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# Urbanization and initial groundwater quality investigation in Malabe, Sri Lanka

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**Abstract**

Malabe, an eastern suburb of the capital city of Colombo, is one of the most rapidly urbanized and industrialized areas in Sri Lanka. Groundwater is a valuable resource in Malabe and it is being polluted. Malabe is located in a wet climatic zone with a lateritic aquifer that normally contains water with a very low pH that can cause quality problems. Our objective was to investigate and analyze the Malabe groundwater quality to understand the characteristics of significant parameters and their correlation so that policy planning can be correctly done. Groundwater samples from 16 water wells were collected and evaluated for eight physicochemical parameters, i.e., pH, turbidity, electrical conductivity (EC), color, nitrate ($NO_3$), nitrite ($NO_2$), sulfate ($SO_4$), and phosphate ($PO_4$). Two biological parameters were also determined for four wells. The essence of this finding is that the groundwater is very acidic, has a very low EC, but high coliform counts. Multivariable statistics of the data were performed using Pearson's correlation and principal components analysis (PCA) using the Princom package in the R statistical package. The first four principal components (PCs) explained 79.8 % of the total observed variance in the data. The most significant parameters from the first principal component, PC1, were the positive correlations of turbidity and $PO_4$, and negative correlations of EC and $NO_3$. A significant positive loading of pH with a negative loading of $SO_4$ was illustrated in PC2. These findings were similar to the correlation results. We concludes that the high acidity of the groundwater is primarily caused by industrial waste. The groundwater pollution of the Malabe area was not cause by inorganic fertilizer but by anthropogenic waste runoff. Our finding is crucial for groundwater quality management in the study area.

**Keywords:** Groundwater quality, Low pH, Principal component analysis, Malabe, Sri Lanka

## 1. Introduction

Groundwater is one of the most precious natural resources of Sri Lanka. It is scattered all over the country in six main aquifer types, i.e., Karstic, deep confined, regolith hard rock, unconsolidated coastal sand, southwestern lateritic, and alluvial aquifers [1-2]. The groundwater characteristics of Sri Lanka vary across the three climatic zones, i.e., dry, intermediate, and wet zones [3]. Malabe, the study location of this study, is a rapidly growing area in the southwestern part of the country. It is located in the wet zone with a lateritic aquifer. The groundwater of this aquifer typically has low pH and EC values those are dominated by anthropogenic activities, but it is not of geogenic origin [2-4]. This aquifer is highly heterogeneous with low mounds [2]. It is always depleted during the dry period of February and March. Then it is recharged with monsoon precipitation during the rest of the year [1]. This phenomenon suggests that the groundwater quality is certainly controlled by anthropogenic activities alone.

The groundwater characteristics of Sri Lanka have been shaped by its climate, topography, geology, and hydrology. The topography of Sri Lanka is unique, with a high mountain region along the central southern part of the country with elevations generally higher than 900 m. The highest point is 2500 m above sea level. The surrounding areas are flat with undulating terrain and rolling hills with elevations up to 100 m. The tropical monsoon is the dominant climate. The southwest monsoon brings heavy rains from the Indian Ocean from May to September. The northeast monsoon also brings lighter rain from a smaller part of the Indian Ocean between December and February [5]. The mountain range acts as a rain barrier. Therefore, the southwest monsoon rain falls upon only the smaller southwestern part of the country, while the northeast monsoon showers the rest of the country. This precipitation pattern separates the country into wet and dry zones with a transition between the two that is an intermediate zone. The wet zone occupies 23% of the country in the southwestern part of the country. It has a mean annual rainfall of >1900 mm while the dry zone covers 65% of the country land from northwestern to the southern region with a mean annual rainfall of <1500 mm (Figure 1). The intermediate region, situated between these two zones, makes up 12 % of the country. Ninety percent of this land consists of Precambrian crystalline non-fossiliferous rocks. The rest is Jurassic, Miocene, and quaternary sedimentary formations primarily located in the northwestern region [6].

As it was stated above, these four factors shape the hydrogeology of the country into six aquifer types, i.e., Jaffna karstic aquifers, northwestern sedimentary formation,

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metamorphic hard rock, coastal sand, alluvial, and lateritic aquifers [1-2]. The Jaffna karstic aquifers are the most studied and utilized. They are shallow limestone cavities underneath Jaffna Peninsula that are recharged by the northeastern monsoon rain. Due to the paucity of surface water, groundwater is the primary source of water for domestic use and irrigation in the region. The pH, EC and nitrate values of this water are quite high. Fresh water lenses float above saline water, therefore over extraction must be avoided [7]. The northwestern sedimentary aquifers, the second type, are also Miocene in age but they were formed at greater depths and are confined or semi-confined in nature. They are located along the northwestern coast up to the north of the country, but are located in separate and discrete basins [8] with similar characteristics to the Jaffna aquifers. The third aquifer group consists of metamorphic hard rock. These occupy a large part of the central north and the far south [9]. This aquifer group consists of two layers. The first is a shallow regolith layer and a deep fractured layer [10]. This aquifer type is sporadic and of low yield. Their pollution sources are geogenic in nature and their waters have fairly high EC values [11]. The fourth type is the coastal sand aquifers which lie along most of the coastal plain of the country. Most of them are shallow unconfined and unconsolidated sand layers except for those on the northwestern coastal plain. They are a Pleistocene deposit and are moderately deep. These aquifers have relatively high pH and EC values. They should not be over exploited to prevent sea water intrusion [12]. Alluvial deposits are the fifth aquifer type. They run along river floodplains all over the country. These aquifers are mostly unconfined and unconsolidated river sand and gravel layers of variable depth and thickness. The groundwaters of these aquifers are high in nitrate and fluorite. The last aquifer type is laterite aquifer, which is the focus of this study.

Lateritic aquifers are found in the southwestern part of the country, which is in the wet zone. This area includes Gampaha, Colombo, Kalutara, and part of Galle-Matara. They extend from the coast to more than 10 km inland and up to 30 m above sea level [2]. The typical profile of this type of aquifer consists of a thin sheet of gravelly soil overlaying a 10-15 m thick layer of laterite with an underlying kaolinitic layer. The main portion of these aquifers is lateritic. Their middle layer has a vesicular honey comb structure of high porosity and hydraulic conductivity. Since they are unconfined, they are replenished quickly during rain storms and also rapidly recede during the dry period between February and Match [13-14]. Well yields are variable depending on the lateritic characters of the aquifers. For example, the laterite portion of the aquifer at Ragama Township is partly filled with particulate kaolin. Therefore the well yields are only about 25 $m^3$/d. However, at Gongitota, the clean laterite allows for well yields up to 300 $m^3$/d, which is 12 times higher than in Ragama [2].

Groundwater quality characteristics of each aquifer vary spatially and with time depending on both natural and anthropogenic factors. The geology of the aquifers and its environments determine its geogenic groundwater quality. Human activity at recharging zone is the cause of anthropogenic influences on the aquifer. The groundwater of the country can be geogenically classified into four types containing Ca, Mg, Na/K, and non-dominant cations [15]. The dry zone aquifers are abundant in Na/K ions whereas the wet zone aquifers contain Ca and non-dominant cations. The intermediate zone aquifers are intermediate in nature. In the semi-arid dry region, groundwater recharge always requires short periods with longer resident times. Therefore, natural processes dominate groundwater quality. In the humid tropical wet zone, the non-recharging period is only 2-3 months. Here, anthropogenic processes dominate groundwater quality. A recent study of groundwater quality for all three climatic zones found that (i) the mean pH values were 6.63, 7.04, and 7.20 for wet, intermediate, and dry zones, respectively, (ii) the mean respective EC values were 275, 465, and 1066 μS/cm, and (ii) the nitrate mean values were 1.5, 3.6, 1.0 mg/L, respectively [3]. The pH values of the groundwater in the wet, intermediate, and dry zones were acidic, neutral, and alkaline, respectively. The acidic feature of the wet region may due to its lateritic porous media [3]. For example, the mean pH values of groundwater from a lateritic aquifer at Kerana in southwestern India were 6.0 and 6.5 for pre- and post-monsoon periods, respectively [16]. The mean EC values show theat groundwater contamination in all three zones is increasing. The highest concentration of nitrate was in the intermediate zone and the lowest was in the dry zone. The high nitrate concentration results from extensive use of fertilizer and human waste disposal [17].

The literature further gives several past studies of the groundwater quality analysis of the country. These analyses can be categorized into two sub-groups, i.e., those of the dry and wet zones of the country. Jayawardana et al. [18] showed the variation of groundwater quality across the dry and wet zones of Sri Lanka. Dissanayake [19] tested groundwater samples in Anuradhapura and Pollonnaruwa districts relating them to dental fluorosis and kidney diseases. Two districts are in north-central province and two are in the dry zone. It was found out that the fluoride levels were greater than the WHO recommended values for drinking purposes. Chemical water quality tests were carried out by Mikunthan and De Silva [20] in other dry zones in Sri Lanka in the north of the country. In groundwater quality analysis on the Jaffna peninsula, over 40 wells showed unacceptable groundwater quality due to heavy fertilizer usage. Edirisinghe et al. [21] did groundwater quality analysis in another dry zone, the Puttlam district. Similar findings were presented. Over-extraction led to increases concentrations of the water quality contaminants. A detailed groundwater quality analysis in the wet zone of the country was done by Song *et al.* [22]. Rathnasiri and Manage [23] conducted a groundwater quality analysis in the Maharagama area of Sri Lanka. They tested 55 wells and found that the groundwater was polluted due to anthropogenic activities. Maharagama is in the Colombo district and it is a suburb near Malabe (about 8 km away). Similar to Malabe, Maharagama is heavily populated and there is rising concern about groundwater quality.

Conducting water quality tests for groundwater is not easy. Field work is required to collect groundwater samples from wells and then these should be processed in laboratories for different water quality constituents. The cost for water quality tests is high. Therefore, selecting the most appropriate parameters for testing is essential.

Groundwater quality maps are popular among planners. They use pre-drawn groundwater quality maps or contours for various planning and development activities. Pebesma and Kwaadsteniet [24] obtained 25 groundwater quality parameters and plotted them with a 4 km x 4 km resolution in the Netherlands. This research used more than 400 monitoring sites across the country. These maps can be further used for quantifying groundwater contamination and as inputs for various groundwater models applied across the Netherlands. Similar studies for various countries can be found in numerous research articles, e.g., [25-30]. However, a comparable study is yet to be conducted in Sri Lanka.

Additionally, principal components analysis (PCA) is very popular and useful among researchers doing groundwater quality modelling. Interpretation of groundwater quality constituents is rather simple using PCA [31-32]. There are numerous examples of the application of PCA in groundwater quality analysis around the world [33-38].

There is a clear research gap along the lines of groundwater quality analysis in Malabe, Sri Lanka. Therefore, this research was done to measure groundwater parameters and to develop groundwater quality contours in the Malabe area. The research was further extended to statistically analyze the measured water quality parameters and to interpret the groundwater quality in of Malabe, Sri Lanka.

## 2. Study area

Malabe is a suburb in the Colombo district and has been recognized as an area of very high urbanization over the last two decades. The city was declared by the government as "Sri Lanka's future cyber city" in late 1990's. After that, there were many important establishments in the surrounding areas, including Millennium IT (an IT firm), the Sri Lanka Institute of Information Technology (SLIIT Campus), the CINEC higher education institute and the South Asian Institute of Technology and Medicine (SAITM). Additionally, the Biyagama Board of Investment free trade zone is a major industrialized area nearby. The entire infrastructure in surrounding areas have increased the impervious areas of the suburb and thus reduced groundwater recharge. The development projects increased not only the working community in the area but also the number of permanent residents (Table 1).

**Table 1** Population of Malabe, Sri Lanka

| Division | Year 2001 | Year 2012 | Percent Increase |
|---|---|---|---|
| Malabe, North | 5653 | 7680 | 36% |
| Malabe, East | 3963 | 5958 | 50% |
| Malabe, West | 5050 | 5141 | 2% |
| Hokandara, North | 5057 | 6238 | 24% |
| Total | 19723 | 25017 | 27% |

Urbanization not only increased the volume of runoff but also the pollutant loads, including oil, grease, metals and various other contaminants. A portion of these pollutants reached the nearby groundwater resources by the infiltration. Had there been greater area for infiltration, lower concentrations of pollutants would have been absorbed by the soil layers [2]. Additionally, the suburb is located in the wet zone of the country (Figure 1). Therefore, there is a clear connection between the water resources and urbanization. This led to increased pollution levels.

## 3. Groundwater quality tests

The primary focus of this research was to examine the quality of groundwater in the Malabe area. Additionally, the rate of urbanization has negatively influenced the groundwater quality of the area. Groundwater quality

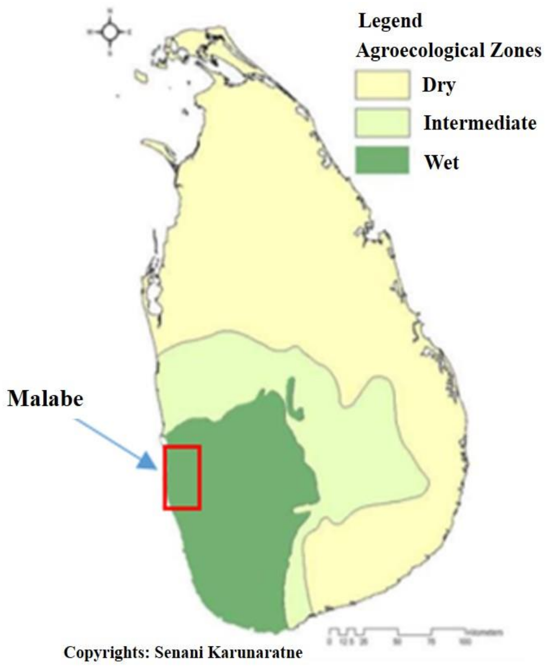


**Figure 1** Three climatic zones in Sri Lanka and Malabe [39]

samples were collected from 16 wells and then, their water quality tested at the Water and Environmental Engineering Laboratory, SLIIT. Table 2 and Figure 2 show spatial information about these 16 sampled wells. The wells were chosen so that they were evenly spread over Malabe. Since Malabe is in the wet zone, the groundwater table is not that deep. Therefore, the wells in this area are shallow with the average depth of 3-6 m.

The following water quality tests were done to check the groundwater quality of the wells. The electrical conductivity (APHA 2150 B), water colour (APHA 2120 C), turbidity (APHA 2130 B), nitrate content (APHA 4500 NO3E), nitrite content (EPA 35.1), pH (APHA 4500 HB), sulphate content (APHA 4500 SO42-2012), and phosphate content (APHA 4500 PE-2012), as well as *Escherichia coli* (SLS:1461 Part 1-2013) and coliform counts (SLS:1461 Part 1-2013) were the groundwater parameters that were tested. Standard tests (as detailed above) were used to test these samples [40].

## 4. Statistical analysis

Principal component analysis (PCA) and Pearson's correlation were done to analyze the groundwater quality. PCA is a useful technique that can be employed to identify patterns among correlated variables. It extracts the Eigen values and Eigenvectors from a correlation matrix of the original variables [41]. We coded the raw data (Tables 3 and 4) and used an R script for statistical analyses.

Tables 3 and 4 show the test results of the physical and chemical parameter tests, respectively.

The pH values were low and all samples were acidic. This is an important finding as many people in the area drink well water with minimal treatment. Many residents boil their well water prior to drinking it. Therefore, it is advisable to determine the pH level of the groundwater in the area. From these physicochemical analyses, the groundwater qualities in the area are acceptable except at locations HN2, HN3, and HN4. These show undesirably high nitrate concentrations.


**Figure 2** Sample locations (obtained from Google Earth)

**Table 2** Sample well locations in the Malabe area

| Sample no | G.N.Division | Sample label notation | Coordinates |
|---|---|---|---|
| 1 | Malabe, North | MN 1 | 6º54’58.88”N 79º58’17.40”E |
| 2 | Malabe, North | MN 2 | 6º54’23.67”N 79º57’56.60”E |
| 3 | Malabe, North | MN 3 | 6º54’49.15”N 79º58’22.52”E |
| 4 | Malabe, North | MN 4 | 6º54’58.27”N 79º58’25.66”E |
| 5 | Malabe, East | ME 1 | 6º54’26.39”N 79º58’27.55”E |
| 6 | Malabe, East | ME 2 | 6º54’27.35”N 79º58’14.86”E |
| 7 | Malabe, East | ME 3 | 6º54’13.02”N 79º58’25.18”E |
| 8 | Malabe, East | ME 4 | 6º54’17.32”N 79º58’23.24”E |
| 9 | Malabe, West | MW 1 | 6º54’18.71”N 79º57’40.42”E |
| 10 | Malabe, West | MW 2 | 6º54’16.18”N 79º57’36.15”E |
| 11 | Malabe, West | MW 3 | 6º54’01.72”N 79º57’53.72”E |
| 12 | Malabe, West | MW 4 | 6º53’51.88”N 79º57’51.88”E |
| 13 | Hokandara, North | HN 1 | 6º53’47.19”N 79º58’22.62”E |
| 14 | Hokandara, North | HN 2 | 6º53’41.66”N 79º58’24.43”E |
| 15 | Hokandara, North | HN 3 | 6º53’41.27”N 79º58’11.89”E |
| 16 | Hokandara, North | HN 4 | 6º53’36.72”N 79º58’19.04”E |

**Table 3** Physical parameters of water quality samples

| Sample | pH | Turbidity (NTU) | Conductivity (µS/cm) | Colour (Pt/co) |
|---|---|---|---|---|
| MN1 | 5.01 | 0.21 | 321 | 4 |
| MN2 | 5.22 | 0.29 | 162 | 2 |
| MN3 | 4.89 | 0.35 | 456 | 3 |
| MN4 | 5.18 | 1.05 | 282 | 12 |
| ME1 | 5.15 | 4.37 | 206 | 1 |
| ME2 | 4.6 | 3.28 | 312 | 2 |
| ME3 | 4.83 | 2.21 | 092 | 5 |
| ME4 | 5.03 | 0.97 | 429 | 8 |
| MW1 | 4.86 | 1.02 | 453 | 6 |
| MW2 | 4.78 | 0.81 | 578 | 5 |
| MW3 | 4.58 | 0.72 | 502 | 2 |
| MW4 | 4.97 | 2.21 | 260 | 12 |
| HN1 | 5.09 | 1.88 | 235 | 10 |
| HN2 | 5.41 | 0.43 | 452 | 1 |
| HN3 | 5.35 | 0.97 | 365 | 8 |
| HN4 | 5.27 | 1.09 | 450 | 7 |
| **Desirable level** | **7.0 – 8.5** | **2** | **750** | **5** |
| **Maximum permissible level** | **6.5 – 9.0** | **8** | **3500** | **30** |

**Table 4** Chemical parameters of water quality samples

| Sample | Nitrate (mg/L) | Nitrite (mg/L) | Sulfate (mg/L) | Phosphate (mg/L) |
|---|---|---|---|---|
| MN1 | 3 | 0.004 | 2.896 | 0.02 |
| MN2 | 3.3 | 0.009 | 1.772 | 0.06 |
| MN3 | 2.7 | 0.005 | 2.08 | 0.05 |
| MN4 | 4.3 | 0.006 | 2.265 | 0.03 |
| ME1 | 4.1 | 0.002 | 1.12 | 0.06 |
| ME2 | 3.9 | 0.009 | 2.687 | 0.09 |
| ME3 | 3.4 | 0.005 | 10.005 | 0.04 |
| ME4 | 5.5 | 0.006 | 3.89 | 0.05 |
| MW1 | 6.9 | 0.006 | 12.169 | 0.03 |
| MW2 | 7.1 | 0.003 | 8.009 | 0.05 |
| MW3 | 6.6 | 0.002 | 9.016 | 0.03 |
| MW4 | 7.7 | 0.008 | 11.543 | 0.08 |
| HN1 | 5.6 | 0.004 | 2.835 | 0.02 |
| HN2 | 10.5 | 0.007 | 2.086 | 0.06 |
| HN3 | 11.5 | 0.004 | 5.556 | 0.02 |
| HN4 | 9.7 | 0.003 | 6.078 | 0.05 |
| **Desirable level** | **10** | **0** | **200** | **0** |
| **Maximum permissible level** | **45** | **0.01** | **400** | **2** |

**Table 5** *E. coli* and coliform levels

| Sample | *E. coli* (per 100ml) | Presumptive Coliform Count (per 100ml) |
|---|---|---|
| MN1 | Nil | 200 |
| ME1 | Nil | 200 |
| MW1 | 33 | 120 |
| MW2 | 8 | 200 |
| **Desirable level** | **Nil** | **Nil** |
| **Maximum permissible level** | **Nil** | **10** |

## 5. Results and discussion

Groundwater quality contours were developed and are presented in Figure 3a-3h. Figure 3a shows pH contours in the area. The blue patches depict areas with low pH values in well water. Therefore, this contour map can be used as an initial guide for suitability of future groundwater wells and in addition to providing focus to investigations of the reasons for acidic groundwater. Low drinking water pH values may result in several health issues including redness of skin and eye irritation [42].

Colour and turbidity can adversely impact the aesthetic features of water. Most of these groundwater wells are neither covered nor walled. This can influence the turbidity and colour of the groundwater. Electrical conductivity indicates the presence of various ions in the groundwater. This is primarily due to human activities. The contours of the physicochemical parameters of the groundwater of the Malabe area demonstrate spatial variations. Waste materials are a major source of anthropogenic nitrate contamination of groundwater. Disposal of human and animal sewage, industrial food waste and polyresins can cause nitrate contamination [43]. The selected research area has several sources of these pollutants in the form of uncontrolled septic tanks that contaminate groundwater. Additionally, phosphorous from various sources can promote algal growth, increasing turbidity. Fertilizers used in agriculture can raise the nitrate and phosphate concentrations of groundwater.

Furthermore, we investigated coliform and *E. coli* levels in four wells. These results are shown in Table 5.

All four samples exceeded the safe coliform count for drinking water (10/100ml). Therefore, the groundwater in these four wells was bacteriologically unsatisfactory as drinking water. The results suggest that MN1 and ME1 samples were not contaminated by faecal bacteria. There was clear evidence of contamination by faecal bacteria in samples MW1 and MW2. Since faecal bacteria contaminated those two wells, use of their water for drinking purposes is prohibited by the public health department. However, tests should be done for other wells to have a sound spatial variation of *E. coli* and coliform levels. Additionally, these tests should be carried frequently to check the temporal variation.

The above results are important to the planners who make decisions about future development programs. Additionally, the piped water tariff in Sri Lanka has increased over tenfold over the past 20 years. Discussions are have recently taken place (Sep-2017) about further increases. Presently, a unit of water (1 $m^3$) ranges from US$ 0.011 for the 1st 10 units to US$ 0.7 a unit for quantities above 40 $m^3$. Such tariff increases surely reduce piped water consumption and consumers tend to use more groundwater, since it is freely available. However, the results of the current study indicate quite poor groundwater quality.

Detailed statistical analyses further support this conclusion. Table 6 shows a summary of these statistical results while Table 7 presents Pearson’s correlation among groundwater quality parameters.

Significant correlation values are bolded. The pH values positively relate to nitrate contents, but negatively correlated with sulfate contents showing that the acidity of the water was enhanced by sulfate but suppressed by nitrate. Turbidity was negatively related to EC but positively correlated to phosphate meaning that water with high turbidity had a low ion exchange, but had a high content of phosphate sediment. This was characteristic of wells without top protection that collect stormwater and agricultural runoff. Phosphate content relates to both to turbidity and nitrite content. The Pearson’s correlation results support the PCA results.

Table 8 presents the pricipal components of the statistical analyses. Principal components 1 to 4 (PC1-PC4) were considered because the Eigenvalues from PC5 onward were less than 1 following Kaiser's rule. The percentage variances for PC1 to PC4 were 28, 19.4, 16.8, and 15.6, respectively. The cumulative variance for PC1-4 was 79.8, which was sufficiently high.

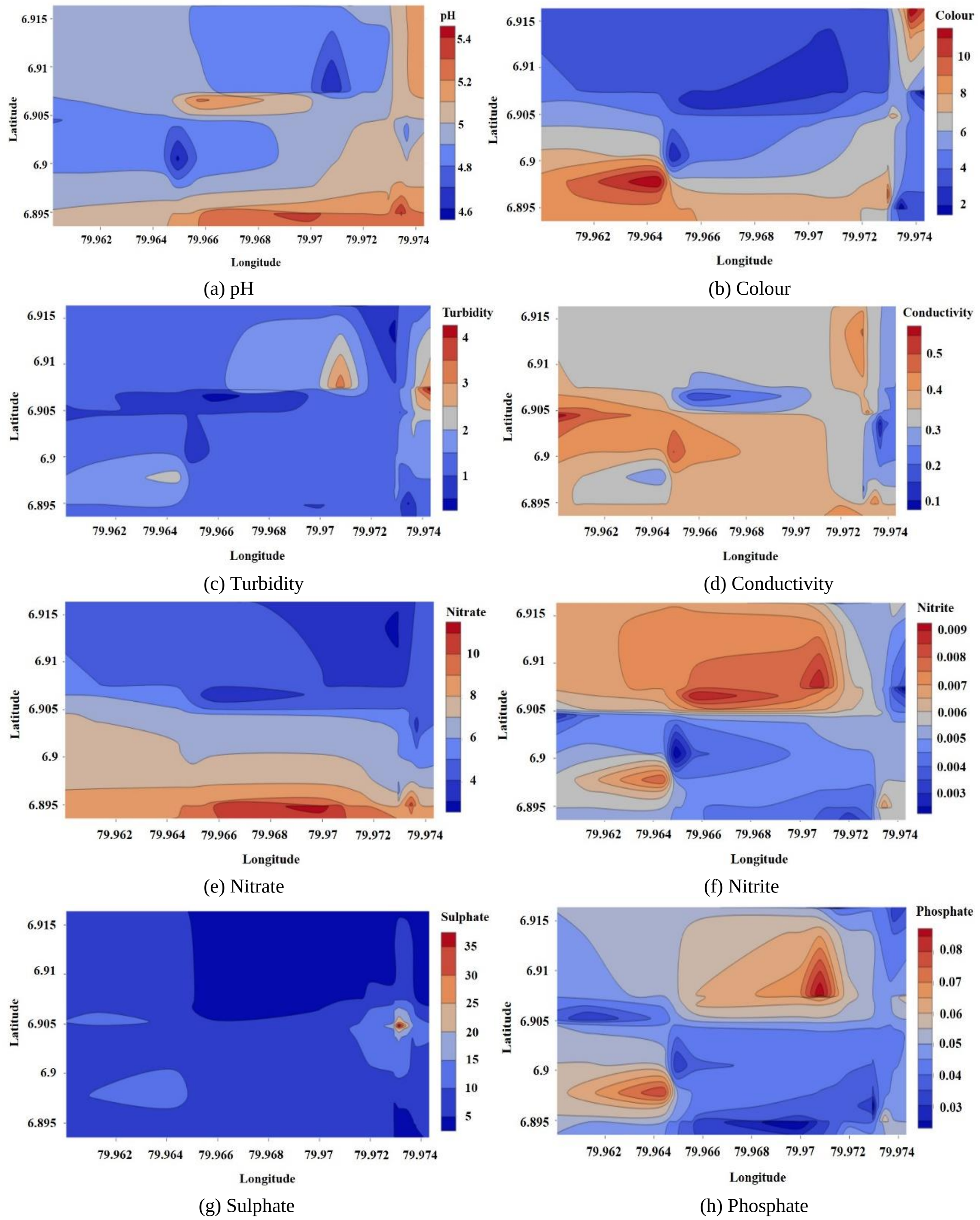


**Figure 3** Water quality contours of eight physicochemical parameters

The first principal component accounts for the positive turbidity and phosphate, but negative EC and nitrate. This means that the wells of high turbidity were also high in phosphate but showed low EC values and low nitrate concentrations. PC2 showed a positive pH with negative sulfate values. This agrees with the Pearson's correlation results, which means that acidity of the groundwater was accompanied by high sulfate concentrations. This finding explains that the acidity of groundwater was caused by uncontrolled release of industrial waste runoff, likely from natural rubber factories [44-45]. PC3 shows negative loading of color with negative sulfate concentrations, meaning that a small number of wells show high color values with high concentrations of sulfate. PC4 shows another group of wells with different characteristics from those of PC1. In these, the EC correlated with the concentrations of nitrite and phosphate. The results from PCA illustrate the complexity of the Malabe groundwater system, in agreement with Panabokke and Perera [1].

**Table 6** Summary of statistical analyses of groundwater quality

| Parameter | pH | Turbidity | EC | Colour | $NO_3$ | $NO_2$ | $SO_4$ | $PO_3$ |
|---|---|---|---|---|---|---|---|---|
| Mean | 5.014 | 1.366 | 347.2 | 5.5 | 5.987 | 0.005 | 5.250 | 0.046 |
| Median | 5.020 | 0.995 | 343.0 | 5.0 | 5.550 | 0.005 | 3.393 | 0.050 |
| Min | 4.580 | 0.210 | 92.0 | 1.0 | 2.700 | 0.002 | 1.120 | 0.020 |
| Max | 5.410 | 4.370 | 578.0 | 12.0 | 11.5 | 0.009 | 12.169 | 0.090 |
| **Desirable** | **7.0-8.5** | **2.0** | **750.0** | **5.0** | **10.0** | **0** | **200.0** | **0** |
| **Permissible** | **6.5-9.0** | **8.0** | **3500.0** | **30.0** | **45.0** | **0.01** | **400.0** | **2.0** |

**Table 7** Pearson correlation and summary of statistical results

| Parameter | pH | Turbidity | EC | Colour | $NO_3$ | $NO_2$ | $SO_4$ | $PO_3$ |
|---|---|---|---|---|---|---|---|---|
| pH | 1.0 | | | | | | | |
| Turbidity | -0.186 | 1.0 | | | | | | |
| EC | -0.173 | **-0.481** | 1.0 | | | | | |
| Colour | 0.196 | -0.041 | -0.115 | 1.0 | | | | |
| $NO_3$ | **0.436** | -0.186 | **0.460** | 0.216 | 1.0 | | | |
| $NO_2$ | 0.036 | -0.036 | -0.305 | 0.0678 | -0.151 | 1.0 | | |
| $SO_4$ | **-0.428** | -0.028 | 0.176 | 0.294 | 0.304 | -0.084 | 1.0 | |
| $PO_3$ | -0.160 | **0.442** | -0.094 | -0.258 | -0.078 | **0.566** | -0.076 | 1.0 |

**Table 8** Principal components of the statistical analyses

| Parameter | PC1 | PC2 | PC3 | PC4 |
|---|---|---|---|---|
| pH | -0.159 | **0.738** | | |
| **Turbidity** | **0.419** | -0.113 | -0.185 | 0.264 |
| EC | **-0.437** | -0.306 | 0.164 | **-0.464** |
| Colour | -0.202 | 0.190 | **-0.598** | 0.368 |
| $NO_3$ | **-0.441** | 0.129 | -0.339 | -0.340 |
| $NO_2$ | 0.352 | 0.178 | -0.377 | **-0.407** |
| $SO_4$ | -0.223 | **-0.504** | **-0.512** | 0.112 |
| $PO_3$ | **0.446** | -0.108 | -0.245 | **-0.527** |

## 6. Summary and conclusions

This study was conducted in Malabe, a rapidly developing area in Sri Lanka. This was a preliminary study that shows the path to investigate the detailed groundwater quality in the area. Many people use groundwater as their drinking water supply. Therefore, this sort of research is very important to promote public health. Generally, the quality of the groundwater in the area is acceptable according to the physical and chemical water quality tests. However, the pH values were low for all tested wells and the nitrate concentrations were high for three wells in the North Hokandara area. Therefore, in terms of physicochemical parameters, Malabe groundwater is quite acceptable apart from its sour taste. However, when it comes to *E. coli* and coliform levels, the scenario changes. People have to think twice before they use groundwater as drinking water since it may contaminated by nearby septic tanks. This conclusion supports the need to frequently conduct detailed water quality tests to monitor the status of the groundwater in the area.

From multivariate statistical analyses, it can be concluded that the high acidity of the groundwater was caused industrial wastes that are high in sulfates, e.g., from the rubber industry. The first principal component of PCA together with the results of biological analyses showed that the Malabe groundwater is polluted by anthropogenic sources. Therefore, a detailed groundwater quality analysis covering more wells in the area is highly recommended.

## 7. Acknowledgements

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