , NO_3^- and HCO_3^- had an increasing trend, while CO_3^{2-} showed a decreasing trend. The observed decadal trend was in the increasing order of dominance of EC (470 $\mu\text{S}/\text{cm}/\text{yr}$) > TDS (310 mg/l/yr) > Cl^- (90 mg/l/yr) > HCO_3^- (80 mg/l/yr) > Total hardness (60 mg/l/yr) > Na^+ (47 mg/l/yr) > SO_4^{2-} (20 mg/l/yr) > NO_3^- (15 mg/l/yr) > K^+ (14 mg/l/yr) > CO_3^{2-} (-7 mg/l/yr). Most of the parameters had a sudden change after 1997. During the summer season, the TDS, EC, K^+ , Cl^- , and NO_3^- showed a significant increasing trend with decadal variation in the sequence of EC (320 $\mu\text{S}/\text{cm}/\text{yr}$) > TDS (190 mg/l/yr) > Cl^- (77 mg/l/yr) > K^+ (13 mg/l/yr) > NO_3^- (4.4 mg/l/yr). Unlike the northeast monsoon, most ions in the summer season had a slight increase in concentrations. The groundwater quality parameters of EC, TDS, Cl^- , K^+ , and NO_3^- had significant increasing trends in both seasons. Study by Pophare et al. (2014) during 2007–2010 shows a statistically significant positive trend in EC in the range of 0.52–46.9 $\mu\text{S}/\text{cm}/\text{year}$; Daughney and Reeves 2006, during 2001–2005 observed K^+ increasing at the rate of 1.9 $\text{g m}^{-3} \text{y}^{-1}$ in shallow and 0.49 $\text{g m}^{-3} \text{y}^{-1}$ in the deep aquifer; Daneshvar Vousoughi et al. 2013 during 1996–2009 found that Cl^- change in the range of -0.07 to 0.68 meq/l/yr, SO_4^{2-} at the rate of 0.5–1.12 meq/l/yr and HCO_3^- in the range of -0.29 to 0.54 meq/l/yr during wet and dry months. Similarly, a statistically significant positive trend was observed during 1991–1998 in K^+ in the range of 1.5–15.5 mg/l/yr, NO_3^- in the range of 55.8–103.2 mg/l/yr and total cations in the range of 0.4–3 meq/l/yr (Broers and Grift 2004). Study by Farid et al. (2019) showed that in some parts of Pakistan during the period 2003–2016, indicated a significant increase in EC during the pre-monsoon season. Certain groundwater quality parameters mapped in QGIS 3.0 (Fig. 5b) showed a wide variation in the northeast monsoon season over the study period.

During the summer season of 2019, the average concentration of NO_3^- (133 mg/l), Na^+ (242 mg/l) and EC (2132 $\mu\text{S}/\text{cm}$) exceeded the permissible limit of drinking water standards, whereas Cl^- (398 mg/l) and TDS (1291 mg/l) exceeded the acceptable limit. Similarly,

during the northeast monsoon season of 2019, the average concentration of EC (2520 $\mu\text{S}/\text{cm}$), Na^+ (264 mg/l) and NO_3^- (89 mg/l) exceeded the permissible limit of drinking water standards, whereas the total alkalinity (591 mg/l) and Cl^- (431 mg/l) exceeded the acceptable limit. Further increase in NO_3^- , Na^+ , EC and Cl^- concentrations would deteriorate the groundwater quality to a great extent. In the primary groundwater quality analysis during January and March 2021 (as shown in Table 5)—the average of TDS in January was 697 mg/l, and March was 871 mg/l, similarly, EC was 1502 and 1734 $\mu\text{S}/\text{cm}$; Cl^- was 107 and 496 mg/l; SO_4^{2-} was 130 and 387 mg/l; HCO_3^- was 128 and 369 mg/l; Total Hardness was 545 and 369 mg/l; pH was 8 and 7.9. The results reveal that TDS, EC, total hardness and the ionic concentration of Cl^- , SO_4^{2-} , and HCO_3^- was high during dry month of March than January, the wet month. Overall, groundwater quality parameters in most of the samples stayed within the limits of permissible standards of BIS. This may be due to the effect of COVID-19 lockdown (Selvam et al. 2020; Karunanidhi et al. 2021), and beyond the scope of this study.

Regression analysis

From the time series analysis, it is evident that the groundwater quality in the Coimbatore region is deteriorating. The regression analysis was plotted with the climatic parameters trend (temperature and TRF) against groundwater quality on a seasonal basis to identify its impact (Fig. 6). The slope from the line equation ($y = mx + c$) provides the change in groundwater quality over unit change in temperature (Reidel 2019). Among the various temperature parameters (MMinT, MMaxT, MAT), MMinT was solely considered as a temperature factor for further analysis. Because MMaxT did not show any significant change over the years; MAT has shown significant change over the years, but might account for any potential bias. The relationship between temperature and groundwater quality was established with regression analysis (Reidel 2019). The regression analysis between TRF and groundwater quality parameters showed no significant relationship during summer and northeast monsoon seasons. This indicates that the rainfall over the study area did not reach the aquifer (which might be due to heavy urbanisation). Meanwhile, temperature showed a significant relationship between groundwater quality parameters of TDS, EC, Na^+ , K^+ , Cl^- and CO_3^{2-} . Comparing the results with trend analysis in summer season it can be understood that the parameters—EC, TDS, Cl^- , K^+ and NO_3^- are impacted by temperature. Welch and Ulman (2000) reported a similar result, where the dissolution rate of K^+ increases by two or three folds with a rise in temperature. The ionic concentration of K^+ and NO_3^- increases in summer and are

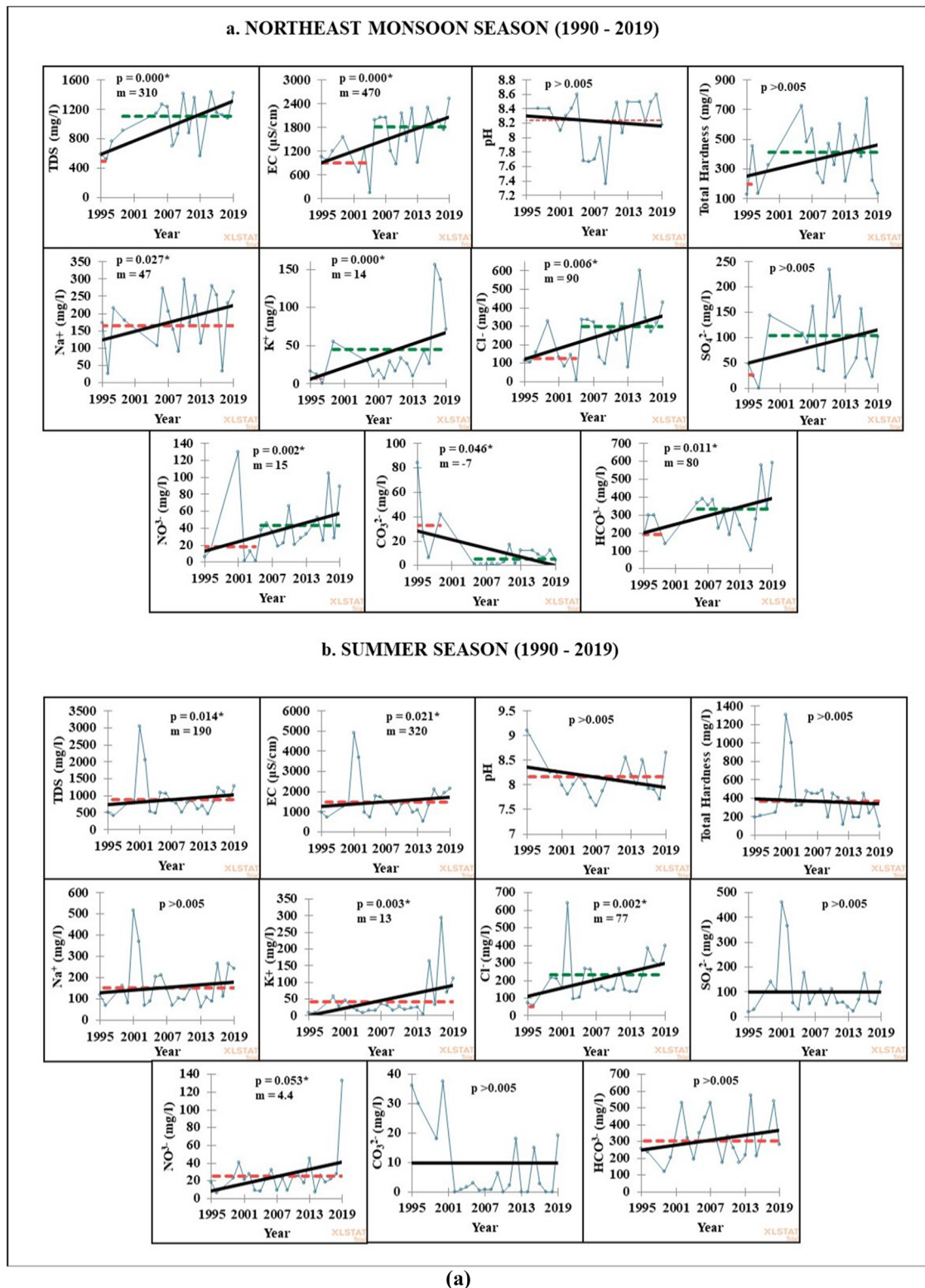
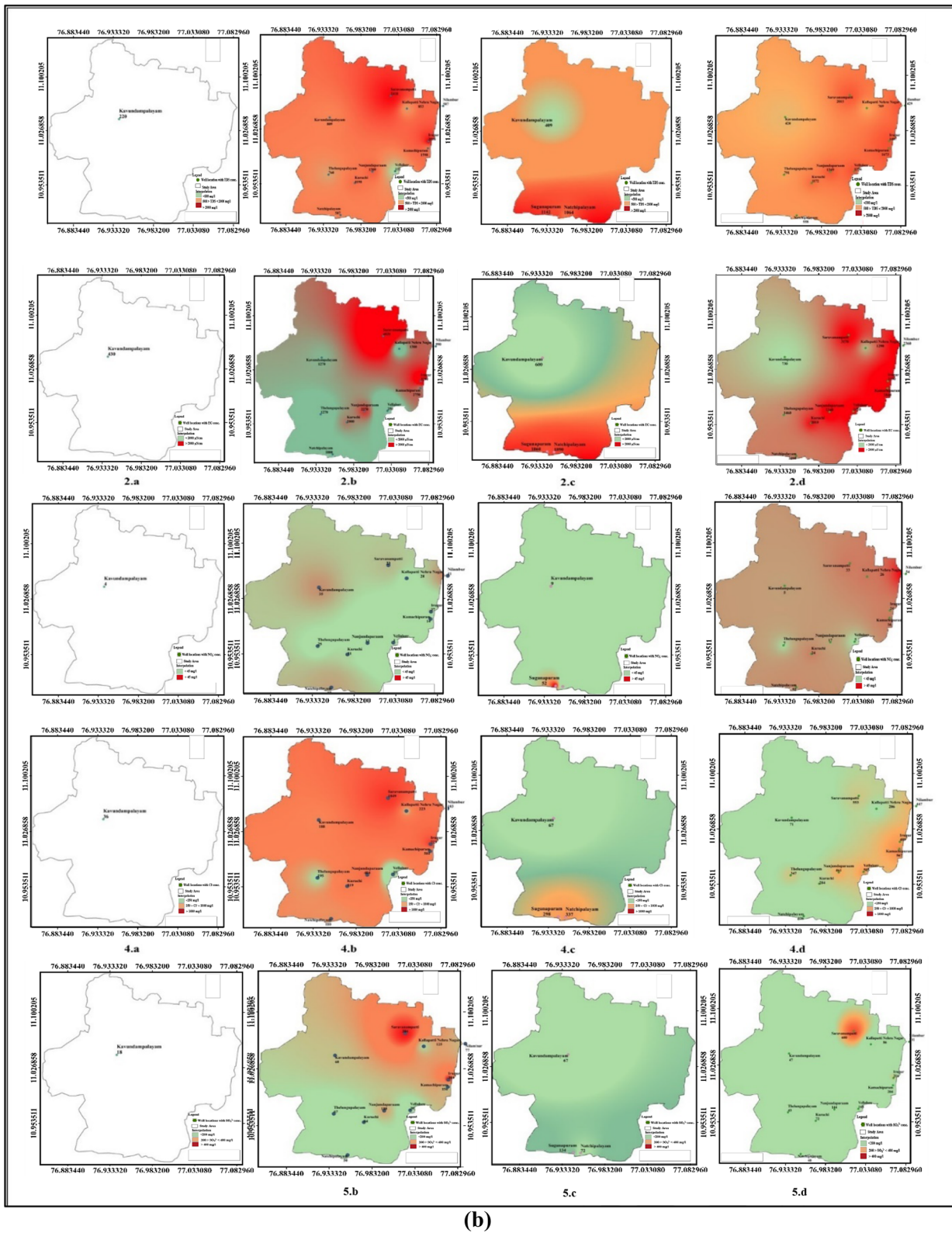


Fig. 5 Time series analysis and map showing changes in groundwater quality. **a** Time series analysis of groundwater quality. * 95% statistical level of significance (p); m represents the Slope, i.e., change in unit of a parameter per decade for the parameters of TDS, EC, pH, total hardness, Na⁺, K⁺, Cl⁻, SO₄²⁻, NO₃⁻, CO₂³⁻, HCO₃⁻ respectively. Unit: pH-no unit; EC-μS/cm; TDS, total hardness, NO₃⁻, Na⁺,

K⁺, Cl⁻, SO₄²⁻, CO₂³⁻, HCO₃⁻—mg/l. **b** Map showing change in groundwater quality in 15 year interval for both northeast monsoon (**a**, **b**) season and summer season (**c**, **d**), respectively, for TDS, EC, NO₃⁻, Cl⁻ and SO₄²⁻. Unit: EC-μS/cm; TDS, NO₃⁻, Cl⁻, SO₄²⁻—mg/l



(b)

Fig. 5 (continued)

Table 5 Primary groundwater quality analysis

2021 Parameter	January			March		
	Mean	Min	Max	Mean	Min	Max
TDS	697	544	993	871	456	1305
EC	1502	1180	1788	1734	912	2610
pH	8	7.6	8.2	7.9	7.5	8.2
Total Hardness	545	470	640	369	250	480
Cl ⁻	107	94	145	496	245	678
SO ₄ ²⁻	130	63	244	387	329	438
CO ₃ ²⁻	0	0	0	0	0	0
HCO ₃ ⁻	128	93	186	369	184	624

Unit: pH-no unit; EC- $\mu\text{S}/\text{cm}$; TDS, total hardness, Cl⁻, SO₄²⁻, CO₃²⁻, HCO₃⁻—mg/l

lowered only by dilution (Senthilkumar and Rajmohan 2023). The increasing temperature has a non-significant decreasing relationship with CO₃²⁻, because at high temperature, the CO₃²⁻ reacts with the cations (Ca²⁺, Mg²⁺) to form its carbonates (Todd and Mays 2005). The significant increase in MMinT also had a vital role in determining the groundwater quality parameters of TDS, EC, Na⁺, K⁺, Cl⁻ and CO₃²⁻ during the northeast monsoon (Reidel 2019; Saito et al. 2016). The change in groundwater quality with respect to increase in MMinT by 1 °C, is tabulated in Table 6. Over the study period, an increase in MMinT by 1 °C has increased the ionic concentration of groundwater quality parameters in the order of EC (176 $\mu\text{S}/\text{cm}/^\circ\text{C}$), TDS (105 mg/l/°C), Cl⁻ (43 mg/l/°C), Na⁺ (24 mg/l/°C), K⁺ (7 mg/l/°C) and CO₃²⁻ (-2.7 mg/l/°C) during the northeast monsoon season, and Cl⁻ (65 mg/l/°C), K⁺ (7 mg/l/°C), NO₃⁻ (10 mg/l/°C) and CO₃²⁻ (-4 mg/l/°C) during summer season.

Temperature-induced changes in groundwater quality

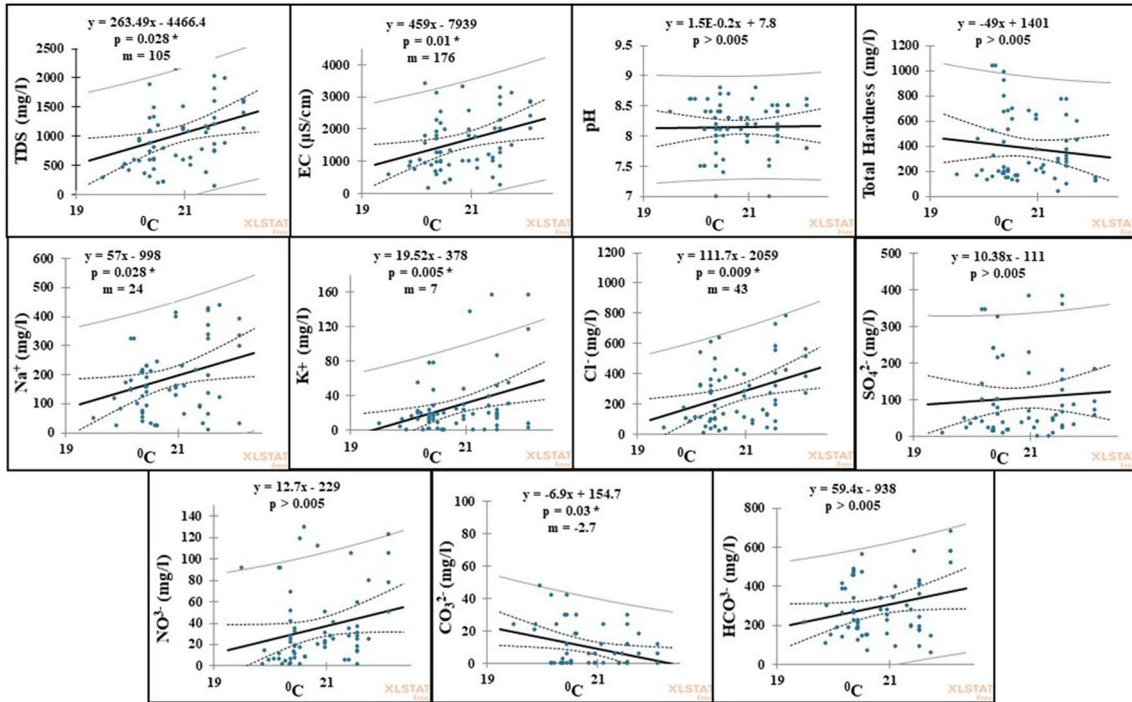
Now, considering the fact that TDS has a significant increase by 310 mg/l in decade from 1990 to 2019. Arithmetically, for 30 years, TDS has increased by 930 mg/l. In addition, the MMinT during northeast monsoon season has increased by 0.6 °C/decade, and 1.8 °C over 30 years. Thus, theoretically evaluating, during 1990–2019, for increase in 1.8 °C, the TDS increase by 517 mg/l. By regression analysis, it was observed that increase in 1 °C has increased TDS by 105 mg/l. Overall, only 20% of the increase in TDS was contributed by temperature. An increase in 1 °C of MMinT increased EC by 22%; Cl⁻ by 29%; K⁺ by 30%; Na⁺ by 31% and decreased CO₃²⁻ by 33%. Therefore, the impact of temperature during northeast monsoon season in groundwater quality was predominantly observed in the order of CO₃²⁻ > Na⁺ > K⁺ > Cl⁻ > EC > TDS. Similarly, the MMinT during summer season has increased by 0.5 °C in a decade, and 1.5 °C in 30 years: inducing

an increase in concentrations of Cl⁻ by 40%; K⁺ by 54%; NO₃⁻ by 111%, and decrease in CO₃²⁻ by 95%. The impact of 1 °C of MMinT has a maximum effect on NO₃⁻ than any other parameter. NO₃⁻ in the groundwater can persist for 17 months (Ruckart et al. 2008); in addition, rising temperature allows its further persistence in the groundwater. It can be also inferred that the ionic concentration of Na⁺ and K⁺ is highly increased in summer season compared to northeast monsoon season, indicating weathering (Reidel 2019; Sajilkumar and James 2016). The decreasing CO₃²⁻ are the results of stable carbonates formed by its reaction with cations (Ca²⁺, Mg²⁺) (Todd and Mays 2005).

Future projections

Time series and regression analyses showed that temperature was the paramount factor in regulating groundwater quality parameters in the study area. The impact of past temperature trends on groundwater quality parameters and recharge was quantified. The Substantial future impact of temperature on groundwater quality parameters and recharge was assessed based on the future temperature projections derived through RCP 4.5 scenario for the years 2050s (2040–2070) and 2080s (2070–2100) with the baseline from 1970 to 2000. The future temperature trends of MMaxT and MMinT for the study region are given in Table 7a. The results are in accordance with the temperature trend analysis of MMinT and MMaxT in the study area during 1990–2019. MMinT has significant increased by 1.5 °C in summer and 1.8 °C in northeast monsoon season, but MMaxT showed a non-significant decreasing trend in summer (-0.22 °C) and a non-significant increasing trend in northeast monsoon season (0.69 °C). This trend reflected in the temperature projections during 2070–2100, where the MMaxT might increase to 3.3 °C but MMinT increases to 3.4 °C. As previously mentioned, only MMinT was considered for further analysis. Based on the past effect of temperature on groundwater quality parameters (baseline data: 1990–2019), the future impact of temperature on groundwater quality was projected for the years the 2050s (2040–2070) and 2080s

a. NORTHEAST MONSOON SEASON (1990 - 2019)



b. SUMMER SEASON (1990 - 2019)

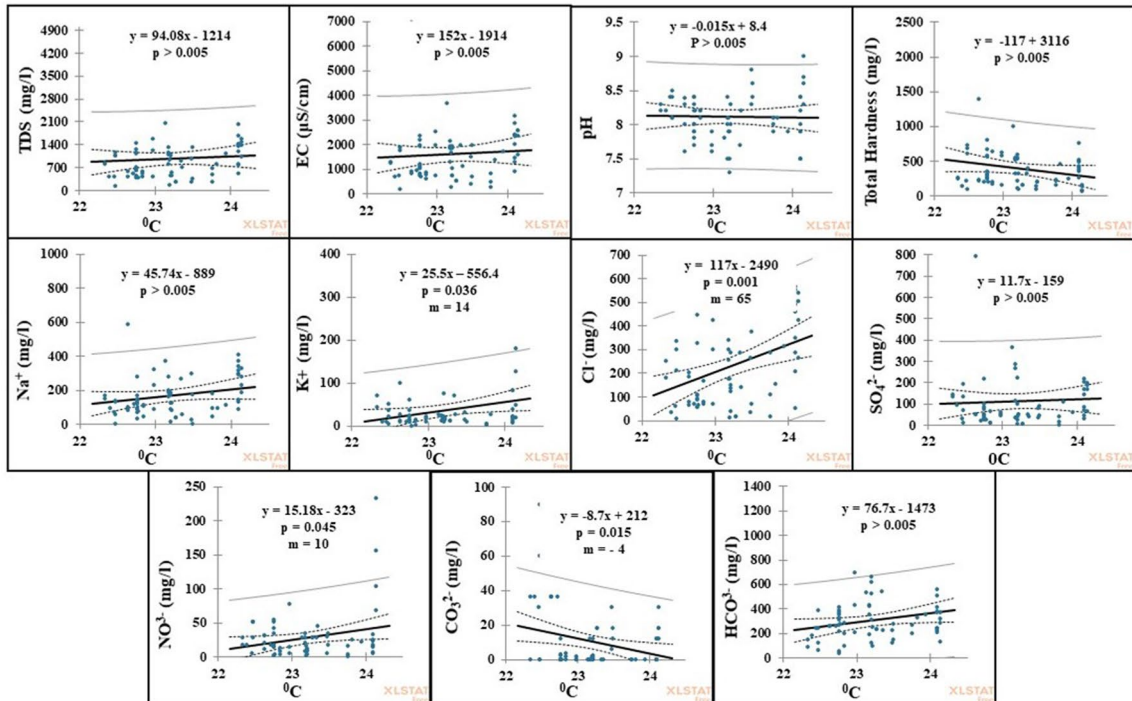


Fig. 6 Linear regression analysis of groundwater quality parameters against temperature. *95% statistical level of significance (p) and m is the slope, i.e., the change in unit of groundwater quality parameter per unit of temperature (°C) in northeast monsoon and summer

season, respectively, for the parameters of TDS, EC, pH, total hardness, Na⁺, K⁺, Cl⁻, SO₄²⁻, NO₃⁻, CO₂³⁻, HCO₃⁻. Unit: pH-no unit; EC-µS/cm; TDS, total hardness, NO₃⁻, Na⁺, K⁺, Cl⁻, SO₄²⁻, CO₂³⁻, HCO₃⁻—mg/l

Table 6 Significant groundwater quality parameters impacted by temperature (a) and the impact of temperature-induced changes in groundwater quality (b) in northeast monsoon and summer season

Parameter	TDS	EC	Na ⁺	K ⁺	Cl ⁻	CO ₃ ²⁻	NO ₃ ⁻
a. Impact of temperature (for 1 °C)							
Northeast Monsoon Season	105*	176*	24*	7*	43*	-3*	-
Summer Season	-	-	-	14*	65*	-4*	10*
b. Impact of Temperature (%)							
Northeast Monsoon Season	20	22	31	30	29	33	-
Summer Season	-	-	-	54	40	95	111

The change in groundwater quality during northeast monsoon and summer season at rate of change in unit temperature

Unit: TDS, Na⁺, K⁺, Cl⁻, CO₃²⁻, NO₃⁻—mg/l/°C; EC—μS/cm/°C; *—significant at 95%

Table 7 Future temperature projections under RCP 4.5 scenarios in 2020s, 2050s and 2080s with the baseline from 1970 to 2000 (a) and Future projections of groundwater quality based on RCP 4.5 temperature projections (b) in northeast monsoon and summer season

(a) Future temperature projections (MMinT and MMaxT) with baseline 1970–2000 under RCP 4.5 scenarios

Parameter	2010–2040 (2020s)	2040–2070 (2050s)	2070–2100 (2080s)
MMinT	+1.1°C	+2.3°C	+3.4°C
MMaxT	+1.1°C	+2.3°C	+3.3°C

(b) Future projections of groundwater quality to temperature based on RCP 4.5 scenarios

Parameters	Northeast Monsoon Season		
	1990–2019 (Reference)	2050s (Projected)	2080s (Projected)
	1.8°C	2.3°C	3.4°C
TDS	105	134	198
EC	176	225	332
Na ⁺	24	31	45
K ⁺	7	9	13
Cl ⁻	43	55	81
CO ₃ ²⁻	-3	-4	-6
Summer Season			
	1990–2019 (Reference)	2050s (Projected)	2080s (Projected)
	1.5 °C	2.3 °C	3.4 °C
K ⁺	14	21	32
Cl ⁻	65	100	147
CO ₃ ²⁻	-4	-6	-9
NO ₃ ⁻	10	15	23

Unit: TDS, Na⁺, K⁺, Cl⁻, CO₃²⁻, NO₃⁻—mg/l/°C; EC—μS/cm/°C

(2070–2100) are tabulated in Table 7b. As the projected temperature increases, ionic concentration of groundwater quality will intensify. Already, an increase of 10 mg/l/°C of NO₃⁻ in summer season has attributed to 21% of samples in northeast monsoon and 11% in the summer season to exceed the permissible limit of 45 mg/L in the study area. Likewise, an increase in Cl⁻ (43 mg/l/°C in northeast monsoon; 65 mg/l/°C in summer season) has put many samples to exceed the acceptable limit of Cl⁻ (250 mg/L) in both seasons (42% in northeast

monsoon and 50% in summer), but as the trend goes by the ionic concentration may increase, and might exceed the permissible limit of 1000 mg/l (BIS 2015). In terms of groundwater recharge, the northeast monsoon rainfall, the primary source of groundwater recharge in the Coimbatore district, has diminished, subsequently reducing groundwater availability. The plot with groundwater recharge versus future temperature projections shows that the district may face a plunge in its groundwater resources, if the groundwater management

continues to persist without any sustainable programs. The decline in groundwater recharge with the increasing temperature effect may threaten food production (Famiglietti 2014).

Adaptation strategies for groundwater management

The direct and indirect climate change impacts with robust urbanisation place a high demand on the availability of groundwater resources. Eventually, it affects the socio-economic dimension and places an unquenchable demand on groundwater during long dry summer spells (Taylor and Stefan 2009; Tanguichi et al. 2007; Kundzewicz and Doell 2009). Improving the groundwater recharge is paramount for protecting the groundwater resources (quality and quantity). In most cases, the only focus is given to water quantity which hides the time and area-specific water quality issues. It also eventually hinders the potential role of future policy in groundwater utilisation and the economic development process for shaping the landscape above aquifers (Holman 2006). The primary measure should include the stringent implementation of rainwater harvesting and stormwater collection structures, which is highly requisite in all buildings (other than huts) as stated in the Buildings Act (1973), Tamil Nadu District Municipal Act (1920), and the Coimbatore City Municipal Corporation Act (1981). Establishing the reuse and recycling of grey water through minimal treatment must also be implemented.

A well-designed policy can attain sustainable development, while a poorly designed policy fails to maintain people within the social foundation and exploits the resources (Raworth 2012). The groundwater policy and/or the engineered groundwater remediation systems often exist only for a short-term period rather than long-term due to their lower economic viability and uncertainties in climate predictions (Green et al. 2016). Hence, any pre-emptive actions in policy should consider the past and future scenarios of climatic factors, groundwater resources, urbanisation growth, and proper fund allocation for long-term groundwater remediation systems and include the measures/suggestions, such as to:

- (i) reduce the dependency on groundwater resources by sustaining surface water and substituting it with any other renewable resources,
- (ii) focus on regenerating the groundwater resources (quantity and quality) as replenishable under future uncertainties,
- (iii) monitor the abstraction and recharge rate for restraining the prudent boundary of groundwater resources (quantity and quality),
- (iv) control and monitor the domestic and industrial discharges and

- (v) conduct various awareness programs for the education of the public about their beneficial role in sustainable groundwater management and rainwater harvesting for groundwater recharge.

Conclusion

The present study reveals that the continuous surge in MMinT (0.48 °C/decade) indicating a paradigm shift toward warmer nights in the study area. The significant increase in the MMinT has contributed toward increase in groundwater quality parameters. Direct effect of temperature, and other indirect effects from increased groundwater development, and anthropogenic activities might have influenced the certain ionic concentrations. Considering the fact that, almost 50% of the study area is urbanised, sustainably managed groundwater practices with pre-emptive adaptation strategies should be implemented, specifically adopting rainwater harvesting structures in individual household; recycling greywaters for gardening; increasing green cover in urban spaces, and decreasing the groundwater development in exploited and over exploited areas. In future, while planning for any recharge methods, it is important to assess the potential method securing the availability and quality of the groundwater resources. Thus, ensuring the future generations to have access over resources at its best.

Acknowledgements The authors are thankful to UGC–DAAD for the project funding under the Indo-German Partnerships in Higher Education Programme on IGCaWR [UGC Ref: F. No. 1-8/2020 (IC)].

Author contributions ANRWS: methodology, performed the analysis and data investigation, writing—original draft preparation; KP: conceptualization, writing—review, supervision, resources, project administration, funding acquisition; SSS: design, writing—first draft preparation, review, editing, validation; BK: writing—review.

Funding This research was supported by UGC-DAAD, UGC Ref: F. No. 1-8/2020 (IC). The author, Dr. S. Sri Shalini, gratefully acknowledges the financial support provided by the Department of Science and Technology (DST), Ministry of Science and Technology, Government of India under Women Scientists Scheme-A (WOS-A) (Grant no. SR/WOS-A/EA-37/2018).

Data availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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