Journal of Applied Sciences

ISSN 1812-5654

science alert

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Journal of Applied Sciences 8 (18): 3096-3107, 2008
ISSN 1812-5654

Temporal and Spatial Variations of Nitrate Levels in Traditional Water-Supply Wells in the Area of Buyo, Côte d'Ivoire

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Abstract: In this study, water nitrate concentration, pH, temperature, conductivity, turbidity and Total Dissolved Solids (TDS) were monitored in 34 water-supply wells, located in the three main districts (Buyo cité, Tchemasso and Buyo provisoire) of the city of Buyo (Côte d'Ivoire, West Africa) and in two villages (Gbili and Logbozoa) around. Each water-supply well was sampled in September and October 2004 and every other month from January 2005 to November 2005. Other variables like depth of the wells and precipitations were also considered over the same period. The nitrate concentrations in the 34 wells ranged from 1.83 to 412 mg L^{-1}. Most contaminated wells were found in the district Buyo cité and in the two villages. All wells at Buyo cité, 8 out of 10 at Gbili and 4 out of 10 at Logbozoa, exceeded at least once the WHO limit (50 mg NO_3^- L^{-1}) for drinking water, indicating that populations are at risk in the study area. In contrast, none of the wells reached the WHO limit in Tchemasso and in Buyo provisoire. Pit latrines, inappropriate waste disposal and insufficient well maintenance were suspected to be responsible for the high nitrate concentrations in well water within the study area. It has been found that each contaminated well had a nitrate source in its close environment that permanently released nitrate in the well water, the recharge water exerting a dilution effect. An appropriately designed education programme directed to the populations should allow improving and protecting well water quality in the study area. The principal component analysis of the data revealed that nitrate, temperature, TDS and conductivity are higher in shallow wells than in deep wells.

Key words: Groundwater contamination, nitrate, water-supply well

INTRODUCTION

Groundwater contamination by nitrates has become a very serious and topical problem in most countries of the world (Thorburn *et al*., 2003; Saadi and Maslouhi, 2003; Liu *et al*., 2005; Wakida and Lerner, 2005; Masetti *et al*., 2008). Indeed, it is nowadays a well established fact that groundwater resource constitutes the main or the only source of potable water for many people in diverse parts of the world (Elbaz-Poulichet *et al*., 2002; Nola *et al*., 2002; Reid *et al*., 2003; Thorburn *et al*., 2003; Liu *et al*., 2005; Kulabako *et al*., 2007). According to former studies, reported by Banton and Bangoy (1997), 50% of the world population relies upon groundwater for its potable water supply. A similar figure was cited by Hudak (1999) for the United States. This already important role of groundwater will certainly increase in the coming years. Indeed, according to the conclusion of a recent conference, groundwater constitutes the most realistic option for increasing the supply of water in rural areas, in an attempt to meet the UN millennium development goal of reducing by half the number of people without access to clean water by 2015 (McDonald, 2005). Therefore, as already mentioned by a number of authors, the contamination of this resource by pollutants such as nitrates can have detrimental effects on human health (Gulis *et al*., 2002; Gardner and Vogel, 2005; Wakida and Lerner, 2005). Nitrate, the focus of this study, is one of the most worrying pollutants of groundwater (Thorburn *et al*., 2003; Widory *et al*., 2004; Gardner and Vogel, 2005; Liu *et al*., 2005; Masetti *et al*., 2008). The primary health effect associated with high nitrate levels in drinking water is methemoglobinemia. This affects infants up to 6 months of age and can ultimately result in the infant's death (Gelberg *et al*., 1999). Other potential health risks from nitrate-rich drinking water, derived from diverse field studies, include gastric and prostate cancer, spontaneous abortions, œsophageal and stomach cancer, diabetes and thyroid hypertrophy (Gelberg *et al*., 1999; Geoffrey *et al*., 1999).

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As one can see it, contamination of groundwater by nitrate is a real public health concern that deserves a due attention. This is particularly important in developing countries where a great part of infant's mortality is attributed to waterborne diseases. A close examination of the works published on the problem of groundwater contamination by nitrate shows that this problem is the subject of intensive investigations in developed countries. The latter countries have already set up national groundwater quality monitoring networks (Dawoud, 2004), in order to prevent or to minimize the problem. On the contrary, developing countries and mostly African ones, seem to pay less or no attention to this problem, although potential risks to human health associated with consumption of nitrate-rich water are well established today.

In the area of Buyo (in the Southwest of Côte d'Ivoire), groundwater, by means of water-supply wells, is the only source of potable water. This study is part of a vast project, intended to assess human and ecosystems health in the area of Buyo. As part of this project, preliminary investigations on nine water-supply wells revealed the presence of nitrate in water, with concentrations exceeding sometimes two to three times the World Health Organisation (WHO) recommended limit of 50 mg NO_3^- L^{-1} (Kouamé, 2002). These preliminary results demonstrated the necessity of a more extended study on the presence of nitrate in well water in this region. This is the goal of the current study. It includes a higher number (34) of sampling points and aims at evaluating the extent of well water contamination by nitrate in the area of Buyo and the risk incurred by the population drinking this water.

The overall objective of this study is to evaluate and to attempt to understand the spatial and temporal variations of nitrate levels in water-supply wells in the area of Buyo, for taking preventive measures to protect the groundwater resources in this region. It is to be mentioned that the causes of the presence of nitrate at abnormal concentrations in groundwater appear to be site-specific (Gelberg *et al*., 1999; Pacheco *et al*., 2001; Masetti *et al*., 2008).

Specific objectives are similar to those outlined by Reynolds-Vargas and Richter (1995):

- Quantifying seasonal variations of nitrate concentrations in water-supply wells in the study area and comparing these results to variations in other water quality parameters (temperature, conductivity, pH, TDS, turbidity) and 2) evaluating the relationships between nitrate concentrations and depth of the wells and precipitation in the region.

MATERIALS AND METHODS

Study area: The Buyo region is located in the north of the southwest part of Côte d'Ivoire between 5°40' and 7°19' latitude North and between 6°11' and 8°23' longitude West (Fig. 1). It covers a surface of about 12,340 km^2. The distribution of precipitations over the year corresponds to the tropical regime, with the alternation of a dry season from November to April and a rainy season from May to October, with a slowdown in July and August. Mean annual precipitation ranges from 1264 to 1614 mm (Kouamé, 2002). From the geological point of view, the region of Buyo develops on a schistose structure with holes of small granite clumps in. The evolution of the substratum gives rise to lateritic soils with conglomerates, ferruginous quartzite and charnockites. The pedological conditions exhibit acidic or neutral soils, more or less clayey, well drained, with a thin gravelly layer, favorable to the farming of food crops and other plants like cocoa and coffee. The materials indicate altered soils with overlapping facies (Kouamé, 2002).

The region is drained by the Sassandra River and its tributaries. A dam is installed on the river at Buyo for electricity production. It gives rise to a lake, which in periods of low water, covers a surface of 900 km^2, contains 8.4 billions m^3 and has a flow of 100 m^3 sec^{-1}.

The study covered the city of Buyo and two villages, Gbili et Logbozoa, ten kilometers around. The city of Buyo can be divided in two parts: the district Buyo cité on the one hand and the districts Tchemasso and Buyo provisoire on the other hand. Buyo cité is older and characterised by a high-density population, while Tchemasso and Buyo provisoire are more recent and less densely peopled. The latter two districts are slightly at a higher altitude than Buyo cité. Villages are considered as opposed to the city to assess the impacts of the activities and the density of the population around the wells.

The population in this area is estimated at 132,573 inhabitants. There is no water distribution network and the modern boreholes (equipped with a pump) installed by the government are often deficient. Hence, the population relies on traditional wells for its potable water supply.

Sampling and analysis: All water-supply wells available in the study area (34 in total) were sampled in September and October 2004 and every other month from January 2005 to November 2005. The wells are distributed as follows: 14 in the city of Buyo, with 7 at Buyo cité, 5 at Tchémasso and 2 at Buyo provisoire and 20 in the villages, with 10 at Logobzoa and 10 at Gbili. Each well position was indexed by its GPS (Global Position System) coordinates (data not presented).

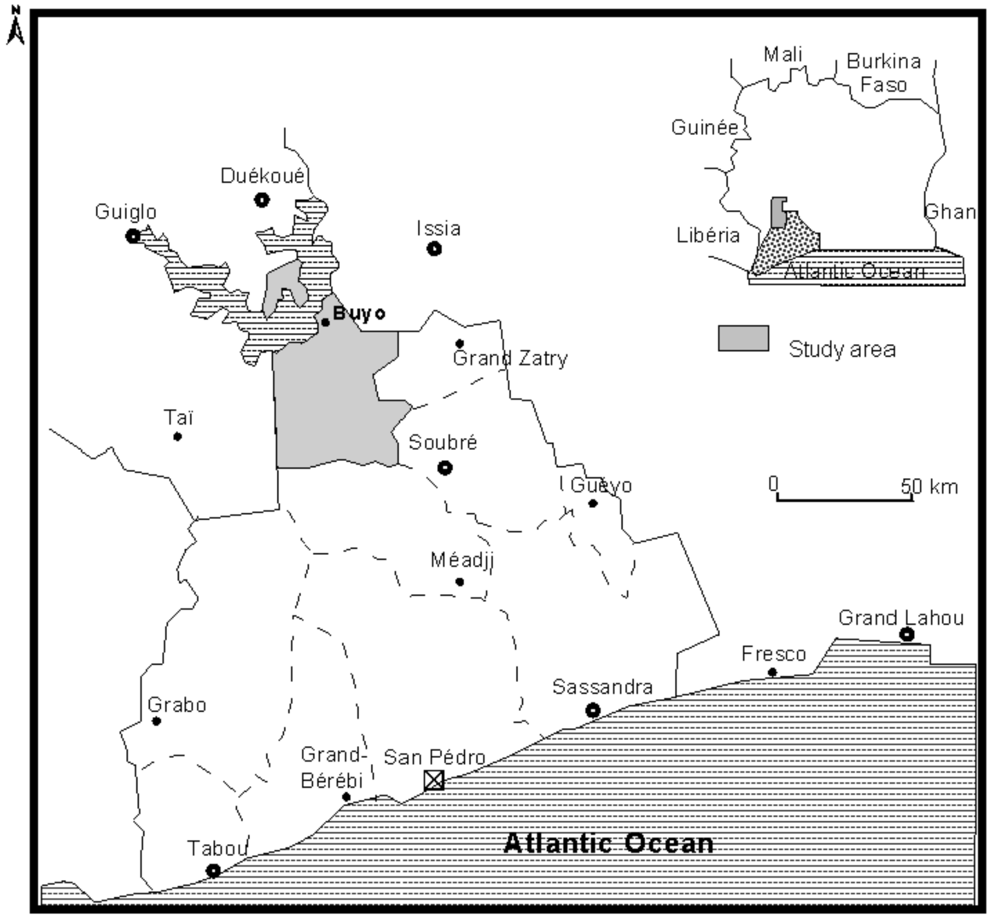

Fig. 1: Localisation of the study area in the southeast of Côte d'Ivoire

Water was sampled by means of a bucket connected to a rope. Temperature, pH, conductivity and total dissolved solids (TDS) were measured in the field, immediately after sampling by means of a field analyser (Model WTW 82362). Similarly, turbidity has been determined in the field using the spectrophotometer DR-2010. The water samples for nitrate analysis were collected in 1-liter polyethylene bottles. Each bottle was first rinsed and then filled with the sample. The samples were kept at low temperature (4°C) in cool boxes containing ice in the field and then in the fridge once back in the laboratory, until analysis. Nitrate analysis was done by molecular absorption spectrometry in the presence of salicylate, using the spectrophotometer SCHIMADZU 1205, according to the french standard NFT 90-012.

For each well, the depth, corresponding to the distance from the water table to the ground surface, was also recorded. Concomitantly, the presence of potential sources of nitrogen (pit latrines or septic tanks, refuse dump, etc.) in the immediate vicinity of each well was noted.

The cumulative precipitations for each month in the study area were provided by the national institution of meteorology.

Careful standardization, procedural blank measurements and spiked and duplicate samples, common lab practices to guarantee analytical data quality (Gelinas *et al*., 1996; Singh *et al*., 2005), were also implemented in this study, especially for the nitrate measurements. The replicability and the repeatability of the analytical methods were evaluated according to the Canadian norm NQ 3600-205 (BNQ, 1987). Three replicates similarly treated were considered for replicability; for repeatability, the results obtained by three different operators on replicate samples were used. The coefficients of variation obtained for replicability and repeatability were 4 and 6%, respectively. Recoveries of nitrate from spiked water samples were found to be between 95 and 106%. Corrections with regard to blanks were applied to the results, if necessary.

Statistical analysis: Means and coefficients of variation were determined for most of the parameters considered. Since the data obtained in this study had multivariate nature and several of the variables could be correlated, Principal Component Analysis (PCA), a data analysis method, was used for the interpretation of the data. This analysis was performed using canoco for windows (version 4) software. As pointed out by Singh *et al.* (2005), techniques like PCA are unbiased methods which can indicate natural associations between samples and/or variables. The same authors noticed that multivariate treatment of environmental data is widely used to characterize and evaluate surface and groundwater quality and found it useful for evidencing temporal and spatial variations caused by natural and anthropogenic factors.

RESULTS AND DISCUSSION

Variation of well water nitrate concentrations in the area of Buyo: Overall, coefficients of variation appear to be very high, ranging from 27 to 155% (Table 1a-d). Apart from three values (27% with BCP3 and GP2, 29% in September at Buyo cité) around 30%, coefficients of variation are close to or largely higher than 40%. This indicates that nitrate concentration varies greatly from month to month for a given well and from well to well for a given month in the study region.

This result is consistent with the observations by Schreiber *et al.* (1999). The latter authors reported significant spatial and temporal chemical variability between wells separated by a distance of less than 3 m. The shortest distance between two wells in this study is over 10 m. Significant variations in nitrate concentrations between wells located at a same site were also reported by Reynolds-Vargas and Richter (1995), Gelinas *et al.* (1996), Elbaz-Poulichet *et al.* (2002), Thorburn *et al.* (2003) and Kulabako *et al.* (2007). This heterogeneous distribution of nitrate levels in the study area suggests that, contamination of the wells by nitrate is primarily the fact of sources or factors related to the close environment of each well.

Table 1a: Nitrate levels (mg L^{-1}), means and coefficients of variation (CV) at Buyo cité

Well	Sept. -04	Oct. -04	Jan. -05	March	May	July	Sept.	Nov. -05	Mean	CV (%)
BCP1	32.40	99.35	120.46	111.13	109.33	97.06	94.88	49.20	89.23	35.16
BCP2	46.31	140.60	158.77	165.15	201.98	143.22	75.20	70.95	125.27	43.56
BCP3	19.63	42.71	41.73	51.06	40.26	36.33	39.50	25.45	37.08	27.08
BCP4	27.49	38.29	31.58	49.09	44.18	36.82	29.37	10.60	33.43	35.27
BCP5	36.16	54.66	45.49	53.68	26.18	36.33	17.51	81.85	43.98	45.32
BCP6	22.74	36.33	47.29	59.90	63.17	44.35	26.98	17.50	39.78	42.41
BCP7	28.31	95.09	83.96	65.79	97.22	112.61	8.90	57.15	68.63	52.31
Mean	30.43	72.43	75.61	79.40	83.19	72.39	41.76	44.67	-	-
CV (%)	29.31	55.09	63.42	54.67	72.80	61.51	75.62	61.43	-	-

Table 1b: Nitrate levels (mg L^{-1}), means and coefficients of variation at Buyo provisoire and Tchemasso

Well	Sept. -04	Oct. -04	Jan. -05	March	May	July	Sept.	Nov. -05	Mean	CV (%)
PP1	3.58	2.52	5.27	7.91	4.06	1.73	1.83	5.25	4.02	51.99
PP2	3.76	2.53	2.21	5.97	3.43	1.90	5.28	4.10	3.65	39.73
TP1	2.90	5.38	10.17	14.99	8.36	3.40	5.28	7.20	7.21	55.20
TP2	2.61	1.98	2.76	4.50	1.37	2.19	19.2	4.35	4.87	120.94
TP3	6.75	1.87	1.99	5.66	2.22	2.77	7.03	16.05	5.54	85.92
TP4	5.02	8.71	4.85	4.75	2.46	1.08	0.95	8.20	4.50	65.33
TP5	21.59	24.54	17.83	34.36	22.58	18.16	1.13	3.55	17.97	60.88
Mean	6.60	6.79	6.44	11.16	6.35	4.46	5.81	6.96	-	-
CV (%)	102.42	120.91	89.44	97.22	118.27	136.55	109.47	62.5	-	-

Table 1c: Nitrate levels (mg L^{-1}), means and coefficients of variation at Gbili

Well	Sept. -04	Oct. -04	Jan. -05	March	May	July	Sept.	Nov. -05	Mean	CV (%)
GP1	25.36	149.27	17.83	142.89	45.66	38.13	75.32	45.85	67.54	76.07
GP2	45.66	70.87	57.44	dry	54.99	38.29	75.32	39.05	54.52	26.89
GP3	108.68	337.68	46.15	224.24	295.12	77.58	81.50	71.15	155.26	73.12
GP4	67.59	241.11	dry	dry	dry	27.32	dry	73.50	102.38	92.54
GP5	12.58	39.11	dry	dry	dry	29.12	dry	dry	26.94	49.74
GP6	293.98	412.82	84.12	269.59	137.49	33.54	81.50	81.85	174.36	77.18
GP7	95.09	179.39	36.16	dry	79.05	38.13	1.83	75.10	72.11	79.02
GP8	17.99	69.06	38.78	112.12	69.06	34.69	64.88	32.95	54.94	54.55
GP9	17.99	53.19	30.92	53.51	31.58	47.46	16.38	8.95	32.5	53.57
GP10	29.62	24.38	16.68	35.18	24.54	19.63	29.04	6.80	23.23	38.01
Mean	71.45	157.69	41.01	139.59	92.19	38.39	53.22	48.36	-	-
CV (%)	113.02	80.99	50.38	60.75	90.54	38.79	56.75	56.00	-	-

Table 1d: Nitrate levels (mg L^{-1}), means and coefficients of variation at Logbozoa

Well	Sept. -04	Oct. -04	Jan. -05	March	May	July	Sept.	Nov. -05	Mean	CV (%)
LP1	78.56	92.31	62.68	52.53	102.95	75.45	62.64	37.90	70.63	29.92
LP2	56.79	92.47	20.28	41.89	65.79	53.68	16.05	73.95	52.61	49.42
LP3	25.36	49.26	18.16	40.75	29.78	38.78	3.00	11.30	27.05	58.19
LP4	22.09	70.87	20.28	39.11	60.88	57.28	9.15	27.35	38.38	58.16
LP5	4.98	3.39	1.17	7.41	4.06	8.06	6.37	46.45	10.24	144.53
LP6	1.51	2.45	0.97	2.81	1.49	2.63	0.44	3.10	1.93	49.74
LP7	2.04	1.60	0.91	4.43	2.62	2.84	2.09	5.60	2.77	55.60
LP8	1.51	4.62	0.91	6.56	4.20	4.68	0.62	1.65	3.09	70.87
LP9	19.3	69.06	28.47	31.42	28.47	30.11	12.05	10.00	28.61	64.10
LP10	29.62	25.69	21.92	32.4	19.14	35.02	6.90	6.80	22.19	48.67
Mean	24.18	41.17	17.58	25.93	31.94	30.85	11.93	22.41	-	-
CV (%)	106.49	92.45	108.70	72.08	107.14	84.21	155.32	106.29	-	-

Influence of seasons on well water nitrate: In order to attempt to understand this spatiotemporal variation of nitrate levels in water-supply wells in the area of Buyo, relationships between nitrate concentrations and other parameters have been examined.

Overall, no evident relationship can be found between rainy or dry months and well water nitrate concentrations with the wells at Buyo cité (Fig. 2a). Only the fluctuations of nitrate concentrations of the well BCP7 tend to reflect a marked seasonal variation. With a delay of one month, nitrate concentrations sharply increase during rainy months (Sept. to Nov. 2004, March to June 2005 and Sept. to Oct. 2005) and decrease during dry or less rainy months (Dec. 2004 to Feb. 2005, July to August 2005). For the wells from Buyo provisoire and Tchemasso, a rough relationship seems to exist between nitrate levels and precipitations (Fig. 2b). Nitrate concentrations tend to decrease further to rainy months (Sept. to Nov. 2004, March to June 2005) and to increase further to dry or less rainy months (Dec. 2004 to Feb. 2005, July to August 2005). Overall, the wells from Gbili displayed a similar trend to those from Buyo provisoire and Tchemasso, apart from well GP2 (Fig. 2c). The nitrate concentration of the latter well tended to remain constant with time (CV: 26.89%). The wells from Logbozoa roughly exhibited low nitrate concentrations during dry months and higher concentrations during rainy months (Fig. 2d). Water wells with and without a relationship between precipitations and water nitrate concentrations have been reported by previously published studies (Reynolds-Vargas and Richter, 1995; Wassenaar, 1995; Arnade, 1999; Pacheco *et al*., 2001; Reid *et al*., 2003; Thorburn *et al*., 2003; Kulabako *et al*., 2007).

Spatial distribution of well water nitrate in the Buyo area: Interesting to be noted from Table 1 and Fig. 2 are the sharply lower nitrate concentrations exhibited by the wells from Buyo provisoire and Tchemasso compared to the wells at Buyo cité, Gbili and Logbozoa. All wells at Buyo cité, 8 out of 10 at Gbili and 4 out of 10 at Logbozoa, exceeded at least once the WHO limit (50 mg NO_3^- L^{-1}) for drinking water. On the contrary, none of the wells from Buyo provisoire and Tchemasso had nitrate concentrations above the WHO limit during the study period. Previous studies have shown that, wells more prone to nitrate contamination are shallow, dug or old ones, or those ones with close proximity to sources of nitrogen, such as septic tanks, latrines, waste disposal site, agriculture using fertilisers inappropriately. At Buyo cité, high-density housing with unsewered sanitation seemed to be the main cause of well water contamination by nitrate, just as reported by Gelinas *et al.* (1996) and Kulabako *et al*. (2007). Indeed, onsite sanitation consisted of pit latrines, which were often observed at less than 5 m from the water-supply wells. The recommended minimum distance between water-supply wells and pit latrines or septic tanks to prevent well water contamination is 15 m (Lewis *et al*., 1981; Conboy and Goss, 2001). At Buyo cité, the high-density housing prevented from complying with such a standard, while at Buyo provisoire and Tchemasso, the low-density housing made it possible. Overall, the wells in the city of Buyo were in good condition (presence of lining, cover and curb).

In the villages (Gbili and Logbozoa), the wells exhibiting high nitrate concentrations were those poorly maintained (no lining of the upper part of the wells, no cover and no curb around the wells) and characterised by the presence of refuse dump or woodpile, potential sources of nitrogen, in their immediate vicinity. Similar observations have been reported by other authors (Gelinas *et al*., 1996; Kulabako *et al*., 2007). Pit latrines are not used in the villages. Villagers defecate in the open and use pitless shower rooms. As already noticed by Geoffrey *et al.* (1999) in Indonesian villages, shower rooms did not seem to play a key role in well water contamination by nitrate in the villages considered in this study.

The most frequently reported sources of ground water nitrate are domestic on-site sewage disposal and fertilizer (Thorburn *et al*., 2003; Gardner and Vogel, 2005; Liu *et al*., 2005; Wakida and Lerner, 2005). Fertilizers can not be incriminated in this study, since they are not known to be intensively used in the current study area and nitrate level is not high in all wells.

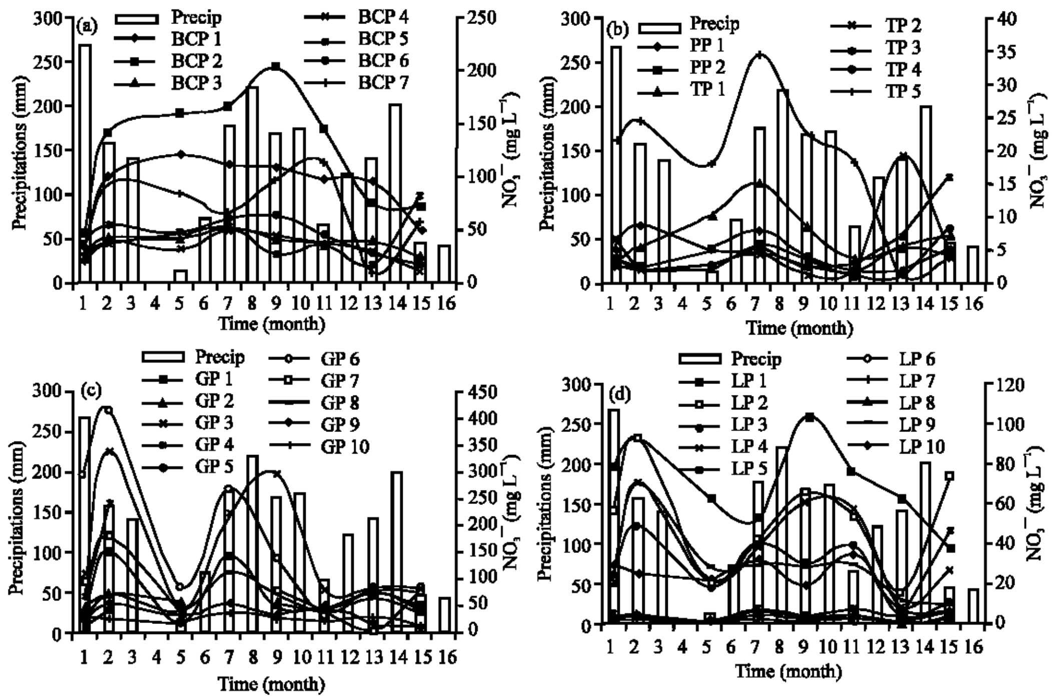

Fig. 2: Monthly precipitations and nitrate concentrations for a) Buyo cité, b) Buyo provisoire and Tchemasso, c) Gbili and d) Logbozoa (month 1 = Sept. 2004 and month 15 = Nov. 2005)

These observations confirm the first conclusion drawn from the high values of coefficients of variation obtained: contamination of the wells by nitrate is primarily the fact of sources or factors related to the close environment of each well. The extremely high nitrate concentrations observed in some of the wells show that populations in the area of Buyo are clearly at risk. An appropriate education project directed to the populations is to be designed and implemented to prevent or to limit contamination of well water with nitrate. The education of the population should be coupled with strong measures, such as implementation of adequate distance between water-supply wells and potential sources of nitrogen, as established in countries like Canada (Conboy and Goss, 2001), to improve water quality in the area of Buyo. Thorough investigations for characterising the hydrogeological environment, should allow establishing appropriate lateral separation between water-supply installations and potential pollution sources for the Buyo area. These investigations, as suggested by Lewis *et al.* (1981), should include: (a) degree of confinement and character of the aquifer horizons, (b) thickness and nature of the unsaturated zone and (c) nitrogen source hydraulic loading. Financial and technical supports from developed countries governmental and non governmental institutions would be helpful. In the immediate time, the results of this study can be cleverly used to mitigate or to reduce the risks associated with consumption of nitrate-rich water. The populations using highly contaminated wells can be invited to use the wells with low nitrate concentrations, after appropriate local arrangements between populations. This is mostly relevant at Gbili and Logbozoa, where wells with low nitrate concentrations can be found not far from wells with high nitrate concentrations.

Influence of monthly precipitations on well depth: Still in the quest for a better understanding of the spatiotemporal variation of nitrate levels in water-supply wells in the studied area, Fig. 3a-d examined relationships between the depth of the wells and monthly precipitations. As it was the case with nitrate concentrations, no evident relationship could be observed between the depth of the wells and precipitations at Buyo cité. The depth of the wells showed very little variation regardless of rainy or dry months. This was confirmed by the lower coefficients of variation observed (from 2.21 to 18.12%). Wassenaar (1995) also found no overall trend in nitrate concentration versus depth in the Abbotsford aquifer. The apparent seasonality observed with nitrate concentrations with the well BCP7 can not be explained by the variations of well depth. At Tchemasso and Buyo provisoire, the wells TP1, TP2, TP3 and TP4 tended to remain constant, while PP1, PP2 and TP3 varied sharply with time, without evident

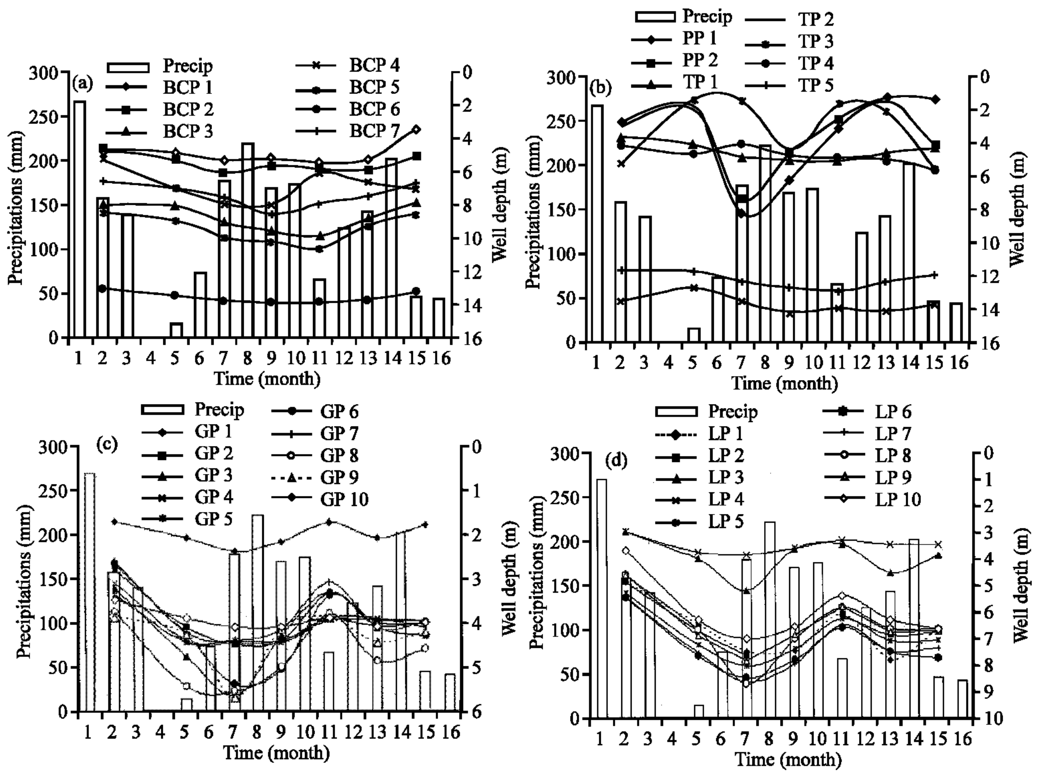

Fig. 3: Monthly precipitations and well depths for a) Buyo cité, b) Buyo provisoire and Tchemasso, c) Gbili and d) Logbozoa (month 1 = Sept 2004 and month 15 = Nov 2005)

relationship with precipitations. The temporal variations of the depth of the wells in the villages (Gbili and Logbozoa) looked very similar and reflected a marked seasonality. The lowest depths occurred at the end of consecutive rainy months and the highest depths at the end of consecutive dry or less rainy months. Similar observations were reported by Geoffrey *et al.* (1999). A sharp relationship between nitrate concentrations and depth of the wells was revealed from Fig. 2c and 3c for the wells from Gbili. Nitrate concentrations appeared to be high when water level was low (March 2005) and were low when water level was high (July 2005). A similar, but less sharp, observation could be made with the wells from Logbozoa. These results indicate that the recharge water does not enrich well water with nitrate, but rather exert a dilution effect. Similar observations were reported by Pacheco *et al.* (2001).

In general, it can be noticed that the wells in the villages appear to be more sensitive to variations in precipitation (seasons) than the wells from the city of Buyo. This could be explained by the proximity of the wells from Buyo to the dam, which water reserve (lake) might feed the aquifer of these wells and allow them to maintain high water level regardless of rainy or dry months. The wells GP4 and GP5 in the one hand and GP2 and GP7 on the other hand, tend to dry out in the same months. This suggests that GP4 and GP5 belong to a same hydrosystem and GP2 and GP7 to another hydrosystem, that can be assumed to be the so-called perched aquifer, known to be more prone to dry out (Banton and Bangoy, 1997). This could be substantiated in further studies.

Spatiotemporal variations of the other physico-chemical parameters: Together with precipitations, well depth and well water nitrate levels, other parameters like well water pH, temperature, conductivity, turbidity and Total Dissolved Solids (TDS), were also considered. Overall, well water temperature varied from 25 to 29°C in the city of Buyo as well as in the villages. The highest values were observed in January and March 2005, corresponding to the dry season and the beginning of the rainy season, respectively.

As for conductivity, in the city of Buyo, values were sharply higher at Buyo cité (ranging from 61 to 430 $\mu S\ cm^{-1}$) than at Tchemasso and Buyo provisoire (ranging from 21 to 52 $\mu S\ cm^{-1}$). Well BCP2 exhibited the highest conductivity values at Buyo cité, exceeding 350 $\mu S\ cm^{-1}$, during the whole study period. In the villages, the wells from Gbili showed higher conductivities (varying from 27 to 710 $\mu S\ cm^{-1}$) than those from

Logbozoa (varying from 26 to 202 µS cm^{-1}). Well GP6 displayed remarkably high conductivity values, varying from 366 to 710 µS cm^{-1}. Well BCP2 and well GP6 exhibiting the highest conductivity values showed also high nitrate concentrations (Table 1a and c, Fig. 1a and c). The wells from Buyo provisoire and Tchemasso, having remarkably low conductivities, displayed also sharply lower nitrate concentrations (Table 1b, Fig. 1b). From these observations, a relationship between nitrate concentrations and conductivity was to be expected.

Total Dissolved Solids (TDS) exhibited very similar values to conductivity and varied exactly like it.

Turbidity was generally low (mostly under 20 NTU) for all wells during the study period, except in July 2005 where higher values (up to 75 NTU) were recorded for all wells.

Concerning pH, it varied from 4.04 to 5.76 in the city of Buyo, while in the villages, it varied from 3.77 to 5.66. All these values are under 7 and show that well water is acidic in the entire study area. Moreover, pH can be considered homogenous in the study area and during the study period due to the lower coefficients of variation (<30) observed. It can be deduced that water pH is governed by environmental factors that are common to all wells in the study area. The most obvious environmental factor is the soil, which is acidic to neutral in the entire area of Buyo (Kouamé, 2002). Similar acidic pH values (3 to 5) were observed in well water from Yaoundé (Cameroon) and ascribed to acidic soils by Nola *et al.* (2002).

Relationships between physico-chemical parameters and well water nitrate: Since the data obtained in this study had multivariate nature and several of the variables could be correlated, the data analysis method, Principal Component Analysis (PCA), was used for the

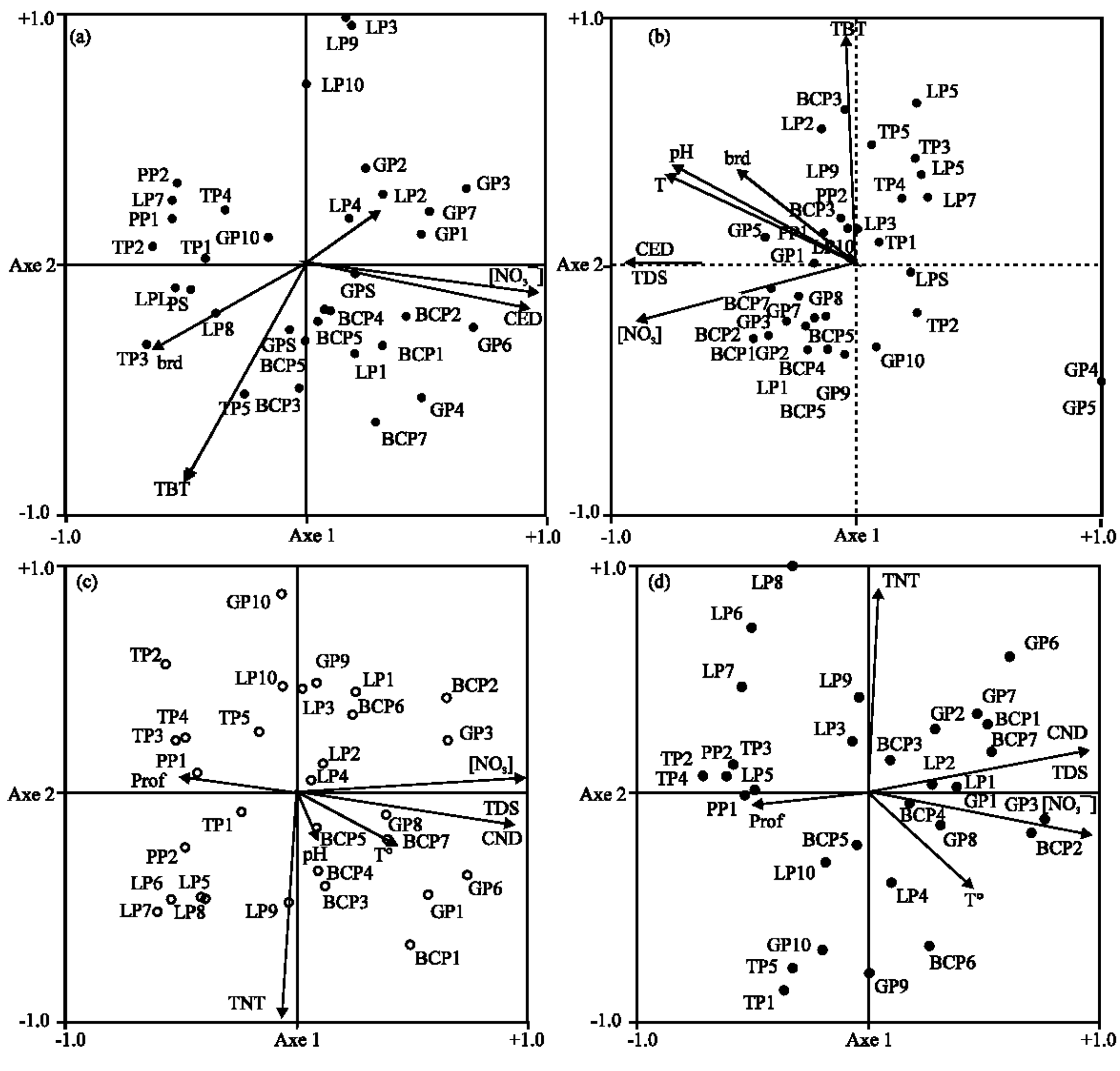

Fig. 4: Continued

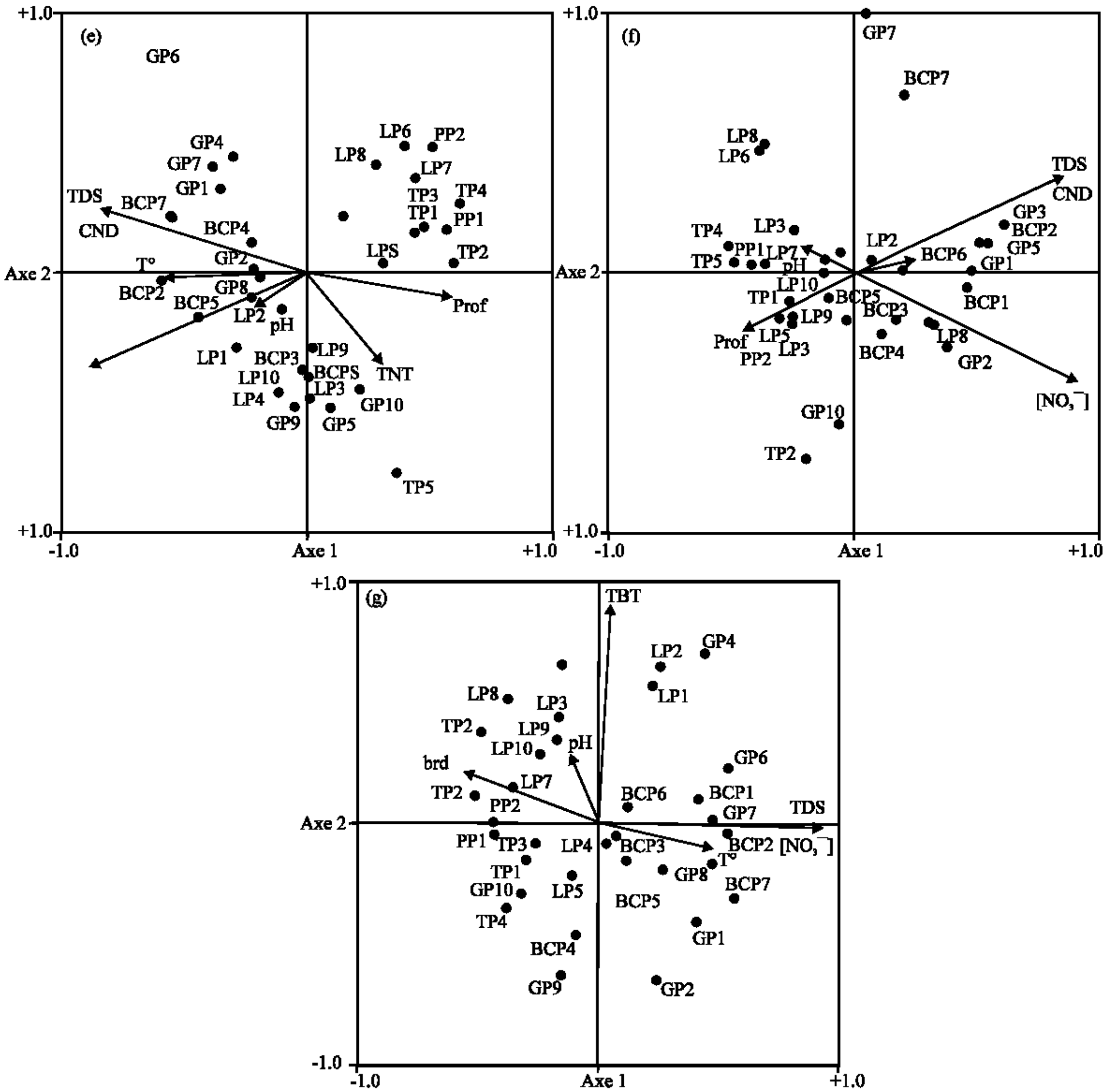

Fig. 4: Plots of variables and samples on the first two axes extracted by principal component analysis of the data set (NTU = turbidity, Prof = depth, CND = conductivity): a) October-04, b) January-05, c) march-05, d) May-05, e) July-05, f) Sept-05, g) Nov-05. (pH not reported in a) and d) for pH meter breakdown)

interpretation of the data. As pointed out by Singh *et al.* (2005), techniques for multivariate treatment of data such as PCA are unbiased methods which can indicate natural associations between samples and/or variables. The adequacy of PCA for the data set was assessed first. Cumulative variances for the first four axes over the study period are indicated in Table 2.

Table 2: Cumulative variances for the first four axes over the study period

Month	Axis 1	Axis 2	Axis 3	Axis 4
Oct. -04	78.7	93.7	97.7	100.0
Jan. -05	58.1	84.8	94.0	99.2
March -05	80.4	91.4	96.3	99.9
May -05	82.7	91.9	96.9	100.0
July -05	79.1	89.5	96.3	100.0
Sept. -05	71.6	86.4	97.2	99.9
Nov. -05	69.5	90.6	97.3	99.9

It can be seen that the first two axes (axis 1 and 2) provide the maximum of information. Nevertheless, axis 1 appears to provide most of the information, as it gives alone more than 50% of the information. Moreover, the cumulative variance for this axis is each time higher than 30% and lower than 90%, indicating the appropriateness of PCA for the data set.

Plots of variables and samples on the first two axes obtained by PCA are presented in Fig. 4a-g. It shows grouping and relationship between the variables and grouping of the samples. Overall, turbidity is the only variable sharply loading on axis 2. Nitrate, temperature, TDS, depth and conductivity load most of the time sharply on axis 1. Apart from January-05, depth is always clearly plotted at one extreme of axis 1 and nitrate, temperature, TDS and conductivity at the other extreme. According to Singh *et al.* (2005), the grouping pattern of the latter variables can be taken as a proof of their mutual correlation. Hence, nitrate is positively correlated with temperature, TDS and conductivity and negatively correlated with depth. It can be drawn that nitrate, temperature, TDS and conductivity are higher in shallow wells than in deep wells. This overall trend is illustrated by the case of nitrate in Fig. 5. It can be seen that nitrate concentrations sharply decrease with increasing well depth. The latter trend has also been mentioned by other authors (Hudak, 1999; Liu *et al.*, 2005). Also interesting to be noted from Fig. 5 is that this trend is valid when considering all wells of the study area on a single graph. A thorough look at Fig. 5 reveals that this trend is not always valid when considering wells site by site. This is particularly the case of the group of wells from Buyo provisoire and Tchemasso (PP1, PP2, TP1, TP2, TP3, TP4 and TP5), where deeper wells tend to result in higher nitrate concentrations than shallower ones. This result is consistent with the findings of Thorburn *et al.* (2003). The latter authors did not observe any relation between nitrate concentrations and depth of the wells in their study. Contrary to them, Elbaz-Poulichet *et al.* (2002) observed higher conductivities and higher nitrate concentrations in shallower wells (>20 m, like in this study). The latter authors attributed this result to the recharge, since the increase in conductivity and nitrate concentrations was concomitant with the rise of water level in the wells and occurred during the rainy season. This can not be the case in this study, since nitrate concentrations (Fig. 2b-d) and conductivity, were observed to decrease further to rainy months and to increase further to dry months. As revealed by the field observations, each contaminated well has a nitrate source in its close environment that permanently releases nitrate in the well water. The recharge water exerts a dilution effect, exactly as observed by Pacheco *et al.* (2001) in their study.

Concerning the samples, no clear grouping can be drawn from the plot in Fig. 4. Wells are not clustered according to their originating site, but according to similar characteristics, confirming that well water quality is primarily governed by local factors related to the close surroundings of each well.

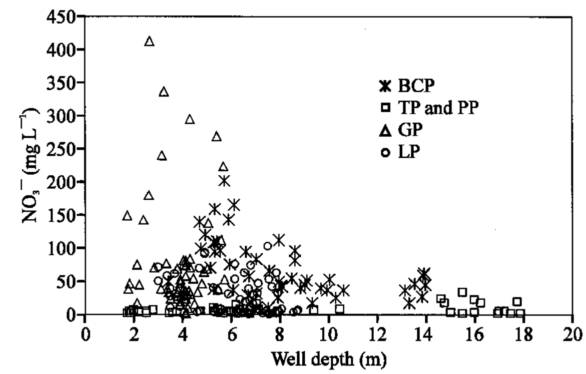

Fig. 5: Nitrate concentration as a function of well depth

The results of this pioneering study need to be supplemented by more in depth investigations, including modelling (Saadi and Maslouhi, 2003; Masetti *et al.*, 2008) and/or specific techniques such as use of isotopes (Wassenaar, 1995; Widory *et al.*, 2004), to unequivocally establish the recharge and the contamination processes of water well in the Buyo area.

CONCLUSIONS

The objective of this study was to evaluate and to attempt to understand the spatiotemporal distribution of nitrate in water-supply wells in the area of Buyo, for groundwater protection purposes. It was found that nitrate concentrations vary greatly from well to well for a given month and from month to month, for a given well. The nitrate concentrations in the 34 wells ranged from 1,83 to 412 mg L^{-1}. Most contaminated wells were found in the district Buyo cité and in the two villages. All wells at Buyo cité, 8 out of 10 at Gbili and 4 out of 10 at Logbozoa, exceeded at least once the WHO limit (50 mg NO_3^- L^{-1}) for drinking water. In contrast, none of the wells reached the WHO limit in the districts Tchemasso and Buyo provisoire. Pit latrines and wastes tips, observed at inappropriate distance from contaminated wells, were suspected to be responsible for the high nitrate concentrations in well water within the study area. An overall trend towards higher nitrate levels in shallower wells was also observed. More in depth investigations, including modelling and/or specific techniques such as use of isotopes, will be needed to strengthen these results and to unequivocally establish the recharge and the contamination processes of water well in the Buyo area.

The study proposed to design an appropriate education programme directed to the populations in order to improve and to protect well water quality in the study area. Meanwhile, populations using contaminated wells can be directed to wells with low nitrate concentrations, after agreements between well owners.

ACKNOWLEDGMENTS

The authors would like to thank the Canadian International Development Research Center (IDRC) for its financial support (Project Number: 100484)

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