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Statistical Tool to Address the Influence of Urbanization in Groundwater Quality in Colombo District, Sri Lanka

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ABSTRACT: Management of groundwater quality is becoming a key feature of a sustainable future while implementing sustainable development goals which are given by United Nations. During past decades, rapid land-use changes, urbanization, and population expansion are highly influenced the groundwater quality. To provide policymakers and water managers with reliable information on groundwater quality is a challenge to achieving sustainable development goals in developing countries. Therefore, this study intended to assess the spatial variability of groundwater quality using selected physicochemical parameters at the 39 available groundwater wells during the southwest monsoon period. Spatial variability is explained in 13 Divisional Secretariat Division (DSD) levels in Colombo district due to easier interpretation and management purposes. Afterward, groundwater quality was related to urbanization using population density and built-up density in 13 DSD levels in Colombo district, Sri Lanka. PCA (Principal Component Analysis) shows that 08 DSD levels are urban and 05 DSD levels are rural. pH (3.22–6.73), COD (8.91–52.9 mg/L), BOD_5 (1.2–9.9 mg/L), and DO (2.17–5.05 mg/L) showed deviations from the given standards by local authorities in Sri Lanka. A significant relationship ($p < .05$) was found between urbanization and physicochemical parameters in regression analysis. The water quality index shows poor water quality indices in urban areas and *vice versa* in rural areas which is similar to the results obtained by statistical analysis. A sustainable urban development plan with continuous groundwater quality monitoring is necessary to protect groundwater resources in Sri Lanka.

KEYWORDS: Colombo district, urbanization, groundwater quality, PCA, sustainable development

TYPE: Original Research

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Introduction

Spatial distribution of groundwater is higher than the surface water while temporal variability of groundwater is less than the surface water. Groundwater is less exposed to pollution than surface water. However, restoration or clean-up procedures are extremely difficult and expensive in case of pollution. Even though many natural and anthropogenic pollution triggering factors are available, they can be varied in different countries due to their geographical location and development status. There are many direct and indirect associations between urbanization and groundwater degradation because groundwater contamination in the urban environment is influenced by various numbers of potential contamination sources (Misra, 2011).

Domestic, commercial, and industrial wastes from urbanized areas are among the prime sources of pollution (Azzellino et al., 2019; Bougherira et al., 2014; Villholth & Rajasooriyar, 2010). On the other hand, increased agricultural use of fertilizers and pesticides are major threats to groundwater quality in rural areas (Elhatip et al., 2003; Hildebrandt et al., 2008; Jeyaruba & Thushyanthy, 2009). These pollutants can percolate into aquifers through seepage and contribute to polluting the groundwater (Kuruppuarachchi, 2012; WHO, 2011). Groundwater resources are widely used for domestic, agriculture, commercial, and industrial purposes, and hence, the demand for groundwater is steadily increasing in Sri Lanka (Herath, 2007; Rajasooriyar et al., 2013). Such large demands on groundwater have caused exploitation and at the same time, groundwater quality in the Colombo district is triggered by both natural and anthropogenic sources (Gunawardhana et al., 2002; Herath & Ratnayake, 2007; Mahagamage et al., 2015; Rathnasri & Manage, 2016). But the monitoring and management of groundwater resources have not been prioritized by the authorities.

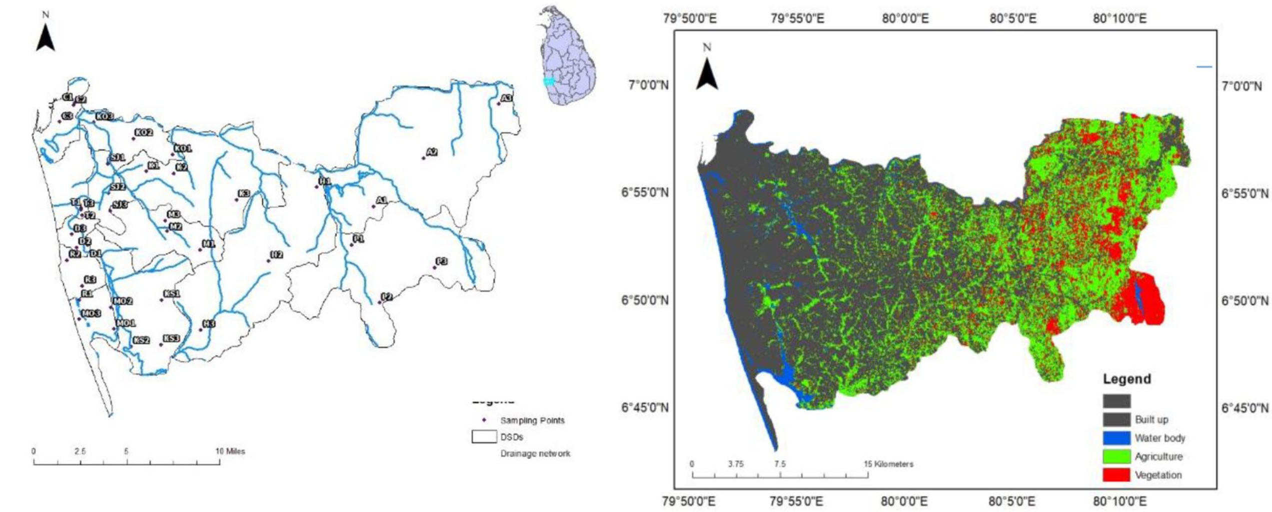
Statistical tools are successfully utilized by researchers for analyzing spatial distribution of the physicochemical characteristics of groundwater over large areas. In addition, many studies have integrated statistical techniques and approaches to establishing strategies to manage groundwater resources (Arulbalaji & Gurugnanam, 2017; Gulgundi & Shetty, 2018).

Therefore, this study aims to assess the groundwater quality by analyzing the selected physicochemical parameters and correlating them with urbanization in the Colombo district.

Methodology

Study area

Rapidly urbanizing Colombo district in western province, Sri Lanka was selected as the study area (Figure 1a). It consists of 13 Divisional secretariats divisions (DSDs) and a total area extent of about 699 km^2. The total population is about 2,375,000 according to the 2015 statistics. Western part of the study area is exposed to the ocean and other directions of the study area are exposed to landmasses of Gampaha, Kegalle, Ratnapura, and Kalutara districts. Drainage network is drained off to the ocean (Figure 1a).



(a) (b)

Figure 1. (a) Study area with sampling points in DSDs and drainage network. (b) Major land use classes.
Note: Blue-water; light green-Agriculture; gray-Built up; Red—Vegetation.

Major land-use classes (built-up, industrial areas, agriculture, waterbody, vegetation) in Colombo district are shown in Figure 1b (Antalyn & Weerasinghe, 2020). The major aquifer types in the study area are alluvium aquifer, laterite (cabook), and a few crystalline limestone (marble) bands. These aquifers are recharged and expand mainly during the wet season and contract during the dry season (Gunawardena & Pabasara, 2016).

Selecting groundwater sampling sites

From each DSD, 3 locations were selected randomly according to the availability of open drinking water wells to cover the entire Colombo district by making altogether 39 well locations (Figure 1a).

Since groundwater does not have a boundary, DSDs were selected as the hypothetical boundary for the analysis of the study and to facilitate interpretation of the results. Therefore, sampling points were selected randomly as three sampling wells from each DSD. In this study the spatial variation is considered but not the temporal variation is considered, hence sampling intervals were not included.

Physicochemical parameters for groundwater quality assessment

Sampling was carried out during the southwestern monsoon from June 2018 to September 2018. From each well, three water samples were collected randomly to make 3 replicates from each well at once during 9 am to 11 am to estimate the errors in the procedures. Standard Errors (SE) show the accuracy level of each method followed. The depth of the wells ranged from 10 to 15 m and water levels ranged from 5 to 10 m from the ground surface. Samples were collected between 0 and 3 m from the water level in open wells by bailing with a clean container. Filtration was done before determining nitrate - N concentration. Preservation was done to the collected samples of Nitrate—N, Total phosphate, Total Suspended Solids (TSS), and Chemical Oxygen Demand (COD) then transported to the laboratory of the Department of Zoology and Environmental Management. Samples were stored at 40°C temperature until to conduct the standard laboratory testing. Selected *in-situ* and *ex-situ* physicochemical parameters were measured using methods as mentioned in Table 1. Standard procedures were followed, and calibrated instruments were used to achieve accurate and reliable results. Instruments were calibrated at room temperature which was ranged from 30°C to 32°C. The results were compared with locally proposed ambient water quality standards.

Data analysis

Collected data showed normal distribution. Principal Component Analysis (PCA) was used to categorize urbanization in Colombo district as urban and rural DSDs in the study area. Regression analysis was done to find the correlation between groundwater quality and the urbanization of the study area.

Categorize urbanization in Colombo district as urban and rural areas using PCA. In order to characterize urbanization in Colombo district, the indicators of population density and built-up density of each DSD level (Table 2) were used. Population data were obtained from Department of census in Colombo, Sri Lanka. The latest land uses of each DSD were obtained from the literature (Antalyn & Weerasinghe, 2020). Population density was derived by dividing usable area of each DSD. Here DSDs were used to visualize and interpret the urbanization in Colombo district effectively.

Table 1. Selected Physicochemical Water Quality Parameters.

WATER QUALITY PARAMETERS	STANDARD METHOD/INSTRUMENT
In-situ parameters	
pH	Calibrated Multimeter HACH/Model: Hq40d multi parameter
Electrical conductivity	Calibrated Multimeter HACH/Model: Hq40d multi parameter
Total solids	Calibrated Multimeter HACH/Model: Hq40d multi parameter
Salinity	Calibrated Multimeter HACH/Model: Hq40d multi parameter
Dissolved oxygen	Calibrated Multimeter HACH/Model: Hq40d multi parameter
Temperature	Calibrated Multimeter HACH/Model: Hq40d multi parameter
Ex-situ parameters	
Chemical Oxygen demand	5220C Closed Reflux, Titrimetric Method
Biochemical oxygen demand	5210B 5-day BOD Test
Nitrate nitrogen concentration	45004,500-NO^3-B Ultraviolet, Spectrophotometric Screening Method
Total phosphate	4500-P E. Ascorbic Acid Method
Total suspended solids	2540D Total Suspended Solids dried at 103°C–105°C

Source. APHA (2012).

Table 2. Population Density and Built-Up Density of DSDs.

ID	DSD	POPULATION	POPULATION DENSITY	BUILT-UP DENSITY
1	Colombo	330,301	18,974.3	0.891
2	Thimbirigasyaya	243,245	10,573.6	0.877
3	Dehiwala	90,901	11,325.5	0.932
4	Rathmalana	97,587	7,459.4	0.863
5	Moratuwa	171,947	8,881.2	0.808
6	Kolannawa	195,864	7,237.8	0.714
7	Kotte	110,277	6,682.5	0.800
8	Maharagama	200,703	5,409.9	0.705
9	Kesbewa	250,576	4,030.0	0.584
10	Kaduwela	257,533	3,023.4	0.494
11	Homagama	243,089	2,071.6	0.369
12	Hanwella	116,287	795.8	0.108
13	Padukka	66,689	634.2	0.099

Source. Department of Census, Sri Lanka (2015) and Antalyn & Weerasinghe, 2020).

Population density and built-up density were subjected to PCA considering all the DSDs using MINITAB version 14.0 software package. A score plot was used to group rural and urban DSDs in Colombo district. Positive PC1 (Principal Component 1) areas were considered as urban areas and negative PC1 areas were considered as rural areas (Table 5). The scores of the principal components were stored in specified columns as PC1_UI (Principal component 1 for Urban indicators) for regression analysis. Scores are the linear combinations of the data using the coefficients.

Groundwater quality analysis using physicochemical parameters. In order to relate with the urbanization, physicochemical parameters of groundwater wells were also determined for the DSD levels. Hence mean value (± *SE*) of groundwater samples in each DSD was taken to represent the groundwater quality of

Table 3. Classification of Water Quality Index.

WQI	SUITABILITY FOR DRINKING PURPOSES
<50	Excellent
50–100	Good water
100–200	Poor water
200–300	Very poor water
>300	Unsuitable for drinking

the particular DSD. Mean values were compared with the proposed ambient water quality standards for inland waters. Administrative area of DSD was used as a hypothetical area boundary for the study, to do the regression analysis between urbanization and groundwater quality in Colombo. Groundwater quality visualization at the DSD level will be an advantage for policymakers in their decision-making toward sustainability as well as water managers to implement their strategies at the administrative level.

Mean values of physicochemical parameters were subjected to PCA using MINITAB version 14.0 software package. The scores of the principal components were stored in specified columns as PC1_WQ (Principal Component 1 for water quality parameters) for regression analysis.

Regression analysis of groundwater quality and urbanization in Colombo district. The stored scores of principal components (PC1_WQ) which is derived from the analysis of physicochemical parameters (dependent variables) were plotted against the stored scores of principal components (PC1_UI) which is derived from the analysis of urbanization indicators (independent variables). The regression analysis results were used to describe the association between physicochemical parameters and urbanization. The first principal components (PC1) with large values were used for explaining the regression plot.

Calculation of WQI in DSDs. WQI (Water quality index) was calculated using pH, TDS, DO, COD, TSS, BOD_5, nitrate, and phosphate. The methodology for calculating WQI was similar to the study done by Rathnasri and Manage (2016).

A weight value from a scale of 1 to 5 was assigned for each of the eight parameters. Parameters with major importance were assigned the maximum weight value of 5. The relative weight was calculated using the following equation.

$$Wi = wi / \sum_{i=1}^{n} wi \qquad \text{Eq1}$$

Where Wi is the relative weight of ith parameter, wi is the assigned weight of the ith parameter. A quality rating scale for each parameter was assigned using the following Equation.

$$qi = 100Ci / Si \qquad \text{Eq2}$$

Where qi is the quality rating, Ci is the concentration of each physicochemical parameter in each water sample and Si is the Sri Lankan drinking water standard or each physicochemical parameter. To calculate the WQI the SI value for each parameter was calculated using the following equation.

$$SIi = Wi / qi \qquad \text{Eq3}$$

Where SIi is the sub-index of ith parameter and Wi is the relative weight of ith parameter and qi is the quality rating. Then the WQI was determined by the following equation.

$$WQI = \sum_{i=1}^{n} si \qquad \text{Eq4}$$

Where n is the number of physicochemical parameters measured in each well water sample. The computed WQI values were classified into five types from excellent water to water unsuitable for drinking (Table 3).

Results and Discussion

Urbanization in Colombo according to the indicators of urbanization

The PCA analysis of urbanization indicators showed eigenvalues of 1.8129, 0.1871, and proportions of 0.906, 0.094 respectively. Since the PC1 component explains 90.6% (proportion of 0.906) of the variations of population density and built-up density, PC1 was used to classify DSDs in Colombo district into urban and rural categories based on population density and built-up density. The results of urbanization in Colombo district shows as urban and rural DSDs are shown in Figure 2.

Spatial variation of selected groundwater physicochemical parameters of Colombo district

Mean values of groundwater physicochemical parameters are shown below in DSD levels of Colombo district. Local standards are also shown in the graphs for visual interpretation.

The mean pH values of the wells ranged from 3.22 to 6.73. The wells in urban (Colombo-1) DSD showed highest mean pH value while the wells in rural (Kesbewa-9) DSD showed the lowest mean pH value. The mean temperature values of the wells ranged from 27.77°C to 31.26°C. The wells in urban DSD (Dehiwala-3) showed highest mean temperature value while the wells in rural DSD (Padukka-13) showed the lowest mean temperature value. The mean DO values of the wells ranged from 2.17 to 5.05 mg/L. The wells in urban DSD (Kotte-7) showed highest mean DO value while the wells in rural DSD (Hanwella-12) showed the lowest mean DO value. The mean COD values of the wells ranged from 8.91 to 52.9 mg/L. The wells in urban DSD (Moratuwa-5) showed highest mean COD value while the wells in rural DSD (Kaduwela-10) showed the lowest mean COD value. The mean TSS values of the wells ranged from 1.50 to 6.17 mg/L. The wells in urban DSD (Moratuwa-5) showed highest mean TSS value while the wells in rural DSD (Hanwella-12) showed the lowest mean TSS value. The mean BOD values of the wells

Figure 2. Illustration of urbanization of Colombo district using DSDs as urban and rural.

ranged from 1.2 to 9.9 mg/L. The wells in urban DSD (Thimbirigasyaya-2) showed highest mean BOD value while the wells in rural DSD (Padukka-13) showed the lowest mean BOD value. The mean nitrate-N values of the wells ranged from 1.31 to 5.6 mg/L. The wells in urban DSD (Thimbirigasyaya-2) showed highest mean nitrate-N value while the wells in urban DSD (Rathmalana-4) showed the lowest mean nitrate-N value. The mean total phosphate values of the wells ranged from 0.0027 to 0.081 mg/L. The wells in rural DSD (Hanwella-12) showed highest mean total phosphate value while the wells in urban DSD (Kotte-7) showed the lowest mean total phosphate value. The mean conductivity values of the wells ranged from 89.8 to 457.7 µS/cm. The mean TDS values of the wells ranged from 39.0 to 221.0 mg/L. The mean salinity values of the wells ranged from 0.04% to 0.22%. Mean values of conductivity, TDS, and salinity were high in the wells in urban DSD (Thimbirigasyaya-2) while the wells in rural DSD (Hanwella-12) showed the lowest. pH (3.22–6.73), COD (8.91–52.9 mg/L), BOD_5 (1.2–9.9 mg/L), and DO (2.17–5.05 mg/L) showed deviations from the given standards by local authorities in Sri Lanka. The results of the regression analysis between urbanization and groundwater quality parameters will effectively discuss the above results in section 3.4.

Results of PCA analysis for groundwater physicochemical parameters and urbanization indicators

The summary of Eigenvectors, and stored principal component scores of PCA analysis based on physicochemical parameters and urbanization indicators are given in Tables 4 and 5. These values were used in regression analysis.

Table 4. Eigenvectors (Loadings).

VARIABLES	PC1
pH	−0.347
Temperature	−0.391
TDS	−0.434
Salinity	−0.433
DO	−0.018
COD	−0.366
TSS	−0.096
BOD	−0.396
Nitrate—N	−0.119
TP	0.189

Coefficients in the linear combinations of variables making up PC's.

Results of regression analysis of PC1_WQ vs PC1_UI

The principal component scores PC1_UI were plotted against principal component scores PC1_WQ to analyze the association (Figure 5). It shows R^2 value of 62.3% at a *p*-value of .001.

In these results, the *p*-value is .001 which is less than the significance level of .05. These results indicate that the association between PC1_WQ and PC1_UI is statistically significant. The graph explains 62.3% (R^2) of the variation of the data and the R^2 value indicates that the model fits the data well. Figure 4 shows that groundwater wells in urbanized DSDs (DSD No 1,2,3,4,5,6,7, and 8) have relatively higher temperature, TDS,

Table 5. Principal Component Scores of Urbanization and Water Quality.

ID	DSD	PC1_WQ	PC1_UI
1	Colombo	−0.95576	2.34502
2	Thimbirigasyaya	−4.16877	1.13819
3	Dehiwala	−1.68441	1.37846
4	Rathmalana	0.34150	0.66913
5	Moratuwa	−1.24195	0.73221
6	Kolannawa	−1.12262	0.27155
7	Kotte	−1.23805	0.40568
8	Maharagama	1.11969	−0.00570
9	Kesbewa	0.00279	−0.49603
10	Kaduwela	2.31411	−0.85798
11	Homagama	1.75767	−1.29840
12	Hunwella	3.05025	−2.11872
13	Padukka	1.82555	−2.16341

salinity, COD, BOD_5, and pH levels. In contrast groundwater wells in rural DSDs (DSD No 9, 10, 11, 12, and 13) show lower temperature, TDS, salinity, COD, BOD_5 and pH levels. Higher groundwater temperature in urban areas than rural areas may be due to more radiation absorption by roads and buildings, lack of vegetation resulting in loss of shades, and inhibited cooling by convection (Tran et al., 2006).

If COD value is high, the water is rich in organic matter and other oxidizable components (APHA, 2012) which indicate pollution. According to locally proposed ambient water quality standards, the standard level of COD should be below 15 mg/L for drinking purposes. But most of the groundwater wells were above the limit and the highest mean values were observed in groundwater wells in Thimbirigasyaya (2), Moratuwa (5), and Kesbewa (9) DSDs. The reasons might be due to high urban runoff and sewage seepage from built-up areas (Fineza et al., 2014). Sewage and industrial contamination were detected through BOD and COD values. Similar results were obtained in other studies (Herath, 2007; Hettige et al., 2014). According to the PCA score plot, groundwater wells in urbanized areas show higher COD values than groundwater wells in rural areas. It may be happened due to wastewater contamination with groundwater through surface water since more industries are located in urbanized areas. It is important to monitor groundwater quality on a regular basis and encourage to installation and maintain wastewater treatment plants in the area. The overall conductivity, TDS, and salinity of groundwater in the study area show an increasing tendency toward the urbanized areas which are located along the coast and lower part of the drainage network. In high tide season, groundwater can be contaminated with seawater. Other than that, due to the accumulation of ionic compounds, contaminants via surface water runoff, and industrial effluent. Also, by natural regosols, soil type in the urbanized area contains a fair amount of weatherable mineral fragments which may contribute to higher EC and TDS (Moorman & Panabokke, 1961).

Saltwater intrusion is another factor that may contribute to the poor water quality in the coastal areas where most of the urbanized DSDs are located (Khan et al., 2011). The interference from seawater can be delineated by using TDS, conductivity, and salinity levels. If TDS values are between 0.998 and 998 mg/L or EC values are between 0 and 1,389 µS/cm, it is considered freshwater (Shin & Hwang, 2020). Another study states that electrical conductivity of groundwater up to 250 µs/cm as excellent, 250 to 750 µs/cm as good, and above 750 µs/cm is considered as poor groundwater quality (Thorne, 1954). Since the measured levels showed the highest TDS value of 221 mg/L and highest conductivity of 457.67 µS/cm, the possibility of seawater intrusion to the coastal aquifers is less likely.

According to the PCA score plot, most of the urbanized groundwater wells' pH falls within the standard range but groundwater wells in rural areas show below standard values. This can be due to natural acidification, including the pH values of red-yellow podzolic soils (generally pH below 6 and often below 5.5) (Moorman & Panabokke, 1961) and acidification from the precipitation, which in its natural state has a pH value of around 5.6. But pH values in rural areas show a significantly lower value ranging between 2.62 and 6.71 and most of them were below pH 5. According to locally proposed ambient water quality standards, the standard level of pH should range between 6 and 8.5 for drinking purposes. This may be due to the removal of crops and timber with nutrient

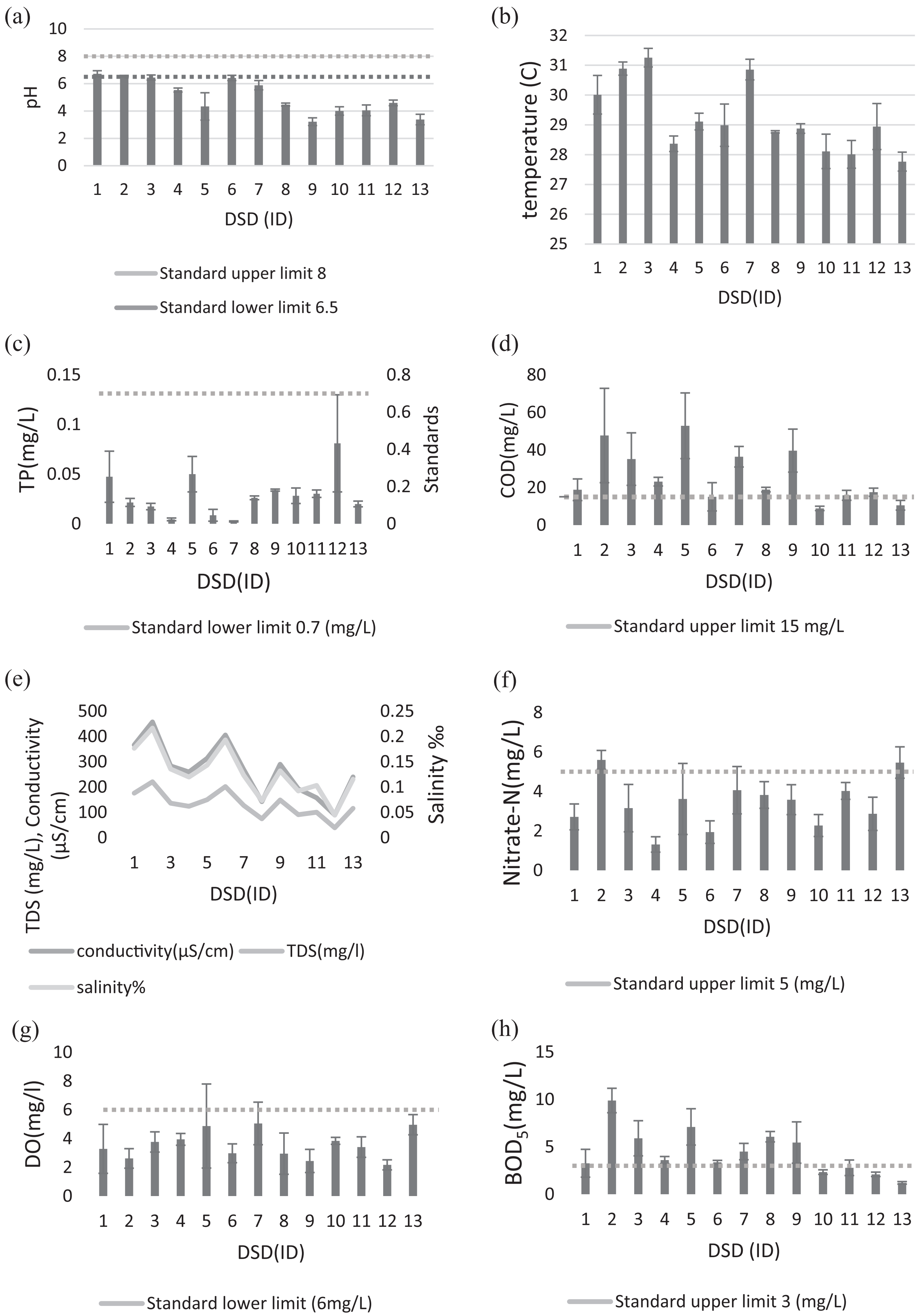


Figure 3. (Continued)

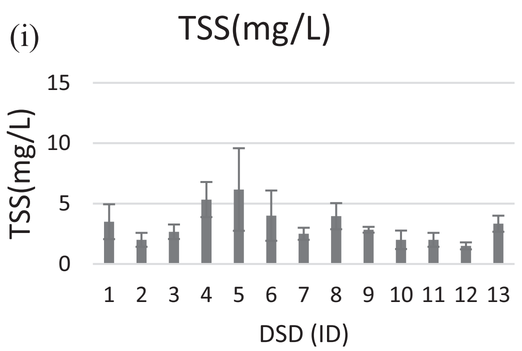


Figure 3. Physicochemical parameters (a) pH, (b) Temperature, (c) Total phosphorus, (d) COD, (e) TDS, Conductivity, Salinity (f) TSS (g) DO, (h) BOD_5, (i) TSS in 13 DSDs.

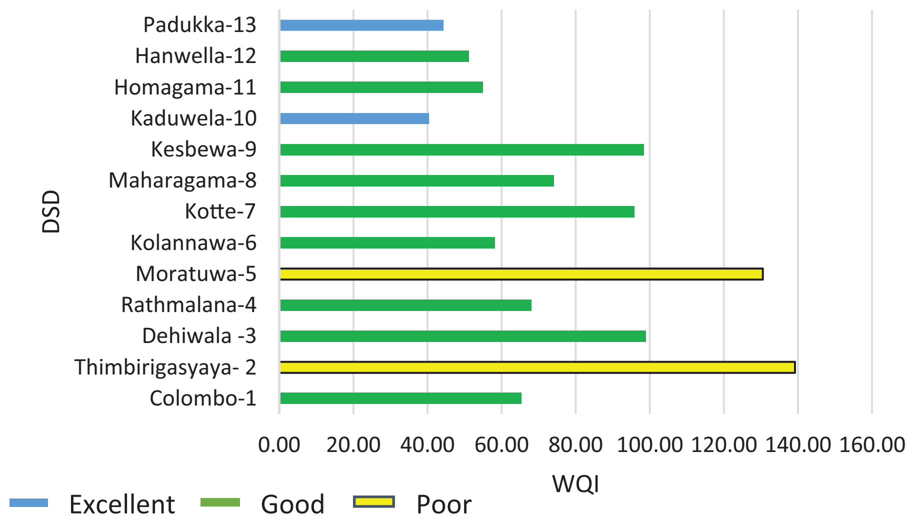


Figure 4. WQI of DSDs.

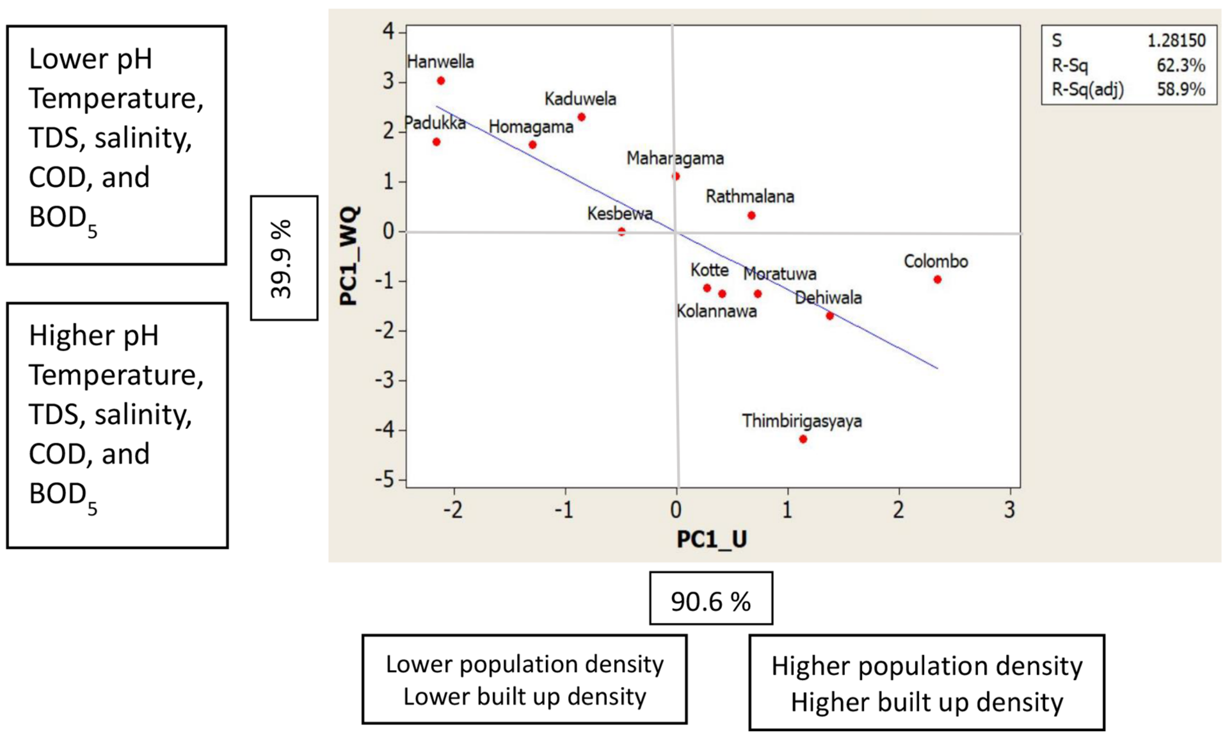


Figure 5. The fitted line plot of **PC1** scores of **urbanization indicators** (build up density and population density) versus **PC1** scores of **water quality parameters.**

uptake of bases, accumulated by long-term intensive cultivation in agriculture, plantations, and natural acidification which resulted in acidification of soils and further deposition by runoff. (Knutsson, 1994; Mikunthan et al., 2013).

No significant correlation was observed between Nitrate—N, TP with urbanization, but some groundwater wells showed higher Nitrate – N levels which are above 5 mg/L (Central Environmental Authority [CEA], 2001). The mean nitrate-N values of the wells ranged from 1.31 to 5.6 mg/L. The wells in Padukka (13) are located near intensive agricultural lands and usage of extensive nitrogen fertilizer application might cause increased nitrate-N levels and TDS levels (Jayasingha et al., 2011; Jeyaruba & Thushyanthy, 2009). Urban groundwater wells in Thimbirigasyaya (2) show an increase in nitrate-N levels due to the effect of non-agricultural nitrogen loading to the subsurface of these areas such as sewage, wastewater disposal from industries and domestic as well as septic tank leakages (Herath, 2007; Hettige et al., 2014).

Conclusion and recommendations

PCA and regression analysis can be effectively used for groundwater quality analysis. In this study, PCA scores were used to classify urbanization as urban and rural areas according to the population density and built-up density of the area. Further PCA scores can be used to classify water quality levels in the study area. WQIs have shown similar results. When considering the association between selected physicochemical parameters of groundwater quality with urbanization, it reveals that pH, salinity, TDS, temperature, COD, and BOD_5 show a significant negative association with urbanization but TP, Nitrate-N, DO and TSS do not show significant association with urbanization indicators. Also, it is observed that groundwater in rural areas showed lower pH values, and groundwater in urban areas showed higher salinity, TDS, temperature, COD, and BOD_5 levels. Long-term agricultural practices and the nature of soil have acidified the groundwater in Hunwella (12), Padukka (13), Homagama (11), Kaduwela (10), and Kesbewa (9). High urban runoff, sewage seepage from built-up areas cause higher COD, BOD_5 levels in urban groundwater wells in Thimbirigasyaya (2), Moratuwa (5), Dehiwala (3), Maharagama (8), and Kotte (7) DSDs.

The study suggests that the evaluation of water quality parameters as well as water quality management practices should be carried out to protect the groundwater resources. Prioritized policies for sustainable urban development and providing proper awareness to people about water quality surveillance programs, conducting an inventory of potential groundwater pollution sources and their management will help to minimize further degradation of groundwater resources in Colombo district, Sri Lanka. A continuous groundwater quality monitoring program is necessary to implement groundwater pollution control strategies in urban areas.

Declaration of conflicting interests

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