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Assessment of Nitrate in Wells and Springs in the North Central Ethiopian Highlands

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Abstract: Under the auspices of the UN Millennium Development Goals, access to safe drinking water in the developing world, including the Ethiopian highlands, has improved greatly. However, in many cases, it is not known how safe the water is. With the intensification of agriculture and increasing applications of fertilizers, high levels of nitrate are a concern. The objective of this study is to assess the nitrate levels in drinking water supply systems. To assess nitrate levels, we sampled 213 water supply points in a 4880 km^2 area in the northwest Ethiopian highlands. The results show that the average concentration was below the World Health Organization (WHO) health standard of 10 mg N-NO_3/L. The average concentration in wells was 3.3 mg N-NO_3/L and in springs was 1.8 mg N-NO_3/L. Only in three wells, that were in agricultural cropped areas, was the WHO standard exceeded. Wells in the agricultural fields had an average nitrate concentration of 3.6 mg N-NO_3/L, which was almost twice that on grazing land and four times that in upland wells. Spatially, the groundwater nitrate concentrations were greater in the moderately sloped parts of the study area where agriculture was intensive and denitrification limited. Thus, although current nitrate levels are safe, in the future, the nitrate concentration could exceed the WHO health standard when fertilizer use increases.

Keywords: Ethiopian highlands; Africa; Sub-Saharan; potable water; drinking water; nitrate; water quality; groundwater; United Nations

1. Introduction

Since safe and reliable drinking water is essential for economic vitality and public health [1], goal 6.1 of the United Nations Millennium Development Goals to "achieve universal and equitable access to safe and affordable drinking water for all by 2030" has been included in the United Nations Inter-Agency and Expert Group on Sustainable Development Goals (SDG) Indicators. Progress is being made but verification is cumbersome due to a lack of data.

Investigations in developing countries on safe drinking water are mainly focused on the incidence of acute infectious diarrhea [1] because it is a cause of death among young children. In addition, chemical agents have been associated with adverse health effects [2–5]. One of these chemicals of concern is nitrate [6,7]. Risks to human health associated with high levels of nitrate in drinking water include thyroid gland dysfunction, gastric cancer, and decrease in the capacity of blood to transport oxygen (known as methemoglobinemia) in infants below six months old [8–10]. In addition, it poses health problems for pregnant women [11]. Finally, excessive nitrates can cause health problems in ruminant animals and once released into the environment, can cause dead zones in the oceans near major rivers [12–17].

Groundwater is preferred as a source of potable water because it is available throughout the year and is less contaminated than surface water [18]. However, according to studies in both developed and developing countries, nitrate levels in groundwater have been increasing [19] and can present serious problems [6,20–26]. In the northeast of Spain, 80% of the groundwater nitrate concentration exceeded 5.6 mg/L due to use of nitrogen-based fertilizers, and animal and human wastes [27]. In the North China plain, 50% of sampled wells exceeded the limit of 10 mg N-NO_3/L concentration due to application of untreated wastewater and excessive fertilizer on agricultural fields [7,20]. Studies in developed countries such as UK found high nitrate concentrations related to intensive agriculture and high-density cattle and pig farms. Nitrate levels ranged from 4.5 to 11.3 mg N-NO_3/L in groundwater and were more than 22 mg N-NO_3/L in surface water in the winter [28–30].

In developing countries, little is known about the impact of agriculture on water quality. Studies in Ghana reported nitrate concentrations reaching 9–10 mg/L in irrigation wells located close to intensively cultivated irrigated fields [31]. Similar studies in India and parts of Africa indicated that 20–50% of the groundwater wells exceed the 10 mg/L nitrate level limit [32]. A rapid assessment of drinking water quality in Ethiopia showed that 32% of the wells were contaminated with nitrate [33]. A study on the Kebean and Akakie rivers of Addis Ababa, Ethiopia found poor quality surface and groundwater due to improper waste management, agricultural activities, poor sanitation, and low levels of hygiene [34]. Research in the Ginchi watershed in southern Ethiopia found that there is pollution of surface water due to human and animal feces, agricultural activities, and a lack of waste disposal systems [35]. Finally, groundwater quality monitoring results in the Ethiopian highlands agricultural watersheds indicated that nitrate levels are rising during the rainy season [36].

Greater amounts of fertilizer are applied on farms because of both the loss of organic matter in the degrading soil base and the need to produce more food for a rapidly increasing population [37,38]. Despite the greater application of fertilizers, the quality of surficial groundwater—which is used as the source of drinking water in the Ethiopia highlands—has not been well documented. The objective of this study is, therefore, to assess nitrate concentrations in the surficial groundwater. The South Gondar Zone in northern Ethiopia was selected as our study area because of widespread use of groundwater as a water supply, intensifying agriculture with increasing fertilizer use, and plenty of rainfall to leach the nitrate to the groundwater.

2. Materials and Methods

2.1. The Study Area

The study was conducted in the Farta, Estie, Dera, and Andabit woredas (districts) in the South Gondar Zone (province) of the Ethiopian highlands, which is located 700 km north of Addis Ababa (Figure 1). The selected study area covers 4880 km^2 and is characterized by rugged topography with steep slopes on the eastern and southern borders, deep gorges in the southeast, moderate slopes in the center, and a plain near Lake Tana in the west. Elevations are 4063 m near Guna Mountain and 1294 m in the southeastern part near the deep Blue Nile gorge (Figure 1). Mean annual rainfall was 1518 mm from 2010 to 2015.

According to land use classification, 45% of the land is cultivated; 26% has a cover of forests, shrub, and bush; 19% is grass lands; and the remaining 10% is water and built-up areas [39]. Grasslands are mainly found in the periodically saturated valley bottom lands and located close to waterways. Croplands are generally at the midslope positions, whereas forest, shrubs, and bush lands are on the steep slope areas with shallow soils.

Land use varies consistently with topographic position in South Gondar. We distinguished bottom, midslope, and upslope landscape units (Figure S1). The valley bottoms have slopes between

0 and 5 degrees, close to shallow waterways, and are located at elevations ranging from 1449 to 3349 m. Midslope areas are situated on hillsides with slopes ranging from 3 to 16 degrees, are not close to the stream network, and are found at elevations starting at 2043 m and ending around 3509 m. Finally, upslope areas on the steepest hillsides have slopes ranging from 10 to 30 degrees and begin at elevations of 2244 m (Table 1).

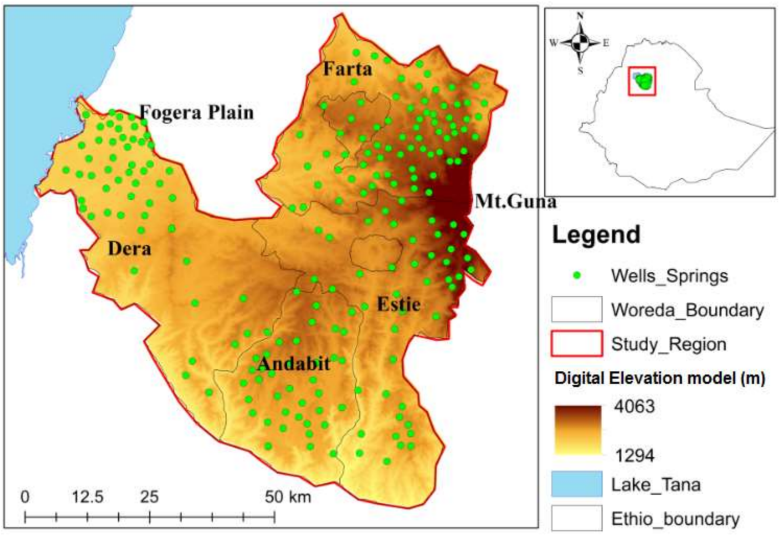

Figure 1. Location of the study area within Ethiopia and the topographic map of the study area with springs and wells.

Table 1. The slope and elevation of the landscape units at various topographic positions in South Gondar.

Topography	Range of Slope (degree)	Range of Elevation (m)	Median Elevation (m)
Valley bottom	0–5	1449–3349	2217
Midslope	3–16	2043–3509	2581
Upslope	10–30	2244–3659	2653

The hydrology is typical for a mountainous degraded landscape with a permeable surface layer overlaying a slowly permeable layer that is recently formed [40]. The valley bottoms become fully saturated after approximately 500 mm of cumulative rainfall by interflow from the hillsides and precipitation. Some of the most degraded land form a perched water table and, together with the periodically saturated valley bottoms, generate surface runoff [40].

Rain-fed agriculture is practiced during the rain phase from May until September [41]. Urea containing 46% ammonia nitrogen, diammonium phosphate with a composition of 20% N and 50% P_2O_5, and ash were applied in modest amounts (Table 2). According to the local agricultural agents, nitrate application varied from 22 kg N ha^{-1} in Farta to 35 kg N ha^{-1} in Andabit and Dera (Table 2).

Table 2. Fertilizer use and amount of fertilizer applied in four woredas in South Gondar, Ethiopia.

Woreda	Total Area (km^2)	Cropland (km^2)	Cropland Coverage (%)	Urea (kg ha^{-1})	Diammonium Phosphate (kg ha^{-1})	Fertilizer N Applied (Gg)	Fertilizer N Applied (kg N ha^{-1})
Farta	1251	652	52%	34	34	1.43	22
Estie	1354	594	44%	39	39	1.49	25
Andabit	794	318	40%	55	55	1.11	35
Dera	1478	625	42%	54	54	2.19	35
Average	1220	547	45%	45	45	1.59	29

2.2. Data Collection and Analytical Methods

The cross-sectional study (i.e., one sample per waterpoint) was conducted to assess the nitrate concentration in drinking water supply points from December 2013 to June 2014 (Table S1). Samples were collected from protected springs and hand-dug wells during the dry phase when the temporal variation was less than during the rain phase when fertilizers were applied. A total of 213 rural water supply schemes were randomly selected from the functional wells in the four woredas: 190 (89%) were wells and the remaining 23 (11%) were protected springs. The main land use of the recharge contributing area and topographic position (upslope, midslope, and bottom slope) were noted for each drinking water point (Table 3). Most waterpoints were located in the valley bottoms and midslopes where most people live. The recharge area for the majority of wells and springs was in agriculture because it was the dominant land use (Table 3).

Table 3. Landscape position and land use of recharge areas contributing to the springs and wells.

Land Use	Valley Bottom	Midslope	Upslope	Total
Agriculture	68	44	13	125
Grass	34	28	0	62
Forest	0	18	8	26
Total	102	90	21	213

Water samples (100 mL) for nitrate analysis were taken from wells and springs after 4 min of pumping or flushing of faucets. Samples were analyzed for nitrate in the field using a Plain Test 7100 Spectrophotometer with a detection limit of 0.001 mg/L [36]. The test was conducted in a special Nitratest tube. This is a graduated sample container with a hopper bottom to facilitate settlement and decanting of the sample. The reduction to nitrite with sulphanilic acid forms a red color in the presence of *N*-(1-naphthyl)-ethylene. The two reagents are provided in a single nitricol tablet. The intensity of the red color is proportional to the nitrate concentration and is measured using a Palintest Photometer.

The nitrate concentrations were compared with the WHO maximum permissible limit and natural background concentration without human influences. The WHO upper limit in drinking water is 10 mg N-NO_3/L [1]. Natural nitrate background levels in the United States were found to be 3 mg N-NO_3/L [42].

2.3. Statistical Analysis

The one-way analysis of variance (ANOVA) statistical test was used to determine whether a statistically significant difference of nitrate concentration existed between the land uses and the topographic landscape positions. A p-value less than 0.05 was considered to show a statistically significant difference.

A map of the spatial distribution of nitrate concentration was developed in ARC GIS 10.4.1 using the inverse distance method.

3. Results and Discussion

3.1. Overview of Nitrate Concentration in South Gondar

3.1.1. Springs versus Wells

The average nitrate concentration in samples from the 190 wells was 3.3 mg N-NO_3/L and significantly greater than the average in the 23 springs, which was 1.4 mg N-NO_3/L (Table 4). The maximum nitrate concentrations were 15.8 mg N-NO_3/L in the wells and 3.7 mg N-NO_3/L in the springs (Figure 2a). The N-NO_3 concentrations in springs were smaller because they were found in places where groundwater intersects with the organic-rich surface and can become anoxic [43], promoting denitrification [44,45]. Water from wells was obtained (by pump) from deeper depths and has typically sufficient oxygen to limit denitrification. Note, however, that the low nitrate concentration in springs was not an indication that other constituents (such as microbial contamination) were also low as there is a greater likelihood of contamination from surface sources in springs than wells [43].

Table 4. Groundwater nitrate concentration based on land use, topographic position and water sources, and ANOVA analysis results.

Categories	Total Sampled		% of Total	Nitrate Concentration mg N-NO_3/L			ANOVA p-Value
				Average	Max	Min	
Land use	Agriculture	125	59	3.6 ± 2.4	15.8	0.1	0.001
	Forest	26	12	2.2 ± 0.9	3.5	0	
	Grass	62	29	2.3 ± 0.5	3.1	0.4	
Slope position	Upper	21	10	0.9 ± 1	3.5	0	0.000
	Mid	90	42	3.7 ± 2.3	15.8	0.4	
	Bottom	102	48	2.9 ± 1.3	9.2	0.8	
Water supply	Well	190	89	3.2 ± 2	15.8	0.1	0.003
	Spring	23	11	1.4 ± 1	3.7	0	
	Total	213					

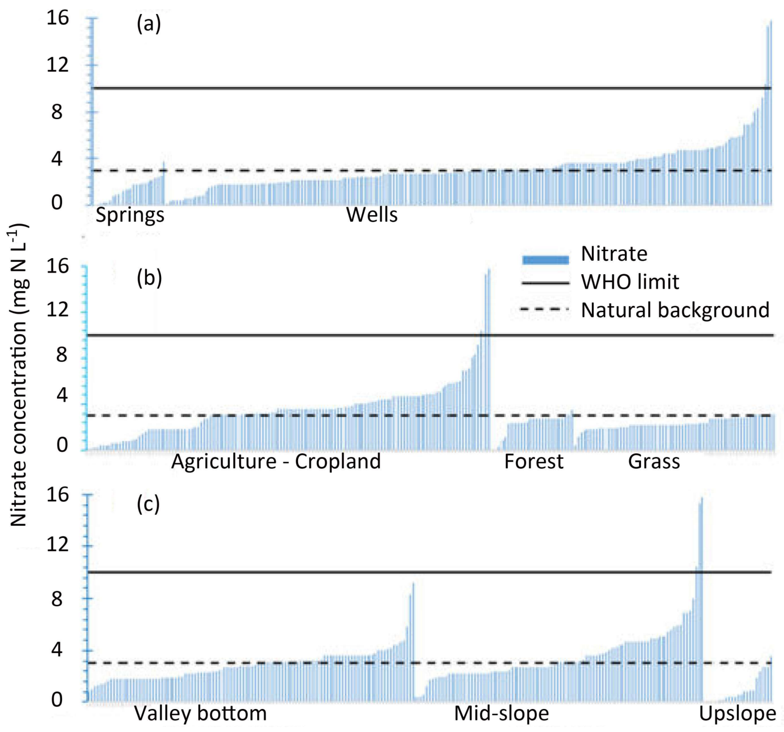

Figure 2. Nitrate concentration in South Gondar Zone sampled in the period from December 2013 to June 2014: (**a**) in springs and wells; (**b**) upstream land use; and (**c**) topographic position. The solid lines indicate the 10 mg/L WHO standard and the 3.4 mg/L natural background.

3.1.2. Land Use Effects

The average nitrate concentration in groundwater in the cropped agricultural areas was 3.6 mg N-NO_3/L while the maximum nitrate concentration in areas with mainly grass and forest was less than that (3.1 mg N-NO_3/L for grasslands and 3.5 mg N-NO_3/L for forests; Table 4, Figure 2b and Figure S1). The statistically greater nitrate concentration under the agricultural land (Figure 2b and Figure S1, Table 4) originates from the modest application of nitrogen fertilizers (Table 2) that are easily leached in the form of nitrate to the groundwater with high rainfall of over 1200 mm in the growing period [46].

Our results are similar to those of observations in Ethiopian highlands and the USA [36,47] where nitrate concentrations in the agricultural watersheds are greater than in forested watersheds. However, the observed concentrations in our area were less than those reported in the regions where fertilizer application was in the order of 100 kg N ha^{-1} or more in many cases [20,45–47].

3.1.3. Topographic Position

Nitrate concentrations were greater midslope than both upslope and downslope in the valley bottom (Figure 2c and Figure S1, Table 4). The average nitrate concentration at midslope, where most of the agricultural crops (including potatoes) are grown, was 3.7 mg N-NO_3/L. This is almost four times that of the upslope areas with mostly brush and forest and minor cultivation of crops due to the steepness of the land, shallow soils, and frost (for the highest elevation above 3400 m). Despite the contribution of interflow with high nitrate concentrations [48], the nitrate concentrations in water supply points in the periodically saturated valley bottoms were less than at midslope. This can be explained by the denitrification of nitrate when soils become saturated, from plant uptake by grasses, and by collecting manure from grazing animals for fuel (Figure 2b and Figure S1, Table 4).

There is an intricate relationship between landscape position and land use. Crop production on the steep lands and shallow soils at higher elevations is not profitable and is therefore not cultivated and is instead covered with forests or brush. These upslope lands with natural vegetation minimally affected by grazing are located above the cropped areas and have low input of fertilizers; therefore, they have good quality groundwater with an average nitrate concentration of 2.3 mg N-NO_3/L (Table 4). The valley bottoms become saturated during the monsoon rain phase [48] and are therefore unsuitable for crop production. Because grass tolerates wet conditions, valley bottoms have become the communal grazing lands. Although the nitrate concentrations are low in the valley bottom lands, bacterial contaminations from manure from grazing animals usually make it an undesirable source of drinking water [49,50].

3.1.4. Fertilizer Application Rate

The fertilizer rate and the amount of cropped agricultural land varies between the four woredas (Table 2). Nitrate concentrations in wells and springs that derive water from catchments with crop land are ranked for each woreda in Figure 3. The Dera and the Farta woredas have the largest number of wells that are at or below the natural background nitrate concentration (Figure 3).

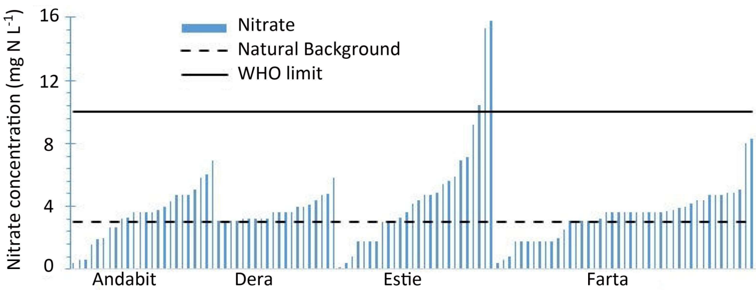

Figure 3. Nitrate concentration in wells and springs in the agricultural lands of Andabit, Dera, Estie, and Farta woredas in South Gondar, Ethiopia.

The Dera watersheds, in which the Fogera Plain with intensive crop agriculture is located, has the highest use of fertilizer on area-wide and per ha bases (Table 2). Despite this, it has the lowest nitrate concentration due to the high groundwater table during the rain phase enhancing denitrification of the nitrate leached.

The Farta woreda, in the northern part of the study area (Figure 1), had the highest density of agricultural land (52%, Table 2), but farmers applied the lowest rate of fertilizers. This explains the fact that, in the absence of denitrification, there were only relatively few concentrations in the wells and springs in the agricultural land above the natural background nitrate level in Figure 3.

Water points in the Estie and Andabit woredas had the most wells with concentrations above the natural background. The rolling topography and the best agricultural soils in Estie woreda (in the center the study area, Figure 1) facilitate the cultivation of various crops such as potatoes, teff, and barley. Of all crops, potatoes receive the greatest amount of fertilizer. Two of the three wells with concentration above 10 mg N-NO_3 /L were located downstream of potato fields. The third well with nitrate in excess of the WHO standard was affected by a compost pile.

The Andabit woreda (located near the Blue Nile gorge in the south, Figure 1) had the highest rate of fertilizer applied per ha but the area-wide application rates were smaller than in the Estie woreda because the area has steep slopes near the Blue Nile gorge with deep gullies and wide, flat lands near the stream. Nitrate concentrations were therefore not as high due to dilution of low-nitrate water from nonagricultural areas.

3.2. Mapping Nitrate Concentrations

The nitrate concentration in the groundwater (depicted in Figure 4) is in accordance with results presented above. The nitrate concentrations below 3 mg N-NO_3/L (dark green) were found at the highest elevations with steep slopes and shallow soils near Mount Guna and in the southern portion of the study area covered with forests and brush. In addition, nitrate concentrations were low in the areas with grass cover in the north–central and northwest part of the study area (compare Figures 4 and 5). Finally, the nitrate concentrations were less than 3 mg N-NO_3/L in the Fogera Plain near Lake Tana; this area has intensive agriculture and is also periodically saturated. Therefore, nitrate that is leached when the groundwater is low is denitrified when it is close to the surface and organic matter is present [45,50]. Beside the Fogera Plain, most intensive agriculture is practiced on the moderately sloping and relatively flat areas located in the central part of the study area in the Estie woreda and along the southeastern boundary in the Andabit woreda (Figures 4 and 5). These areas are relatively well drained and have nitrate concentrations in the groundwater of over 5 mg N-NO_3/L (yellow and red colors in Figure 3).

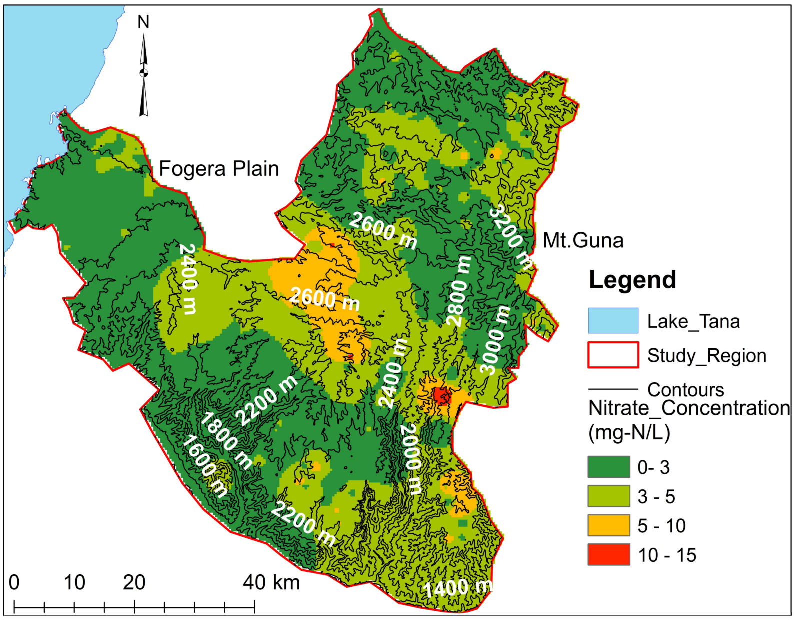

Figure 4. Topographic map (Black line denotes the elevation contours white color fonts denotes elevation contour) and the spatial distribution of nitrate concentrations in the study area in the Ethiopian highlands from wells and springs sampled from December 2013 to June 2014.

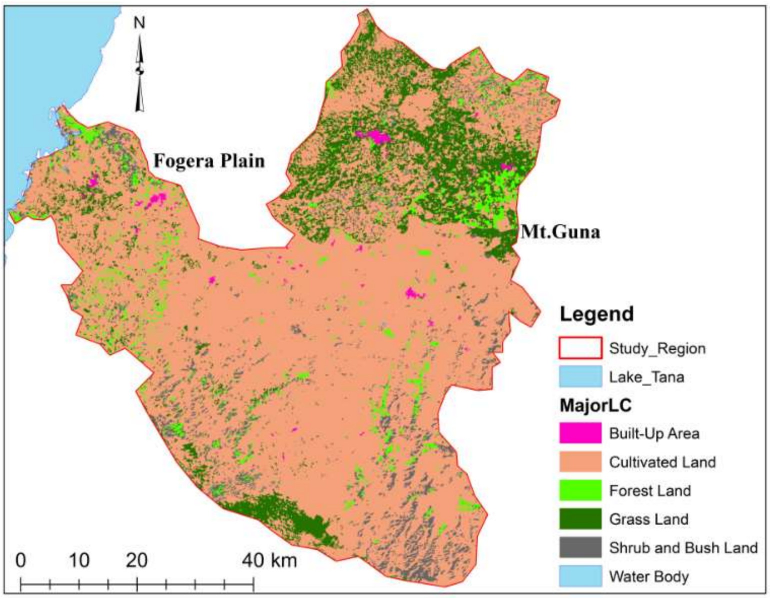

Figure 5. Land use map of study area.

In general, nitrate concentrations in the drinking water are currently not worrisome. Fifty-five percent of the area had nitrate concentrations below the natural nitrate background concentrations in the USA of 3 mg N-NO_3/L [42]. Likely, it will not stay that low in the future because fertilizer use is increasing from the current use (on average, 29 kg N ha^{-1} $year^{-1}$, Table 2). When fertilizer use in the Ethiopian highlands approaches that in developed countries, we expect to find similar concentrations over the WHO standard [12,24–27], especially since the precipitation is much higher than in the temperate regions, promoting leaching of the applied nitrogen before the plant can take it up. In our study site, we already found concentrations above the WHO standard where potatoes, that were fertilized at a greater rate than other field crops, were grown. In addition, we confirmed the impact of fertilizers in a related study [36] where we found that nitrate concentrations were elevated shortly after fertilizers were applied.

Thus, although a large portion of the population will have access to drinking water under the goals set by UNESCO, at the same time, pollution is increasingly making it unsafe to drink. Consequently, a careful monitoring program is needed to ascertain that the drinking water is safe.

4. Conclusions

Nitrate concentrations were assessed in groundwater and the distribution of these concentrations was mapped in four woredas of South Gondar Province in the north–central part of the Ethiopian highlands. The results show that out of the total 213 randomly selected water points, consisting of springs and wells, only three wells had nitrate concentrations that were above the WHO permissible health standard. Nitrate concentrations in well water was almost twice those in spring water. As expected, nitrate concentrations in agricultural land, located mainly at the midslope position of the landscape, had the greatest concentration of groundwater, averaging 3.6 mg N-NO_3/L. Upslope forest and shrub land had the lowest concentrations.

The mapped spatial distribution of nitrate concentrations shows that the lowest nitrate concentrations were found both in the highly productive Fogera Plain near lake Tana due to denitrification, and in the mountainous and steep areas in the upper parts of the watersheds without agriculture. Intermediate and high nitrate concentrations were found in the central portions of the study area with intermediate slopes and where agriculture was practiced. Since overall fertilizer use is still modest for most crops, with average application rates varying from 22 to 35 kg of N/ha, and less than can be taken up by the crop, most nitrate concentrations in groundwater for the major crops are below the WHO standard of 10 mg N-NO_3/L. Two of the three wells with high nitrate concentrations were observed near potato fields with high levels of fertilizer. We expect that nitrate concentrations in drinking water from wells and springs will rise when fertilizer use increases. This will likely be more severe than in temperate climates because of the high rainfall over a four-month period in the (semi)humid climates; this rainfall promotes fast leaching of the nitrate before it can be taken up by the crop.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/4/476/s1. Figure S1: Boxplots of the nitrate concentrations in groundwater measured in developed springs and wells at three hillslope positions and land use in the waterpoint drinking area in South Gondar Zone from December 2013 to June 2014. Table S1: Number of water points sampled each month in the four woredas in South Gondar, Ethiopia.

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Conflicts of Interest: The authors declare no conflict of interest. The sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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