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Article *in* Water Science & Technology Water Supply · February 2023

DOI: 10.2166/ws.2023.028

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Water Supply Vol 23 No 2, 867 doi: 10.2166/ws.2023.028

Assessment of groundwater quality in Vavuniya and Mullaitivu, Sri Lanka using multivariate statistical techniques and a Water Quality Index

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ABSTRACT

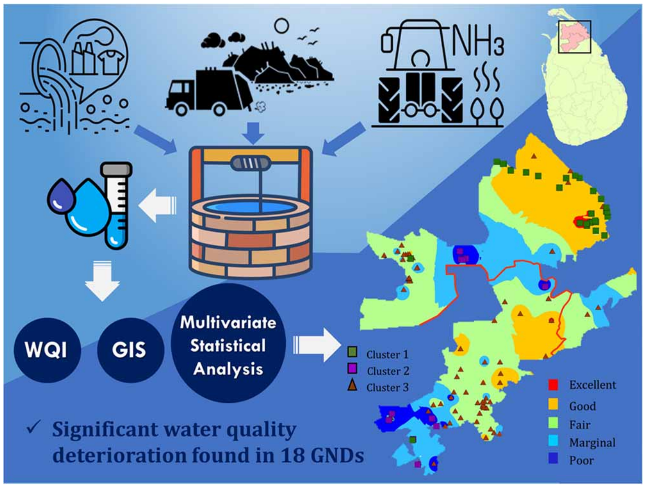
Groundwater is the primary source of potable water in the Northern province of Sri Lanka. Extensive development projects, comprising resettlements after the civil war, resulted in more groundwater extraction. This study focused to assess water quality considering drinking by developing a Water Quality Index (WQI), applying Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA), and developing spatial distribution maps. Findings revealed more than 50% of samples reported total dissolved solid (TDS), hardness, and alkalinity values above the Sri Lankan drinking water quality standards (SLS 614:2013). 7 and 13% of sampling sites were in the 'Excellent' and 'Poor' subclasses, respectively. PCA results explained >77% of variability by the first four principal components (PCs). PC1 and PC2 reflect geogenic processes while PC3 reflects natural processes like high rainfall and PC4 indicates anthropogenic pollution sources. HCA rendered 122 sampling sites into three clusters. An integrated map of the WQI and three clusters discovers a predominant analysis of potable water quality, highlighting the deterioration of groundwater quality mainly in the study area's 18 Grama Niladhari Divisions (GNDs). Artificial recharging at the household level and introducing proper sanitation facilities and regulations in agricultural practices shall be implemented to improve the WQI further.

Key words: groundwater quality, HCA, PCA, spatial distribution maps, Water Quality Index

HIGHLIGHTS

- Groundwater quality in an arid climate with health issues is investigated.
- Three clusters of sampling sites are identified based on the groundwater quality.
- Integrated multivariate and the WQI approach revealed significantly poor water quality areas.
- Geospatial maps indicate areas affected by anthropogenic and natural causes.
- The WQI contributes to a sustainable groundwater management strategy in the dry zone.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The exploitation of groundwater drastically increased in the 20th century, resulting in greater benefits to mankind. But it has triggered unpredicted changes in the state of groundwater systems and the rate of increasing water consumption is greater than double the population growth (van der Gun 2012). Thus, it has been contributing to two significant problems: a decrease in the quantity of available groundwater and a decline in the quality of that water. Numerous natural and man-made variables have an impact on groundwater quality. Some of the natural elements are weathering of rocks, mineral dissolution, aquifer depth, recharge rate, ion exchange, and evapotranspiration rate (Liu *et al.* 2003; Balasooriya *et al.* 2021; Subba Rao *et al.* 2021) and over-extraction, domestic wastes, septic tank leakages, excessive use of agrochemicals, and pesticides are only a few anthropogenic activities that have a negative impact on water quality (Balasooriya *et al.* 2021; Subba Rao *et al.* 2021).

The study area for this study was the Vavuniya and Mullaitivu districts of the Northern flat terrains of the dry zone of Sri Lanka which suffers from low rainfall, high temperature, and droughts. Since perennial rivers are not available throughout the region and limited availability of waterbodies, drinking water supply merely depends on the groundwater sources. The groundwater sources in the study area have faced severe risks over the past decade (Piyasiri & Senanayake 2016; Athapattu *et al.* 2018). Overexploitation due to large-scale infrastructure development projects, intensive resettlement, rapid urbanization, and extensive agricultural activities after the civil war had created serious issues such as depletion and deterioration of groundwater quantity and quality in Northern Province, Sri Lanka (Loganathan 2011; De Silva 2016; Ravi *et al.* 2016; Akther & Tharani 2017; Rajapakse *et al.* 2017; Shah *et al.* 2019; Gobalarajah *et al.* 2020).

Akther & Tharani (2017) assessed groundwater quality in Vengalacheddikulam Divisional Secretariat Division (DSD) in the Vavuniya district of Sri Lanka and found nearly 21.5% of the area is not suitable for human consumption. Rajapakse *et al.* (2017) assessed groundwater quality in the Sinnasippikulam area of Vavuniya and found dental fluorosis is a highly endemic problem in several areas of the Vavuniya District. Domestic wells located around the urban council limits of Vavuniya were contaminated severely with Fecal Coliform (Loganathan 2011; Ravi *et al.* 2016), and high nitrogen levels were observed in the city area and Thandikulam and Kurumankadu areas of Vavuniya district in Sri Lanka (Loganathan 2011; De Silva 2016). Piyasiri & Senanayake (2016) assessed the fluoride and hardness levels in groundwater in Vavuniya city, Sri Lanka, and found higher concentrations of fluoride and hardness in North Western part of the city whereas South Eastern part of the city indicated lower concentrations of fluoride and hardness. Athapattu *et al.* (2018) assessed the quality of drinking water sources in Vavuniya MOH division and found several parameters exceeded the maximum permissible levels of SLS 614:2013. A limited number of groundwater quality studies in Mullaitivu district can be found to date. Gobalarajah *et al.* (2020) assessed the impact of water quality on CKDu in Thunukkai area in Mullaitivu, Sri Lanka and found a significantly positive correlation ($p < 0.05$) between total dissolved solids (TDS) and arsenic.

Modern approaches like multivariate statistical analysis have been widely employed for differentiating natural or anthropogenic groundwater contamination sources, data reduction, and classification (Singh *et al.* 2004; Nosrati & van den

Eeckhaut 2012; Machiwal & Jha 2015; Balasooriya *et al.* 2021). To determine the underlying reasons for poor groundwater quality, these methodologies provide information on the links between parameters and sampling sites as well as an idea of similarities and differences between parameters (Nosrati & van den Eeckhaut 2012; Noshadi & Ghafourian 2016; Balasooriya *et al.* 2021).

Tajmunnaher & Chowdhury (2017) evaluated the water quality parameters along the Kushiyara River in Bangladesh and found strong and moderate positive relationships among BOD, COD, TDS, TS, and SS. Liu *et al.* (2003) examined groundwater in the coastal Blackfoot disease area of Yun-Lin, Taiwan, and found strong positive correlations between EC, TDS, Cl^-, SO_4^{2-}, Na^+, K^+, and Mg^{2+}. Strong positive relationships between EC, Ca^{2+}, Mg^{2+}, Na^+, and TDS are found in Coimbatore city in India (Selvakumar *et al.* 2017).

Machiwal & Jha (2015) applied PCA for groundwater sources of the Udaipur district, India and the PCs explained 75–80% of the total variance. Nosrati & van den Eeckhaut (2012) applied PCA to assess the groundwater quality of Hashtgred plain in Iran. Liu *et al.* (2003) employed PCA and identified parameters influencing the geochemical processes in the aquifer system of Yun-Lin, Taiwan. Selvakumar *et al.* (2017) applied PCA for groundwater in Coimbatore, India. Balasooriya *et al.* (2021) analyzed principal in 25 districts of Sri Lanka and found >69% of variability by the first six significant components. Rajapakshe & Rathnayake (2018) applied PCA for groundwater sources located in the very urbanized Malabe area in Sri Lanka and found first four principal components (PCs) explained 79.8% of the total observed variance in the data.

Machiwal & Jha (2015) performed HCA and found two clusters from 53 sampling sites in the Udaipur district in India. Selvakumar *et al.* (2017) investigated hydrogeochemical characteristics and groundwater contamination in Coimbatore, India by employing HCA. Noshadi & Ghafourian (2016) investigated the quality of groundwater in Fars province, southern Iran by employing HCA and found three clusters of Ca-HCO_3 and Na-Cl types. Bencer *et al.* (2016) applied HCA for groundwater sources in Ain Djacer (Eastern Algeria). Belkhiri *et al.* (2011) applied HCA and found three sampling clusters in Ain Azel plain, Algeria. Balasooriya *et al.* (2021) employed HCA and found two clusters during the study conducted in all administrative districts of Sri Lanka.

The structure of the models, the parameters included and their weightings, as well as the techniques for sub-indexing and aggregation, have all been altered in several Water Quality Index (WQI) models (Sun *et al.* 2016; Uddin *et al.* 2021). Ravi *et al.* (2016) calculated the WQI using the weighted arithmetic index for groundwater in Vavuniya, Sri Lanka and found that the WQI of 4 GNDs fall under the 'Poor and Very Poor' water subclasses while only 6 GNDs fall under 'Good and Excellent' subclasses out of 10 GNDs. Mahagamage *et al.* (2006) used CCMEWQI to investigate the suitability of groundwater in the Kelani River basin for drinking, irrigation and livestock purpose. Sinha & Saxena (2006); Latha & Rao (2010); Harshan *et al.* (2017) have used the method proposed by Horton (1965) and modified by Tiwari & Mishra (1985) to calculate the WQI. Nevertheless, they have categorized water subclasses according to their regions and considered water quality guidelines. Cooray *et al.* (2019) also developed a WQI using the weighted arithmetic method without imposing an upper limit.

GIS is a very valuable and essential tool that is used widely all over the world by water-related environmental planning and management professionals (Tsihrintzis *et al.* 1996). Brhane (2018) developed the spatial distribution maps for several parameters in the Adigrat area in Tigray, northern Ethiopia. Akther & Tharani (2017) developed the spatial distribution maps over the Vengalacheddikulam DSD in Vavuniya, Sri Lanka. Piyasiri & Senanayake (2016) incorporated GIS maps to depict the spatial distribution of EC, fluoride, total hardness, and pH. Jeihouni *et al.* (2014) developed spatial distribution maps for sulphate, chloride, hardness, EC, pH, and WQI. Gobalarajah *et al.* (2020) developed spatial distribution maps and identified vulnerable areas in Thunukkai DSD of Mullaitivu, Sri Lanka. Spatial distribution maps were developed employing the Kriging method by Machiwal & Jha (2015) for a hard-rock aquifer system in Udaipur, Rajasthan in India.

The literature has ultimately led to the conclusion that groundwater quality and geochemical parameters vary widely depending on the temperature, topography, geological formations, hydrogeological conditions, and anthropogenic activities. Among the districts of the Northern province, Mullaitivu and Vavuniya have been considered 'at risk' for the occurrence of CKDu with nine other districts from North Central, Central, and Uva provinces of Sri Lanka (Kafle *et al.* 2019; Gobalarajah *et al.* 2020). Few groundwater-related studies are available for Vavuniya and Mullaitivu districts and are only limited to Vengalacheddikulam DSD, town area of Vavuniya and Thunukkai DSD, Mullaitivu (Loganathan 2011; De Silva 2016; Piyasiri & Senanayake 2016; Ravi *et al.* 2016; Akther & Tharani 2017; Athapattu *et al.* 2018; Shah *et al.* 2019; Gobalarajah *et al.* 2020). In such a backdrop, it is aimed to assess groundwater quality by incorporating individual wells scattered within Vavuniya and Mullaitivu districts during this study. By developing WQI and spatial distribution maps, and employing multivariate statistical approaches the ultimate aim is to enhance and safeguard the sustainability of groundwater resources in the Vavuniya and Mullaitivu districts as there is no such study carried out in the identified research area.

2. MATERIALS AND METHODS

2.1. Description of the study area

Northern Province is the upper part of Sri Lanka and it is located between the 8° 45′N and 9° 51′N latitudes and 79° 39′E and 80° 57′E longitudes. Vavuniya and Mullaitivu are two adjacent districts in the province's southern and southeast regions as shown in Figure 1. The vicinity is usually hot and dry from February to September and experiences rain between October to January from Northeast monsoonal rain and June to October from Southwest monsoonal rain. The average temperature is between 28° and 32°, and there is less than 1,250 mm of annual precipitation.

Geologically, Precambrian metamorphic hard rock, which belongs to Wanni Complex, dominates the Vavuniya district. Prominent rock types in the area are Chanokitic gneiss, Granitic Gneiss, and Hornblende biotite gneiss (Athapattu *et al.* 2018). In Mullaitivu district, in the upper reaches of Pali Aru and Parangi Aru basins existence of Vijayan rocks is predominant. Furthermore, along the streams, Quaternary Alluvium deposits exist. The shallow regolith aquifers of the metamorphic terrain are the dominant type of aquifer found in the research area.

2.2. Sample collection and testing

The National Water Supply & Drainage Board (NWS&DB), Vavuniya, Sri Lanka, provided secondary data on groundwater wells that were gathered and tested between 2018 and 2020. All samples have been collected either from a dug well or a tube well which is being used regularly by the dwellers. Therefore, these data fairly denote the characteristic status of groundwater quality in the vicinity. There were altogether 122 number (62 and 60 samples in Mullaitivu and Vavuniya, respectively) samples including 15 NWS&DB intake wells have been tested for 10 physical and chemical parameters (color, turbidity, pH, TDSs, total alkalinity, total hardness, chlorides, fluorides, nitrates, and nitrites).

TDS and pH of the water samples have been measured using a conductivity meter (HACH EC 7) and pH meter (HACH pH1) respectively while turbidity has been tested by the Nephelometric method using a turbidity meter (HACH 2100N).

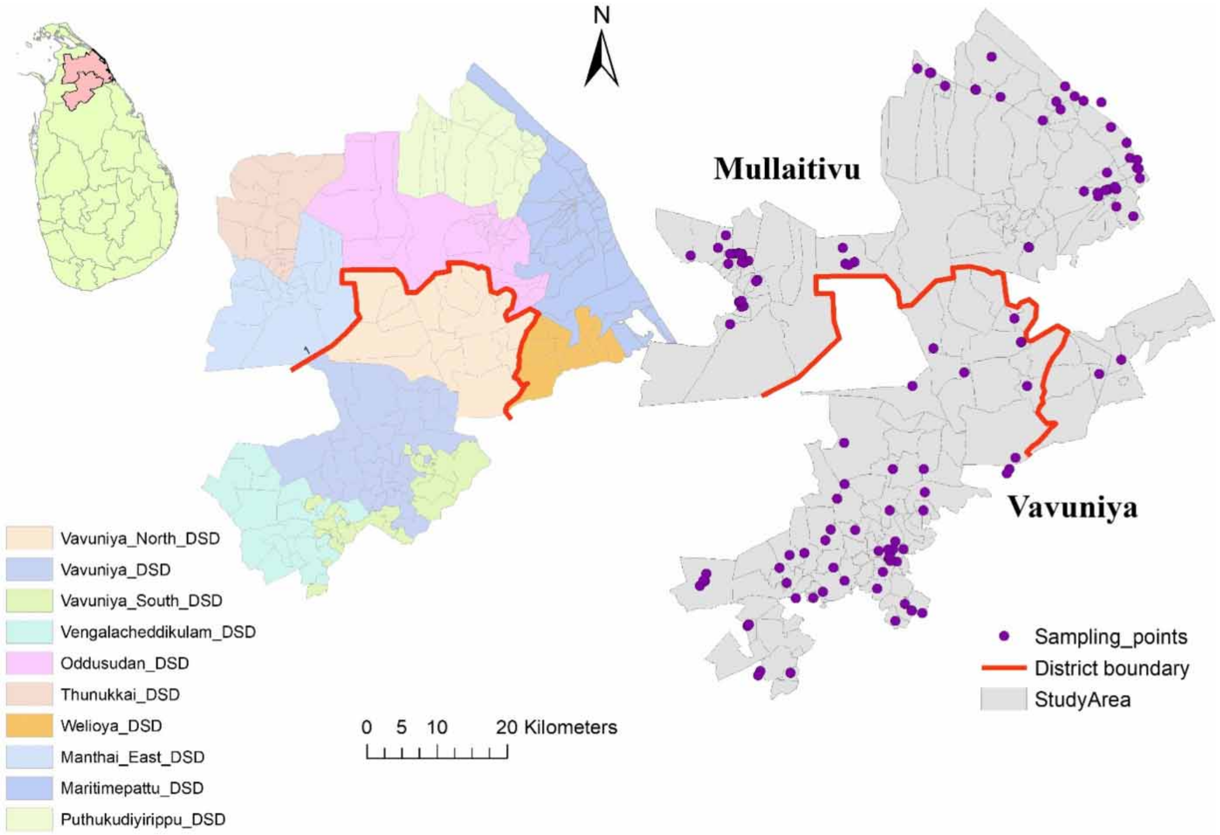


Figure 1 | Study area and distribution of sampling locations.

Hardness and alkalinity of the samples have been tested by EDTA Titrimetric Method following APHA standard method 2340 and Acidimetric titration adhering to APHA standard method 2320 (APHA 2017) respectively while chloride has been tested by the silver nitrate titrimetric method (argentometric titration) adhering to APHA standard method 4500-Cl^- B (APHA 2017). Nitrate, nitrite, and fluoride have been tested using a spectrophotometer (HACH DR 5000) following (Hach method 8039) and (Hach Method 8029), respectively.

2.3. Multivariate statistical analysis

Uncorrelated PCs can be obtained by transforming actual variables (Nosrati & van den Eeckhaut 2012), and the variance of correlated variables and lowering data set dimensionality can be explained (Subba Rao *et al.* 2020) by applying PCA. Before PCA, the suitability of data for PCA was assessed by employing Kaiser–Meyer–Olkin (KMO) and Bartlett's tests. KMO values of 0.65 and a χ^2 value of 682.17 (p-value <0.0001) from Bartlett's test of sphericity show that the data set has a sufficient variance to be subjected to PCA or Factor Analysis (FA).

In this work, HCA was carried out utilizing a single linkage amalgamation algorithm and a Euclidean distance similarity measure on 1,220 data. Since there is no reliable method to establish the ideal number of clusters, the researcher must decide how many clusters to use. Hence, the only approach which can be adopted to choose the clusters in the dendrogram is visual inspection (Güler & Thyne 2002; Belkhiri *et al.* 2011) similar to (Subba Rao *et al.* 2021). Accordingly, clusters were identified by drawing a phenon line at linkage distance 15.

Prior to both PCA and HCA, the following equation was employed to standardize the observed water quality data,

$$z = \frac{X - x}{S} \tag{1}$$

where X, x, and S refer to the tested parameter value, mean and standard deviation, respectively.

PCA, HCA, KMO, and Bartlett's tests were carried out by SPSS (SPSS version 26.0) software. By computing Pearson's correlation coefficient (r), the inter-relationship between physio-chemical characteristics was examined using Microsoft Excel 2013 software for 10 parameters. It produced the correlation matrix which depicts the correlation between any two parameters considered.

2.4. Developing the WQI and spatial distribution maps

The WQI proposed by Horton (1965) and modified by Tiwari & Mishra (1985) was employed to compute the WQI considering 10 water quality parameters.

The following equation was employed in calculating the WQI.

$$WQI = Antilog\left[\sum_{i=1}^{n} W_i * Log_{10} q_i\right] \tag{2}$$

where W_i is the relative weight and q_i is the quality rating.

The below equation was employed to calculate q_i.

$$q_i = \left(\frac{V_a - V_i}{V_s - V_i}\right) \tag{3}$$

where V_s is the standard value (SLS 614:2013); V_i is the ideal value (pH = 7 and 0 for all parameters); V_a is the actual value received after testing.

Relative weights (W_i) of water quality parameters were calculated using the below equations and tabulated in Table 1.

$$W_i = \frac{K}{V_s} \tag{4}$$

$$K = \frac{1}{\sum_{i=1}^{n} \frac{1}{V_s}} \tag{5}$$

where V_s is ith parameter's standard value and (SLS 614:2013 standards) and k is a constant.

Table 1 | Calculated relative weights (W_i) of selected parameters

S. No	Parameter	Standard value (SLS 614:2013) – V_s	Ideal value – V_i	Relative weight – W_i
1	Turbidity	2	0	0.244
2	Color	15	0	0.032
3	pH at 25 ± 2 °C	6.5–8.5	7	0.057
4	Chloride	250	0	0.002
5	Total hardness	250	0	0.002
6	Total alkalinity	200	0	0.002
7	Total dissolved solids	500	0	0.001
8	Nitrate	50	0	0.009
9	Nitrite	3.0	0	0.162
10	Fluoride	1.0	0	0.487

Obtained WQI values were classified into five subclasses operationally similar to Harshan *et al.* (2017).

Using the spatial interpolations feature in GIS software, values of characteristics at unsampled sites can be predicted by employing the already obtained values at identified sites (Akther & Tharani 2017). ArcGIS 10.4.1 was used to implement the ed (IDW) interpolation approach during the study.

3. RESULTS AND DISCUSSION

3.1. Physio-chemical quality analysis

Table 2 provides overall data on the water quality parameters that were assessed.

The color of groundwater samples ranged between 0 and 271 Pt/Co units. 85.2% of the groundwater samples were below 15 Pt/Co units. The groundwater samples' turbidity ranged from 0.1 to 33.4 NTU. 79.5% of the groundwater samples were below 2 NTU as per the SLS 614:2013 standards. pH values of 93.4% of samples were within the range of 6.5–8.5 as stipulated in Sri Lankan standards.

TDS values were in the range of 44–3,533 mg/l and with a mean of 588.74 mg/l while the maximum permissible level of 500 mg/l in SLS 614:2013 was exceeded in 59.8% of the samples. This represents a wide range of variance in the salinity of the water in terms of the numerous ions dissolved in it. Because of the chemical process of silicate weathering the dissolved ions are released into the groundwater body (Subba Rao 2021). Total hardness values ranged from 4 to 1,050 mg/l. 63.9% of

Table 2 | Overall statistics of analyzed water quality parameters (SLSI 614 (First Revision) 2013)

	Samples[a]				
Water quality parameter	Max	Min	SD	Maximum permissible level SLS 614:2013[a]	Percentage of samples exceeding SLS value (%)
Color	271	0	48.41	15	14.8
Turbidity	33.4	0.1	12.70	2.0	20.5
pH	8.42	6.26	0.40	6.5–8.5	6.6
Total hardness (mg/l)	1,050	4	183.68	250	63.9
Total alkalinity (mg/l)	570	22	147.98	200	64.8
TDS	3,533	44	408.40	500	59.8
Nitrate	44	0	7.77	50	0.0
Nitrite	0.15	0	0.02	3.0	0.0
Fluoride	2.45	0	0.64	1.0	40.0
Chloride	950	10	114.16	250	6.6

[a] All values are in mg/l except color (Pt/CO), turbidity (NTU) and pH.

samples were above the permissible limit of 250 mg/l in Sri Lankan standards for potable water. Total alkalinity ranged between 22 and 570 mg/l. 64.8% of samples exceeded the permissible limit of 200 mg/l in SLS 614:2013. The amount of hardness and alkalinity are the same when calcium and magnesium carbonates are present alone. Various dissolved ions, predominantly Ca^{2+} and Mg^{2+} cause the hardness in water. Most of the water in the regions of the dry zone in Sri Lanka is Ca–Mg-rich water (Rubasinghe *et al.* 2015). The dissolution of calcium and magnesium ions is the dominant factor for occurrence of harness in groundwater while dissolved alkali substances resulting total alkalinity in groundwater.

The observed nitrate concentrations were between 0 and 44 mg/l and none of the samples exceeded the maximum permissible limit of SLS 614:2013. Nitrite (NO_2^-) is not usually present in significant concentrations. Observed nitrite values ranged

Table 3 | Calculated Pearson's *r* values for groundwater samples

	Turbidity	Color	Cl^-	Total Hardness	Total alkalinity	TDS	NO_3^-	NO_2^-	F^-	pH
Turbidity	1									
Color	***0.756***	1								
Cl^-	0.306	0.151	1							
Total hardness	0.182	0.217	**0.694**	1						
Total alkalinity	0.062	0.196	0.159	**0.645**	1					
TDS	0.261	0.179	***0.935***	***0.847***	0.414	1				
NO_3^-	0.207	0.150	0.202	0.297	0.305	0.243	1			
NO_2^-	0.347	0.219	***0.887***	**0.518**	0.118	***0.761***	0.328	1		
F^-	−0.062	−0.066	−0.031	−0.005	0.222	0.156	0.020	−0.037	1	
pH	0.129	0.155	0.028	0.060	−0.148	−0.013	0.087	0.065	**− 0.729**	1

Note: Bold italic values show a strong (>0.75) correlation among parameters while bold values show a moderate (0.5–0.75) correlation among parameters.

Table 4 | Explaining total variance with four main components

PCs	Eigenvalue	% Of Variance	Cumulative %
1	3.400	34.005	34.005
2	1.801	18.014	52.019
3	1.490	14.902	66.920
4	1.034	10.336	77.256

Table 5 | Rotated factor loadings with communality estimates

Parameter	PC1	PC2	PC3	PC4	Communalities
Turbidity	−0.027	−0.091	***0.894***	0.054	0.794
Color	0.081	0.087	***0.881***	− 0.046	0.801
pH	−0.247	***0.790***	0.105	−0.087	0.658
Cl^-	***0.960***	− 0.205	0.013	−0.131	0.897
Total hardness	***0.844***	0.187	0.056	0.149	0.874
Total alkalinity	0.484	**0.536**	0.030	0.240	0.750
TDS	***0.971***	0.030	−0.018	−0.016	0.946
NO_3^-	−0.189	0.083	0.007	***0.847***	0.721
No_2^-	0.135	−0.135	0.003	***0.830***	0.716
F^-	0.221	**0.680**	− 0.100	0.061	0.569

Note: Parameter loadings greater than 0.75 are indicated in bold italics and parameter loadings between 0.5 and 0.75 are indicated in bold values.

from 0 to 0.15 mg/l and none of the samples exceeded the maximum permissible limit of 3 mg/l as specified in the SLS 614:2013. Nitrate is considered as a non-lithological pollutant and reaches groundwater from nitrate-fertilizers, human and animal excretes, septic tank leakages, domestic effluents and irrigation return flows (Zhang *et al.* 2018; Li *et al.* 2019; Subba Rao *et al.* 2019, 2021). A higher level of NO_3^-, greater than 10 mg/l, indicates water contamination as a result of anthropogenic activities (Subba Rao 2021). Extensive agricultural activities using fertilizers and domestic wastes cause higher nitrate values in the area. Observed fluoride values ranged from 0–2.45 mg/l and 40% of samples were above 1 mg/l. Piyasiri & Senanayake (2016) also revealed higher fluoride concentrations in some areas of the Vavuniya district. During the study carried out in Thunukkai DSD, Mullaitivu by Gobalarajah *et al.* (2020), it was found that 39% of samples exceeded 1 mg/l while

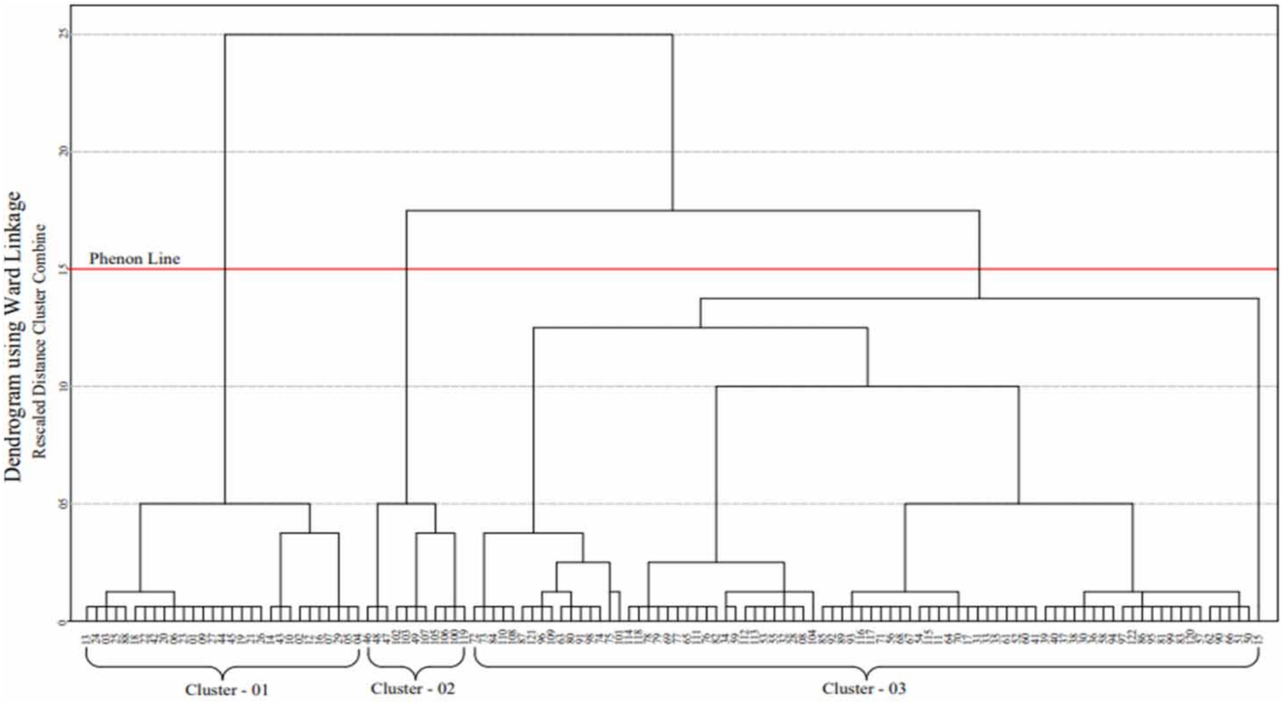


Figure 2 | Dendrogram resulting from HCA.

Table 6 | Cluster-wise statistics of measured parameters

	C1 (29 sites)			C 2 (11 sites)			C 3 (82 sites)		
Variables	**Average**	**Std. Dev**	**Exceedance (%)**	**Average**	**Std. Dev**	**Exceedance (%)**	**Average**	**Std. Dev**	**Exceedance (%)**
Turbidity	2.77	6.88	14	18.72	10.01	91	1.10	1.51	15
Color	5.90	13.87	7	141.73	91.51	91	5.50	10.42	7
pH	7.09	0.56	0	7.59	0.25	0	7.35	0.30	0
Cl^-	57.93	28.42	0	117.18	42.84	0	135.21	134.04	11
Total hardness	97.35	60.27	3	378.00	115.30	91	374.88	163.61	82
Total alkalinity	71.66	31.29	0	353.64	107.50	100	318.54	117.49	83
TDS	209.00	116.79	3	641.91	141.55	82	716.03	416.64	77
NO_3^-	2.45	2.25	0	7.02	4.84	0	6.94	8.95	0
NO_2^-	0.004	0.01	0	0.02	0.01	0	0.02	0.03	0
F^-	0.29	0.36	7	1.14	0.46	55	1.06	0.61	50

the mean fluoride value was found as 1.73 mg/l. According to Chandrajith *et al.* (2020), fluoride levels in Thunukkai were comparatively higher than those in Sri Lanka's dry zone. The presence of fluoride containing minerals in basement rocks, such as hornblende, biotite, and apatite, is the principal source of fluoride content in subterranean water, which degrades groundwater quality due to extended interaction of water with aquifer elements in an alkaline condition (Subba Rao 2021). Thus, leaching fluoride from fluoride-bearing minerals results in higher fluoride values in the study area. Observed chloride values ranged from 10 to 950 mg/l while 6.6% of samples exceeded 250 mg/l as stipulated in SLS 614:2013. Chloride is also considered as non-geogenic source and presence of higher chloride levels in groundwater is an indication of possible anthropogenic activities like septic tank leakages and extensive irrigation practices (Subba Rao *et al.* 2019; Subba Rao 2021). Higher evaporative conditions would also lead to increased chloride concentrations (Marghade *et al.* 2021), as the study area lies in the dry zone of Sri Lanka.

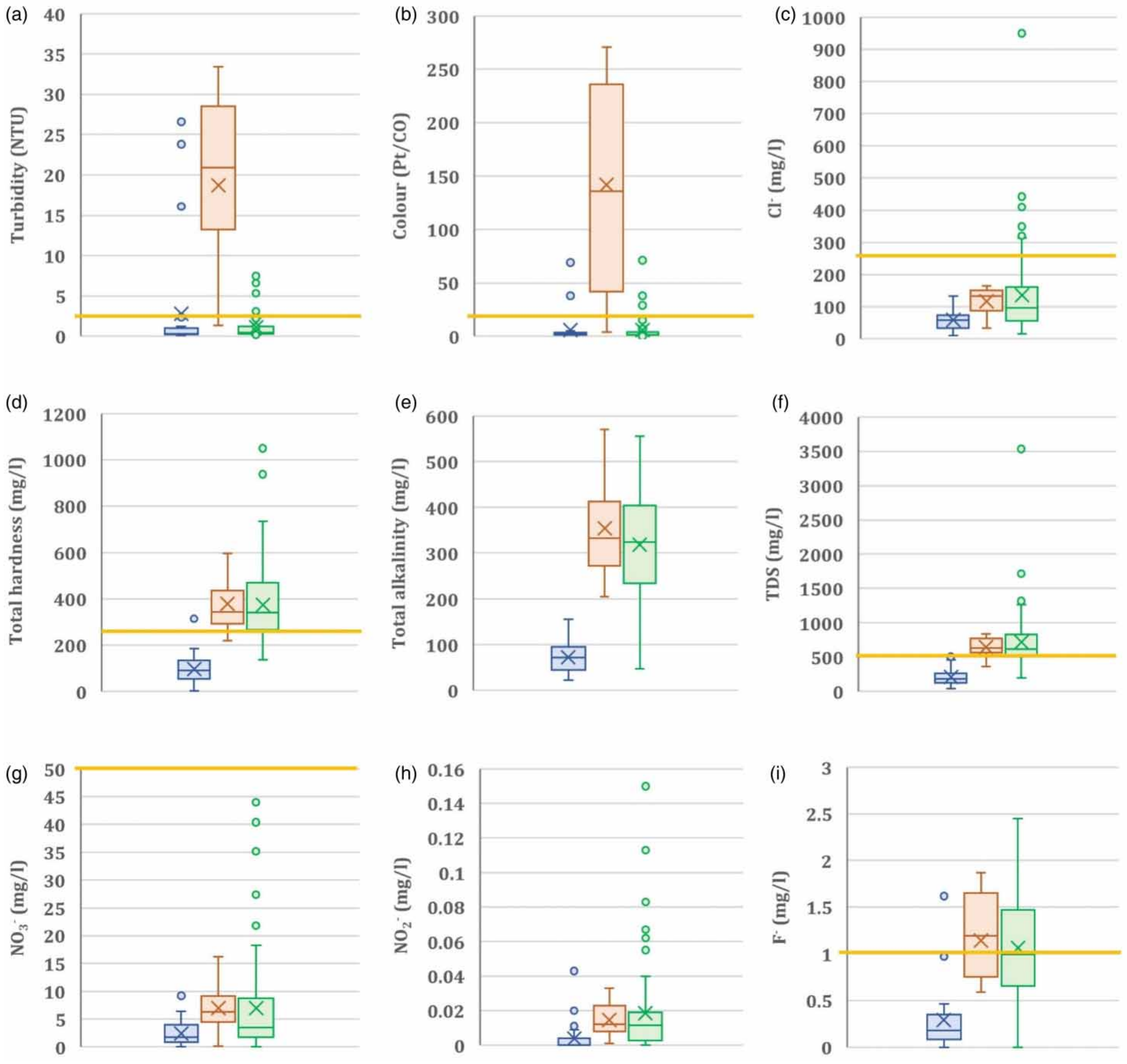


Figure 3 | Box–whisker plots of groundwater quality parameters.

3.2. Correlation among water quality parameters

TDS showed solid positive links with chloride ($r = 0.935$) and total hardness ($r = 0.847$). Water hardness is mostly caused by the Calcium and Magnesium cations, whereas TDS is made up of inorganic salts that are dissolved in water and primarily include calcium, magnesium, sodium, potassium, bicarbonates, chlorides, and sulphates (NWS&DB 2020). Thus, TDS, chloride, and total hardness are caused by ions dissolved in the water, these parameters were strongly and positively correlated. TDS and hardness of groundwater mainly occurred due to geogenic processes like weathering of minerals (Marghade *et al.* 2021). Yet, TDS is strongly correlated with chloride, it indicates the possible anthropogenic contamination.

It is found strong positive correlations between turbidity with color ($r = 0.756$) and nitrite with chloride ($r = 0.887$) and TDS ($r = 0.761$). Nitrate and nitrite predominantly resulting due to man-made activities (Marghade *et al.* 2021). As nitrite is positively linked with chloride both ions have the same source, i.e. anthropogenic activities. It is revealed that fluoride has a moderate negative correlation ($r = -0.729$) with the pH value of the water as tabulated in Table 3. Fluoride absorption in soils reduced from humid to dry regions and from acidic to alkaline soils (Wang *et al.* 2002; Balasooriya *et al.* 2021). Furthermore, fluoride, pH, and total alkalinity occupied a separate parameter loading in PCA (Table 5). Thus, this explains the increased fluoride leaching from fluoride-bearing minerals in an acidic environment.

3.3. Principal component analysis

PCA demonstrated >77% of the variance of the measured variables by its four initial components (PCs) as tabulated in Table 4.

PCs elucidated >97% of variance in TDS; >96% in chloride; >88% in color and turbidity; >83% in total hardness, nitrate and nitrite; >68% in fluoride and pH; and >53% in total alkalinity as shown in Table 5.

The highest proportion (34%) of the total variance was explained by PC1, PC2, PC3, and PC4 explain approximately 18, 15, and 10% of the total variance by the component, respectively. Factor loadings were categorized according to Liu *et al.* (2003).

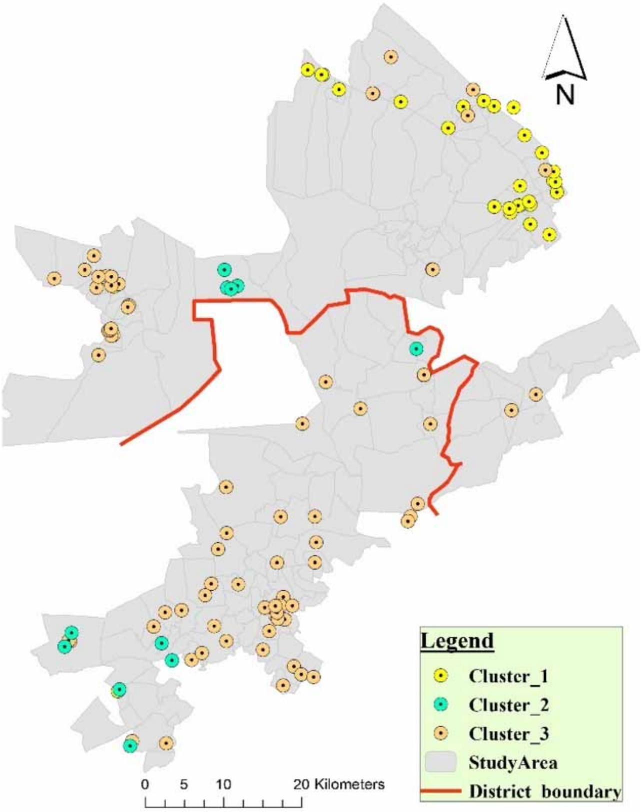


Figure 4 | Distribution of cluster-wise sampling points.

Table 7 | Soil types belong to sampling sites of three clusters (Ministry of Lands 2016a, 2016b)

Cluster	Available soil types
Cluster 1	• Solodized Solonetz and Solonchaks • Red-Yellow Latosols • Alluvial soils of variable drainage and texture
Cluster 2	• Reddish brown Earths and low humic Gley soils • Eroded land
Cluster 3	• Rock knob plain • Grumusols • Reddish brown Earths and low humic Gley soils • Eroded land • Red-Yellow Latosols • Alluvial soils of variable drainage and texture

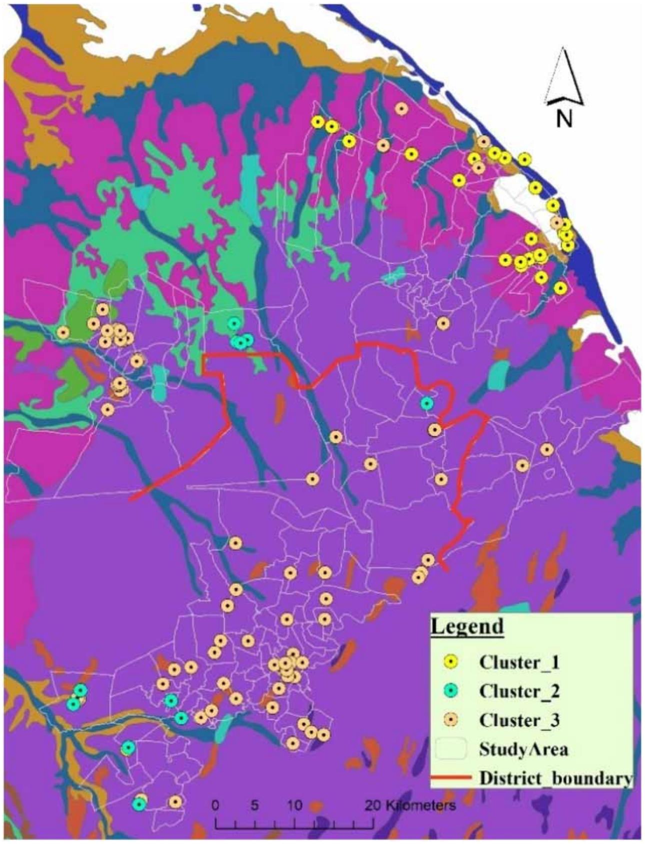


Figure 5 | Different soil types available in the research area.

Chloride, TDS, and total hardness loadings on PC1 are strongly positive. The main contributors to total hardness are carbonate, calcium, and magnesium ions. Gathering the aforementioned ions in one factor typically reflects how groundwater develops naturally through groundwater-geological interaction (Nosrati & van den Eeckhaut 2012; Noshadi & Ghafourian 2016; Balasooriya *et al.* 2021). Therefore, it is hypothesized that PC1 represents groundwater and natural geological interactions.

Table 8 | Classification of water subclasses

WQI value	Water subclass	No. of sampling sites	Percentage (%)
$0 < \text{WQI} \leq 5$	Excellent	9	7
$5 < \text{WQI} \leq 20$	Good	44	36
$20 < \text{WQI} \leq 35$	Fair	34	28
$35 < \text{WQI} \leq 55$	Marginal	19	16
$55 < \text{WQI} \leq 100$	Poor	16	13

Fluoride and total alkalinity do seem to have positive loadings, and pH has a significant positive loading in PC2. Fluoride-rich minerals readily leach fluoride. Thus, this could be the driving factor for presenting higher fluoride concentration in groundwater.

From wet to dry locations, and from acidic to alkaline soils, fluoride absorption in soils shows a decline (Wang *et al.* 2002). This may help in explaining the inter-relationship between fluoride, pH, and total alkalinity in groundwater. Therefore, PC2 also reflects the natural geological interactions with groundwater.

Strongly positive loadings on color and turbidity are present in PC3. Hence, PC3 explains the natural processes like high rainfall and a higher rate of infiltration. Nitrate and nitrite show significantly positive loadings on PC4. Shah *et al.* (2019) explained the wells that were dug nearby an agricultural field had a high nitrate content in Vavuniya. The usage of nitrogen-containing fertilizer for agricultural activities is the reason behind that. Hence, it is apparent that PC4 indicates the anthropogenic pollution sources.

3.4. Hierarchical cluster analysis

Groundwater sampling sites were grouped using HCA so that the sites within a cluster had almost similar groundwater quality, but were distinct from those in other clusters. Ward's approach was used to perform HCA on the standardized data set (1,220 observations) by employing the SPSS Statistics Version 26.0 software package.

The dendrogram divided the 122 sampling sites into three clusters that were statistically significant by drawing a phenon line at linkage distance 15 as shown in Figure 2. According to this line, clusters 2 and 3 are linked to each other, showing parallel qualities of these two groups. Yet, cluster 1 is rather different than the other two, indicating different characteristics rather than clusters 2 and 3. The first cluster of the three clusters has 29 sample sites, the second cluster has 11, and the third cluster has 82 sites. Mean and Standard Deviations and percentage exceedance of maximum permissible limits of measured parameters of three clusters were calculated and they were discovered to vary greatly as tabulated in Table 6. The average concentrations of all the measured parameters were notably above in clusters 2 and 3 than in cluster 1. Figure 3 shows the Box and Whisker plots that were developed to distinguish between the variations of three clusters.

Sampling sites of cluster 1 are located in Maritimepattu and Puthukudiyirippu areas in Mullaitivu where deep confined aquifers of the sedimentary limestone and sandstone formations are available (Panabokke & Perera, 2005). Sampling sites of clusters 2 and 3 are mainly located in Oddusudan, Vavuniya South, and Vengalacheddikulam areas where hard rock aquifers are available (Panabokke & Perera, 2005). Total hardness, total alkalinity, TDS, and fluoride in groundwater mainly occur due to mineral dissolution by water–rock interactions (Rubasinghe *et al.* 2015; NWS&DB 2020; Subba Rao 2021). Geogenic processes of hard rock aquifers might be the possible causative factor for having higher average concentrations of total hardness, total alkalinity, TDS, and fluoride in clusters 2 and 3 than in cluster 1. Presence of higher chloride and nitrate values in groundwater is possibly due to anthropogenic pollution sources like septic tank leakages and extensive irrigation practices. Puthukudiyirippu and Maritimepattu areas have a lesser number of irrigable lands than Vavuniya South, Oddusudan, and Vengalacheddikulam DSDs as they are closer to the sea. Hence, it is apparent that the extensive usage of fertilizer and irrigation return flows are the possible causative factors for having higher average values of chloride and nitrate in clusters 2 and 3 than in cluster 1.

The WQI has varied considerably among the three clusters. In cluster 1, 24, 55, 17, and 4% of samples were in the Excellent, Good, Fair, and Marginal categories, respectively, while none of the samples were observed in the Poor category. In cluster 2, none of the samples were observed in the Excellent, good, and Fair categories while 18 and 82% of samples were observed in Marginal and Poor categories, respectively. In cluster 3, 2, 34, 35, 20, and 9% of samples were observed in the Excellent, Good, Fair, Marginal, and Poor categories, respectively.

Figure 4 depicts all the sampling points of cluster 1 located in Maritimepattu and Puthukudiyirippu DSDs in Mullaitivu where relatively good quality water can be found. Sampling points of cluster 2 are located in the Oddusudan DSD in Mullaitivu and Vavuniya South and Vengalacheddikulam DSDs in Vavuniya where the worst quality of groundwater was observed. Cluster 3 sampling locations are scattered over the area which were observed to have the intermediate quality of water between cluster 1 and cluster 2 sampling sites.

Three main lithological units can be distinguished in Sri Lanka's Proterozoic crust based on its lithological, geochronological, and geochemical characteristics. The study area falls under Wanni Complex (formerly the western Vijayan Complex) (Dissanayake & Chandrajith 2018). Since the entire study area belongs to the Wanni complex, there may be some other factors for the separation of clusters like land use types or soil types. Soil types belonging to sampling sites of three clusters are tabulated in Table 7. Figure 5 shows that soil types belonging to cluster 1 and cluster 2 are different. Cluster 3 sampling sites have all soil types of clusters 1 and 2 except Solodized solonetz and solonchaks. Since the lithological characteristics are same for the cluster 1 and cluster 2, having different types of soils might be a possible causative factor for the variation of groundwater quality.

3.5. WQI and spatial distribution maps

Supplementary material, Table A1 illustrates the calculated WQI values and water subclass classification. Obtained WQI classes were classified into 5 water subclasses as shown below. According to Table 8, there are 7% of samples are in the 'Excellent' category while 36, 28, 16, and 13% of samples are in the 'Good', 'Fair', 'Marginal' and 'Poor' water subclass categories, respectively.

Poor groundwater quality was found in Olumadu, Mankulam GNDs of Oddusudan DSD in Mullaitivu, Nedunkerny North, Nedunkerny South, Mamadu GNDs of Vavuniya North DSD, Pampaimadu, Poomaduwa and Rankethgama GNDs of Vavuniya and Vavuniya South DSDs, respectively, and Sinnasippikulam, Neriyakulam, Maradanmaduwa, Pavatkulam unit 2,4,5 and 6, Awaranthulawa, Kurukkalputhukulam and Andiyapuliyankulam GNDs of Vengalacheddikulam DSD in Vavuniya. In

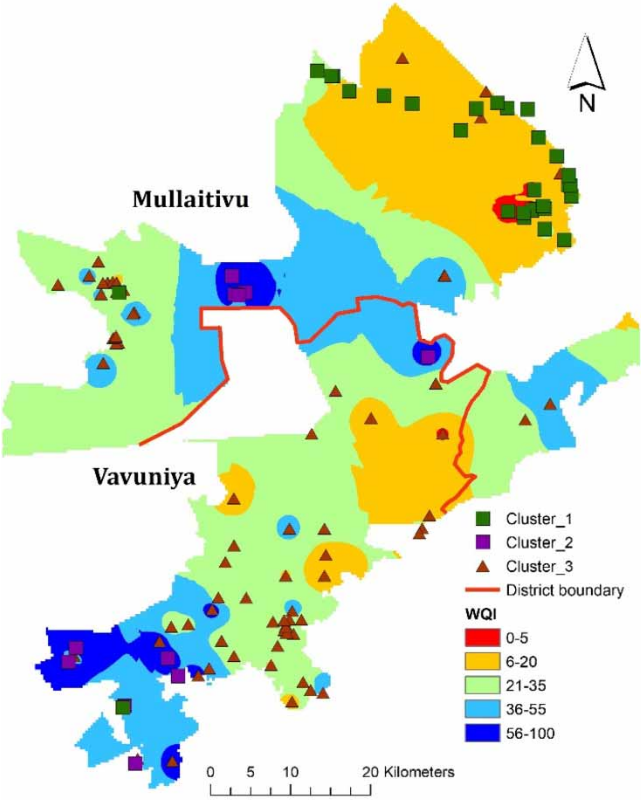


Figure 6 | Integrated map of the WQI and three clusters.

addition to that 8 GNDs of Oddusudan DSD in Mullaitivu and 4,6 and 8 GNDs of Vavuniya North, Vengalacheddikulam and Vavuniya DSDs, respectively, in Vavuniya were observed under the Marginal category.

An integrated spatial map of the WQI and three clusters obtained from HCA was developed. As depicted in Figure 6, cluster 1 has relatively good water quality sites while cluster 2 has the most deteriorated water quality sites. According to Figure 6, cluster 1 sites are located in the Maritimepattu and Puthukudiyirippu areas of Mullaitivu, which have Excellent and Good water subclasses while cluster 2 sites are located with Oddusudan DSD of Mullaitivu and Vengalacheddikulam DSD of Vavuniya, which have Poor and Marginal water subclass. Thus, it was observed that the WQI and HCA results are parallel to each other. Furthermore, spatial distribution maps of TDS, total alkalinity, total hardness, chloride, fluoride, nitrate and nitrite, and pH were developed over the study area as depicted in Figure 7.

Altogether 26 GNDs of the study area fall under Poor and Marginal water subclasses. It reflects the potential health threats of directly consuming groundwater for drinking. The groundwater quality is predominantly controlled by the geology as most of the contaminants are present in groundwater due to the geogenic processes. Hard rock aquifers are available in the identified Poor and Marginal water quality areas. Higher mineral weathering is possible due to the higher residence time in hard rock aquifers. Thus, artificial groundwater recharging at household levels shall be effectively used to dilute the dissolved ion concentration and improve the WQI in individual wells. Furthermore, introducing proper sanitation facilities and practical regulations in agricultural practices can reduce anthropogenic pollution sources and improve the WQI in the vicinity.

4. CONCLUSIONS

This study provides an integrated strategy using multivariate statistical techniques and GIS-based spatial distribution maps, including the WQI, for the first time in Sri Lanka. CA revealed strong positive relationships among TDS, chloride, total hardness, and between turbidity, and color. PCA explained >77% of variability by the first four PCs in terms of measured

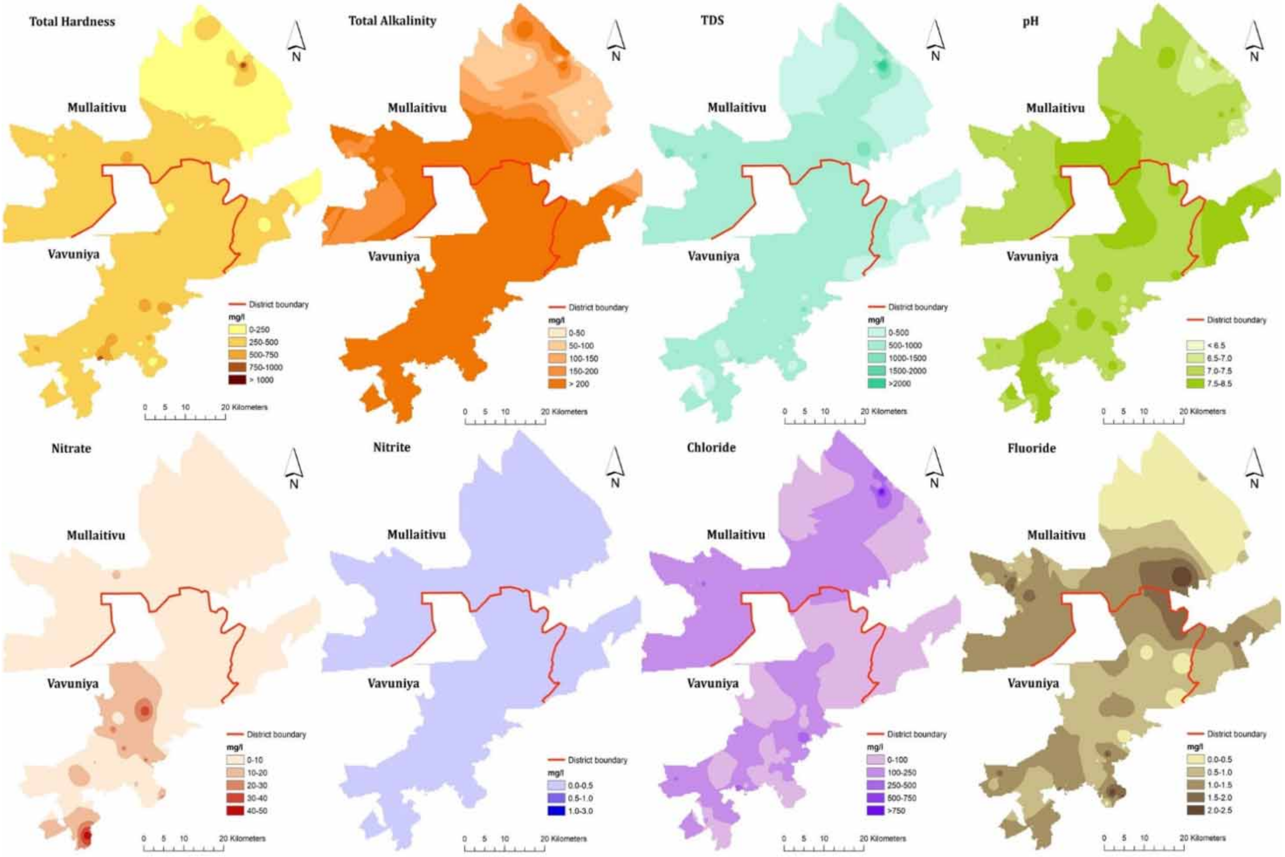


Figure 7 | Spatial variation of groundwater including the WQI over the study area.

groundwater quality parameters. HCA classified 122 sampling sites into three statistically significant clusters. Resulted WQI values with the combination of spatial distribution maps revealed significant deterioration of groundwater quality mainly in the 18 GNDs in study area. The integrated map emphasized that sampling sites of the above three clusters are parallel with the spatial distribution of water subclasses. Moreover, groundwater sources of Maritimepattu and Puthukudiirippu DSDs showed comparatively much lower average concentrations of measured water quality parameters than the rest of the region. Promoting artificial recharging at the household level, introducing proper sanitation facilities, and imposing regulations in agricultural practices shall be implemented to improve the WQI further. The findings can be used to develop policies for handling groundwater management issues in the vicinity and to make decisions on groundwater activities in the other parts of the dry zone to guarantee a safe and high-quality groundwater supply.

ACKNOWLEDGEMENTS

The National Water Supply & Drainage Board, Vavuniya is gratefully acknowledged by the authors for providing data on groundwater quality, and to the reviewers whose comments and suggestions have significantly contributed to the improvement of this manuscript.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 19 October 2022; accepted in revised form 27 January 2023. Available online 4 February 2023