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On-site Sanitation Influence on Nitrate Occurrence in the Shallow Groundwater of Mahitsy City, Analamanga Region, Madagascar

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Abstract

Nitrate contamination of groundwater has inclined to be a critical issue in areas where groundwater is the only available resource for water supply for drinking use purpose. In developing countries such as Madagascar, on-site sanitation can be a significant source of nitrate contamination of shallow groundwater, depending on the type of sub-surface layer and hydrogeological environment, the arrangements and behavior of sanitation, and the design of sanitation used for defecation. This study was carried out to investigate the nitrate occurrence in shallow groundwater of Mahitsy city, Analamanga Region of Madagascar, and to assess the on-site sanitation influence on nitrate concentration in drinking water well. Water samples were collected from dug wells in rainy and dry seasons.

The analytical results showed that the measured nitrate concentration was in the range of 1.5 mg/L and 580 mg/L with an average of 348 mg/L for all water samples. Thirteen out of fifteen samples had nitrate concentration exceeding the WHO guideline value (50mg/L). Data analysis indicated that nitrate concentration in dry season (average 409 mg/L) was greater as compared to rainy season (371 mg/L). However, the difference was not significant at the 0.05 level. Significant positive correlation (0.849, $p < 0.01$) was found between nitrate and chloride concentration with chloride/nitrogen ratio of about 1:2.23, suggesting the same source for nitrate and chloride. Nitrate concentrations of well waters were strongly correlated to distance between water wells and sanitation facilities (-0.466, $p = 0.08$), to water table level (-0.558, $p < 0.05$) and to age of water wells (0.655, $p < 0.01$).

Keywords: nitrate contamination, groundwater, on-site sanitation, Mahitsy

1. Introduction

Nitrate occurs naturally in soil and groundwater, but at low concentrations (less than 3 mg/L) in water unaffected by human- related activities according to Madison & Brunett (1984). It is part of the nitrogen cycle. Nitrogen is a key element for all living organisms and large amounts of inorganic nitrogen as well as other essential nutrients are needed specifically by plants for their sustainable high yields (Blumenthal, Baltensperger, Cassman, Mason, & Pavlista, 2008).

While used in fertilizers, nitrate can be released into groundwater when nitrogen fertilizer is applied indelicately. Plants take up the amount of nitrate they need for their growth and the exceeding nitrate stays in the soil, to further finds its way into groundwater through the downward movement of soil water into aquifer (Tredoux, Engelbrecht & Israel, 2009). That constitutes the main source of nitrate groundwater pollution known as diffuse source in the zone where fertilizers are used in excessive amounts and/or without proper management.

Other potential sources of nitrate contamination of groundwater include the use of animal manure and sanitation system leaching. Animals and human excreta increase the soil organic nitrogen, which is converted into nitrate by a series of bacterial transformations under aerobic conditions. It enhances the leaching of nitrate into groundwater (Assessing Risk to Groundwater from On-Site Sanitation [ARGOSS], 2002).This last phenomenon is well known in the rural villages and the urban cities in developing countries due to the inadequate use of sanitation facilities and the improper design of animal waste storage.

Whereas on-site sanitation is now recognized as one of the major sources of nitrate contamination to groundwater in the Southern African sub-continent such as South Africa, Botswana and Namibia, use of nitrogen fertilizer is the main anthropogenic source of nitrate in groundwater for the USA and the European countries (Tredoux, et al., 2009). Several authors reported that inadequate on-site sanitation design and the hydrogeological conditions of terrain are potential sources of groundwater pollution, including fecal contamination (ARGOSS, 2001; Dzwairo, Hoko, Love, Guzha, 2006; Pujari, Padmakar, Labhasetwar, Mahore, Ganguly, 2011). In Botswana, Staudt (2003) found that eleven out of thirty-one sampled boreholes in the Ramotswa area had nitrate concentrations exceeding the nitrate concentration guideline value of 45 mg/L for drinking water (World Health Organization [WHO], 2006). The pit latrines were identified as the major source of the groundwater pollution. In Zimbabwe, the investigation carried out by Dzwairo et al. (2006) depicted that on-site sanitation negatively impacted on the groundwater quality in the Kamangira village, resulting from the sandy nature of the soil and the pit latrine technology. In addition, Oday & Dugbantey (2003) showed in the case study of Ashanti region in Ghana that the distance between the water points and the sanitation facilities had influence on the groundwater pollution level: the greater the distance of groundwater source from the on-site facility, the lower the fecal and nitrate contamination level.

Although nitrate is harmless when ingested at low concentration, exposure to high level of nitrate can affect human health, particularly infants under the age of three months (WHO, 2011). Nitrate reduction occurs in the infant digestive system, leading to nitrite production. Nitrite is highly toxic, as it mediates the oxidation of hemoglobin in the blood to methemoglobin, causing the condition called methemoglobinemia. The methemoglobin cannot transport the oxygen and carbon dioxide to the tissues, resulting in dysfunction to the system and a bluish-tinge in the lips or other body parts well-known as “bleu-baby syndrome” in case of excessive nitrate exposure (Agency for Toxic Substances and Disease Registry [ATSDR], 2011).

In Madagascar, only about forty percent (39.6%) of the total population had access to safe drinking in 2005with a rate of 31.2% for rural areas (Institut National de la Statistique [INSTAT], 2006). In 2010, slightly less than forty-five percent of the population of Madagascar had access to potable drinking water according to the demographic household survey (INSTAT, 2011). Over fifty percent (50.4%) of the population in the rural areas use groundwater as source of drinking water supply. In addition, only two percent (2%) of the rural population have modern latrines while around forty six percent (46.2%) do not use latrines at all, opting to defecate in nature for convenience (INSTAT, 2006).

Few data are available for nitrate occurrence in groundwater in Madagascar (Smedley, 2002). Groundwater contamination, including nitrate hazard is of concern insofar as the population do not have access to or do not use at all appropriate sanitation facilities because of cost constraint and/or culture barrier. The on-site livestock breeding appears as well to be a potential risk of groundwater pollution, regarding animal waste management practices.

In this sense, the purpose of the present work is to provide an overview of the nitrate occurrence in the shallow groundwater of Mahitsy city and to assess the on-site sanitation influence on nitrate concentration in drinking water well.

2. Study Area Description

2.1 Study Area Location and Characteristics

Mahitsy is located in the Highlands Plateau of central Madagascar, in the Ambohidratrimo district within the Analamanga region, at a distance of about 30 km northwestwards from the Capital city, Antananarivo. It stretches between longitudes 47^0 20’ 00” E and 47^0 21’ 25”E, and latitudes 18^0 44’30” S and 18^0 45’ 25”S. The area elevations lie between 1250 m and 1280 m above mean sea level from the north-west boundary to south-east extremity of the city, respectively.

Most of the study area population is from lower to medium income categories with an average household size of 5 members. It consists of a mid-urban city, where small trading and farming make the population livings. The agglomeration is overcrowded, where housing is built in unorganized way and regardless of space for recreational use due to the lack of appropriate urban plan (Figure 1). Additionally, there is no sewage system in place and the domestic wastewater is discharged through open drains or is simply scattered around the yard. The local population mainly use pit latrines for sanitation purpose. Whilst some people in the north-western part of the city are using tap water, groundwater still constitutes the main source for drinking and domestic use in the area since the provision of water supply by the Mahitsy Commune Authorities cannot cover the whole population.

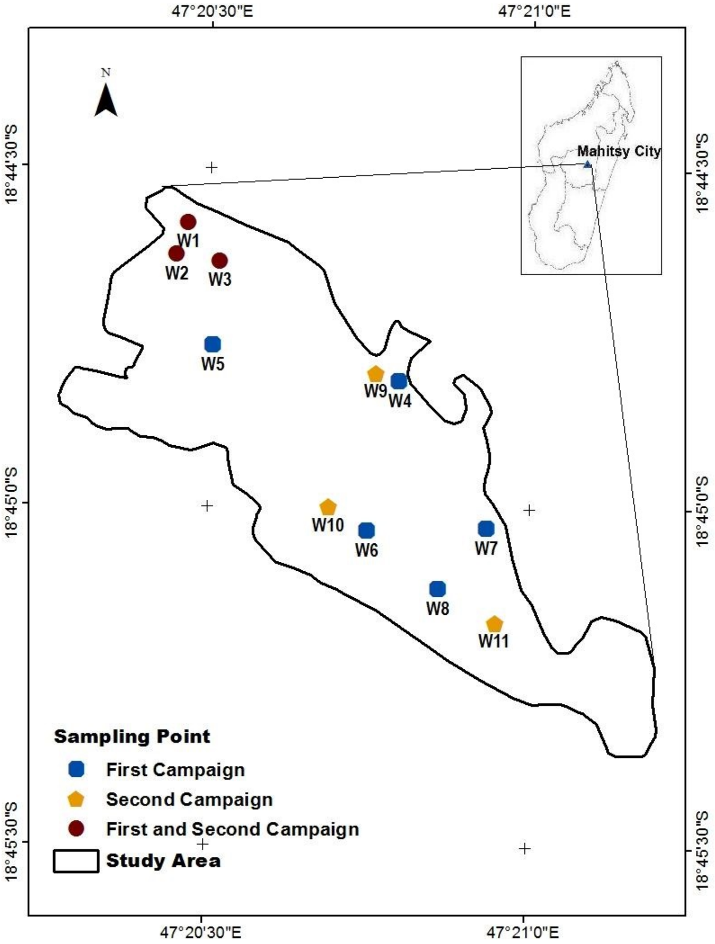

Figure 1. Sampling point location

2.2 Geological and Hydrogeological Overview

The study area lies on crystalline rocks of Precambrian age (Besaire, 1973). It is a gneissic-granitic basement, which consists of late Archaean, and Neoproterozoic gneisses, and granitoids (Goncalves, Nicollet & Lardeaux, 2002). The basement is deeply weathered and eroded, resulting in formation of thick red lateritic soils covering plains, dark brown soils deposited on volcanic rocks or grey alluvial soils in the valleys (Jeffrey, 2009). The weathering profile showing ridged lateritic layers at near surface level indicates that weathering affects the unsaturated zone and continues at depth down to the basement rocks, the layer base constituting the weathering front (Jeffrey, 2009).

Groundwater in the study area is mainly stored in weathered zones, including unconfined aquifer in weathered laterite and a semi-confined aquifer in fissure granitic basement, separated by clayey layer (Grillot, Blavoux, Rakotondrainibe, Raunet & Randrianarisoa, 1987; Dussarrat & Ralaimaro, 1993).There is interaction between these aquifers, as some infiltration from upper weathered laterite aquifer moves down through the interface clayey layer as a recharge to the deeper basement aquifer (Grillot & Ferry, 1990). Recharge to the two aquifers takes place preferentially within the interfluve zone (Grillot and Blavoux et al, 1990).

2.3 Climate, Temperature and Rainfall

The central highlands, where is located the study area experience a tropical mountain climate with mean temperature ranging from 16˚ C to 24˚ C. The rainy season occurs from November to April (warm summer), and the dry season from May to October (mild winter). Annual rainfall ranges between 1200 mm and 1400 mm. Heavy rains occurs during the rainy season mainly inside the period from December to March.

3. Methods

3.1 Sanitary Condition Surveying

Inspection of the physical installations was performed to identify any eventual water contamination source. For that, a survey questionnaire was developed to collect the distances between the water points and any potential source of well water pollution, including sanitation facilities, solid waste disposal area, animal manure storage site and/or livestock breeding location. The type of sampled well was also reported in the survey questionnaire.

3.2 Sampling

Two sampling campaigns were carried out in March 2005 and July 2005. A total of fifteen (15) water samples were collected, including eight (8) in the first campaign and seven (7) during the second campaign. Four out of eight wells (W1, W2, W3 and W7) were resampled within the second campaign. The water samples were collected from private traditional dug wells, which tap the upper unconfined aquifer. They are relatively protected, cased with bricks or stones, of about 1 m of diameter and was covered with a wooden cap. The best protected wells are installed inside a small shed equipped with door. In general, the groundwater table is shallow and is in the range of 2.2 m and 20 m under the land surface, depending on the well location topography.

Two 100 mL polyethylene (PE) bottles were filled with water sample for anion and cation measurements for each sampled well. Containers were rinsed with the water to be sampled prior to sample collection. All samples collected were filtered using cellulose nitrate membrane (0.2 µm) in the field. Samples for cation analysis were acidified with HNO_3 after filtration for preservation purposes(Barcelona, Gibb, Helfrich & Garske, 1985).

3.3 Field Measurement

Water quality parameters measured in the field were pH, Potential Redox (Eh), Electrical Conductivity (EC), Dissolved Oxygen (DO), Temperature (T), Total Dissolved Solids (TDS), Alkalinity and groundwater level. The first five parameters were measured using portable multimeter (Multi 340i model). The measurement of Total Dissolved Solids was done using Hach conductimeter (SensION 5). Alkalinity as the concentration of bicarbonate was determined by acidic titration (H_2SO_4) using digital titrator. Field measurements except for groundwater table were performed on aliquots of well waters immediately following collection. The groundwater level was measured by water level meter.

3.4 Analysis of Anions and Cations

Analysis of ions such as ammonium (NH_4^+), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chloride (Cl^-), bromide (Br^-), nitrate (NO_3^-), and sulfate (SO_4^{2-}) were done using two separate Dionex Ion Chromatograph systems DX-120, one system for anion and one system for cation measurements. For the anion, the Chromatograph is equipped with AS 14A and for the cation, with a CS 12A analytical column. 20 mmole/L of CH_3SO_3H and a combination of 8 mmole/L of Na_2CO_3 with 1 mmole/L of $NaHCO_3$ were used as eluent for cationic and anionic measurements, respectively. All water samples were measured in duplicate. The analytical results precision varied within 5%.

4. Results and Discussion

4.1 Physico-chemical and Chemical Parameters

The measured pH values ranged from 3.93 – 6.38 (averaging 5.1) in the first campaign to 4.14 – 5.87 (averaging 4.88) during the second campaign. All sampled waters were of acidic conditions and more likely to be corrosive.

Groundwater temperatures varied between 19.4^{0}C and 24.6^{0}C for all sampling points, averaging 22.6^{0}C and 21.2^{0}C in warm summer (first campaign) and mild winter (second campaign), respectively. Well water temperatures reflected seasonal air temperatures. They were warmer in March than in July.

The dissolved oxygen values ranged between 6.14 mg/L and 8.35 mg/L, averaging 6.81 mg/L for samples collected during the first campaign. They varied from 2.31 mg/L to 6.36 mg/L with an average of 3.76 mg/L within the second campaign. The second batch of water samples were under reducing conditions, as compared to the first batch.

As far as electrical conductivity was concerned, it varied in the range 118 µS/cm – 1734 µS/cm during the first sampling campaign and in the range13µS/cm – 1353 µS/cm in the second campaign. Samples collected during the first campaign were more charged with dissolved ions with a mean electrical conductivity value of 1096 µS/cm than those collected in scope of the second campaign (with an average of 904 µS/cm). Electrical conductivity of resampled wells recorded a decreasing trend, except for that of W1 well.

The measured Total Dissolved Solids (TDS) values ranged from 59 mg/L to 868 mg/L and from 7 mg/L to 813 mg/L for waters sampled during the first and second campaigns, respectively. The average values of TDS were 548 mg/l and 495 mg/L for the first and second lot of samples, respectively. Only two wells, namely W8 and W11, presented a TDS value less than 400 mg/L.

Bicarbonate measured during this investigation ranged from less than 1 mg/L to 46.7 mg/L, averaging 22.2 mg/L and 8.9 mg/L for the first and second sampling campaigns, respectively. The regression analysis between bicarbonate and pH values showed that bicarbonate decreased with a decrease of pH values (Figure 2).

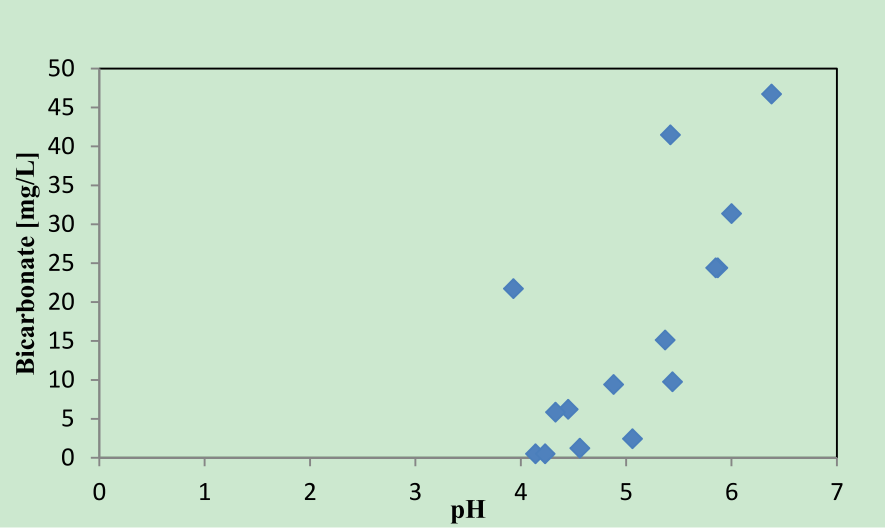

Figure 2. Relationship between chloride concentration and pH value for all well waters

Regarding chloride parameter, its concentrations were in the range of 6 mg/L – 205 mg/L with an average of 114 mg/L in the well waters sampled during the first campaign. Its contents varied from 0.2 mg/L to 195 mg/L (averaging 111 mg/L) for samples collected during the second campaign. Statistical analysis of data showed that there was no significant difference (p=0.935) between the concentrations of chloride measured within the two sampling campaigns. A plot of electrical conductivity and chloride data indicated correlation between the two parameters (Figure 3). Such correlation was stronger for samples collected during the first campaign (0.929, $p < 0.01$), as compared to those sampled within the second campaign (0.822, $p < 0.05$).

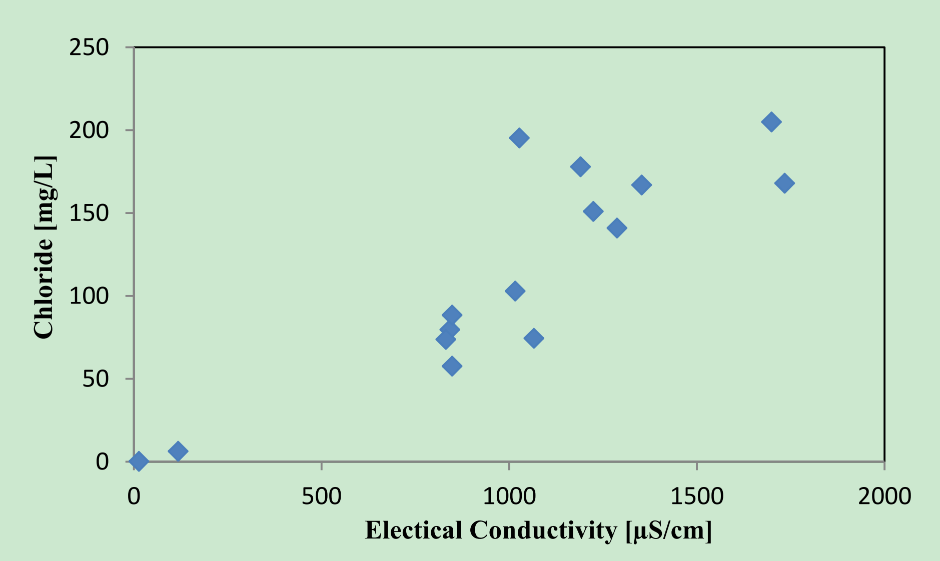

Figure 3. Relationship between chloride concentration and electrical conductivity for all well waters

4.2 Nitrate Seasonal Variation

Measured nitrate concentrations stretched between 1.5 mg/L and 580 mg/L for all water samples collected from wells in scope of the present investigation. Of the fifteen water samples analyzed from wells in Mahitsy city, only two samples (W8 and W11) did not exceed the maximum recommended nitrate concentration value of 50 mg/L nitrate for drinking water (WHO, 2006). All wells revealing nitrate concentration higher than the WHO recommended value were of nitrate contents exceeding 250 mg/L. Amongst them, W3 and W4 samples presented nitrate concentration values greater than 500 mg/L.

Regarding nitrate seasonal variation, water samples collected within the first batch had nitrate concentration values varying from 16 mg/L to 580 mg/L. Well waters sampled during the second collection batch presented nitrate content in the range of 1.5 mg/L – 556 mg/L. The mean value of nitrate concentration of drinking water from wells W1, W2, W3 and W7 sampled in the first campaign was less (371 mg/L) than that of the same samples but collected during the second campaign (409 mg/L).Statistical analysis of data demonstrated that there was no significant difference between the mean values of the first and second set of samples, as the p recorded value was 0.192 (greater than 0.05).Although the observed variation of mean values (from 371 mg/L to 409 mg/L) was not statistically significant, it presented a trend of nitrate seasonal variation. The obtained results recorded a slight increase of nitrate concentration during dry season, which was accompanied by a decrease of water level from 0.4 m to1.3 m. The dilution occurring from recharge of upper groundwater by rain infiltration could explain the reduced nitrate concentration in rainy season, since the recharge travel time to saturated zone can be of days or weeks in thin weathered basement (ARGOS, R68692). In addition, measured dissolved oxygen for the samples of interest (W1, W2, W3 and W7) varied from 2.57 mg/L to 5.22 mg/L during dry season, suggesting a condition favorable to the accumulation of nitrate to high level. Denitrification process occurs only when dissolved oxygen concentration falls below 2 mg/L in the groundwater (Rissmann, 2011).

A plot of nitrate concentration versus electrical conductivity for all samples (Figure 4) indicated that there was a good relationship between them (0.899, $p < 0.01$), suggesting that nitrate plays a major role in the electrical conductivity variation: the greater the nitrate concentration, the higher its influence on electrical conductivity.

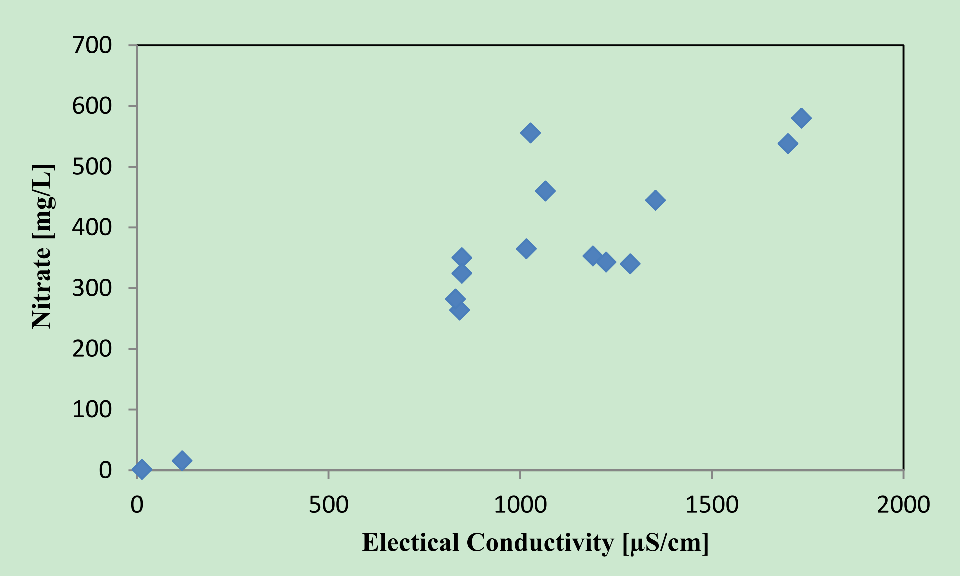

Figure 4. Relationship between nitrate concentration and electrical conductivity for all well waters

Considering separately nitrate concentration data for each sampling campaign, Figure 5 showed that nitrate concentration of the first batch of samples presented better relationship (0.960, $p < 0.01$) with electrical conductivity, as compared to the second batch of samples (0.872, $p < 0.05$).

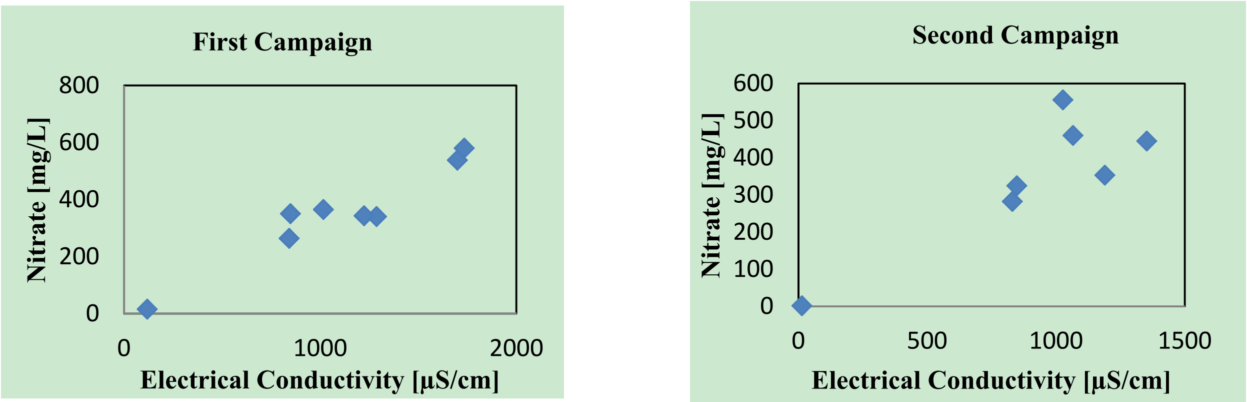

Figure 5. Relationship between nitrate concentration and electrical conductivity for sampled well waters during the first and second campaigns, respectively

The slight difference implied that the mechanism of nitrate groundwater contamination did not present the same magnitude of influence on the electrical conductivity values of samples collected within the two campaigns.

4.3 Variation of the Nitrate Concentrations along the Groundwater Flowpath

To investigate the variation of the nitrate concentrations along the groundwater flowpath, the graph between the nitrate concentration and the elevation (assuming the groundwater flows from high to low elevation) was plotted as shown in Figure 6. The graph showed scattered plotted points. However, two trends can be distinguished: (i) a clear increase of the nitrate concentration along the groundwater flowpath (blue oval), indicating a stronger occurrence of a nitrification process at shallower depth while approaching the discharge zone (ii) a rather obvious stagnant nitrate concentration along the groundwater flowpath (red oval), suggesting a rapid flushing of nitrate along the groundwater flowpath.

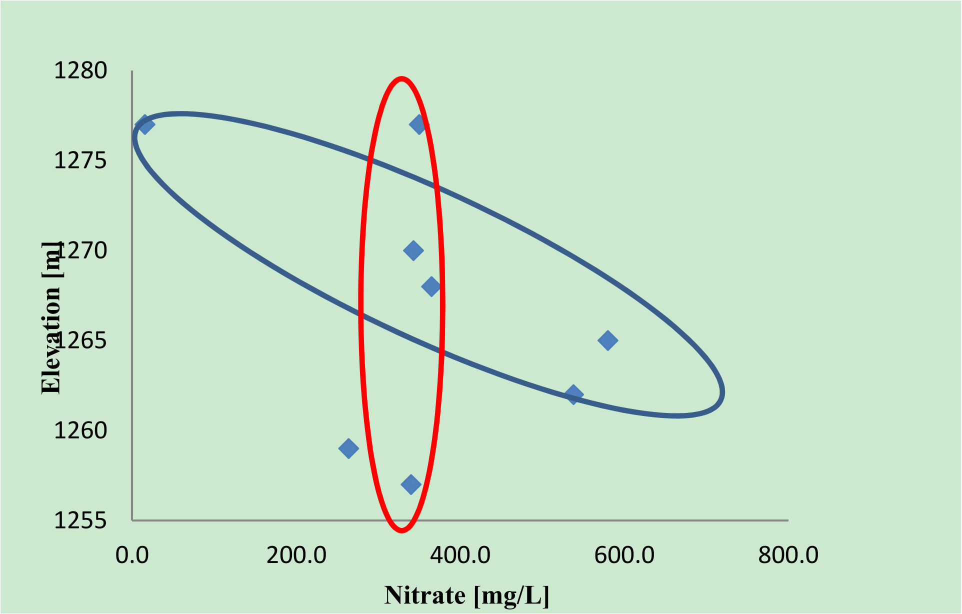

Figure 6. Graph between nitrate concentration and elevation in the study area

4.4 On-site Sanitation Effect on Nitrate Concentration

The sampled wells were located within the range of 3 – 20 m from the sanitation facilities. Population in the study area used mainly dry pit latrines where were stored the wastes. The pit latrines were not sealed and the liquid part of the wastes infiltrated into the soil.

According to Assessing Risk to Groundwater from On-Site Sanitation (ARGOSS) scientific review (2002), nitrate and chloride were found to be the major chemical contaminants generated from on-site sanitation.

ARGOSS (2001) report showed that released nitrogen through human excreta is of about 4 kg/year/person. Nitrification occurs in the unsaturated zone under an aerobic condition and converts a significant percentage of organic nitrogen into nitrate. Human waste also contains a large amount of chloride. Each person discharges on average 4 g/day of chloride through urine, feces and sweat (ARGOSS, 2001).

Figure 7 indicated that the nitrate and chloride concentrations were correlated, suggesting that the concentration rise was related with chloride/nitrogen ratio of around 1:2.23. In addition, the bivariate correlation test showed a significant correlation between nitrate and chloride concentration with a Pearson correlation coefficient of 0.849 (p-value less than 0.01). That fact implied that nitrate and chloride in the shallow groundwater could be the same source. They could be released from the human excreta in pit latrines, as the ratio of chloride to nitrogen in human excreta was approximately 1:2 (ARGOSS, 2002).

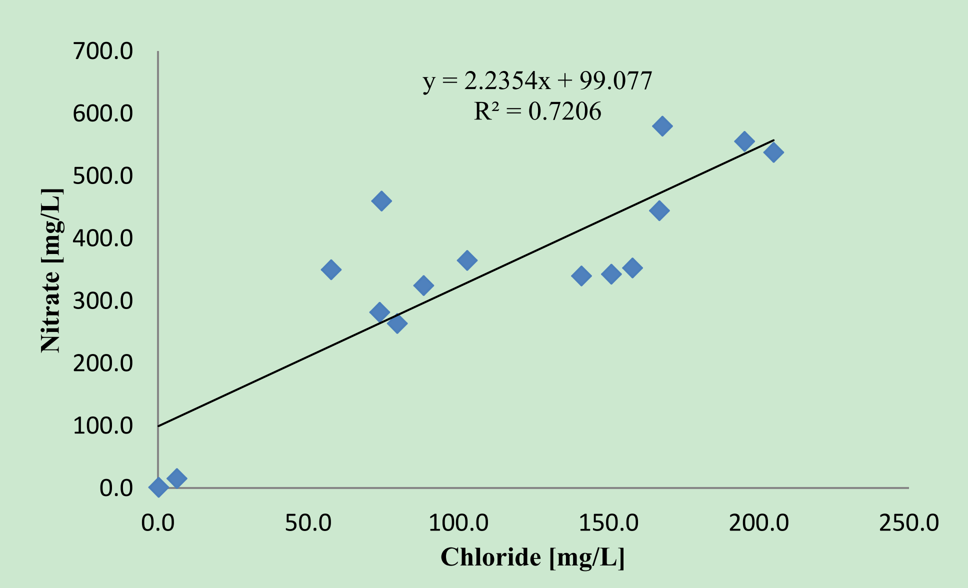

Figure 7. Nitrate versus chloride concentration plot with points for all well waters sampled during the first and second campaigns

Regarding sanitation facility arrangement, a plot of nitrate concentration versus pit latrine location showed that there was a negative correlation between them with a Pearson correlation coefficient of -0.466, but it was not significant as the p-value was 0.08.

Considering the water table level parameter, the statistical correlation indicated that there was a significant correlation between nitrate concentration and water table level, as Pearson correlation coefficient was estimated at -0.558 with a p-value of 0.031(significant at the 0.05 level). The nitrate concentration tended to increase as the water table level decreased. Boxplot diagram of water wells of water level less than 10 m, and those of water level beyond 10 m (Figure 8) represented that the nitrate concentration average values were 415 mg/L and 213 mg/L for the first and second categories, respectively. The ANOVA test indicated that the difference between the average values was statistically significant (p-value less than 0.05).

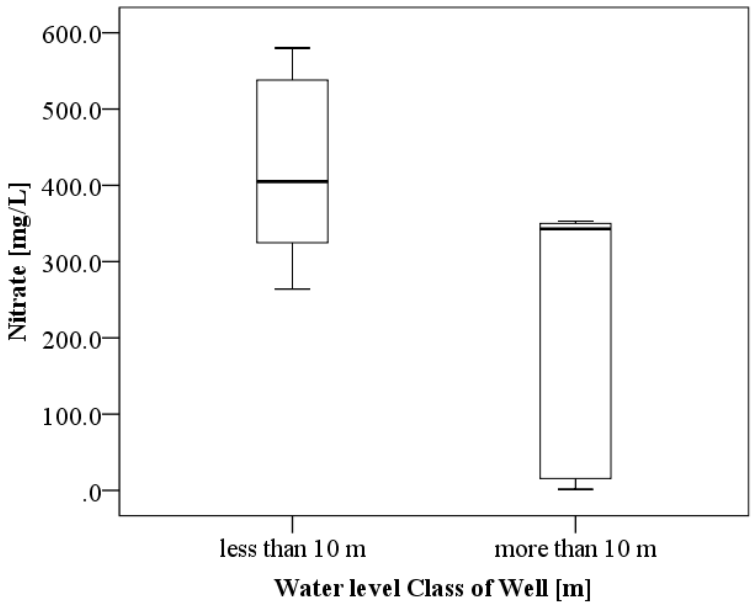

Figure 8. Boxplots of wells of water level less than 10 m and beyond 10 m versus nitrate concentration

Considering the age of water wells, correlation analysis showed that the correlation between nitrate concentration and age of water wells was significant at the level of 0.01 (p-value of 0.008) with a Pearson correlation coefficient of 0.655: the greater the age of water wells, the higher the nitrate concentration of well waters. Referring to the three categories of water wells by age (Category I: wells of age under 10 years; Category II: wells of age between 10 and 20 years; Category III: wells of age beyond 20 years), Figure 9 depicted that the average value of nitrate concentration in well waters increased from Category I (213 mg/L) to Category III (500 mg/L). The difference of the average values between three categories is statistically significant at the 0.05 level (p-value equal to 0.012).

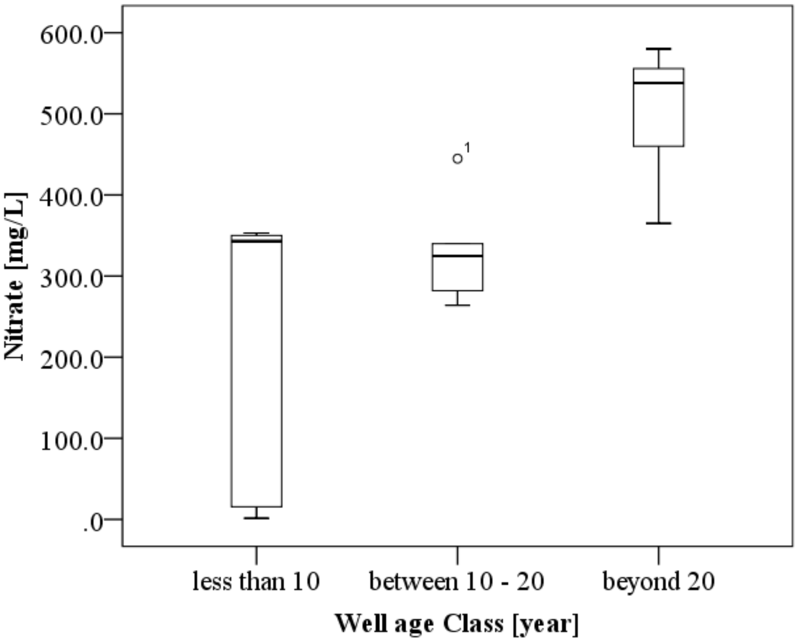

Figure 9. Boxplots of Category I, Category II and Category III of wells versus nitrate concentration

5. Conclusion

Very high nitrate concentrations were measured in most of sampled water wells in Mahitsy city, varying from 1.5 mg/L - 580 mg/L. Of the fifteen collected samples, thirteen had nitrate concentration exceeding the WHO recommended value (50 mg/L) for drinking water. For seasonal variation, investigation on set of resampled wells (W1, W2, W3 and W7) showed that the average nitrate concentration in rainy (371 mg/L) season was less than in dry season (409 mg/L). The reduced nitrate concentration in wet season could be due to the dilution resulting from recharge infiltration into the shallow groundwater. Additionally, content of dissolved oxygen of well waters (greater than 2 mg/L) could contribute to the increase of nitrate concentration during the dry season.

The on-site sanitation had influence on nitrate concentration, since there was a strong relationship between nitrate and chloride. In addition, data analysis resulted in the following findings:

- Nitrate concentration of shallow groundwater in the study area was negatively correlated to the distance between pit latrines and water point facilities: the closer the pit latrines, the higher the nitrate concentration.
- There was also a significant relationship between the nitrate concentration and the water table level: the deeper the groundwater table, the lower the nitrate concentration.
- Significant positive correlation was found between nitrate concentration and water well age as well: the older the water wells, the higher the nitrate concentration.

The upper groundwater in Mahitsy city will pose health issue when used for drinking purpose as far as nitrate concentration was concerned. The Mahitsy Commune authorities should reinforce the public water system, which provides drinking water supplies from mountain spring.

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