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Research paper

Use of the water quality index and multivariate analysis to assess groundwater quality for drinking purpose in Ratnapura district, Sri Lanka

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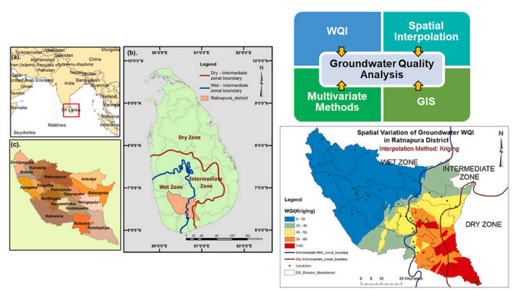
HIGHLIGHTS

- Water Quality Index as an important tool to represent the overall quality of water.
- Mapping the spatial variation of groundwater quality in Ratnapura district.
- Rapid deterioration of groundwater quality in the district's dry and intermediate zones.
- Mineralization of groundwater in the dry zone area of the district.
- Climate and soil properties have a significant impact on groundwater quality.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater is a key source of freshwater for communities in many nations, including Sri Lanka. However, with the current trends of population growth and climate change, stress on groundwater is increasing at an alarming rate. Groundwater quality in Sri Lanka has already been depleted over time as a result of both anthropogenic and natural factors, and there is a significant likelihood that such issues will get worse in the near future. The overall groundwater quality in Ratnapura district has not been the subject of any prior studies, despite the fact that many residents depend on groundwater as their primary source of water. Under these circumstances, this groundwater quality study was conducted to assess the groundwater quality in Ratnapura district with respect to the drinking water quality standards. In this study, available data on 10 water quality parameters from 50 groundwater sources was utilized to analyze the groundwater quality using several statistical and graphical methods. In particular, the Water Quality Index (WQI), geostatistical modeling, Hierarchical Cluster Analysis (HCA), Principal Component Analysis (PCA), and spatial autocorrelation analysis were used to assess the overall water quality and potential causes for variations over the area. Overall results revealed significant deterioration of groundwater quality in the eastern and south-eastern areas of the district. Multivariate analysis results revealed substantial differences between groundwater in the wet zone and the dry zone of the district, implying increased mineralization of groundwater in the dry zone. Furthermore, the results demonstrate that both climate and soil properties have a substantial impact on groundwater quality variation across the district. Future hydrogeological research in the area, as well as water engineers, policy makers, government officials, donor agencies, etc., will benefit from the findings of this study.

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1. Introduction

Since it is the primary supply of water for those who live in arid and semi-arid regions of the planet, groundwater is just as important to human society as surface water (Jeihouni et al., 2014). The main sources of drinking water for 36.4% and 3.2% of Sri Lanka's population, respectively, are domestic wells and tube wells (Ministry of City Planning and water Supply, 2018). However, due to both natural and anthropogenic activities, deterioration of groundwater quality has been a common issue across the country. Groundwater sources in many areas are accumulated with contaminants from residential sewage, urban runoff, and agricultural seepage (Mahagamage and Manage, 2015; Gunatilake, 2016). When considering natural processes, high fluoride and hardness in the dry zone groundwater (Jayawardana et al., 2010; Rubasinghe et al., 2015), and high iron content in hard rocky alluvial soil areas are common groundwater issues in the country (Bandara, 2003). Further, in some coastal areas, salinity intrusion into groundwater has been escalating to a water crisis, particularly in the Jaffna peninsula (Gopalakrishnan et al., 2020). On top of all of this, the recently discovered Chronic Kidney Disease of uncertain etiology (CKDu), which is frequently linked to groundwater quality, has been a common acute health issue in most dry zone areas (Dissanayake and Chandrajith, 2017; Udeshani et al., 2020). In this background, monitoring and identifying groundwater sensitive areas in the country is critical for ensuring public health, which in turn aids the country's economic and social development.

Given the foregoing, Ratnapura district was particularly selected for this research since there is no previous study focused on the overall quality of groundwater in the district, and it is a highly vulnerable area towards climate change and its negative impacts (Navaratne et al., 2019). Despite having substantial rainfall throughout the year, Ratnapura district is overwhelmed with drinking water issues both in terms of quality and quantity. This is partly due to the lack of pipe-borne water supply coverage in the district and the inadequate treatment of raw water in the community-controlled water supply schemes in the area. The poor quality of the water delivered by some community water supply schemes has been a persistent problem in other districts as well (Ratnayake et al., 2006; Asian Development Bank, 2015). Therefore, the lack of groundwater quality studies in Ratnapura district can be considered as a significant research gap in the drinking water supply sector in the area. Accordingly, this study was planned to evaluate the groundwater quality in the district in terms of drinking water quality standards as well as to identify the possible underlying causes for the deterioration of groundwater quality in the area.

2. Study area

Sri Lanka is a tropical country with three climate zones, which are mainly characterized by the Indian Ocean monsoons (KaleelM.I.M, 2018). As shown in Fig. 1b, the dry zone is the largest climate zone in the country, which receives a mean annual rainfall of around 1000 mm, primarily from the northeast monsoon from October to January. The south-western part of the country belongs to the wet zone, which receives mean annual rainfall of around 2500 mm, mostly from the southwest monsoon from May to August (Jayasena et al., 2008; Rubasinghe et al., 2015). The intermediate zone, which combines traits from both the dry and wet zones, is squeezed between these two distinct climate zones. As shown in Fig. 1b, Ratnapura district uniquely placed across all three climate zones which has caused diverse environmental and climate conditions within the district. As a result, mean annual rainfall highly varied across the district from over 4000 mm in the western side to around 1000 mm in the southeastern side, according to unpublished data of Central Environmental Authority (2016).

Ratnapura district contains an area of 3239 km^2 (KaleelM.I.M,

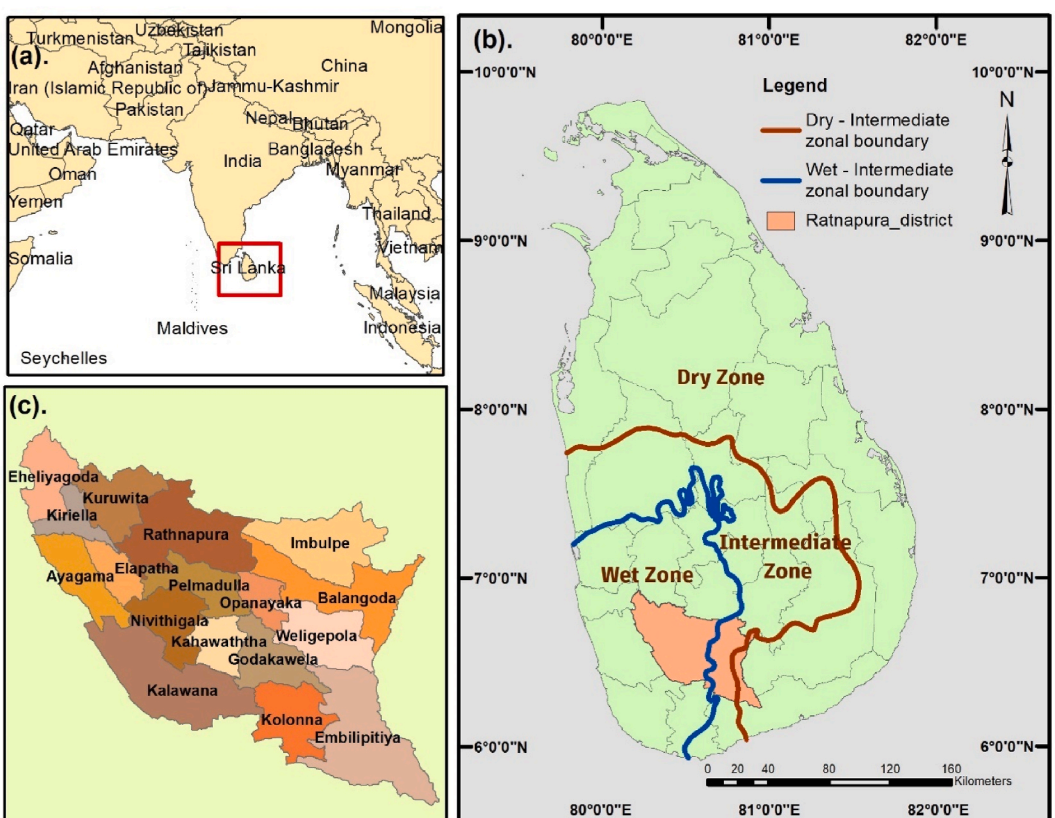

Fig. 1. (a). Location of Sri Lanka in South Asia (source: Public.opendatasoft.com, 2022) (b). Location of Ratnapura district and climate zone boundaries of Sri Lanka (source: Department of Agriculture Sri Lanka, 2022) (c). Divisional Secretariats of Ratnapura district (Source: Munasinghe et al., 2017).

2018). For administrative purposes, it has been divided into 17 Divisional Secretariats (DS), as depicted in Fig. 1c. Red yellow podzolic soils are the predominant soil category in Ratnapura district, according to the soil profile of the district (Fig. 2) created using the Sri Lankan soil map (European Commission, 2022). In fact, it is the dominant soil group in the wet zone of Sri Lanka (Leelamanie et al., 2013). However, in the eastern and south-eastern areas of the district, reddish brown earth soils are the most common group of soils. It is also the most widespread soil group in the dry zone of Sri Lanka (Leelamanie et al., 2013). No hydrogeological research has specifically addressed the common aquifer types in Ratnapura district. However, based on the country's aquifer map (United Nations EducationalScientific and, 2006), it can be fairly determined that shallow regolith aquifers with underlying deep fractured aquifers are the most common aquifer type in Ratnapura district.

3. Methodology

3.1. Water quality data collection

In this study, the results of 10 water quality parameters from 50 groundwater sources were analyzed. This set of data was collected in Ratnapura district as part of the World Bank-funded Water Supply and Sanitation Improvement Project, which aimed to develop rural water supply schemes. All of the samples were collected either from dug wells or natural springs. The pH, color, turbidity, electrical conductivity (EC), alkalinity, hardness, chloride, sulphate, iron, and Total Dissolve Solids (TDS) were the available parameters. From these parameters, the pH and EC were measured at site using a pre-calibrated YINMIK portable meter which contains a glass electrode bulb specifically sensitive to the hydrogen ion concentration, and separate conductivity sensors for EC measurements. Samples were then transported to the National Water Supply and Drainage Board (NWS&DB) laboratory at Ratnapura. Standard methods recommended by APHA (2017) for testing water quality parameters were followed while storing and transporting the samples.

3.2. Spatial autocorrelation analysis of water quality parameters

Spatial autocorrelation is an important aspect in any environment-related spatial data analysis. In particular, a key element in determining the precision of spatial interpolation is the degree of spatial autocorrelation (Radocaj et al., 2021). Since its introduction in 1950, the Moran's I index (Moran, 1950) has been the most widely employed indicator to quantify the spatial autocorrelation of a data set in spatial distribution studies (Ijumulana et al., 2020; Radocaj et al., 2021). The Moran's I value ranges between −1 and +1. The spatial autocorrelation increases as the positive values increase, which denotes a higher degree of spatial clustering of data. On the other hand, if the negative values are lower, the autocorrelation is lower and the data are more dispersed. A Moran's I value of zero means results are completely randomly distributed in space (Moran, 1950; Wang et al., 2022). Moran's I value was calculated according to the following equation (1).

$$I = \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (1)$$

where n represents the number of samples; x_i denotes the selected parameter value at the location i; x_j represents the values of the same parameter at all other locations; x represents the average of all values of the same parameter; and w_{ij} denotes the spatial weight, which represents the spatial relationship among two nearby samples (Ijumulana et al., 2020). Moran's I index was calculated for water quality parameters, as well as, for WQI values using ArcGIS 10.2.1 software.

In addition to spatial autocorrelation, high/low clustering and hot spot analysis were performed using the Getis-Ord General G tool available in ArcGIS 10.2.1 software. This tool enables the identification of clustering patterns of high or low values related to the attributes of spatial data in a given area. Hot spot analysis visually identifies the areas

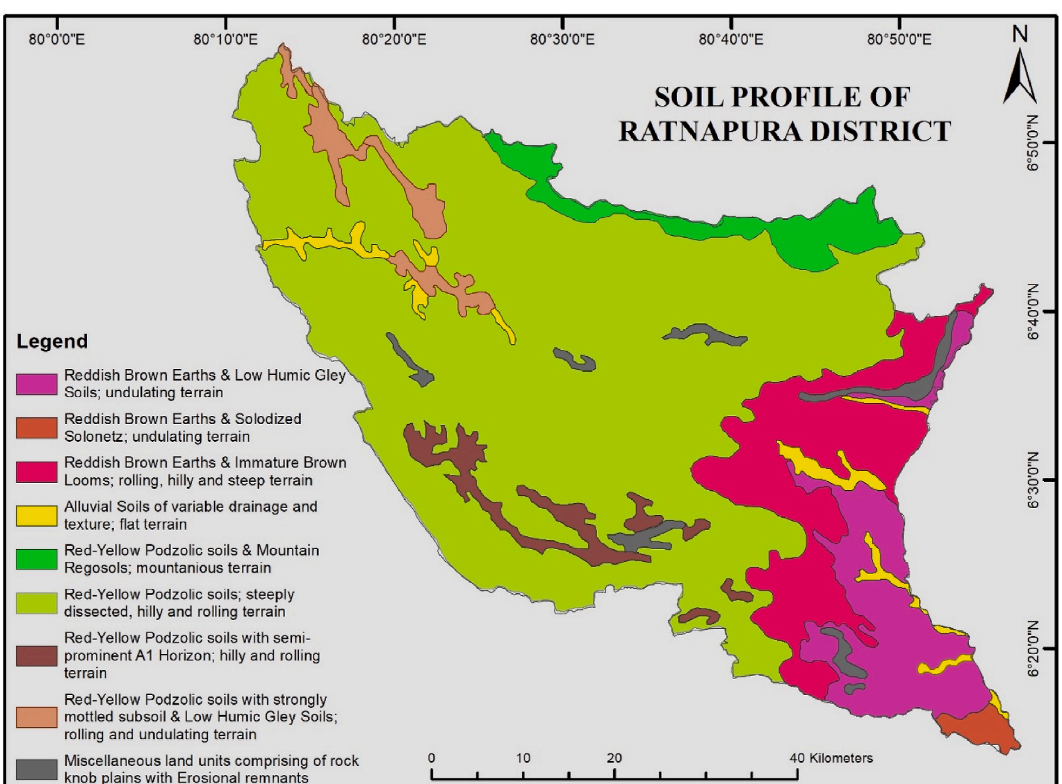

Fig. 2. Soil profile of Ratnapura district (source: European Commission, 2022).

where there are statistically significant clusters of high or low values in the given data set (Shen et al., 2017). The formula for the calculation of G statistic is given in equation (2).

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}x_i x_j}{\sum_{i=1}^{n}\sum_{j=1}^{n} x_i x_j} \tag{2}$$

where, x_i and x_j are the parameter values at locations i and j, respectively. $W_{i,j}$ represents the spatial weight between locations i and j. n is the number of samples in the given dataset (Villar-Navascues et al., 2020).

3.3. Development of water quality index (WQI)

The idea of the WQI is to represent the overall water quality by encompassing many water quality parameters in to single numeric value such that it reduces the complexity involved with interpretation of overall water quality. In recent decades, the WQI has been extensively used for assessment of water quality across the world (Ramakrishnaiah et al., 2009; Kachroud et al., 2019; Das et al., 2022) and also, in some parts of Sri Lanka (Rathnasiri and Manage, 2015; Cooray et al., 2019; Udeshani et al., 2020). Furthermore, the integration of WQI with GIS technology has enabled the preparation of spatial distribution maps which can graphically represent the overall variation of groundwater quality over a large area (Alexander et al., 2017; Mahrokh et al., 2019; Tefera et al., 2021).

The idea of the WQI was initially proposed by Horton (1965). After that many experts in the field have introduced different forms of water quality indexes which have their own merits and demerits (Kachroud et al., 2019). In this research, weighted arithmetic method was used to develop WQI since it is the most widely used method for both surface and groundwater studies (Ramakrishnaiah et al., 2009; Patel and Vadodaria, 2015; Ibrahim, 2019). In this method, assigning weightages to parameters and the calculation of relative weights for each parameter (equation (3)) can be considered as the first steps in the calculation process.

$$Wi = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

where, W_i = relative weight, w_i = assigned weightage, n = number of parameters.

However, the final index value can vary greatly depending on the weights assigned, necessitating the knowledge of experts in the field (Kachroud et al., 2019). Therefore, it was decided to look into the literature and, accordingly, the most regularly used weightages for each parameter were selected based on similar groundwater studies. Table 1 shows the selected weightages for each parameter.

Table 1
Assigned weightages for each parameter and tolerance limits as per the SLS 614:2013 guidelines.

No.	Parameter	Assigned weightage	Unit	SLS 614: 2013 - Tolerance limits
1	pH	4	–	6.5–8.5
2	Turbidity	3	NTU	2
3	Color	2	Hazen	15
4	EC	4	μS/cm	–
5	Alkalinity	3	ppm as $CaCO_3$	200
6	Total Hardness	3	ppm as $CaCO_3$	250
7	Chloride	3	ppm	250
8	Sulphate	4	ppm	250
9	Total iron	4	ppm	0.3
10	TDS	4	ppm	500

In the next step, a quality rating scale (Q_i) was derived for each parameter (equation (4)). In this study, SLS 614:2013—the Sri Lankan standards for drinking water quality (SLSI, 2013) was used to obtain the standard limits for water quality parameters (Si), which are also given in Table 1. However, there is no recommended maximum limit on EC in both SLS 614 and WHO standards (World Health Organization, 2017). Therefore, the maximum limit of 750 μS/cm for EC was used to evaluate the WQI as adopted by Mahagamage et al. (2016), Patel and Vadodaria (2015).

$$Qi = \frac{(Ci - Ii)}{(Si - Ii)} \text{ x } 100 \tag{4}$$

Where: C_i = Concentration/Measured value of ith parameter.

S_i = Standard limit of ith parameter in drinking water.

I_i = Ideal value of ith parameter (I_i for pH = 7 and for all other parameters = 0).

Finally, in order to compute the water quality index, Equations (5) and (6) were used.

$$SI_i = W_i \text{ x } Q_i \tag{5}$$

$$WQI = \sum_{i=1}^{n} SIi \tag{6}$$

where "SI_i" is the Sub-Index of the ith parameter and the WQI value is the arithmetic sum of sub-indices of all the measured parameters of the given sample. The WQI results from these calculations were categorized using the Brown et al. (1972) classification scale, which was used in many other previous studies (Saleem et al., 2016; Balamurugan et al., 2020; Udeshani et al., 2020). Accordingly, samples were put into one of five categories based on WQI scores: Excellent (0–25), Good (26–50), Poor (51–75), Very Poor (76–100), and Unsuitable (>100).

3.4. Preparation of spatial distribution maps

Spatial distribution maps were used to represent the spatial variation of WQI for groundwater in Ratnapura district. The spatial distribution map of WQI was created using ArcGIS 10.2.1 software. ArcGIS offers a variety of spatial interpolation techniques, although no technique is completely accurate for all types of studies (Bronowicka-Mielniczuk et al., 2019). However, many studies have found that Kriging methods, in particular the OK method, produce more precise prediction surfaces than other approaches (Coulibaly and Becker, 2007; Shamsudduha, 2007; Ohmer et al., 2017). Yet, IDW method is the most frequently used deterministic method and often in the context of comparison with Kriging methods (Li and Heap 2011; Bronowicka-Mielniczuk et al., 2019). Geostatistical methods such as Kriging are reliable for interpolation when a high spatial autocorrelation exists among the data and IDW method is more suitable when the data with a low level of spatial autocorrelation has to be analyzed (Jie et al., 2013). Therefore, the spatial autocorrelation result of WQI values was considered for selecting the best suited method among IDW and Kriging methods. However, the resulted Moran's I value of WQI was only 0.288, which indicated a positive yet reduced degree of spatial correlation among the data. Therefore, as an additional check, the cross-validation approach (Davis, 1987) was used to assess the accuracy of prediction surfaces generates by both methods.

Mean Error (ME), Root Mean Square Error (RMSE), Mean Standardized Error (MSE) and Root Mean Square Standardized Error (RMSSE) are among the error measures which are most widely used for assessment of spatial interpolation methods (Li and Heap 2011; Wu, 2016; Radocaj et al., 2021). ME is derived from equation (7) and is used to assess the level of bias in interpolations (Li and Heap, 2011). For greater interpolation accuracy, the mean error value must be as close to zero as possible. A measure of error size is provided by RMSE, and it can be denoted as in equation (8).

$$ME = \frac{1}{n}\sum_{i=1}^{n}(p_i - o_i) \quad (7)$$

$$RMSE = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}(p_i - o_i)^2\right]} \quad (8)$$

where n is the number of sample points, and p_i denotes the predicted value at point i. Similarly, o_i denotes the observed value at point i.

The ME and RMSE values of the OK and IDW methods were compared for the given data set using the geostatistical analyst tool available in ArcGIS 10.2.1 software. The ME value was found to be 0.1537 for the OK interpolation method, which is significantly better than the IDW method's ME value of 3.6075. The RMSE value of Kriging method (35.1839) was also slightly better than the relevant value of IDW method (39.4601). In addition, MSE and RMSSE values were also calculated for the OK method (these functions are not available for the IDW method in ArcGIS 10.2.1). The MSE and RMSSE values for a given dataset need to be as close as possible to 0 and 1, respectively, for higher accuracy, and the formulas for these two measures are given in equations (9) and (10) (Li and Heap, 2011; Esri, 2022).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(p_{si} - o_{si}) \quad (9)$$

$$RMSSE = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}(p_{si} - o_{si})^2\right]} \quad (10)$$

where, p_{si} and o_{si} stand for standardized predicted value and standardized observed value at point i, respectively. For the provided dataset, the MSE and RMSSE values for the OK interpolation method were found to be 0.0014 and 0.9263, respectively, demonstrating a satisfactory level of accuracy. Therefore, considering both spatial autocorrelation and these results, the OK method was used to produce the spatial distribution map for WQI.

3.5. Multivariate statistical analysis

Modern multivariate statistical techniques have emerged as effective tools for analyzing and managing groundwater quality (Machwal and Jha, 2015; Selvakumar et al., 2017; Bodrud-Doza, 2019). Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA) are the two multivariate statistical techniques used to analyze groundwater data in this research. Cluster analysis is a useful method of sorting a large set of data into groups based on similarities and dissimilarities of data between the selected data points. In this analysis, "agglomerative" or a bottom-up approached, was utilized using SPSS Statistics 25.0 software. As the method of clustering, Ward's method with squared Euclidean distance was utilized as in many other previous studies (Machwal and Jha, 2015; Selvakumar et al., 2017; Walter et al., 2017). A dendrogram was derived to graphically represent and distinguish the clusters formed. ArcGIS 10.2.1 software was used to identify the spatial distribution of main clusters and to visually analyze the relationship between the spatial distribution of clusters with underlying soil conditions and climate conditions.

Principal Component Analysis (PCA) is a multivariate statistical analysis method as well, which linearly transforms original variables into new variables called principal components. Similar to HCA, SPSS Statistics 25.0 software was used to perform PCA. The extracted Principal Components (PCs) were further used to identify the major differences in groundwater quality over the study area.

4. Results and discussion

4.1. General and geostatistical analysis results of water quality parameters

A summary of the results of 10 water quality parameters from 50 groundwater sources and a comparison with Sri Lankan water quality standards-SLS 614 (SLSI, 2013) are given in Table 2. According to the findings, it is evident that, out of the 10 parameters, 4 values in particular have significantly surpassed the standard limitations outlined in SLS 614. Those are turbidity (by 24%), alkalinity (by 14%), hardness (by 18%), and iron (by 14%). In this study, global Moran's I value was used to analyze the spatial autocorrelations of parameter values in the area. Results of Moran's I analysis are given in Table 3. Five parameters, including EC, alkalinity, hardness, sulphate, and TDS, showed strong spatial autocorrelation in the area. Each of these parameters had a Moran's I value more than or close to 0.5. All five of these parameters have a Z-score value (critical value) larger than 2.58 and a P-value (significance level) less than 0.05, indicating that the high and/or low values of each parameter are geographically clustered in the given data set (Ijumulana et al., 2021; Atabati et al., 2022; Esri, 2022). These five parameters were further examined using Getis-Ord G statistics to analyze the spatial patterns in the area. High-low clustering results are given in Table 4, and the resulted hot spots maps are given in Fig. 3, separately for each parameter.

Turbidity is the most deteriorating parameter among the tested parameters, with 24% of samples having turbidity levels higher than the SLS tolerance limit of 2 NTU. Turbidity is an optical characteristic of water that measures the relative clarity of water. The common assumption for turbidity in groundwater is the contamination of groundwater with surface runoff. In particular, in high rainfall areas, the continual process of dissolution and leaching of organic material on the surface due to frequent rain could lead to high turbidity in groundwater (Ojo et al., 2012). Moran's I value of 0.0323 indicates high and low values of turbidity are scattered across the district, without significant spatial autocorrelation. This suggests that higher turbidity levels are caused by localized factors such as unprotected wells.

As per Table 2, hardness and alkalinity are among the parameters which have comparatively lower compliance with standard limits. Hardness is the presence of polyvalent cations in water, especially Ca^{2+} and Mg^{2+} (World Health Organization, 2010), while alkalinity can be defined as the acid neutralizing capacity of water (APHA, 2017). Both hardness and alkalinity have shown high spatial autocorrelation and clustering. Fig. 3(b) and (c) show a clustering of higher values (hot spots) in the district's south-eastern part (Embilipitiya and Weligepola DS divisions), which is in the country's dry zone. In fact, all five parameters in Fig. 3 have shown hot spots in the same area, which indicates higher mineralization of groundwater in the dry zone of the district.

Both alkalinity and hardness in groundwater are functions of the geology of the area and the percolation of rain water, which has dissolved CO_2 from the atmosphere (Raju, 2014). When considering geological inputs, limestone is the major source for both hardness and alkalinity, though its composition varies, ranging from calcite ($CaCO_3$) to dolomite ($CaCO_3 \cdot MgCO_3$). However, calcite is the most abundant substance in limestone, which makes Ca^{2+} ions the most accountable cation type for groundwater hardness (Boyd et at., 2016). The presence of crystalline limestone rocks has been well identified even from the early studies of the area (Panabokke, 1962). The limestone cave located at Wawulpane (near the border of Embilipitiya and Kolonna DS divisions) is another sound indication of the presence of limestone in the area (Thamodi and Kumara, 2020).

Total iron concentrations exceeded the standard limit of 0.3 mg/l in 14% of the samples. Groundwater in the area has a minimal level of spatial autocorrelation with respect to iron, as indicated by the Moran's I value of 0.0564 and the p value of 0.4089. Since iron is the most

Table 2
Summary of water quality parameters and WQI.

Climate Zone	No. of samples	Statistics	Color (Hazen)	Turbidity (NTU)	pH	Electrical Conductivity (us/cm)	Total Alkalinity (mg/l as $CaCO_3$)	Total Hardness (mg/l as $CaCO_3$)	Chloride (mg/l as Cl)	Sulphate (as SO_4)	Total Iron (as Fe)	TDS	WQI
Overall	50	Mean	0.68	2.93	7.25	277.87	126.79	116.29	33.33	11.94	0.20	150.35	44.98
		Max.	12.00	29.20	8.49	1243.00	412.00	620.00	160.00	100.00	0.79	611.00	184.64
		Min.	0.00	0.30	5.77	16.56	6.30	5.00	2.00	0.00	0.02	8.70	8.00
		S. Deviation	1.98	4.90	0.67	279.92	131.37	129.65	34.67	20.06	0.18	142.00	35.11
Wet Zone	25	Mean	0.46	2.32	7.28	130.70	57.26	52.58	20.70	2.67	0.22	78.87	33.59
		Max.	4.00	13.20	8.49	436.00	256.00	196.00	78.20	21.00	0.61	290.60	118.55
		Min.	0.00	0.30	5.77	16.56	6.30	5.00	2.00	0.00	0.02	8.70	8.00
		S. Deviation	1.15	3.20	0.75	117.37	57.68	48.26	20.98	5.05	0.19	71.94	24.34
Intermediate Zone	18	Mean	0.95	3.81	7.18	305.08	144.06	129.09	37.97	11.26	0.18	167.81	49.87
		Max.	12.00	29.20	8.19	841.00	380.00	350.00	114.00	54.00	0.79	474.67	184.64
		Min.	0.00	0.50	6.14	29.00	10.50	8.00	2.90	0.00	0.05	13.30	13.59
		S. Deviation	2.72	6.65	0.58	264.15	141.30	120.93	37.71	13.76	0.20	141.13	42.91
Dry Zone	7	Mean	0.71	2.60	7.37	708.57	318.29	300.00	64.00	45.57	0.17	348.00	70.77
		Max.	5.00	9.70	8.09	1243.00	412.00	620.00	160.00	100.00	0.28	611.00	113.90
		Min.	0.00	0.30	6.69	459.00	240.00	92.00	28.00	0.00	0.15	221.00	46.03
		S. Deviation	1.75	3.58	0.51	247.57	60.05	155.84	40.90	29.07	0.05	121.73	24.44
SLS Tolerance Limits			15	2	6.5–8.5	–	200	250	250	250	0.3	500	–
Percentage Compliance			100%	76%	96%	–	86%	82%	100%	100%	86%	98%	–

abundant metallic element in the Earth's outer crust (Hem, 1985), iron in these groundwater samples could have originated from various mineral sources (Ngah and Nwankwoala, 2013). Iron is also added to the groundwater from the leaching of organic waste and plant debris from the surface (APHA, 2017). The limonitic iron ores are abundant in Ratnapura district and the deposits are highly scattered, with nearly 50 such deposits identified in the district (Jayawardena, 1984). This explains the scattered nature of the groundwater sources with high iron content.

4.2. Water quality index (WQI)

Resulted WQI values for considered groundwater sources varied from the lowest of 8.00 (in Kalawana DS division) up to the maximum of 184.64 (in Weligepola DS division). The mean and standard deviation of the resulting WQI values were 44.98 and 35.11, respectively. As per the WQI classification scale proposed by Brown et al. (1972), most samples fell into "Excellent" and "Good" categories, with each having 16 (32%) and 18 (36%) samples. From the rest of the samples, 10 (20%), 2 (4%), and 4 (8%) samples fell into the "Poor", "Very poor" and "Unsuitable" categories, respectively. The Moran's I value of WQI was found to be 0.2881 with z and p values of 3.3982 and 0.0007, which indicate moderate spatial autocorrelation in the district.

Fig. 4 shows the spatial distribution map for WQI in the district, produced using the Ordinary Kriging (OK) interpolation method. As per Fig. 4, WQI values increased from north-west to south-east directions across the district, which indicates deterioration of groundwater quality from wet zone to dry zone. Eheliyagoda, Kuruwita, Kiriella, Ayagama, and Ratnapura DS divisions which are located in the wet zone showed lower levels of WQI values (less deterioration of groundwater quality), while Emiblipitiya, Weligepola, and Godakawela DS divisions exhibited higher levels of WQI values, which represents relatively high deterioration of groundwater quality.

4.3. Water quality statistics in different climate zones

Table 2 also summarized the general statistics of the different water quality parameter values as well as the WQI in each climate zone. Both the resultant mean WQI values and the spatial distribution map of WQI confirm the deterioration of groundwater quality from wet zone to dry zone. Results in Table 2 indicate six water quality parameters have considerably contributed for deteriorated groundwater quality in dry zone of the district. Those are EC, TDS, alkalinity, hardness, sulphate and chloride, and all these parameters are either direct or indirect representatives of dissolved ions in water (World Health Organization, 2017).

The increase of dissolved solids or ions in groundwater in dry climate conditions can be due to several reasons. Low rainfall and high evaporation rates, exacerbated by high ambient temperature, cause salt accumulation in groundwater in the country's dry zone (Rubasinghe et al., 2015). In particular, sodium, potassium, and chloride ions are abundant in the groundwater of the dry zone, credited to excessive evaporation (Dissanayake and Weerasooriya, 1985). In contrast, high precipitation and continuous leaching of rain water, ions and other dissolved particles dilute them considerably and flush them out with the underground flow of water (Jayawardana et al., 2010). The underground lithology of the area also plays a major role in the mineral content of groundwater (Dissanayake and Weerasooriya, 1985; Ligate et al., 2021). For instance, groundwater in contact with mafic rocks contains high dissolved solids, while quartzose metaclastic rocks causes the groundwater to have low dissolved solids (Jayasena et al., 2008). The effects of soil conditions in the area on groundwater are further discussed in section 4.5.

Table 3
Global Moran's I for groundwater parameters.

Parameter	Color	Turbidity	pH	EC	Alkalinity	Hardness	Chloride	Sulphate	Iron	TDS
Moran's I	−0.0242	0.0323	0.1327	0.5907	0.5427	0.4851	0.2027	0.5790	0.0564	0.5238
Variance	0.0052	0.0061	0.0091	0.0088	0.0091	0.0085	0.0085	0.0077	0.0086	0.0089
Z score	−0.0580	0.6673	1.5983	6.5179	5.8823	5.4891	2.4127	6.8118	0.8258	5.7736
P value	0.9537	0.5046	0.1100	0.0000	0.0000	0.0000	0.0158	0.0000	0.4089	0.0000

Table 4
High/Low clustering results generated using G statistics for the selected parameters.

Parameter	EC	Alkalinity	Hardness	Sulphate	TDS
Getis-Ord G	0.0329	0.0324	0.0331	0.0562	0.0303
Variance	0.000005	0.000006	0.000008	0.000031	0.000004
Z score	5.5659	4.9765	4.7408	6.4848	4.9255
P value	0.000000	0.000001	0.000002	0.000000	0.000001

4.4. Hierarchical Cluster Analysis (HCA)

In groundwater studies, cluster analysis has been effectively used to group groundwater sources in a selected area and also to identify areas with degraded groundwater quality (Deepesh and Madan, 2014; Wali et al., 2022). In this study, 10 water quality parameters of 50 groundwater sources were utilized for HCA using SPSS software, and the resulted dendrogram (Fig. 5) revealed two distinctive clusters. Cluster 1 and 2 are comprised of 32 and 18 sampling locations, respectively. The mean values of water quality parameters and WQI in both clusters were compared in Table 5.

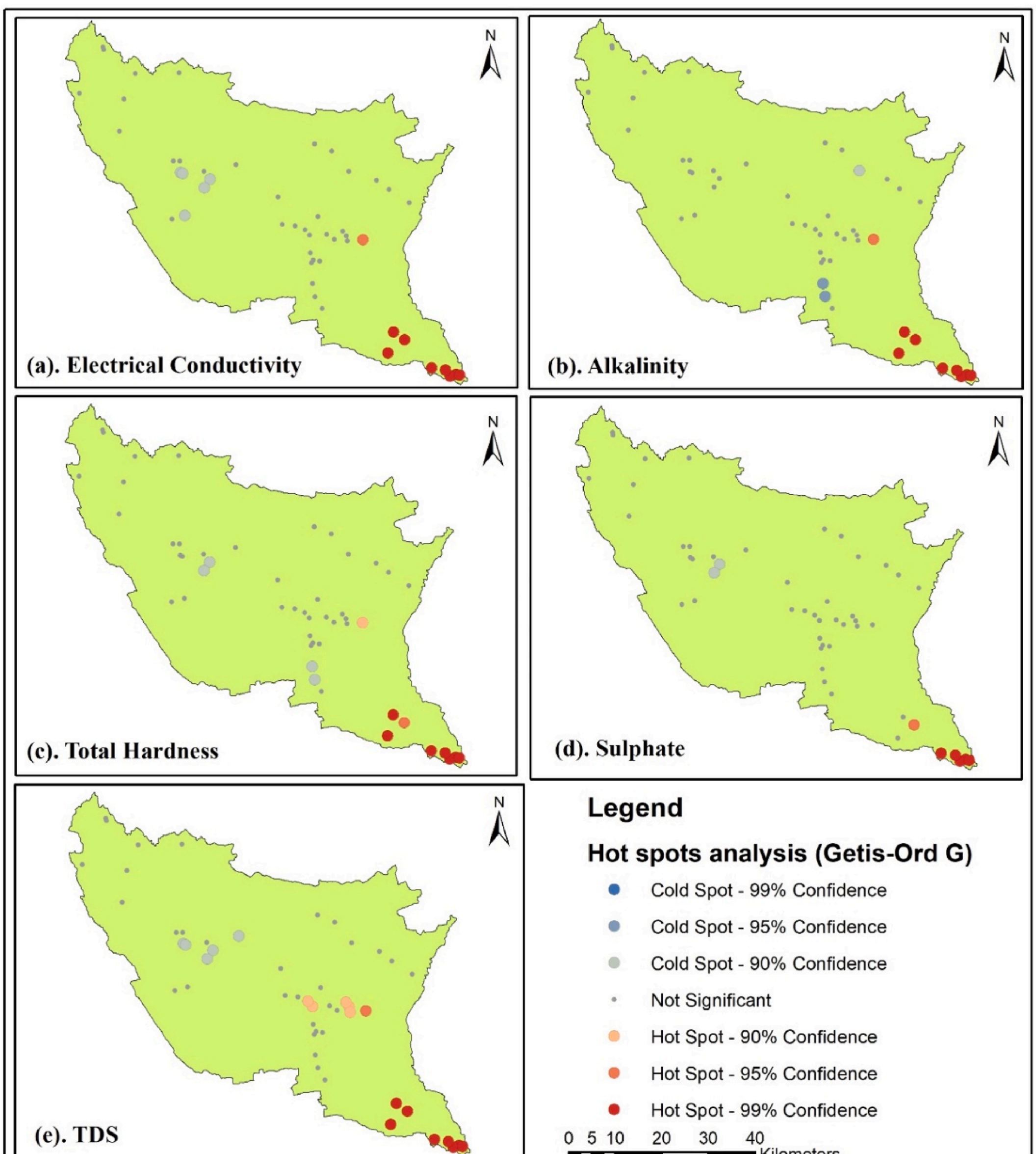

Fig. 3. Hot spot analysis results of the selected parameters; (a). EC (b). Alkalinity (c). Total Hardness (d). Sulphate (e). TDS.

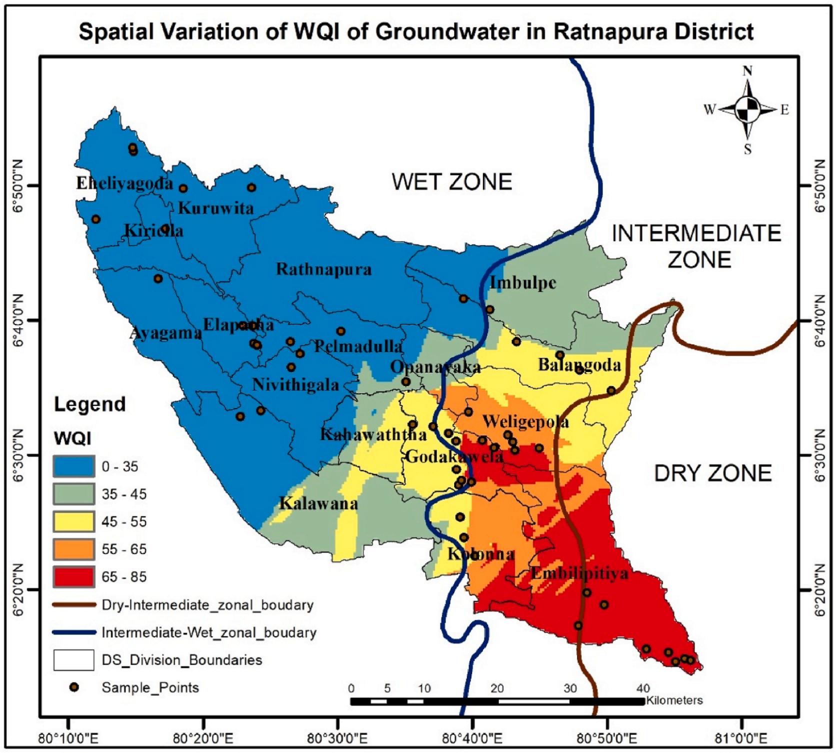

Fig. 4. Spatial distribution map of WQI of groundwater in Ratnapura district, derived using Kriging interpolation method.

One of the major observations from Table 5 is the deterioration of overall water quality in cluster 2 (WQI = 60.78) when compared with cluster 1 (WQI = 30.75). Out of the 10 parameters measured, 6 parameters clearly stand out as the contributors to higher WQI in cluster 2 (increments ranging from 245% to 743%). Those parameters are EC, alkalinity, hardness, chloride, sulphate, and TDS, which indicate higher mineralization of groundwater in cluster 2.

The spatial distributions of these two clusters were visually analyzed by marking the sampling points of the two clusters on the Ratnapura district map as shown in Fig. 5. The constituents of groundwater are highly affected by the prevailing climate conditions and the underlying geology of the area (Dissanayake and Weerasooriya, 1985). Therefore, the soil map of Ratnapura district and climate zone boundaries were also inserted in the map, which would provide some valuable insight on the possible reasons for variations in clusters.

When considering the underlying soil conditions, most of the district soil profile consists of red-yellow podzolic soils and most of the cluster 1 sampling points are located in this soil type (30 out of 32). In contrast, the majority of the cluster 2 sampling points are located on reddish brown earth type soils in the eastern and south-eastern parts of the district. The red-yellow podzolic soils are the dominant soil group in the wet zone of the country (Leelamanie et al., 2013). In this type of soil, pH values are often less than 5.5 and the cation exchange capacity of this soil type tends to be relatively low (Moormann and Panabokke, 1961). In contrast, reddish brown earth type soils are the most widespread soil group in the dry zone (Leelamanie et al., 2013) and have pH values of between 6.0 and 7.0, usually, together with higher cation exchange capacity (Moormann and Panabokke, 1961). It is obvious that the underlying soil features play a significant effect in influencing the chemical composition of groundwater because of the spatial distribution of the two clusters in these two different types of soils.

All the sampling points of Cluster 1 are distributed in wet and intermediate zones only, while cluster 2 mostly distributed in dry and intermediate zones (Fig. 6). This indicates the influence of climate conditions for the variation of groundwater quality in the two clusters. Distribution of Cluster 1 dominantly in the wet zone can also explain the possible reasons behind the higher mean value of color in Cluster 1 (Table 4). Color in natural water typically caused by the presence of organic substances, mainly originated from decaying of surface vegetation. Higher percolation of surface water due to continual rainfall in the wet zone can carry relatively high loads of decaying organic matter to groundwater which causes the increment of color in groundwater (Ojo et al., 2012).

4.5. *Principal Component Analysis (PCA)*

Principal Components (PCs) with eigenvalues greater than 1.0 were considered for further analysis since those are the PCs that best explain the variance of analyzed data (Machiwal and Jha, 2015; Harman, 1960). Accordingly, 3 PCs were extracted and Table 6 shows the software-generated "component matrix" which presents the influence of each parameter for the given PC. The first, second, and third PCs represent the majority of the variance in the data set, with 49.2%, 25.3%, and 10.3% of the total variance, respectively (table A1). These three PCs collectively represent 84.8% of the total variance, and the rest of the PCs account for small amounts of percentages and hence can be considered as negligible (Ganegoda et al., 2018). Figure A1 shows the resultant scree plot or the graph of PC numbers vs. respective eigenvalues.

The first PC, which explains the majority of the total variance, has been mainly contributed by the following parameters: EC (0.987), TDS (0.977), total hardness (0.958), total alkalinity (0.890), sulphate (0.792) and chloride (0.747). These results of PC1 match with the HCA results in Table 6, both indicating a strong correlation between the mineralization process and the formation of two distinct water quality patterns. Natural chemical processes such as cation exchange, dissolution of calcite, dolomitization, and sulphate reduction can lead to such a high concentration of minerals in groundwater (Celestino et al., 2018).

The second principal component (PC2) is mostly dominated by turbidity (0.927), color (0.890) and total iron (0.806). Turbidity and

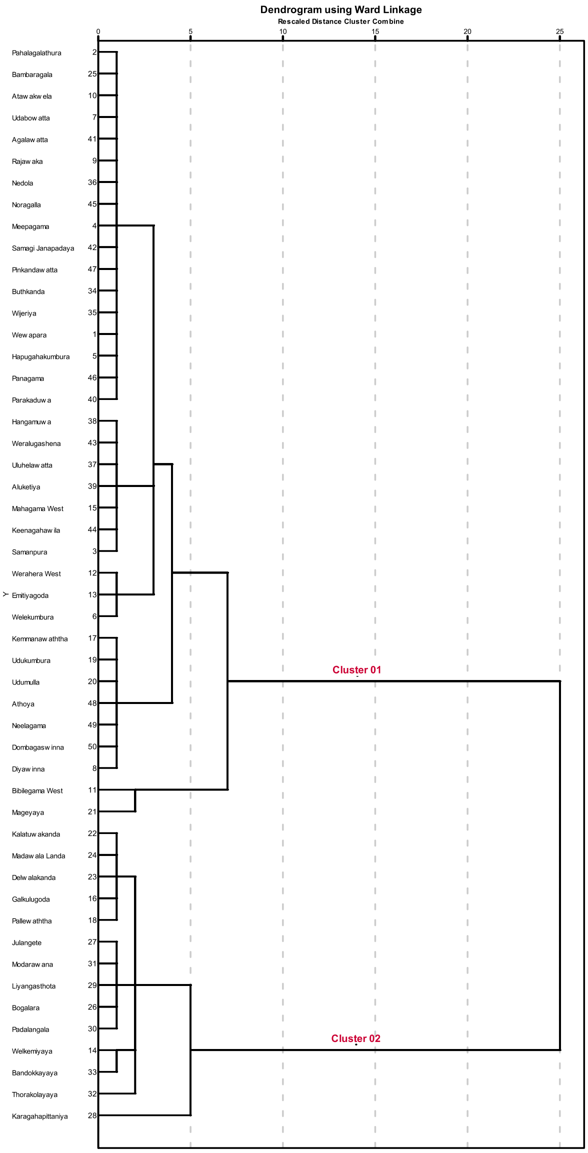

Fig. 5. Resulted Dendrogram from HCA with the indication of two clusters.

color in groundwater are mostly related to the leaching of surface water. In particular, in areas with high rainfall, the continual process of dissolution and leaching of organic material and other particles on the surface due to frequent rain could lead to high turbidity and color in groundwater (Ojo et al., 2012). Further, continual leaching of rainwater dilutes the ionic concentrations of groundwater and negates the effects of the mineralization process (Dissanayaka and Weerasoorya, 1985), which might have led to lowering the parameters such as EC, TDS, sulphate, chloride, hardness, and alkalinity in PC2.

4.6. Limitations

This study was based on the data collected by the Water Supply and Sanitation Improvement Project as a base line survey in the area. Though extreme weather conditions were avoided during sample collection, seasonal variations were not covered by the sample collection process. Sample density was also restricted due to the limited resource availability. Furthermore, anion and cation concentrations were not measured separately, considering the availability of resources and the requirements of the project. In particular, major cations and anions concentration could have revealed intriguing aspects of the groundwater in the area such as groundwater types in the area and their origins. Therefore, advanced experiments incorporating the measurement of ionic concentrations are recommended for better understanding of the groundwater constituents in this diverse area.

5. Conclusions

This study is the first comprehensive investigation on overall groundwater quality in Ratnapura district, and for the first time, the dramatic variances in groundwater quality across the area were highlighted in this study. The resultant spatial distribution map of WQI revealed significant deterioration of groundwater quality in the eastern and south-eastern parts of the district. This area of concern includes Weligepola, Embilipitiya, and Madampe DS divisions as well as eastern parts of the Kolonna and Balangoda DS divisions. In particular, the hardness, alkalinity, and turbidity levels of the groundwater in these regions are either over or very close to the recommended maximum limits for drinking water. These parameter concentrations may not pose a direct threat to human health on their own. However, objectionable taste and other related issues of hardness (scaling, soap consumption, etc.) can make the groundwater of the area unsuitable for direct human consumption. Therefore, unless there is no other viable water source, it is best to avoid using groundwater in the area or to apply substantial hardness removal technologies before consumption.

The results of two multivariate statistical analysis used (HCA and PCA) provided valuable insight on groundwater quality variation in the area. Hierarchical Cluster Analysis (HCA) results indicated two major clusters: cluster 01 dominating the wet zone, and cluster 02 concentrated in the dry and intermediate zones of the district. Principal Component Analysis (PCA) revealed EC, TDS, hardness, alkalinity, and chloride as the parameters that contributed to the development of two clusters of sampling points with different characteristics.

Overall results suggest that the climate conditions and underlying soil conditions play a major role in deciding the physical and chemical constituents of groundwater in Ratnapura district. Mineralization of groundwater is high in dry zone areas compared to the wet zone. Natural chemical processes such as ion exchange, reverse ion exchange, dissolution of calcite, dolomization, sulphate reduction, etc. Could have contributed to the higher ionic concentration in the dry zone groundwater. This process of mineralization in the dry zone has also been facilitated by higher evaporation due to high ambient temperatures and the lack of rainfall for the dilution effect to take place.

Further, this study demonstrates the potential of the integration of statistical methods such as WQI, HCA, PCA, etc. with spatial analysis

Table 5
Mean values of water quality parameters in the two clusters.

Parameter	Color (Hazen)	Turbidity (NTU)	pH	Electrical Conductivity (us/cm)	Total Alkalinity (mg/l as CaCO3)	Total Hardness (mg/l as CaCO3)	Chloride (mg/l as Cl)	Sulphate (as SO4)	Total Iron	TDS	WQI
Cluster 01	0.53	2.32	7.27	105.32	45.31	38.87	17.71	3.25	0.20	63.79	30.75
Cluster 02	0.94	4.01	7.22	584.61	271.63	253.94	61.09	27.39	0.20	304.22	60.78
% increment from cluster 01 to 02	78%	73%	−1%	455%	499%	553%	245%	743%	3%	377%	98%

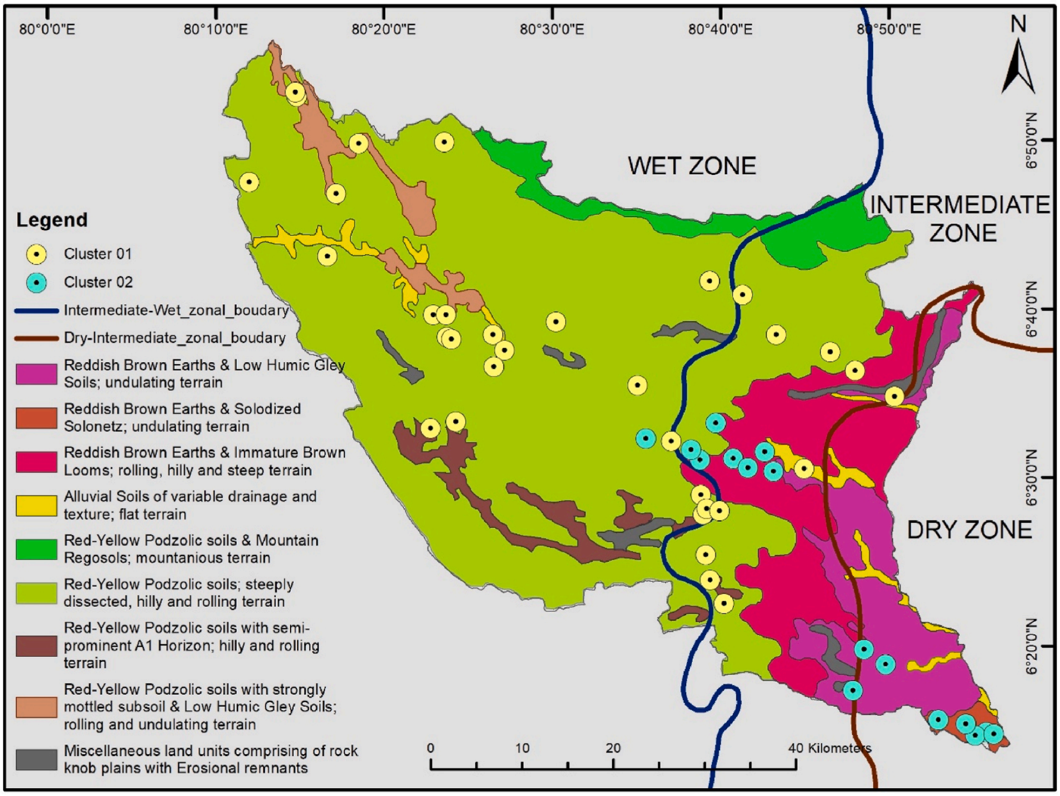

Fig. 6. Spatial distribution of the two main clusters: sampling locations of cluster 1 in yellow color and cluster 2 in blue color. Soil profile of Ratnapura district in the background. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 6
Resulted component matrix in PCA.

	Component		
	1	2	3
Electrical Conductivity (us/cm)	0.987	−0.065	−0.030
TDS	0.977	−0.007	0.018
Total Hardness (mg/l as CaCO3)	0.958	−0.103	−0.091
Total Alkalinity (mg/l as CaCO3)	0.890	−0.236	−0.127
Sulphate (as SO4)	0.792	−0.152	0.240
Chloride (mg/l as Cl)	0.747	0.083	0.085
Turbidity (NTU)	0.197	0.927	−0.187
Color (Hazen)	0.098	0.890	−0.274
Total Iron (as Fe)	0.209	0.806	0.108
pH	−0.001	0.353	0.902

techniques for the investigation of groundwater quality over a large area as well as identifying the possible causes of groundwater deterioration. The findings of this research can be successfully utilized by water supply engineers, policymakers, and other experts in the planning and design of drinking water supply schemes in the area. Further, this study provides a basis for future hydrogeological studies in Ratnapura district, which in turn will be helpful for sustainable management of groundwater sources in the area.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2023.100910.

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