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ORIGINAL ARTICLE

Assessing groundwater quality using the Water Quality Index (WQI) and GIS in the Uva Province, Sri Lanka

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Abstract

The prime objective of this study is to develop a water quality index (WQI) to identify the relationship between the drinking water quality and the prevalence of Chronic Kidney Disease of Uncertain Etiology (CKDu) in the Uva Province (UP). For this, all CKDu patients in the province were recorded. 251 groundwater samples were collected and analyzed for their major cations and anions. Following this procedure, the spatial distribution maps for CKDu patients, water quality parameters and WQI were generated. The results revealed that, 20.3% of groundwater samples are categorized under "excellent" in terms of the drinking water quality, 21.2% of the samples are categorized under "good", 20.3% of the samples are categorized under "poor", 9.9% of the samples are categorized under "very poor", and 28.3% of the samples are categorized under "unsuitable" in terms of the WQI. According to the results, the most significant correlation was recorded between fluoride content in the samples and WQI (0.96). Statistical analysis showed that the WQI has a strong positive correlation (0.68) with the spatial distribution of CKDu patients in the UP inferring that groundwater quality has a significant effect on the prevalence of CKDu in the UP. Moreover, these maps can be effectively used by decision makers for groundwater quality management activities in the UP, Sri Lanka.

Keywords CKDu · GIS · Groundwater · Uva Province · Water quality parameters · WQI

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Introduction

Groundwater is defined as the water that exists beneath the earth surface mostly in the aquifers (Chaurasia et al. 2018; Narsimha and Sudarshan 2017). It plays a vital role in water supply for various purposes viz. drinking, industrial and agricultural purposes (Adimalla et al. 2018). According to the previous studies, approximately 65% of groundwater in the world is utilized for drinking purposes whereas 20% and 15% of groundwater are being used for agricultural and industrial activities respectively (Adimalla and Venkatayogi 2017; Adimalla et al. 2019; Salehi et al. 2018; Subramani et al. 2005). The suitability of groundwater especially for drinking purposes depends mainly on its quality and therefore the latter has gained immense importance in the recent past (Alcamo 2019). In Sri Lanka, 80% of groundwater sources are utilized for domestic, commercial, and other industrial purposes due to the increasing the demand for groundwater daily (Panabokke and Perera 2005). Furthermore, as explained by Panabokke and Perera (2005), the majority of rural people in Sri Lanka heavily depend on dug and tube wells since the groundwater is the safest drinking water source that can be self-managed. Therefore, the quality of the groundwater deteriorates rapidly due to geological and anthropogenic activities (Udeshani et al. 2020). According to the finding of past researches, groundwater resources have been highly vulnerable within the country due to anthropogenic activities viz. agricultural activities, land-use practices, cultivation practices, and industrial activities as compared to natural causes (Gunatilake and Iwao 2009, 2010; Rubasinghe et al. 2015; Villholth and Rajasooriyar 2010). As explained by Aravinna et al. (2017), residues, pollutants, and contaminants of pesticides and other agrochemicals applied on agricultural lands reach groundwater by leaching, and move to offsite water bodies by direct runoff, soil erosion, and spray drift. Thus it has been revealed that contamination of this groundwater due to various causes may ultimately result in the availability of poor drinking water, reduction in the quantity of water sources, high cost for water purification, high cost for alternative water supplies and most importantly potential for human health problems (Chandrajith et al. 2020; Dissanayake and Chandrajith 2017; Rajasooriyar et al. 2013; Villholth and Rajasooriyar 2010). Moreover, groundwater pollution may also highly threatens economic development, and social prosperity (Milovanovic 2007; Shah 2007).

Chronic Kidney Disease of uncertain Etiology (CKDu) in Sri Lanka has received much attention over the last two decades and many scientists assumed and proposed that prolonged consumption of drinking water with high levels of contaminants like fluoride (Dissanayake 2005; Ileperuma et al. 2009), Cadmium (Bandara et al. 2008; Wanigasuriya et al. 2011), Arsenic (Jayasumana et al. 2013), hardness forming agents, high ionicity (Dharmawardana et al. 2015), and agrochemical residues like Glyphosate (Jayasumana et al. 2013) are the root causes for the progression of the CKDu. Furthermore, another contributory factor for the cause of CKDu explained by (Chandrajith et al. 2011a) is the Na/Ca ratio in drinking water with high levels of Fluoride. In Sri Lanka, North Central Province (NCP) is the most affected province with CKDu while Eastern and Central Provinces are the most prominent CKDu distributed provinces. As explained by Wanasinghe et al. (2018) the pattern of distribution of CKDu was spread outside the NCP again and it was diverted to the UP where 85% of the drinking water requirements of the rural communities are acquired from shallow and deep wells (Perera and Gonawala 2008). Therefore, regular monitoring and characterizing the groundwater quality in the UP is of utmost importance since they aid to examine its suitability for drinking and adopting appropriate measures for protection. Thus the UP was selected to investigate the root geochemical factor that contributes to the prevalence of CKDu.

Development of water quality indices is considered as the most effective tool of assessing water quality. In water quality indices, a number of water quality parameters viz. pH, major anion levels, major cation levels, and levels of trace elements are incorporated in a mathematical equation to rate the water quality defining its suitability for human consumption (Lkr et al. 2020; Logeshkumaran et al. 2015). Water quality indices condenses the bulk of various water quality parameters into a single value in a logical and simplified form (Sharma and Kansal 2011). The concept of WQI was first proposed by Horton (1965) and since then number of water quality indices have been suggested by experts which can identify the overall water quality status of a particular geographical location at a certain time easily, efficiently, and promptly. The water quality indices are easily interpretable and enable the comparison of the water quality status among different sites (Bora and Goswami 2017). In these water quality indices, the weights of each incorporated water quality parameters are derived based on the significance and impacts on such parameters on the overall water quality. Furthermore, WQI values can be classified into several categories as excellent water; Good water; Poor water; Very poor water; and Unsuitable water owing to the characteristics of particular WQI (Akther and Tharani 2017; Alobaidy et al. 2010; Udeshani et al. 2020). In a high CKDu endemic area like the UP of Sri Lanka, evaluating the availability of safe drinking water and sustainable management of water is one of the challenging areas towards development.

Thus the prime objective of this study is to develop a water quality index (WQI) to identify the relationship between the groundwater quality and the prevalence of CKDu in the UP, Sri Lanka. The results of the research findings on the groundwater quality status of the UP are presented based on spatial distribution maps of water quality parameters, WQI map, and statistical analysis of water quality results. Moreover, these maps aims to rapidly distinguish the location of most and least suitable water for drinking purposes in the UP and by mapping the index, the areas of high and low water quality can easily be distinguished by researchers as well as decision makers and/or the general public. In addition, these maps provide an important contribution for the understanding of relationships between the groundwater quality and the spatial distribution of the CKDu patients in UP, Sri Lanka.

Material and methods

Study area

Sri Lanka, is a South Asian island country which lies at 7.8731° N and 80.7718° E. The country is surrounded by the Indian Ocean, southwest of the Bay of Bengal, and southeastern part of the Arabian Sea. UP is located in the southeast part of Sri Lanka and lies between longitude 80°40′0″E to 80°41′0″E and latitude 6°20′0″N to 7°40′0″N with an area of about 8500 Km^2. The study area is mainly bordered by the Eastern Province, Southern Province, Sabaragamuwa Province and the Central province (UPC 2019). It comprises of 8,335 Km^2 land and about 165 Km^2 of inland water bodies. UP consists of two main administrative districts namely, Badulla and Moneragala. The total land area of the Badulla district is 2,861 Km^2 and the total land area in Moneragala District is 5639 Km^2.

Geology, soil and hydrology

Over 90% of Sri Lanka is made up of Precambrian high-grade metamorphic rocks in which primary porosity and permeability are negligible. The study area is also a part of the metamorphic terrain composed mainly of meta-sedimentary and meta-igneous rocks with few granitic intrusions. Migmatites, augen gneisses, granitic gneisses, biotite gneisses, and hornblende biotite gneisses are predominant in the region. Groundwater in this region is mostly from the weathered overburden and fractured zones (Fig. 1b).

The physical landscape of the Badulla district consists of mountain ranges, divided plateaus and narrow valleys. Geologically the Badulla district is located towards the East of the Central Highland complex and the prominent soil types include Red Earth and Brown Loams, Red-Yellow Padzolic and Reddish Brown soils (RDA 2017). The average annual rainfall in Badulla district varies from 900 mm to over 2500 mm. Rainfall is received in four seasons namely, first inter monsoon (March–April), Southwest Monsoon (July–September), second inter monsoon (October–November) and Northeast monsoon (December-January). Also, the average annual temperature of the district varies between 16 and 30 °C.

The Moneragala district is located in a transition zone within central highland to flat terrain. Mountainous terrain is marked in the western boundary of the region in which the elevation varies between 550 and 1500 m. Major soil types of the Moneragala district are Reddish Brown Earth and Red-Yellow Padzolic soils (RDA 2017). The annual precipitation of the district is about 1000 mm. Over 85% of rain in the district is received during the north-east monsoons while frequent drought conditions create an average evapotranspiration of 1200 mm per annum. The annual temperature of Moneragala district varies from 21.6 to 35 °C (RDA 2017). Since the climate is semi-arid to subtropical due to low rainfall and high evapotranspiration, water scarcity is a major problem in the district. The low rainfall and high

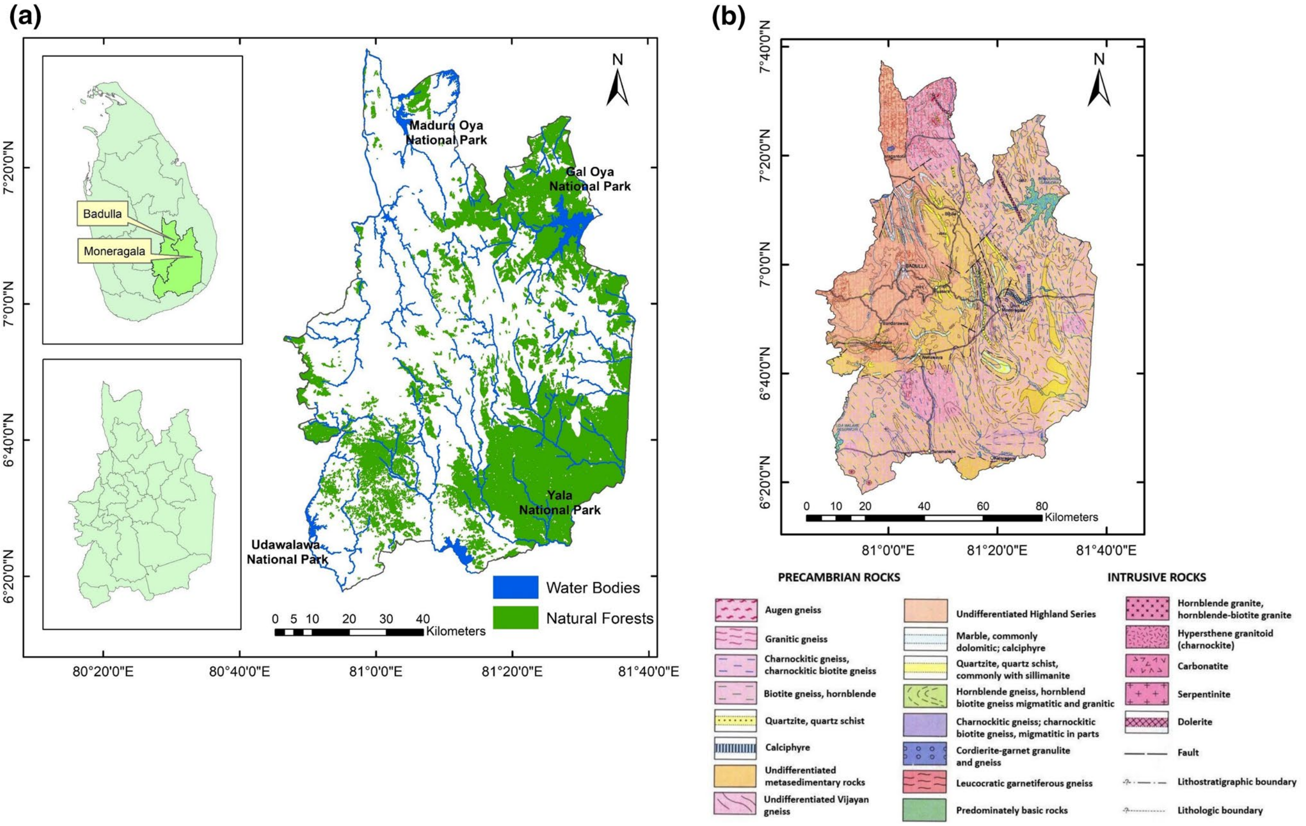


Fig. 1 **a** Hydrology and protected nature reserves of the UP **b** Geology map of the UP

evaporation rate drastically impacts on the groundwater storage and water quality, consequently the community health.

Ecological environment

The total extent of the land under protection in the UP exceeds 2000 Km^2. The forest cover is mainly comprised of montane, sub-montane tropical, dry, evergreen, mixed forests. Also, important wildlife areas within the district include Gal Oya National Park, Yala National Park, Udawalawa National Park, and Maduru Oya National Park (Fig. 1a). The considerable land area of the province covers mainly forest areas (31.4%), scrublands (22.12%), home gardens (14.78%), rice (20.9%), and Chena cultivation for short-term crops (10.72%). In the Badulla district, the majority of the farmers are engaged in vegetable farming including potatoes, carrots, beans, leeks, cabbage, green chili, tomatoes, and beetroot. In the Moneragala district, paddy and field crops such as maize, cowpea, groundnut, and green grams are grown. Irrigation is largely practiced in the Moneragala district and it increases the sodicity of the soil.

Sampling procedure

The groundwater sampling program was designed following the stratified random sampling procedure. The total area of the entire UP was divided into 100 Km^2 grids using the topographic maps prepared by the Survey Department of Sri Lanka. After completing the reconnaissance surveys, the sampling locations of dug wells and tube wells were randomly selected from each grid according to the availability. Then, groundwater samples were collected from each grid by applying American Public Health Association (APHA 2005) standard methods for sample collection and preservation. Groundwater samples were collected from both CKDu prevalent and non-prevalent areas covering the entire study area. The groundwater samples collected from CKDu non-prevalent areas were used as control samples of the study.

The sampling process has been carried out covering the whole of UP while the Geographical Positioning System (GPS) coordinates of the locations were recorded using a MAGELLAN™ GPS receiver. Groundwater samples were collected into properly labeled high-density polyethylene bottles which were acid-soaked overnight and then washed thoroughly with deionized water and oven-dried for 3 h at 50 °C. At the time of sampling, bottles were thoroughly rinsed 2–3 times with groundwater to be sampled. In the case of sampling from tube wells, samples were collected after pumping for 10 min to remove groundwater stored in the well. Two subsets of samples were collected for laboratory analysis in which one was filtered and acidified by adding several drops of Conc. Nitric acid ($pH < 2$) for cation analysis, while the un-acidified sample was used for anion analysis. The samples were placed in a cooled ice box during transportation and stored refrigerated until analysis (at 5 °C). The sampling points were plotted using GIS-ArcMap™ 10.4 mapping software to be used in data analysis (Fig. 2).

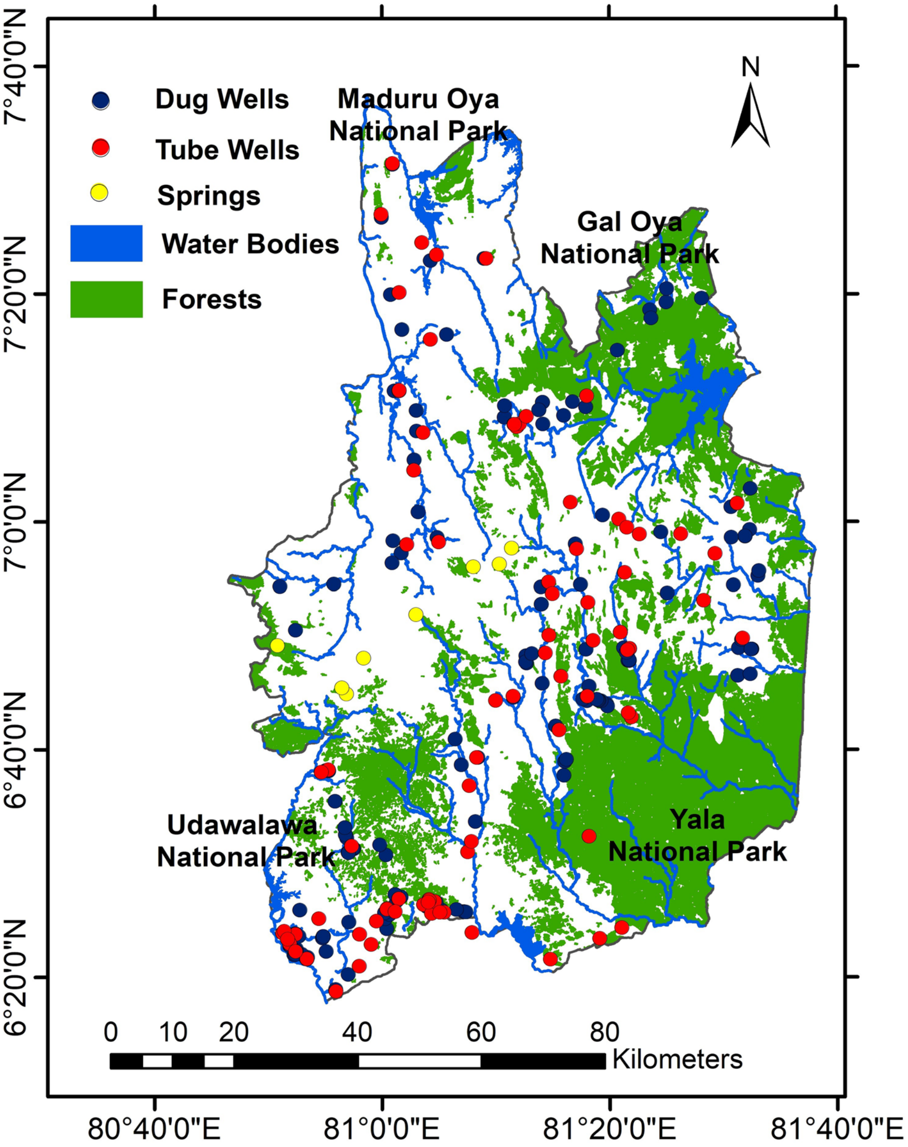
Analysis of physico-chemical parameters of groundwater

Onsite measurements of water quality parameters (Temperature, pH, Electrical Conductivity) of collected groundwater samples were recorded using a pre-calibrated Thermo Scientific Orion Star A325™ Multiparameter test kit. The reliability of pH and EC analysis was tested after every five samples using standard buffer solutions of pH 7 and 10, whereas that of standard EC solution $EC = 1413$ µS/cm. All other chemical parameters were determined using standard procedures described by APHA (2005). Total alkalinity, total hardness, and Chloride (Cl^-) of the samples were analyzed using a Hach™ digital titrator within 24 h of sampling. To measure alkalinity, the sulfuric acid method was used whereas the EDTA method and Silver nitrate method was used, respectively, for the analysis of total hardness and chloride. Nitrate (NO_3-N), Sulfate (SO_4^{2-}), Phosphate (PO_4^{3-}), and Fluoride (F^-) contents were determined using a Hach™ DR 2700 spectrophotometer within 24 h of sampling. Major cations (Sodium-Na^+, Potassium-K^+, Calcium-Ca^{2+}, and Magnesium-Mg^{2+}) were measured using Atomic Absorption Spectrometer (AAS-Varian 240FS) at the Sabaragamuwa University of Sri Lanka, while trace metals (Aluminum-Al, Chromium-Cr, Manganese- Mn, Iron-Fe, Cobalt-Co, Nickel-Ni, Copper-Cu, Zinc-Zn, Arsenic-As, Cadmium-Cd, and Lead-Pb) were measured by Thermo ICapQ Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the University of Peradeniya, Sri Lanka. The detection limits for Na^+, K^+, Ca^{2+}, and Mg^{2+} on the AAS-Varian 240FS are 0.05, 0.05, 0.10, and 0.10, ppm at 589, 769, 422, and 285 nm, respectively. Overall, measurement reproducibility and precision for each analysis was less than 2%. Furthermore, blank samples and standard solutions were used to check for possible errors during the analysis. Moreover, based on the method explained by Appelo and Postma (1996), the ion balance errors was calculated to verify the accuracy of the chemical analysis. The ion balance error yielded about ±4% for all the ion concentrations. This means that the data quality is sufficient for drawing simple conclusions about water quality.

Preparation of spatial distribution maps

Spatial distribution maps of water quality parameters such as pH, EC, TDS, alkalinity, Total Hardness (TH), anions (NO_3-N, SO_4^{2-}, PO_4^{3-}, Cl^- and F^-) major cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) were prepared using GIS techniques. In this,

Fig. 2 Map showing the sampling locations of the UP



ArcMap™ 10.4 mapping software was used and the Inverse Distance Weighted (IDW) which is more accurate method with power 2 was used to generate spatial distribution maps of measured water quality parameters. Furthermore, Spatial distribution of CKDu patients map was generated based on the data collected from the main hospitals, regional hospitals, and previously published data of the UP, Sri Lanka.

Estimation of water quality index (WQI)

To get a comprehensive overall quality of the groundwater in the UP, the WQI method was used. As explained by Walsh and Wheeler (2012), the WQI method has been widely used as a prominent approach to convey the water quality status of an area of interest to the general public and policymakers. Furthermore, WQI can be effectively used in the determination of the suitability of drinking water for human consumption (Poonam et al. 2013; Ramakrishnaiah et al. 2009).

In this study, the weighted arithmetic WQI method was applied based on the recommended guidelines for drinking water quality by the SLS 614:2013 (Sri Lankan Standard) for drinking purposes. The weighted arithmetic WQI is calculated using Eq. (1) (Adimalla et al. 2018; Akther and Tharani 2017; Sadat-Noori et al. 2014; Udeshani et al. 2020)

$$\mathrm{WQI} = \sum_{i=1}^{n} \frac{w_i q_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

where, w_i is the unit weightage of ith water quality parameter and q_i is the quality rating scale of the ith parameter. The WQI calculation procedure can be further divided into five steps as shown in Fig. 3.

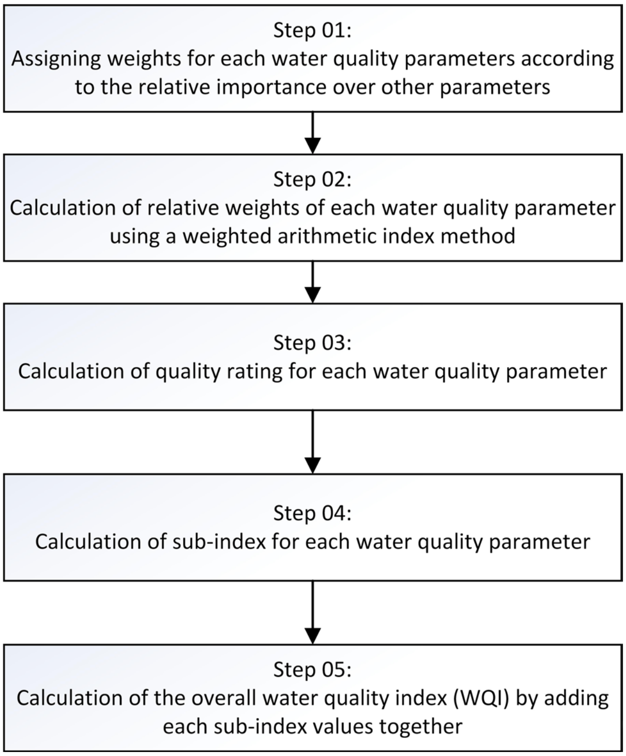


Fig. 3 Flow chart showing the five steps followed to calculate the WQI

In the first step, each of the twelve parameters (pH, NO_3-N, SO_4^{2-}, PO_4^{3-}, Cl^-, F^-, HCO_3^-, Hardness, Na^+, K^+, Ca^{2+} and Mg^{2+}) has been assigned a weight (w_i) based on their relative effects on primary health over other parameters (Akther and Tharani 2017). The weightage for various parameters is assumed to be inversely proportional to the SLS 614:2013 maximum permissible limit for the corresponding parameters (Sadat-Noori et al. 2014). As explained by Harshan et al. (2016), the w_i for each parameter is calculated using Eqs. (2) and Eq. (3).

$$w_i = \frac{k}{v_i} \tag{2}$$

where, w_i is the weightage for the ith parameter, k is a constant proportionality and v_i is the standard value of ith water quality parameter.

$$k = \frac{1}{\sum_{i=1}^{n} \frac{1}{v_i}} \tag{3}$$

where, k is a constant proportionality and v_i is the standard value of i^{th} water quality parameter.

In the second step, the relative weight (W_i) of each parameter is computed using Eq. (4).

Table 1 Summary table of the calculated weights (w_i) and relative weights (W_i) and recommended SLS 614:2013 limits of each water quality parameter

Water quality parameter	SLS 614:2013	Relative weight (W_i)
pH	6.5–8.5	0.069
NO_3^--N (mg/L)	10	0.012
PO_4^{3-} (mg/L)	2	0.293
SO_4^{2-} (mg/L)	250	0.002
F^- (mg/L)	1	0.585
Cl^- (mg/L)	250	0.002
HCO_3^- (mg/L)	200	0.003
Total Hardness (mg/L)	250	0.002
Na^+ (mg/L)	200	0.003
Ma^{2+}(mg/L)	30	0.020
K^+(mg/L)	200	0.003
Ca^{2+}(mg/L)	100	0.006

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{4}$$

where, W_i is the relative weights of each water quality parameter, w_i is the calculated weights of each water quality parameter and, n is the number of water quality parameters. The calculated weights (w_i) and relative weights (W_i) values are presented in Table 1.

In the third step, a water quality rating scale (Q_i) was calculated for each parameter using Eq. (5).

$$Q_i = \left(\frac{v_a - v_s}{v_i - v_s}\right) \times 100 \tag{5}$$

where, Q_i is the quality rating scale, v_a is the actual value obtained from laboratory analysis of ith parameter, v_i is the recommended standard value of ith water quality parameter, and, v_s is the ideal value (pH = 7 and 0 for all other parameters).

In the fourth step, a sub-index SI_i for each ith water quality parameter and WQI were calculated using Eq. (6) and Eq. (7) respectively.

$$\mathrm{SI}_i = W_i \times Q_i \tag{6}$$

$$\mathrm{WQI} = \sum SI_i \tag{7}$$

Computed WQI values were classified into five categories as excellent water (WQI < 25); Good water (WQI < 25–50); Poor water (WQI < 50–75); Very poor water (WQI < 75–100); and water Unsuitable for drinking (WQI > 100) (Akther and Tharani 2017; Alobaidy et al. 2010; Udeshani et al. 2020).

Data analysis

Statistical correlation analyses has been carried out to interpret the relationship among various water quality parameters, the relationship between the water quality parameters and WQI and, the relationship between the WQI and the prevalence of CKDu in the UP. To identify the most significant water quality parameters that influence the WQI, the correlation matrix of 12 water quality variables and WQI was determined. Furthermore, the statistical correlation has been calculated for the spatial distribution of WQI and the spatial distribution of the CKDu patients in the UP based on the Pearson correlation coefficient using the Minitab 17 statistical package.

Table 2 Descriptive statistics of the water quality parameters of the study area

Variable	Mean	Standard deviation	Minimum	Maximum
pH	7.04	0.50	5.04	8.37
EC	724.20	620.70	0.03	5129.00
NO_3^- -N(mg/L)	2.80	1.57	0.12	11.51
PO_4^{3-}(mg/L)	0.68	0.86	0.02	5.86
SO_4^{2-}(mg/L)	33	52	1	540
F^-(mg/L)	0.98	0.83	BDL	5.65
Cl^-(mg/L)	60.21	92.15	7.00	1100.00
HCO_3^-(mg/L)	262.6	166.5	12.0	820.0
Hardness(mg/L)	234	170	4	1464
Na^+(mg/L)	66.26	84.65	0.17	608.74
Mg^{2+}(mg/L)	23.05	29.60	0.26	262.68
K^+(mg/L)	2.11	1.83	0.21	11.56
Ca^{2+}(mg/L)	56.01	36.65	14.18	206.23

Results and discussion

Spatial analysis of groundwater quality

The pH is one of the most important water quality parameters which determines the acidity or alkalinity of the groundwater. A pH 7 in the groundwater at 25 °C is considered neutral (Nelson 2002). Measuring the pH of the groundwater is essential when carrying out a water quality assessment because this parameter regulates the quantity and chemical structure of some organic and inorganic constituents that have been dissolved in the groundwater (Sadat-Noori et al. 2014). As recommended by the SLS 614:2013 water quality guidelines, the pH of the drinking water should range from 6.5 to 8.5. The pH of the groundwater in the UP varies between 5.04 and 8.87 whereas the mean pH of the UP was recorded as 7.04 with a standard deviation of 0.49 (Table 2). According to the results, 12% of the collected 230 samples were not in the permissible level (greater than 8.5) with slightly alkaline conditions. Spatial distributions of pH variation is shown in Fig. 4. The map reveals that except for very insignificant areas, most of the areas consist of the desirable limit of pH. As explained by Chaurasia et al. (2018), the electrical conductivity (EC) in the groundwater is a measurement of the dissolved constituents in an aqueous solution.. As shown in Table 2, the EC of the groundwater in the UP ranged between 3.4 and 5129.0 µS/cm which has the mean value of 724.2 ± 620.7 µS/cm. According to SLS 614:2013 specification, only a single groundwater sample location exceeds the allowable limit (3500 µS/cm) that indicates the suitability of the groundwater for drinking purposes. The spatial distribution map of the EC is shown in the Fig. 4.

The nitrate (NO_3-N) concentration of the groundwater in the UP ranged from 0.12 to 11.51 mg/L with the mean value of 2.79 ± 1.56 mg/L (Table 2). According to the SLS 614:2013 drinking water quality guidelines, the maximum contaminated limit of the NO_3-N in the groundwater should not exceed 10 mg/L as NO_3^--N. The results of the NO_3-N concentrations in all the sampling locations reveals that 2% of the samples are not contaminated (less than 1 ppm), 34% of samples are less contaminated (less than 3 ppm), 63% of the samples are contaminated (3–10 ppm) and 1% of the samples exceed the desirable levels of NO_3-N in the drinking water. However, the majority of the people in the UP are farmers, and the major occupation of the UP is the cultivation of crops viz. rice, vegetables, tea, etc. (Piyathilake et al. 2020). Therefore, it can be hypothesized that there is a harmful effect of the application of nitrogenous fertilizers on the crop fields in terms of the NO_3-N accumulation in the groundwater. The spatial distribution of the NO_3-N concentration in the samples is shown in Fig. 4.

Phosphate (PO_4^{3-}) is another significant water quality parameter that has a significant potential to effect the overall quality of groundwater. In this study, PO_4^{3-} concentrations of all the samples ranged between 0.02 and 5.86 mg/L whereas the mean was recorded as 0.67 ± 0.86 mg/L. According to World Health Organization guidelines WHO (2004), PO_4^{3-} concentration in all water samples exceeds the contaminated levels for an aquatic organism. According to the results, 77.4% of water samples were showed a PO_4^{3-} concentration less than 1.00 ppm, and 14.6% of the sample were between 1.00 and 2.00 ppm with higher PO_4^{3-} concentration. 8% of the samples were not in the permissible level (2 mg/L) with very high phosphate conditions. This may be due to the long-term application of chemical fertilizers on crop fields for many decades. Since the majority of phosphate levels in groundwater samples were higher than the recommended level, the contamination of groundwater by the application of phosphate fertilizer should be

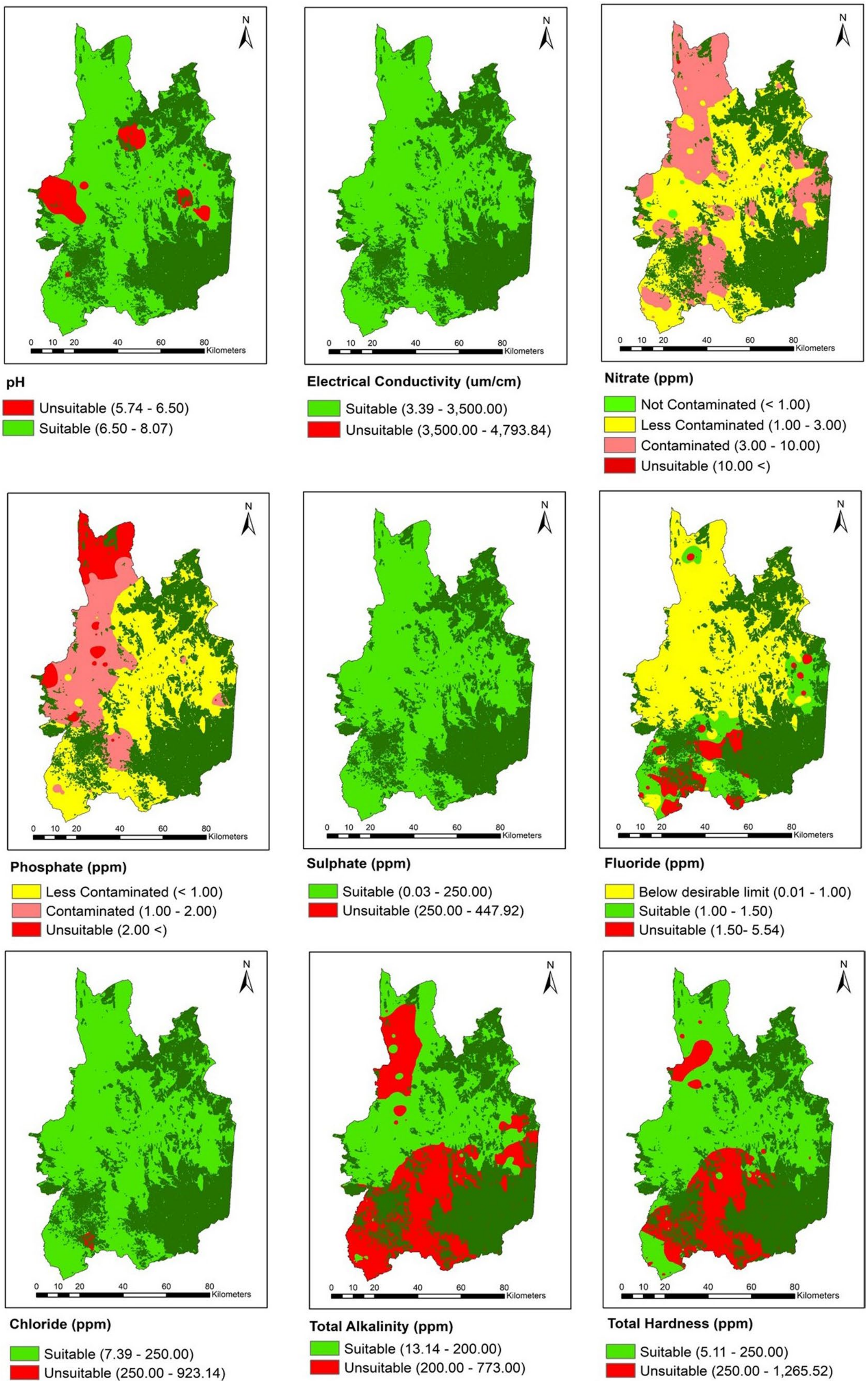


Fig. 4 Maps show spatial distribution of groundwater quality parameters (pH, EC, NO_3^-N, PO_4^{3-}, SO_4^{2-}, F^-, Cl^-, HCO_3^-, hardness) in the UP

controlled. The spatial distribution of the phosphate in the UP is shown in Fig. 4.

Sulfate (SO_4^{2-}) in groundwater is mostly available due to the dissolution of rocks which contain compounds viz. gypsum, iron sulfides, and other sulfur-containing materials (Chaurasia et al. 2018). As revealed by the results of this study, only 1% of the groundwater samples collected exceeded the permissible limit of SO_4^{2-} (250 mg/L) for drinking water. The values of SO_4^{2-} concentrations ranged from 0 to 540 mg/L with the mean SO_4^{2-} concentration of 33 ± 52 mg/L. The spatial distribution of SO_4^{2-} concentrations in the samples is shown in Fig. 4.

Fluoride (F^-) is an essential element for human beings for development and growth (Chattopadhyay et al. 2011). Although it is beneficial at low recommended doses (0.5–1.0 ppm), the higher levels of F^- may cause human kidney damage and accumulation of F^- in hard tissues of the body and endemic skeletal/ teeth fluorosis may be caused (Chandrajith et al. 2011a). However, 40% of the groundwater samples out of analyzed 230 samples exceeds the permissible limit of 1 mg/L with the mean F^- concentration of 0.97 ± 0.83 mg/L. According to Cooray (1994), Sri Lanka is dominated by Precambrian metamorphic rocks and can be divided into four main lithotechtonic units namely, the Highland Complex, the Vijayan Complex, the Kadugannawa complex and, the Wanni Complex. Among these, the Highland complex is the largest while it is comprised of mostly Garnet—sillimanite–graphite gneiss, charnockite, quartzites, marbles, and calc gneisses whereas the Vijayan and the Wanni complexes consist of mainly biotite—hornblende gneisses, scattered bands of metasediments, charnockitic gneisses, and granites. Furthermore, as mentioned by Chandrajith et al. (2012), most of these rocks consist of F-bearing minerals such as micas, hornblende, and apatite, and minerals such as fluorite, tourmaline, and topaz also contribute to the general geochemical cycle of fluorine in the physical environment. Thus, the mechanism of leaching of F^- into groundwater is clearly explained by Chandrajith et al. (2012), and according to their explanation, intense weathering of rocks and minerals in the tropical climate tends to enhance the entry of F^- into the aqueous phase and is therefore leached out from the F-bearing minerals. The spatial distribution map of the F^- variability in water samples is shown in the Fig. 4.

Chloride (Cl^-) is also considered as one of the most important water quality parameters since higher levels of Cl^- may cause severe health effects to human beings (Pius et al. 2012). Furthermore, as in the case of SO_4^{2-} the high Cl^- levels of the groundwater may impart a change in the taste of the water (Sadat-Noori et al. 2014). However, only 3% of the groundwater samples exceeded the recommended higher permissible limit (250 mg/L) with the mean value of 60.21 ± 992.15 mg/L whereas the minimum and maximum values were 7.00 and 1100.00 respectively. The spatial distribution of the Cl^- in the UP is shown in Fig. 4.

In water quality analysis, HCO_3^- is given a minimum weight since it plays an insignificant role in water pollution (Ketata et al. 2012). As explained by Chaurasia et al. (2018), HCO_3^- may enter groundwater due to the action of carbon dioxide in the water on carbonated rocks viz. dolomite and limestone. However, 57% of the collected groundwater samples, the HCO_3^- level exceeded the permissible limit (200 mg/L) with the range of 12.0 and 820.0 mg/L. The mean value of the HCO_3^- concentration of the UP was recorded as 262.6 ± 166.5 mg/L. The spatial distribution of the HCO_3^- ions of the samples is shown in the Fig. 4.

The Total Hardness (TH) of the groundwater is also considered an important factor that determines the groundwater quality for drinking purposes. As explained by Ravikumar et al. (2011), Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, CO_3^{2-} and HCO_3^- of the water may cause water hardness. The hardness values ranged between 4.0 to 1464.0 mg/L and the water with hardness above 250 mg/L is considered as the highest permissible limit according to the SLS 614:2013. However, in this study, the mean hardness of the study was recorded as 234.4 ± 169.7 mg/L in which 41% of the water samples have exceeded the recommended limits. The spatial distribution of groundwater hardness is shown in Fig. 5. As revealed by Ramesh and Elango (2006), the regular consumption of water with a hardness above 300 mg/L may lead to human heart diseases and kidney diseases.

The major cation concentrations of the collected groundwater samples are mentioned in Table 2 and the spatial distribution of each major cation is shown in Fig. 5.

The major cation trend in the groundwater of the UP is $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. Sodium is the dominant cation and the levels of sodium ranged between 0.17 to 608.74 mg/L with a mean value of 66.26 ± 84.65 mg/L where the maximum permissible limit of the sodium is 200 mg/L. In this study, 6% of the groundwater samples were recorded as exceeding the limits. Calcium is the second dominant cation in the UP which shows a mean value of 56.01 ± 36.65 mg/L with a range of 14.18 to 206.23 mg/L. The maximum permissible limit for calcium is 100 mg/L and it was calculated that 12% of groundwater samples exceeded this limit. The mean value of magnesium is recorded as 23.05 ± 29.60 mg/L whereas the values are ranged between 0.26 to 262.68 mg/L. In this study, 24% of the groundwater samples exceeded the maximum permissible limit of magnesium (30 mg/L) in the drinking water. The least dominant major cation of the UP is potassium and the mean value of the potassium was recorded as 2.11 ± 1.82 mg/L that the value ranged between 0.21 to 11.56 mg/L. However, all the groundwater samples were within the desirable limits recommended by the SLS 614:2013 water quality guidelines.

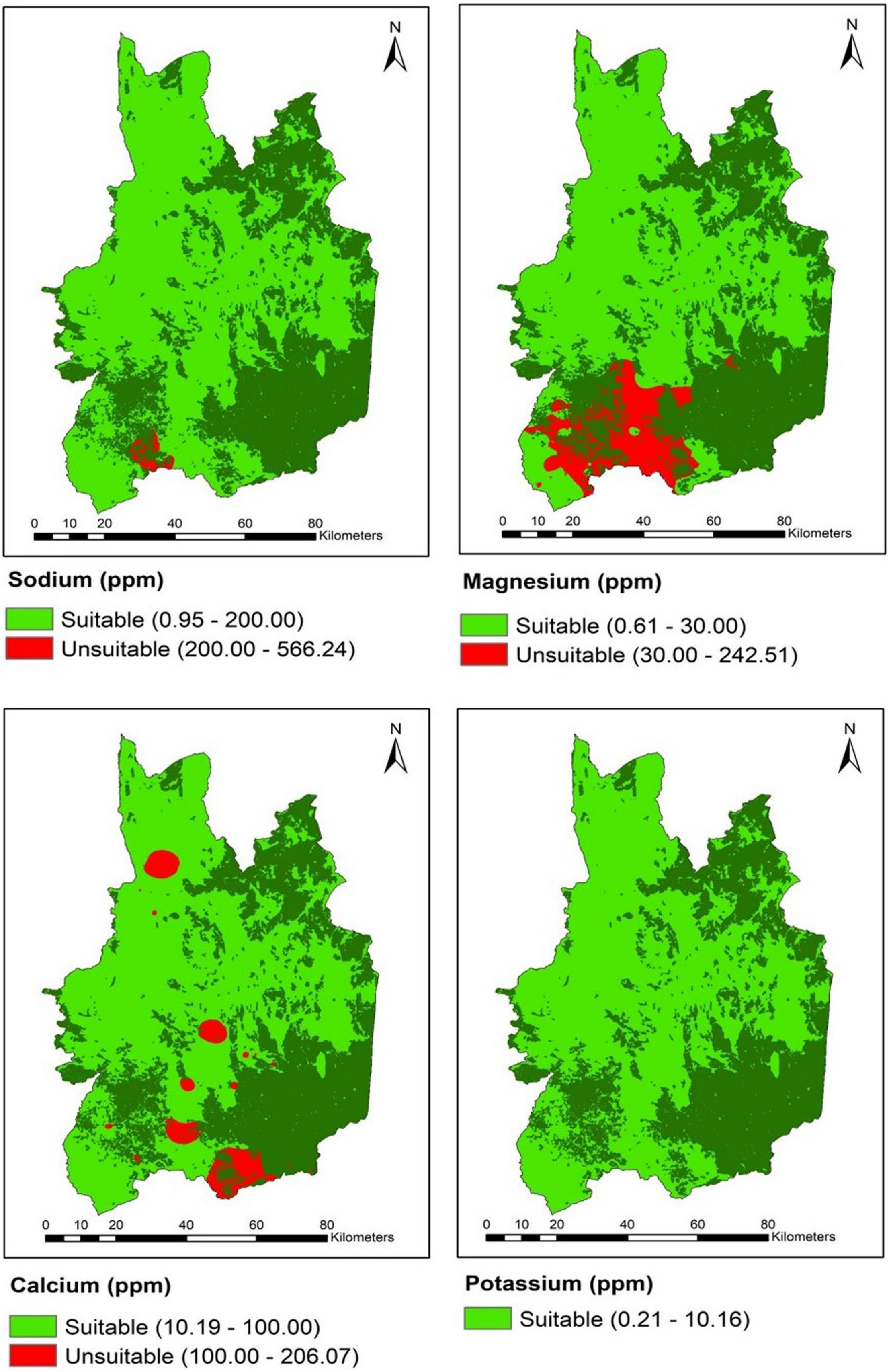


Fig. 5 Maps show spatial distribution of major cations in the UP

Furthermore, the trace element concentrations of the groundwater in the UP were analyzed and all the statistical data are presented in Table 2. According to the results, none of the trace elements in all the groundwater samples had exceeded their highest permissible limits recommended by the SLS 614:2013. Due to this insignificant effect of the trace elements in the overall quality of the groundwater in the UP, trace elements are not considered when developing the WQI for the UP, Sri Lanka.

Water quality index (WQI)

Water quality index for the groundwater in the UP is calculated and mapped to determine the suitability of groundwater for drinking purposes. The calculated WQI values for each of the 251 groundwater sampling locations are shown in Table 3. According to the sampling procedure, there are 164 dug wells, 87 tube wells which were sampled and analyzed to generate the WQI. Furthermore, as shown in the Fig. 6, groundwater samples can be comprehensively categorized into five water quality levels (excellent,

Table 3 Groundwater classification based on the WQI

WQI category	Well type	No. of wells	Percentage (%)	Percentage (%)	Quality of water
< 25	Dug well	39	23.8	20.3	Excellent
	Tube well	12	13.8		
25–50	Dug well	32	19.5	21.2	Good
	Tube well	21	24.1		
50–75	Dug well	32	19.5	20.3	
	Tube well	19	21.8		Poor
75–100	Dug well	15	9.1	9.9	
	Tube well	10	11.5		Very poor
> 100	Dug well	46	28.1	28.3	
	Tube well	25	28.8		Not suitable

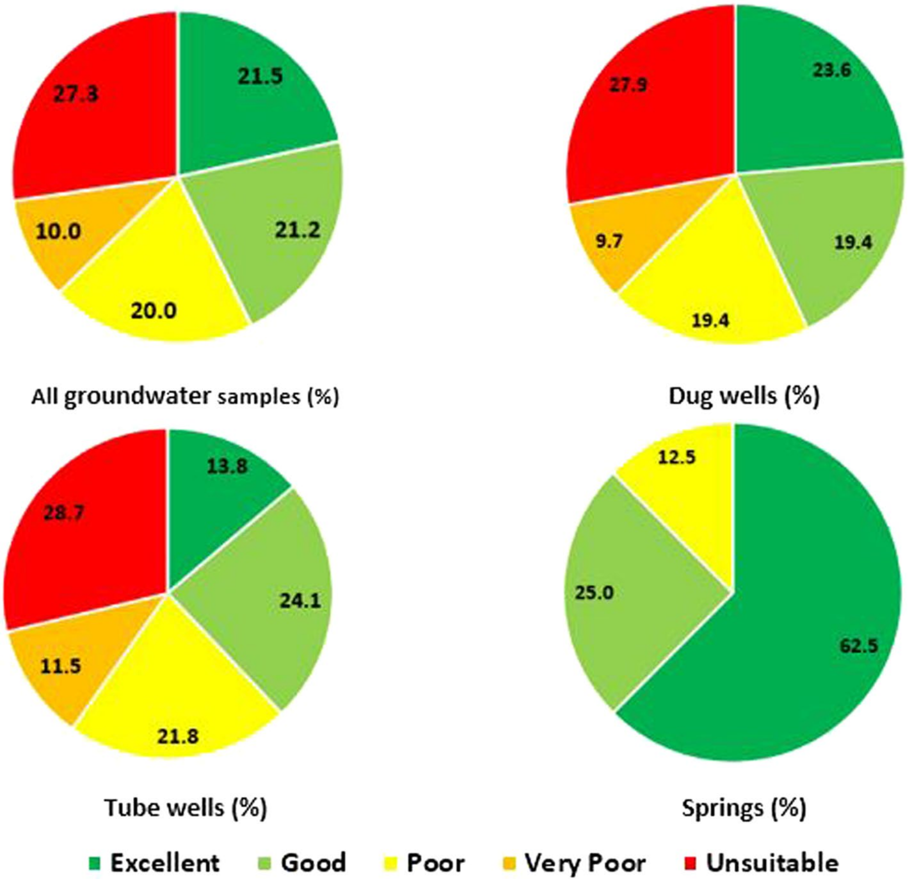
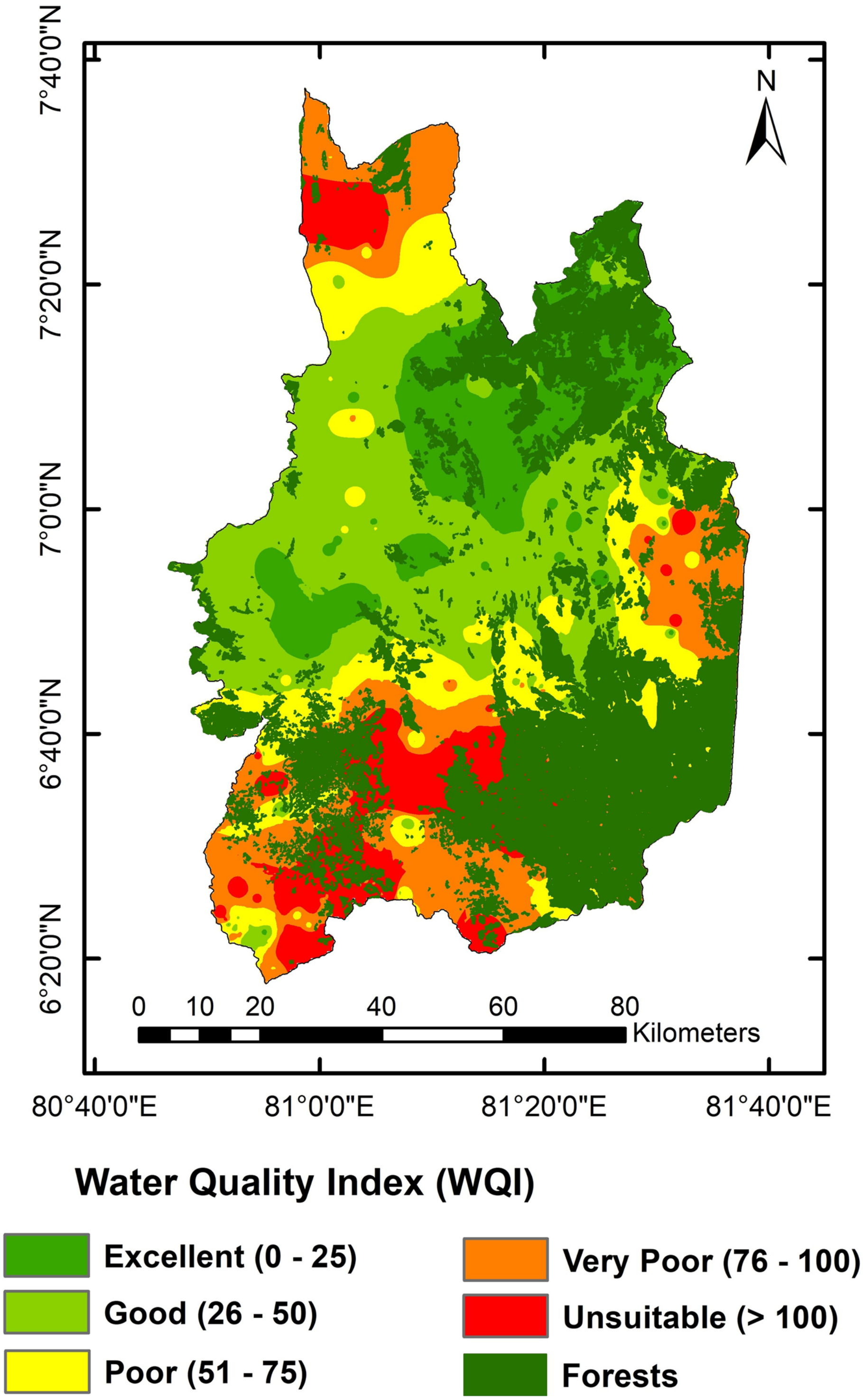


Fig. 6 Pie charts show groundwater quality classification based on the WQI categories and type of groundwater sources

good, poor, very poor and unsuitable) by considering the type of groundwater sources (dug wells and tube wells). According to the results, 20.3% of groundwater samples are categorized under excellent in terms of the drinking water quality, 21.2% of the samples are categorized under good, 20.3% of the samples are categorized under poor, 9.9% of the samples are categorized under very poor, and 28.3% of the samples are categorized under unsuitable category in terms of the WQI.

Figure 7 illustrates the spatial distribution of the WQI map. The WQI map revealed that the central high elevated areas of the UP are the safest zone in terms of groundwater quality for drinking purposes. In those high elevated areas, nearly all the WQI values of the groundwater samples are

Fig. 7 Map shows the spatial distribution of the WQI in the UP



in excellent and good categories where groundwater can be highly recommended for drinking purposes. In general, the groundwater quality decreases from high elevated areas to flat terrain mostly in the Moneragala district and upper part of the Badulla district.

Relationship between WQI and water quality parameters

A correlation matrix of twelve water quality parameters, namely, pH, NO_3-N, SO_4^{2-}, PO_4^{3-}, Cl^-, F^-, HCO_3^-, hardness, Na^+, K^+, Ca^{2+} and Mg^{2+} among themselves and WQI was generated and it is shown in Table 4.

According to the results, TH exhibits significantly strong positive correlation with HCO_3^- ($r = 0.78$), SO_4^{2-} ($r = 0.70$), Mg^{2+} ($r = 0.73$), and Ca^{2+} ($r = 0.74$). Also, significantly a strong positive correlation was observed between HCO_3^- and F^- ($r = 0.70$) whereas HCO_3^- is moderately correlated with Na^+ ($r = 0.63$), Mg^{2+} ($r = 0.62$), Ca^{2+} ($r = 0.54$), SO_4^{2-} ($r = 0.59$), and Cl^- ($r = 0.51$). Moreover, the correlation analysis exhibits significantly strong positive correlation between SO_4^{2-} and Cl^- ($r = 0.79$), Na^+ and Cl^- ($r = 0.71$), Mg^{2+} and Cl^- ($r = 0.77$), and Mg^{2+} and Na^+ ($r = 0.80$). Furthermore, the correlation of all the water quality parameters with the WQI was evaluated to identify the significant impact of each water quality parameter on the overall quality of the groundwater in the UP. According to the results, the most significant correlation was recorded between F^- and WQI (0.96). This is a strong positive correlation and it can be recognized that F^- has the most significant impact on the overall quality of the groundwater in the UP since F^- has been identified as and water quality parameter which has severe human health impacts. Furthermore, WQI has significant positive correlations with HCO_3^- (0.71), and Mg^{2+} (0.62). But these are not parameters that severely impact human health. Moreover, SO_4^{2-}, Cl^-, and TH show a moderate positive correlation with the WQI whereas pH, NO_3-N, PO_4^{3-}, K^+, and Ca^{2+} show a week positive correlation with the WQI.

Furthermore, the WHO maximum permissible limits of water quality parameters were compared with WQI to comply with water quality data for drinking purposes (Table 5). In excellent WQI category, 100% of the samples were ranged within the WHO safe limits in terms of all the assessed parameters. In good WQI category, pH, NO_3—N, PO_4^{3-}, SO_4^{2-}, F^-, Cl^-, Na^+, K^+, Ca^{2+} and Mg^{2+} of all the samples ranged within the WHO safe limits whereas 33%, 20% and 11% of samples exceeded the WHO safe limits of HCO_3^- (200 mg/L), Ca^{2+} (100 mg/L), and Mg^{2+} (30 mg/L) respectively. In poor WQI category, pH, NO_3—N, SO_4^{2-}, Cl^-, Na^+, and K^+ of all the samples ranged within the WHO safe limits whereas 12%, 26%, 65%, 13%, and 20% of samples exceeded the WHO safe limits of PO_4^{3-} (2 mg/L), F^- (1 mg/L), HCO_3^- (200 mg/L), Ca^{2+} (100 mg/L), and Mg^{2+} (30 mg/L) respectively. In very poor WQI category, pH, NO_3—N, SO_4^{2-}, Cl^-, Na^+, and K^+ of all the samples ranged within the WHO safe limits whereas 11%, 85%, 81%, 12%, and 38% of samples exceeded the WHO safe limits of PO_4^{3-} (2 mg/L), F^- (1 mg/L), HCO_3^- (200 mg/L), Ca^{2+} (100 mg/L), and Mg^{2+} (30 mg/L) respectively. In unsuitable WQI category, pH, NO_3—N, SO_4^{2-}, Cl^-, Mg^{2+} and K^+ of all the samples ranged within the WHO safe limits whereas 8%, 97%, 93%, 51%, and 13% of samples exceeded the WHO safe limits of PO_4^{3-} (2 mg/L), F^- (1 mg/L), HCO_3^- (200 mg/L), Na^+ (200 mg/L), and Ca^{2+} (100 mg/L) respectively.

As explained by Young et al. (2011), high F- levels in the dry zone areas of Sri Lanka is recorded due to the effects of underlying rocks. The UP is mainly composed of meta-sedimentary and meta-igneous rocks with few granitic intrusions with dominant hornblende and biotite bearing migmatites

Table 4 Correlation coefficient matrix of physico-chemical parameters of groundwater quality

	pH	TH	HCO_3^-	NO_3^-	PO_4^{3-}	SO_4^{2-}	F^-	Cl^-	Na	Mg	K	Ca
pH	1.00											
TH	0.03	1.00										
HCO_3^-	0.08	0.78**	1.00									
NO_3^-	0.05	0.01	0.05	1.00								
PO_4^{3-}	0.09	− 0.07	− 0.04	0.49**	1.00							
SO_4^{2}	0.03	0.70**	0.59**	0.04	− 0.06	1.00						
F^-	0.09	0.41**	0.70**	0.01	− 0.10	0.45**	1.00					
Cl^-	0.01	0.71**	0.51**	0.07	− 0.02	0.79**	0.33**	1.00				
Na	0.07	0.52**	0.63**	0.06	− 0.04	0.63**	0.62**	0.71**	1.00			
Mg	0.02	0.73**	0.62**	0.04	− 0.04	0.66**	0.43**	0.77**	0.80**	1.00		
K	0.02	0.19**	0.30**	0.14*	0.15*	0.20**	0.16**	0.13*	0.21**	0.28**	1.00	
Ca	0.01	0.74**	0.54**	− 0.03	− 0.02	0.40**	0.19**	0.33**	0.17**	0.29**	0.03	1.00

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

Table 5 Comparison of WQI with WHO and SLS 614:2013 water quality guidelines

Water Quality Parameter	WHO	SLS 614:2013	Consideration for the WQI	WQI Category	Samples (%)	Exceeded parameters
pH	6.5–9.2	6.5–8.5	Considered	< 24 (Excellent)	21.5	None
EC	300	750–3500	Not considered	25–49 (Good)	21.2	HCO_3^- Ca^{2+} Mg^{2+}
Nitrate	50	10	Considered	50–74 (Poor)	20.0	PO_4^{3-} F^- HCO_3^- Ca^{2+} Mg^{2+}
Phosphate	–	2	Considered	75–100 (Very poor)	10.0	PO_4^{3-} F^- HCO_3^- Ca^{2+} Mg^{2+}
Sulfate	250	250	Considered	> 100 (Unsuitable)	27.3	PO_4^{3-} F^- HCO_3^- Na^+ Ca^{2+}
Fluoride	1.5	1	Considered			
Chloride	250	250	Considered			
Bicarbonate	–	200	Considered			
TH	500	250	Considered			
Sodium	200	200	Considered			
Magnesium	50	30	Considered			
Potassium	–	200	Considered			
Calcium	75	100	Considered			

and gneisses (Malaviarachchi et al. 2021). These hornblende and biotite rocks has been identified as F^- bearing minerals (Wilson et al. 2013). Thus, basement rocks in the area seem highly favorable subsurface sources supplying F- to the groundwater. Though it is not known with certainty that the host rock where rock–water interaction taking place is same as the bedrock exposed where the wells are located, thick rock profiles of hornblende and biotite bearing rocks with low dip angles are very likely to host for the wells. Also, as explained by Karunaratne and Pathmarajah (2002), the underlying basement rock in the study area consist of shallow regolith aquifers (2–10 m) and deep fracture zone aquifers (> 30–40 m) with fractures allowing a long residence time for groundwater. Therefore, these bedrocks are capable of activating the processes of dissolution of F- in the groundwater and increase the F^- concentrations of the groundwater (Rao et al. 1993). Saxena and Ahmed (2003) explained that the alkaline nature of the groundwater could increase the F- levels as the alkaline water can mobilize F^- from minerals. Moreover, Gibbs plots were employed to understand the relationships between functional sources of dissolved chemicals due to influences of controlling processes such as water–rock interaction, evaporation, and precipitation in water (Gibbs 1970). In this study, the majority of the groundwater samples were distributed in the rock weathering zone indicating the groundwater is primarily controlled by the chemical weathering of rocks (Srinivasamoorthy et al. 2012) (Fig. 8).

Relationship between WQI and the spatial distribution of chronic kidney disease of uncertain etiology

The prevalence of the CKDu in the UP, Sri Lanka has received much attention recently and many scientists assumed and proposed that persistent consumption of poor quality drinking water might be the root causes for the progression of the disease (Bandara et al. 2008; Chandrajith et al. 2011b; Dissanayake 2005; Gunatilake et al. 2014; Ileperuma et al. 2009; Jayasumana et al. 2013; Wanigasuriya et al. 2011). As explained by Perera and Gonawala (2008), approximately 85% of rural people in the UP obtain drinking

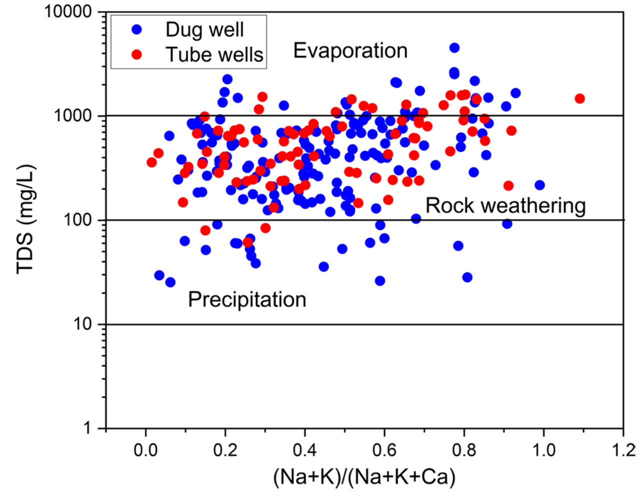


Fig. 8 Gibbs diagrams, illustrating the mechanisms controlling the chemistry of groundwater samples

water from dug wells and tube wells. Therefore this study aims at investigating the relationship between WQI and the prevalence of CKDu to check whether water quality directly impacts on CKDu in the UP. The UP of Sri Lanka consists of twenty-six Divisional Secretariat Divisions (DSDs) as shown in Fig. 9a. The spatial distribution of CKDu patients of the UP was developed based on the results of the survey that has been conducted by de Alwis and Panawala (2019). According to de Alwis and Panawala (2019), each DSD of the UP have been categorized into five categories as shown in Fig. 9b. According to the developed map, Mahiyanganaya is the highest vulnerable DS division for CKDu while Madulla, Medagama, and Katharagama are the lowest vulnerable DS divisions for CKDu in the UP. Katharagama may be recorded as the lowest vulnerable due to the majority of the Katharagama area is covered by the Yala national park. Also, using the ArcGIS 10.4 mapping software the statistical data of WQI of each DS division were extracted as shown in Table 6.

Ultimately the correlation coefficient between WQI and the CKDu distribution was evaluated. According to the results, WQI has a strong positive correlation (0.68) with the spatial distribution of CKDu patients in the UP. That means, it can be inferred that groundwater quality has a significant effect on CKDu distribution in the UP. Since F^- has the most significant correlation (0.96) with WQI, ultimately it can be hypothesized that in the UP CKDu directly has

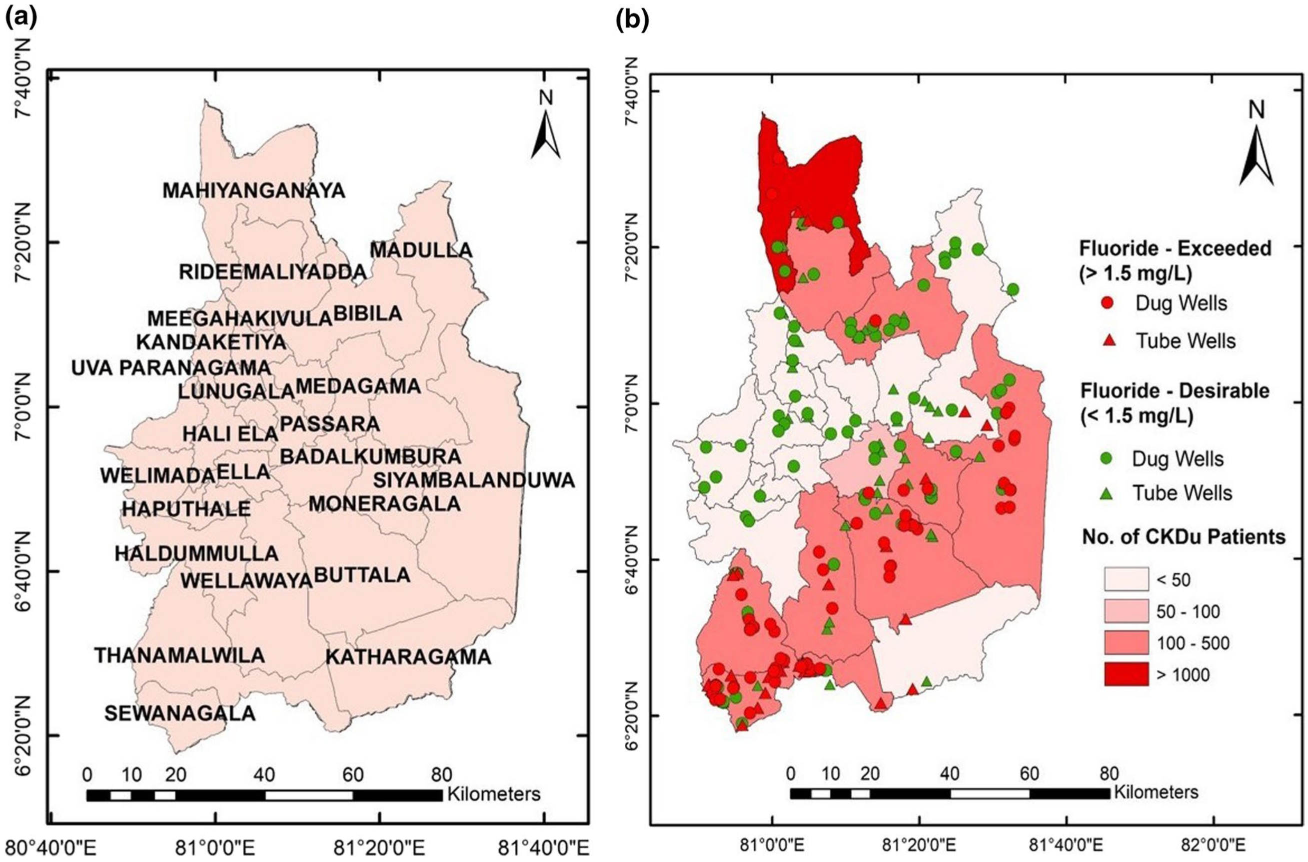


Fig. 9 **a** Map showing DS divisions of the UP, **b** map showing the spatial distribution of CKDu patients' density in the UP

Table 6 Statistical data of WQI in each DS divisions

Ds division	Minimum (WQI)	Maximum (WQI)	Standard deviation (WQI)	Mean (WQI)
Badalkumbura	21.04	69.21	8.07	37.46
Badulla	16.29	55.58	6.25	36.52
Bandarawela	8.05	39.60	5.39	23.16
Bibila	3.75	42.76	5.43	19.12
Buttala	27.46	158.43	28.51	85.73
Ella	21.56	44.69	4.64	26.80
Haldummulla	21.34	120.66	20.61	66.32
Hali ela	19.14	56.67	5.97	31.67
Haputhale	7.39	47.16	8.06	24.77
Kandaketiya	30.98	63.84	3.23	44.98
Katharagama	50.24	119.97	13.25	85.66
Lunugala	11.75	41.91	6.95	21.66
Madulla	3.42	103.97	17.13	30.94
Mahiyanganaya	28.46	174.86	22.60	86.78
Medagama	13.46	28.36	3.73	21.74
Meegahakivula	11.55	83.33	13.44	40.48
Moneragala	25.59	75.09	7.86	45.84
Passara	16.43	44.09	6.66	27.96
Rideemaliyadda	2.90	174.86	22.10	43.82
Sewanagala	15.01	332.13	45.98	98.62
Siyambalanduwa	2.03	129.90	16.91	68.37
Soranathota	35.76	57.37	3.48	44.49
Thanamalwila	17.99	182.00	22.67	96.04
Uva paranagama	18.56	47.98	5.99	32.92
Welimada	18.52	48.77	6.64	29.98
Wellawaya	29.54	210.65	27.78	95.32

a relationship with F^- content in groundwater. Moreover, Chandrajith et al. (2011b) explained that kidney tabular damages are possible due to the formation of CaF_2 which is insoluble in water. Further, he observed that a low Na/Ca ratio in groundwater is favorable to form CaF_2 complex, which enhances the toxicity of F- ions in the human body and the incidence of CKDu in endemic CKDu regions. The spatial distribution map of the F^- in UP shows that the areas where high F^- varied in the Moneragala district overlapped with high CKDu prevalent areas indicating to some extent, that the F^- content of drinking water might contribute to the CKDu (Dissanayake and Chandrajith 2017).

Conclusions

In this study, WQI method was applied to investigate the water quality status of the UP of Sri Lanka. Out of the analyzed samples 21.5%, 21.2%, 20.0%, 10.0%, and 27.3% are categorized under excellent, good, poor, very poor, and unsuitable category respectively in terms of the WQI. Moreover, based on the results it can be determined that the groundwater quality has a significant effect on the CKDu distribution in the UP. Since F^- has the most significant correlation with WQI, ultimately it can be inferred that, in the UP, CKDu directly has a relationship with F^- in groundwater. These various water quality indices can be effectively used as a valuable tool for policymakers to be able to recognize the status of the water quality in a specific area of interest and to have the capability to make suitable decisions regarding the management of natural groundwater sources. This study has shown the valuable combination of GIS and WQI to monitor and assess groundwater quality in any area of the world.

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C.B.Dissanayake. Acquisition of data, Analysis and interpretation of data and Drafting of manuscript: I.D.U.H. Piyathilake.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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