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Groundwater Quality Impacts Due to Population Growth and Land Use Exploitation in the Coastal Aquifers of Sri Lanka

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Groundwater Quality Impacts Due to Population Growth and Land Use Exploitation in the Coastal Aquifers of Sri Lanka

1. Introduction

Groundwater represents about 98% of available fresh water of the planet. Management of groundwater in rural coastal aquifers is essential especially when no other water supplies available and in the presence of competition for land use activities and population growth. Groundwater in unmanaged coastal aquifers is not only vulnerable to land use activities but also for sea water intrusion. High pumping rates causes salt water intrusion. High salinity and/or nutrient concentrations can make groundwater unsuitable for public consumption as well as for agricultural activities. Consumption of contaminated groundwater can produce various health problems. Furthermore, nutrient contaminated groundwater can trigger dense algal blooms that result in habitat changes, oxygen depletion, and ultimately the functions of coastal ecosystems. Therefore, protection of groundwater is much cheaper than remediation, and the management of contaminated aquifers requires good understanding of existing and future condition, vulnerability, and health impacts.

Previous studies have tried to investigate the impact of agriculture on groundwater quality of coastal aquifers but not tried to assess the overall water quality impacts considering sea water intrusion effects, vulnerability, and public health impacts. This study is focused on studying vulnerability of coastal aquifers producing groundwater quality concerns in the presence of sea water intrusion, population growth, and agriculture dominated land use activities.

2. Study Area

Kalpitiya is a low-lying sand peninsula in the north-west coast of Sri Lanka and it covers a total land area of about 160 sq km (Figure 1). Geographically, it is bordered by the Indian Ocean from one side and Puttalam lagoon from inland. Coconut lands, sand dunes, and scrub lands occupy about 50% of the land area in Kalpitiya peninsula. Coconut plantations and intense agriculture fields are the two dominant agricultural land use types in the peninsula. Intense agriculture is practiced by most farmers with high applications of fertilizer and irrigation. Due to the increasing population, land area is exploited for agriculture. Therefore, water is in high demand for irrigation and domestic use.

Rain fed agriculture is not practiced due to low average rainfall, unreliable rainfall, and high evaporation rates especially in the dry season. There are no reservoirs or irrigation canal systems to provide irrigation water, and groundwater is the only available water source. Climate is characterized by high temperatures throughout the year. The average daily maximum temperature is between 29⁰C to 33⁰C and the minimum is between 24⁰C to 27⁰C. Kalpitiya peninsula receives an average annual rainfall of 950 to 1050 mm. The average annual relative humidity in the Kalpitiya peninsula is about 76%. The average annual maximum and minimum temperatures are about 31 and 26⁰ C, respectively. The average annual wind speed in peninsula is about 2 m per second.

The geological succession of Kalpitiya peninsula consists of regosols overlying 15-20 m of fine-coarse sands of marine/aeolian origin. Beneath the sands are clays which in turn overlie a

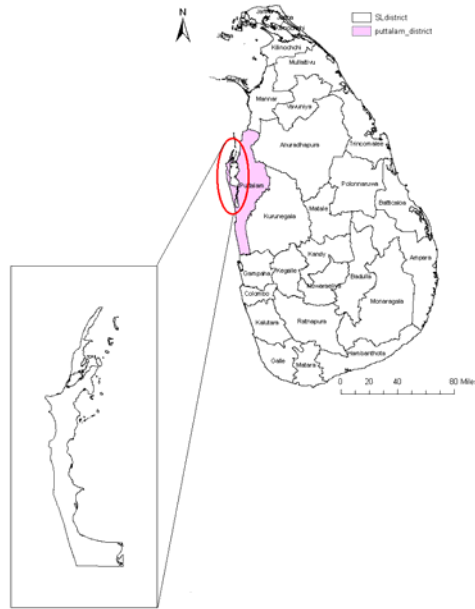


Figure 1. Kalpitiya peninsula on the northwest coast of Sri Lanka.

Miocene limestone. Limestone is at least 20-30 m thick and karstic in some areas (Kuruppuarachchi, 1995). The sandy aquifer overlies the Miocene limestone and is recharged mainly during the 3-4 months of rain and water in these aquifers forms fresh water 'lens' floating above the dense saline water. The volume of fresh water in this aquifer usually expands during the rainy season and contracts during the dry season with a fluctuating brackish and saline interface. The thin fresh water lens occurs in sands lies at depths below 1-3 m over most of the peninsula (Kuruppuarachchi, 1995).

Recharge is by direct infiltration from both rainfall and from irrigation return flows. Despite the relatively low rainfall, groundwater recharge exceeds 400 mm/yr (Kuruppuarachchi, 1995). The observed minimum water level change is 0.01 m and maximum water level change is 1.13 m during the cropping season from January to June in 2006. The average annual water table fluctuation is about 0.8-2.5 m reflecting the high specific yield of the aquifer (Kuruppuarachchi, 1995).

The total number of agricultural holdings and the total number of home gardens in the Kalpitiya peninsula are 7232 and 6588, respectively (Department of Census and Statistics, 2002). The estimated total agricultural area is about 96.1 sq. km and it is about 60% of the total land area (Department of Census and Statistics, 2002). This area is occupied by intense agricultural fields and coconut cultivation lands. In intense agricultural lands, mainly tobacco (*Nicotiana rustica*), onion (*Allium cepa*), and chili (*Capsicum spp*) are cultivated extensively in every cropping season with intense fertilizer application. These crops have an average cropping cycle of 3-6 months.

The agricultural lands are divided into three broad categories based on the intensity of fertilizer and pesticide applications. These are (i) lands under intense agriculture, (ii) lands under semi-intensive agriculture, and (iii) coconut cultivation lands. In intense agriculture lands, the frequency of fertilizer application varies from 8 to 15 days whereas in semi-intensive agriculture lands it varies from 30 days up to 2-3 months. Mostly, coconut cultivations lands are fertilized once a year depending on the weather and the preference of landowners.

The total population of Kalpitiya peninsula is 81,780 about 11.5% of the Puttalam district's total population (Figure 1). The population density of Kalpitiya peninsula is about 511 per km² which is comparatively high compared to the population density of Sri Lanka which is 316 per km². The average annual population growth rate of the region is about 1.8% which is moderately high. Agriculture and fisheries are the main industries of the area. Fishing is avoided during the period from early June to late November due to high blown winds and turbulence of sea waves.

3. Methodology

3.1 Water Quality Assessment

A water quality assessment was performed to identify various contaminants present in groundwater. The water quality analysis was performed in intensive, semi-intensive, and coconut cultivation lands. This is to identify the types and concentrations of constituents in groundwater under different fertilizer application conditions. The calculated capture zone of a conceptual groundwater well is approximately 85 m. Due to the uncertainty associated with pumping rates, a distance of 50 m was considered as the capture zone. Fifty eight wells inside agricultural fields, thirty wells outside fields having an active agricultural field within 50 m boundary, and thirty wells without active agricultural fields within 50 m boundary were selected. The types and concentrations of contaminants under above conditions were compared with the drinking water quality standard of Maximum Contaminant Levels (MCL). The critical contaminants were identified based on the concentrations, exceedance of water quality standards, and the potential for public health impacts. This study identified nitrate as the most critical contaminant in groundwater for different land uses.

3.2 Sea Water Intrusion Effects

Groundwater in a coastal zone is also vulnerable to sea water intrusion and contaminations by nutrients. This study developed maps and graphs of continued occurrence of chloride concentration above 100 mg/L in groundwater. Chloride levels in Kalpitiya peninsula can be compared with the average groundwater chloride levels of other areas of the country.

3.3 Vulnerability Assessment

3.3.1 Model Development

DRASTIC model is named for seven variables considered: **D**epth to water table, **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone media, and **C**onductivity of the aquifer (Aller et al., 1985). Each of the above mentioned hydrogeologic factors is assigned a rating from 1 to 10 based on a range of values (Aller et al., 1985). The ratings are then multiplied by a relative weight ranging from 1 to 5. The depth to water and the impact of vadose zone have a weight of 5, net recharge of 4, aquifer media and hydraulic conductivity have a weight of 3, soil media of 2, and topography of 1.

Eq.1 shows D, R, A, S, T, I, and C parameters representing the seven hydrogeologic factors where subscript *r* denotes rating, and *w* is the weight. The DRASTIC Index (DI) is determined using Eq. 1. The qualitative DI risk categories are, i.) low (1-100), ii.) moderate (101-140), iii.) high, and iv.) very high (>200).

Depth to water table was measured at 118 well locations. Net recharge was estimated using rainfall and irrigation recharge and subtracting the reference crop evapotranspiration (ET). Irrigation recharge was calculated by accounting for soil moisture storage.

$$DI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \quad (1)$$

Kurupparachchi (1995) estimated the infiltration fraction from rainfall is 0.4. Volume of water stored in soil available to plant was quantified as,

$$S = \left(\frac{\pi D_b^2}{4} \right) (Z) \left(\frac{AWHC}{100\%} \right) (MAD) \quad (2)$$

where S is the volume of water storage in soil available to plant, (m³); D_b is the diameter of the basin, (m); Z is the root zone depth, (m); AWHC is the available water holding capacity, (%); and MAD is the management allowable depletion. The root zone depth was assumed as 0.5 m and the available water holding capacity of sandy soil texture is 8%. The assumed management allowable depletion value is 0.5 for plants. The fraction of irrigation water recharge to groundwater was estimated by taking the difference between the average irrigation water input and the soil water storage and the calculated value was 0.62. It was assumed that the soil media, aquifer media, and the impact of vadose zone are having properties of sand. The estimated hydraulic conductivity of the peninsula is 49.5 meters per day.

3.3.2 Modified DRASTIC

The DRASTIC model is modified to estimate the specific vulnerability of groundwater to nitrate contamination and to integrate the effect of land use, implicitly due to agricultural activities and non-agricultural activities. Assigned ratings and weights to the on-ground nitrogen loading are then added to the final DRASTIC index values obtained using Eq. 1 to produce a composite DRASTIC model of specific groundwater vulnerability for nitrate as shown by Eq. 3.

$$CDI = DI + N_w N_r \quad (3)$$

CDI is the composite DRASTIC index, and N_w and N_r are the weight and ratings given to the total on-ground nitrogen loading. Fertilizer nitrogen loading was considered as agricultural nitrogen loading and estimated by on-site investigations. Septic nitrogen loading by population was considered as non-agricultural. Urine and the faeces are the two forms of human excreta that contains nitrogen. Each year, one person produces 500 kg of urine as compared to 50 kg of faeces. The faeces contain 10 kg of dry matter. Thus, one person produces approximately 5.7 kg of nitrogen per year. Human urine contains 90% nitrogen (Wolgast, 1993). The total nitrogen produced by the population per year was computed. A weight of five was used for total on-ground nitrogen loading in DI computation due to fertilizer. Ratings corresponding to the total septic nitrogen loading were assigned based on equal loading intervals and ratings were assigned from 1 to 5. The composite vulnerability index maps combining agricultural and population were produced using ArcGIS tools (Figure 2).

3.3.3 Influential Parameters for NO₃-N Elevation in Groundwater

This study identifies the influential parameters for the elevation of nitrate in groundwater. Thirty wells were used for this analysis. The assumed predictor variables are, i) Sodium Adsorption Ratio (SAR), ii) ECSAR ratio, iii) total fertilizer nitrogen input (kg), iv) distance to the closest active agriculture field (m), v) irrigation water input to the command area (m³/ day), vi) Pumping duration (hrs/day).

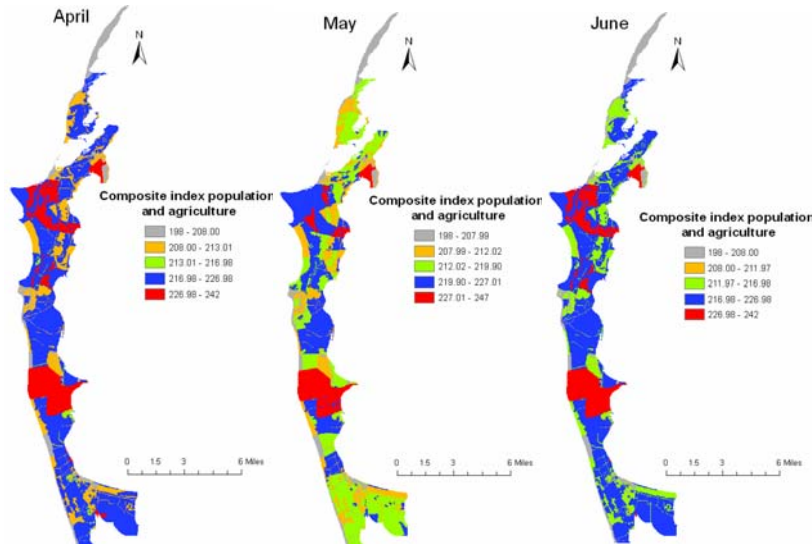


Figure 2. Composite vulnerability index maps for agricultural and non-agricultural nitrogen loading.

A multiple linear regression model is developed to estimate the effect of predictor variables. Based on the linear association and R² value, ECSAR ratio, total nitrogen fertilizer input, and distance to field are considered in the model.

4.4 Public Health Impacts Assessment

4.4.1 Methaemoglobinaemia (“blue baby syndrome”)

Nitrate is reduced to nitrites in the human body causing *methaemoglobinaemia*. Methaemoglobinaemia is a fatal condition in infants under 3 months of age due to high levels of methaemoglobin in blood. This study also focused on assessing the public health impacts in relation to the blood methaemoglobin levels in humans. Blood samples were analyzed for methaemoglobin obtained from randomly selected people in intensive agricultural areas. The goal was to find the relationship between high methaemoglobin (methHb) levels in blood, age groups, and drinking water NO₃-N levels. World Health Organization (WHO) has established a standard methHb level in blood for adults and infants. The standard methHb for adults are 2% and 3% in infants.

4.4.2 Pesticides

This study reveals that farmers in the Kalpitiya area are using various types of pesticides. Improper methods and use of equipments, and poor sanitation may cause various health effects due to long term exposure to agro-chemicals. This study assesses the agro-chemical leaching potentials and their cancer classification according to the US Environment Protection Agency (US EPA) classification.

5. Results and Discussion

5.1 Overall Groundwater Quality

Different types of constituents and high concentration were observed in intensive, semi-intensive and wells located near to agricultural lands. Ferrous iron, manganese and nitrate-nitrogen concentration have exceeded the MCL in agricultural areas (Table 1).

Table 1. Maximum concentration of different contaminants and their MCL for drinking water quality standards.

Contaminant	Observed Maximum (mg/L)	MCL (mg/L)
Chloride	471.0	-
Bicarbonate	427.0	-
Calcium	361.0	-
Magnesium	78.0	-
Sodium	126.0	-
Potassium	58.0	-
Iron	11.2	0.30
Manganese	2.3	0.05
Aluminum	29.0	-
Phosphorous	2.0	-
Zinc	5.0	5
Nitrate-N	127.8	10
Sulfate	1070.0	-

Nitrate has exceeded the MCL of 10 mg/L of NO₃-N established by the World Health Organization (WHO) in agricultural areas. Low nitrate levels were observed in wells which are not located in close proximity to intensive agricultural lands and in bare land (Figure 3). High nitrate levels in wells located in intense agricultural lands and close proximity to agricultural fields may be due to nitrogen fertilizer application. The wells which are not close proximity to agricultural lands also contain nitrate-N levels above the MCL (Figure 3). This may be due to the effect of non-agricultural nitrogen loading to the subsurface.

The WHO has established a guideline value (GV) for nitrite and nitrate in drinking water due to the possibility of simultaneous occurrence (WHO, 1998). The sum of ratios of observed concentrations (C) of each to its GV should not exceed 1 as shown in Eq. 4.

For infants 3 mg/L of nitrite was derived as the guideline value whereas for adults a guideline value of 0.2 mg/L of nitrite was derived. Guideline value for nitrate concentration in water is 50 mg/L for both infants and adults.

The calculated guideline value exceeds the sum of ratios of observed concentrations of each to its WHO recommended level of 1 for infants. This study found that the calculated guideline values for infants have exceeded the WHO recommended level of 1 in 51, 42, 42, and 40% of sample wells from March, April, May, and June 2006, respectively. The calculated guideline values for adults have exceeded the WHO recommended level of 1 in 59, 52, 52, and 49 % of sample wells from March, April, May, and June 2006, respectively.

$$\frac{C_{\text{nitrite}}}{GV_{\text{nitrite}}} + \frac{C_{\text{nitrate}}}{GV_{\text{nitrate}}} \leq 1 \quad (4)$$

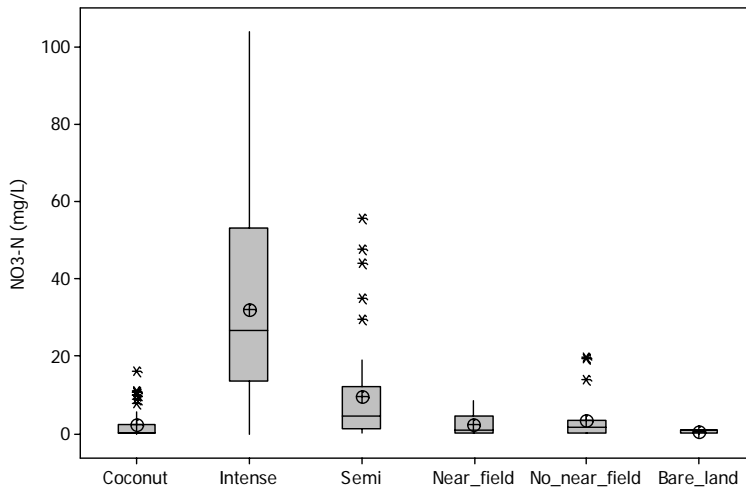


Figure 3. A box plot of NO₃-N concentration for different land use and proximity to fields.

5.2 Rainfall and Water Abstraction

The mean abstraction rate is approximately 63 m³ per day. The average annual abstraction of groundwater from the Kalpitiya peninsula is approximately 166 million m³ (MCM) mostly for irrigation. The estimated average annual rainfall for the entire Kalpitiya peninsula is about 1010 mm. The approximated average annual groundwater recharge by rainfall is about 161.6 MCM over the land area of 160 km². A comparison of above approximated groundwater abstraction and recharge values show that the present average annual groundwater abstraction is higher than the average annual groundwater recharge. The average annual groundwater abstraction for irrigation exceeds the recharge by approximately 5 MCM.

5.3 Evapotranspiration

The estimated maximum and minimum reference crop evaporation are 15.4 and 3.0 mm per day, respectively. The estimated average reference crop evaporation is about 9.66 mm per day. The variation of relative humidity, difference between the maximum and minimum temperatures, and the variation of wind speed is relatively low during May and June. The above parameters vary significantly during other periods of the year resulting in increasing reference crop evapotranspiration.

5.4 Intrinsic and Specific Vulnerability to Contamination

Vulnerability assessment shows 86.5% of the area is having “high” intrinsic vulnerability to contamination while rest of the area is “very high”. Specific vulnerability to nitrate shows 88.8 % of the area is having “very high” vulnerability to contamination.

5.5 Sea Water Intrusion Effect

Continued occurrence of chloride levels higher than 100 mg/L mainly in intense agricultural areas and other land use types gives a general implication of sea water intrusion effect (Figure 4). Occurrence of percentage areas having chloride concentrations above 100

mg/L have increased during the study period. The natural groundwater flow system is disturbed due to pumping of water in the agricultural areas where most of the pumps are operated for irrigation purpose.

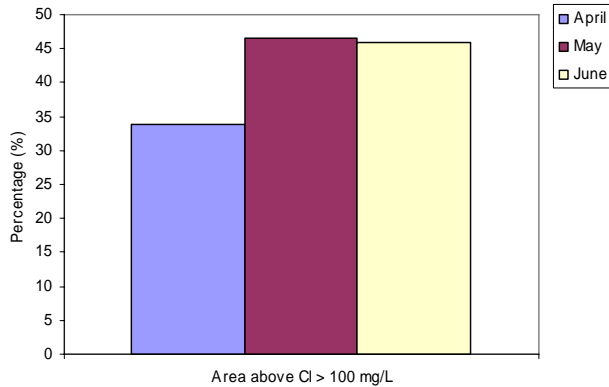


Figure 4. Percentage areas of chloride concentration above 100 mg/L.

5.6 On-Ground Nitrogen Loading

Agricultural lands occupy about 60% of the land area. On average, agricultural nitrogen input average agricultural nitrogen loading intensity is 7.2 metric tons of N per km² per year compared to the 233 metric tons of N per km² per year from domestic septic systems. The main source of nitrogen is from septic nitrogen loading compared to agricultural nitrogen loading of Kalpitiya peninsula (Figure 5). Therefore, this result is unusual and overrides the general notion that nitrogen from fertilizer input provides the major contribution of nitrogen to groundwater in agriculture intensive areas. Instead, these results indicate that agriculture may be responsible for high nitrogen loading from most agricultural lands, but in regions where agriculture and population growth are competing factors, nitrogen loading due to population growth can be a significant contribution.

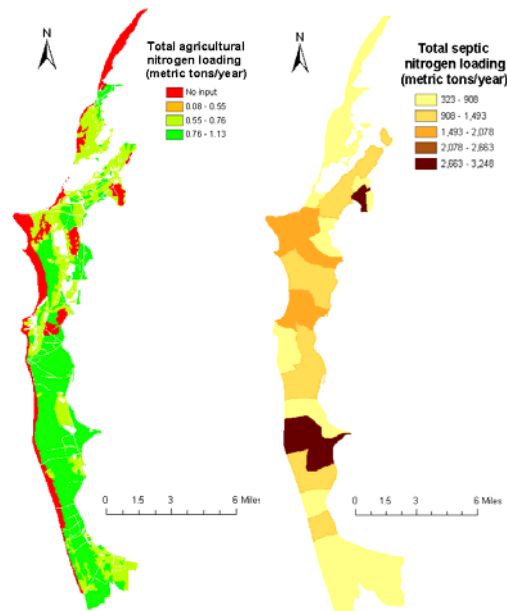


Figure 5. Comparison of agricultural and population nitrogen loadings.

5.7 Parameters Elevating NO₃-N in Agricultural Areas

Multiple linear regression analysis was performed to estimate the parameter for each predictor variable. The predicted NO₃-N with observed showed R² of 0.71. ECSAR ratio shows the highest parameter estimate ($\beta = 0.1255$) thus it is the most influential parameter for the elevation of nitrate in groundwater. This is due to the sodium, and salinity determines good water infiltration properties. Total nitrogen fertilizer input ($\beta = 0.8164$) is the second significant parameter. Distance to the agriculture field ($\beta = -0.0176$) also has a significant effect on groundwater quality.

5.8 Public Health Impacts

5.8.1 Pesticides

Farmers in the peninsula are using various types of agro-chemicals without proper protective practices or considering public health concerns. Among the pesticides use in the area, Benomyl, Carbaryl, Chlorothalonil, Dimethoate, Mancozeb, and Maneb have some potential to cause cancer in humans. US EPA has classified Benomyl and Dimethoate as “possible human carcinogen” while Chlorothalonil, Mancozeb, and Maneb are classified as “probable human carcinogen.”

5.8.2 Methaemoglobinaemia

Figures 6 and 7 show the methHb in different age groups and with different drinking water NO₃-N levels. Figure 7 shows that high methHb levels occur at low NO₃-N of less than 10 mg/L in drinking water and all age groups. This gives a good indication that high methHb levels can also occur at low NO₃-N levels in drinking water. Methaemoglobin analysis shows most residents have high methaemoglobin levels compared to the WHO standard level of 2%.

Gupta et al. (1999) observed high methHb level in all age groups (from less than 1 year to greater than 45 years) at 10.1 - 21.4 mg/L NO₃-N in drinking water. Bootstrapping analysis for uncertainty shows the observed 95% confidence level for mean NO₃-N concentration (13.1-21.6 mg/L) of Kalpitiya peninsula is within the range of 10.1 – 21.4 mg/L NO₃-N. Therefore, it is probable that high methHb levels can exist in all age groups in this area and can cause various health problems. Other potential public health impacts include cancers, and adverse reproductive outcomes.

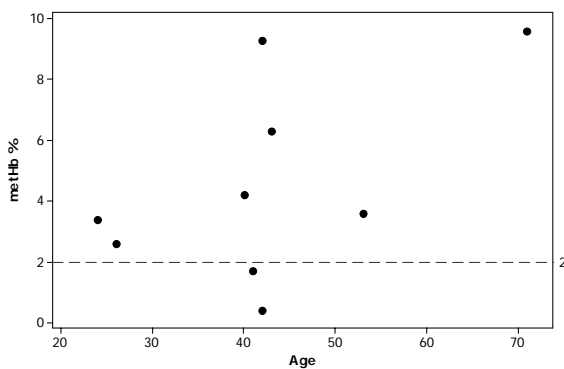


Figure 6. Methaemoglobin level in blood with WHO standards.

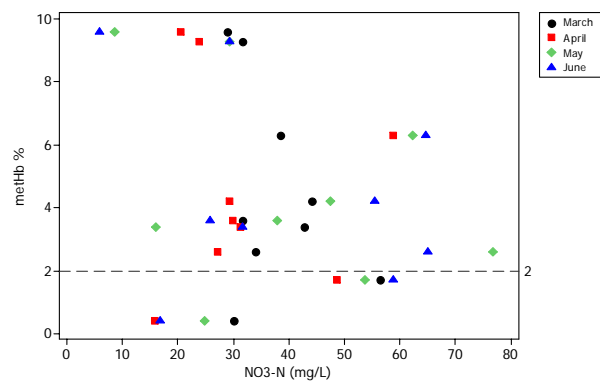


Figure 7. Methaemoglobin level in blood with drinking water NO₃-N.

6. Summary and Conclusions

Kalpitiya peninsula is affected by high population density, unmanaged agricultural and groundwater withdrawal practices, and sea water intrusion. Population nitrogen loading from septic systems provide the major source of nitrogen. This is unusual finding overrides the general assumption that nitrogen from fertilizer input provides the major contribution for high nitrate in groundwater. Therefore, management implications and policy making should be more geared towards mitigating septic nitrogen loading, wastewater treatment and proper training, design, and maintenance of septic systems.

Total nitrogen input, ECSAR ratio, and distance to agricultural field are the most influencing parameters for elevation of nitrate in groundwater in these agricultural areas. Geologically, the Kalpitiya peninsula is highly vulnerable to contamination. About 86% of the area is in “high” vulnerable zone whereas rest of the area is in very high vulnerable zone. Over abstraction of groundwater has also occurred in the Kalpitiya peninsula. Continued existence of chloride levels above 100 mg/L indicates the presence of salt water intrusion that could affect long-term fresh water supplies to the region. This may be as a result of over abstraction of groundwater. Population growth will result in further increase of population density in the area and will produce more land use exploitation for both septic systems and agriculture. This population growth and land use exploitation will increase the demand for groundwater for urban use and irrigation while further deteriorating water quality. Existence of the current condition over a long time period is not sustainable and ultimately will deplete the quality and quantity of groundwater in the Kalpitiya peninsula.

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