IMPACT OF NATURAL AND ANTHROPOGENIC CONTAMINANTS ON THE GRANADA AQUIFER; NICARAGUA

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Abstract - The water supply of the city of Granada has been impacted by elevated nitrate concentrations (78 mg NO_3^-/L), which led to interest in a study of the groudwater quality of the Granada Aquifer. Groundwater samples were collected in March 1998 existing wells withing the basin during a campaign in March 1998. A plume of high-TDS (up to 1200 mg/L), high-pH (up to 8.0) water appears to be infiltrating from Laguna Apoyo, a closed-basin, saline (5,840 mg/L TDS), alkaline (pH = 8.4), volcanic lake, with sodium-chloride-sulfate type waters, located just west of the city. Groundwater levels agree that the direction of groundwater is from the Laguna Apoyo toward Lake Nicaragua, except for the southern area of the aquifer (south of Granada), where groundwater recharge occurs on the flanks of Mombacho Volcano. High concentrations of nitrate (up to 190 mg/L) have been observed in wells in the north, and also in portions of the southern part of the aquifer. Future development of groundwater will have to take these present sources of contamination into account, and furthermore, the city of Granada should create groundwater protection zones for the relatively small water resource which remains uncontaminated.

Key words - contamination, nitrate, salinity

INTRODUCTION

The city of Granada, Nicaragua, located on the northwest shore of Lake Nicaragua, approximately 50 km south of Managua, is an excellent example of an

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urban area that needs to protect its scarce groundwater resources (Figure 1). With a rapidly-growing (approximately 2.9%) population of 95 400, the city is entirely supplied by groundwater, given the surface water supplies are very limited or of poor quality (Vamme, 1995). Furthermore, agricultural concerns and the rural population of the Granada Basin also depend on this limited resource.

In 1997, nitrate concentrations were recorded consistently (up to high as 78 mg/L NO_3^- /L) above the drinking water limit (50 mg/L) (CAPRE, 1994), in one of the five municipal water supply wells (Espinoza, 1999). This discovery resulted in an interest by the municipality to discover what sources of nitrate might be impacting the aquifer. This study, conducted by the University of Costa Rica (UCR), was completed to investigate the sustainable exploitation and protection of the groundwater resource in the basin.

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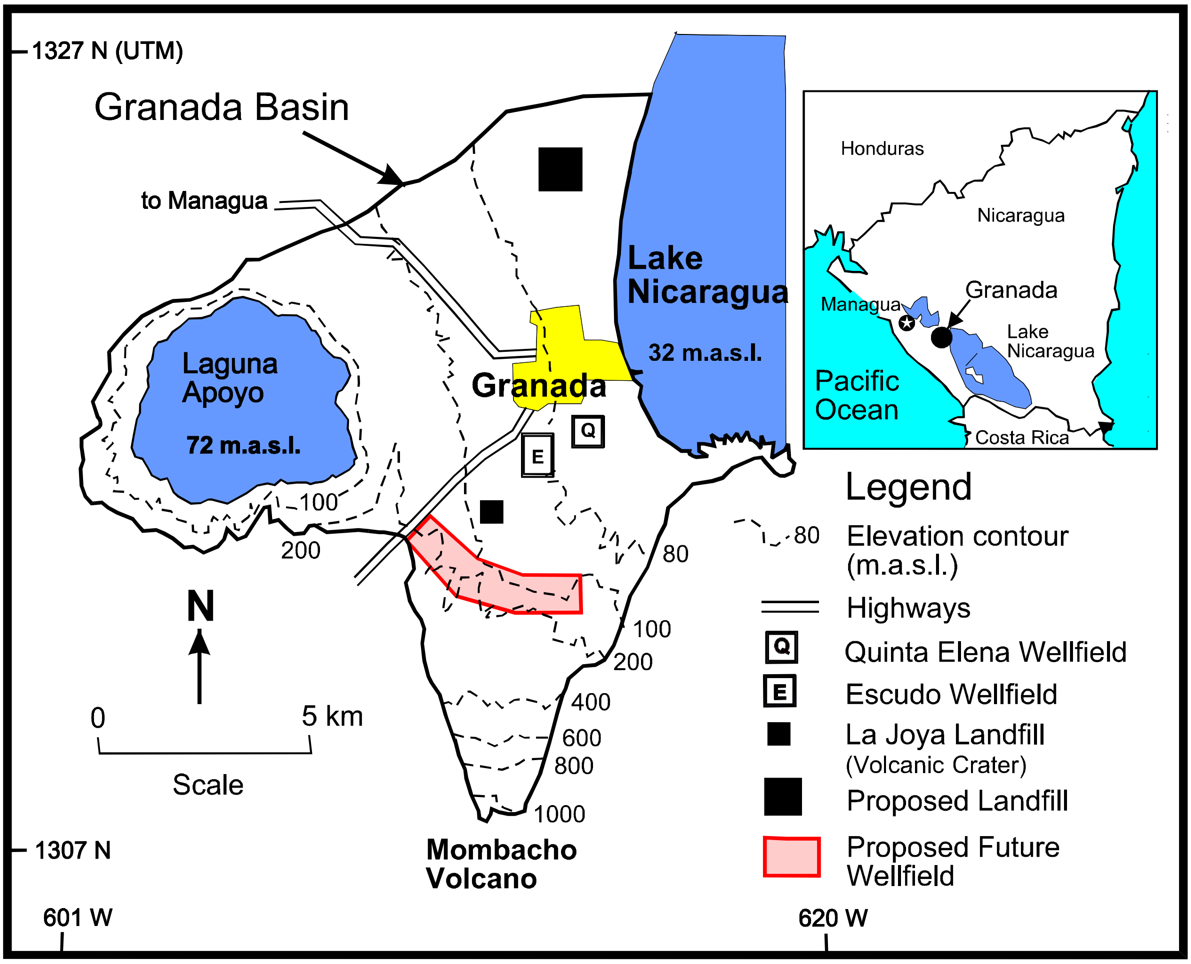

Figure 1: Location Map of Study Area

Granada for centuries, since its foundation by the Spaniards in 1524, depended on springs on the side of Mombacho Volcano, located 10km sourth of Granada, and Lake Nicaragua for their water supply. Unfortunately, spring discharges are extremely limited, and Lake Nicaragua became contaminated as the population and industries (detergents in particular) developed, which led to the drilling of municipal water wells, starting in 1943. The Quinta Ena Wellfield (4 wells) (Figure 1) was developed between 1958 and 1973, and, at the beginning to the 1990s, a second wellfield, El Escudo (2 wells), was drilled to supply the growing demand. The total extraction of groundwater in the basin is 10 970 000 m3/year, of which some 78% is from the domestic wells (Espinoza, 1999).

In recent years, further plans to construct several more wells south of the El Escudo Wellfield have been tabled, but their location has been determined solely according to a geophysical study of the aquifer (ITS-LOTTI-LAMSA, 1995; Vázquez, 1996), and not considering sources of contamination.

There are several important sources of groundwater contamination which could be creating the high nitrate concentrations in the municipal water supply. Although potable water reaches approximately 95% of the population, only 50% have sewage connection. Their untreated sewage is conducted to several, open, unlined canals, with no protection against infiltration, which ultimately drain into Lake Nicaragua. Furthermore, the population deposits wastes in septic wells and latrines, which are directly connected to the aquifer.

The accelerated unplanned growth of Granada has led to the expansion to the city limits to and beyond the two wellfields, which were originally constructed well outside of the city. Thus, sources of groundwater nitrate contamination exist upgradient of the municipal water supply.

Solid waste deposition is also of concern. The La Joya Landfill, located inside two extinct volcanic cones, is approximately 1.7 and 2.7 km upgradient from the El Escudo and Quinta Ena Wellfields respectively (Figure 1), and has been receiving waste for the last thirty years (Vado, 1997). The landfill has no lining, and the fracture systems associated with these volcanic vents make them particularly prone to contaminant transport. Animal husbandry, which occurs mostly in the northern portion of the basin, also is a possible source of nitrate contamination.

Man-made contaminants, such as nitrate, are not the only groundwater contamination consideration in the Granada Basin. A study by the United Nations first noted that groundwaters in the northern portion of the basin were highly saline (United Nations, 1973). Laguna Apoyo, a 600-meter deep and 7-kilometer wide volcanic lake is located upgradient from this portion of the aquifer. High concentrations of TDS (4056 mg/L) (Vamme, 2000) are known to exist in the lake.

This study examines the major ion and nitrate chemistry of groundwaters in the Granada Basin, based on a sampling campaign of 21 wells in the basin (Figure 2), in order to determine the probable sources of contamination and to suggest the best areas of future water supply development.

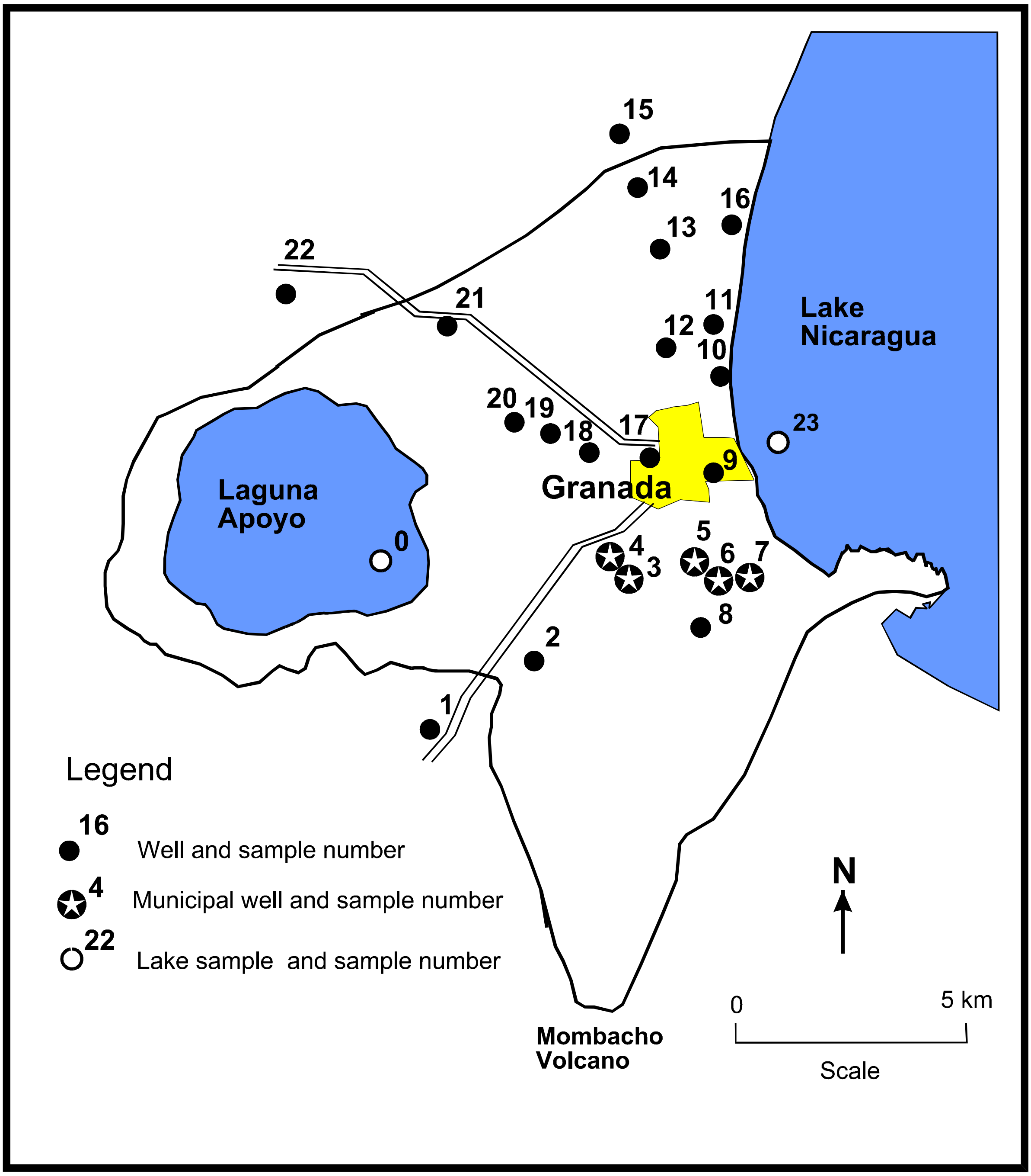

Figure 2: Sampling Locations

GEOLOGY AND HYDROGEOLOGY

The Granada Basin (140 km^2) is located in the Nicaragua Depression, a large volcanic graben structure that stretches from the Consigηina Volcano in the Gulf of Nicoya to the volcanic islands of Zapatera, Ometepe and Solentiname in Lake Nicaragua. The active volcanism in the graben, caused by the subduction of the Cocos Plate beneath the Carribbean Plate, has created thick formations of Pliocene to Holocene volcanic and sedimentary formations. The volcanic activity has occurred along the regional Los Marrabios fracture zone.

In the study area, the volcanic sequence, from oldest to youngest, includes the Las Sierras Formation, the Laguna Apoyo Formation, the Mombacho Volcano Formation, and Recent Alluvial Deposits (Figure 3).

The Las Sierras Formations (TQps) is of Pliocene to Pleistocene age and is composed of volcanic and fluviovolcanic deposits, including tuffaceous sandstones and brecciated, pisolitic lapillitic and pumitic tuffs, of andesitic to basaltic composition, with occasional fossil soil horizons in the upper portion of the formation (United Nations, 1973). The formation on average has a thickness of 650 meters and thus is only partially penetrated by water wells in the study areas, which have a maximum depth of 150 meters (Figure 3). The base of the Las Sierras Formation is comprised of volcanic lacustrine formations that were deposited during a transgression which inundated the graben.

The Pliocene Laguna Apoyo Formation (Qva) consists of pumitic tuffs which were deposited in most of the study area by Krakatoa-type eruptions from the Laguna Apoyo Crater, and to a lesser degree, from the La Joya Craters, which occurred approximately 23 000 years ago (Sussman, 1985 in Espinoza, 1999). The Mombacho Vocano Formation (Qvl) is Holocene and consists of andesite and andesitic basalt flows that originated from Mombacho Volcano (United Nations, 1973). The Recent Alluvial Deposits (Qal) occur along the shore of Lake Nicaragua, as a result of fluvial deposition of ash, tuff conglomerates, and clay (Figure 3).

The climate is classified as Dry Humid Tropical, with average temperatures between 26.1 and 31.4 °C and a marked rainy season from May to October with an annual precipitation of 1450 mm/year. Studies of the infiltration rate indicate that although the formations are highly permeable, the high evapotranspiration allows only approximately 10 to 25% of the precipitation to recharge the aquifer (140 to 375 mm/year) during the rainiest months (Espinoza, 1999).

Groundwater levels indicate that groundwater flow is occurring from Laguna Apoyo towards Lake Nicaragua (Figure 4), with a hydraulic gradient of approximately 0.01, even though topographically-speaking Laguna Apoyo is a closed hydrologic basin (Figure 1). Gradients toward the southern portion of the study area (approximately 0.03) are much higher due to the abrupt increase in altitude towards the Mombacho Volcano. This creates a mound of groundwater along the southeast corner of Laguna Apoyo, which impedes groundwater flow from the southern part of Laguna Apoyo. Gradients become much reduced nearing Lake Nicaragua.

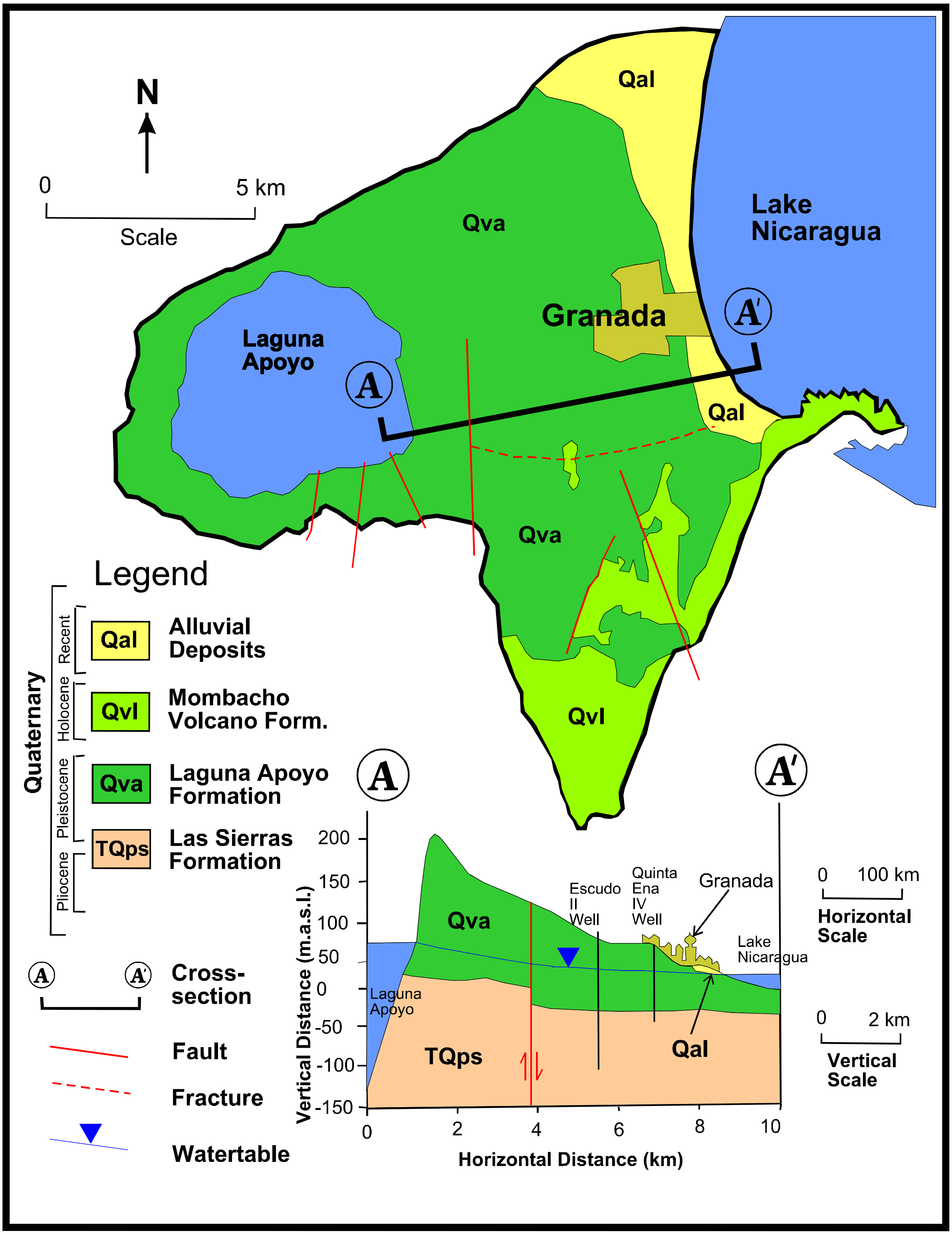

Figure 3: Geologic Map and Cross-section of the Granada Aquifer

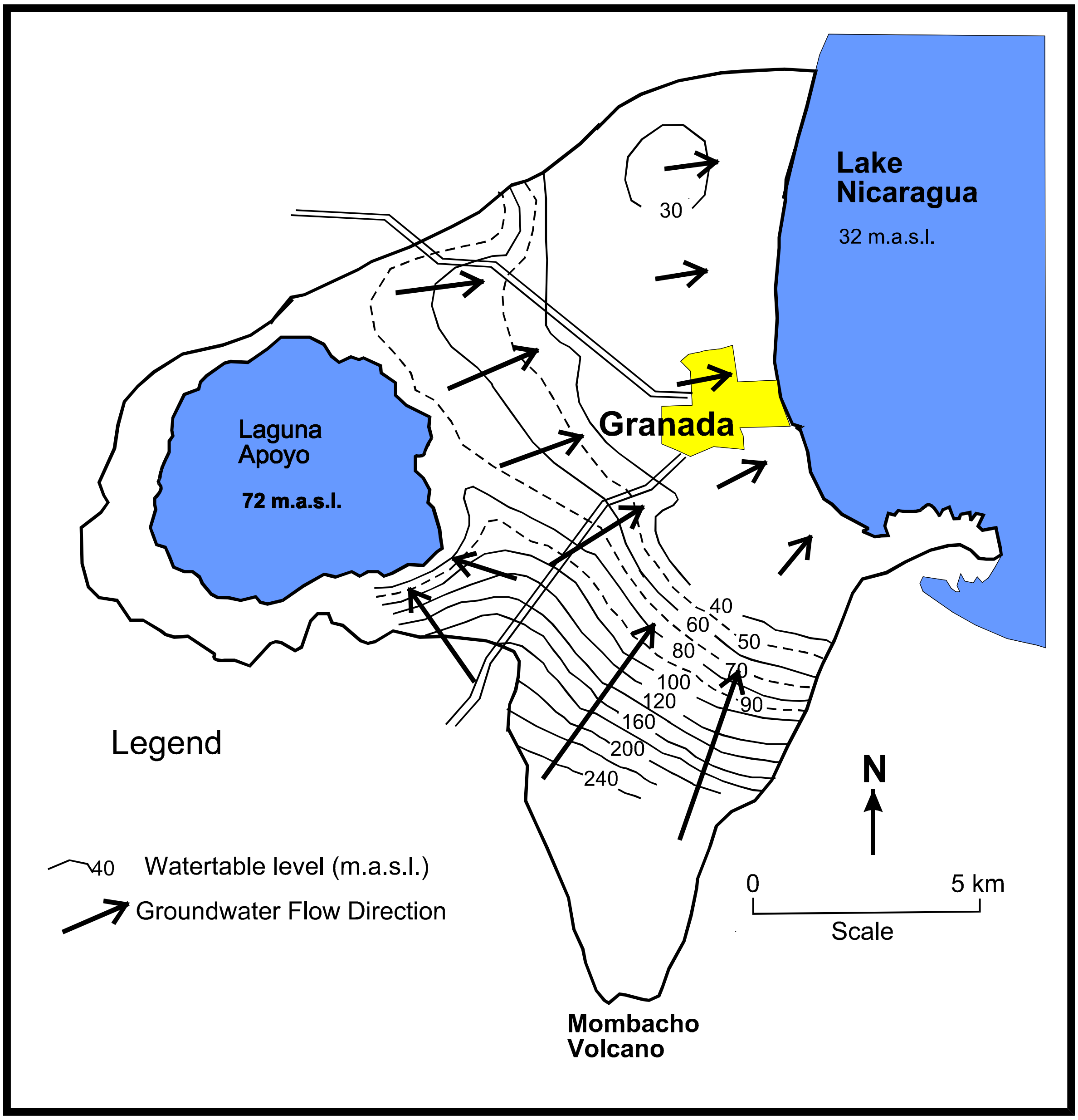

Figure 4: Water Level Measurements and Groundwater Flow Directions of the Granada Acuifer

Average transmissivities from aquifer pumping tests ranged between 4 800 and 700 m^2/day and the storage coefficiente indicated unconfined to semiconfined conditions (0.02 to 0.0002) (Espinoza, 1999). Given the complicated geology and relatively small range of transmissivity values, the aquifer hydrogeologically can be considered as one unit.

Total recharge of the aquifer is approximately 53 000 000 m^3/year, of which 48% is recharged from the side of Mombacho Volcano, 30% from Laguna Apoyo, and 22% in the lowlands and around Laguna Apoyo, according to water balance calculations (Espinoza, 1999). Therefore, Laguna Apoyo is an important source of recharge for the northern portion of the aquifer.

METHODS

Water level measurements were conducted during March 1998 with an electric probe. Water levels reported from Lake Nicaragua and Laguna Apoyo are from INETER (Instituto Nicaragüense de Estudios Territoriales) data (Vamme, 2000). Elevations of wells was determined with a geographic position device (GPS).

Groundwater sampling was conducted March 11 to 12, 1998. All wells were pumped for at least 10 minutes before sampling and field measurements of pH, electrical conductivity and temperature were determined. Major ion and nitrate samples were collected in plastic containers, with no air space, and refrigerated.

Nitrate was analyzed at CIRA (Centro Internacional de Recursos Acuáticas) in UNAN (Universidad Nacional Autónoma de Nicaragua) within two days of sampling, using ion chromatography, and replicate samples were sent to CIA (Centro de Investigaciones Agronómicas) at UCR. There was good concordance between replicate samples.

Major cation and anion analyses were conducted at the Central American School of Geology (ECAG) at the UCR. Calcium, magnesium, sodium, potassium, and iron were analyzed with atomic adsorption. Alkalinidad was titrated with H_2SO_4 within 2 days of sampling. Chloride was titrated with $AgNO_3^-$. Sulfate was determined by precipitation with $BaCl_2$. The EPM error of the analyses was within or near 15% EPM error, except for Sample 16 (Table 1).

GROUNDWATER CHEMISTRY

The depth, temperature, electrical conductivity (EC) and groundwater chemistry of the 21 wells and two lake samples are presented in Table 1, and the sample locations are illustrated in Figure 2. EC measured in the Granada Aquifer delineates clearly a plume of saline groundwater emanating off of Laguna Apoyo, that becomes less concentrated from east to west in the northern portion of the study area (Figure 5). EC decreases from 2100 μS/cm in Sample 20, some 60% of the concentration measured in Laguna Apoyo, to values near 500 μS/cm near Lake Nicaragua. One sample has an exceedingly high value of EC (Sample 16; 3410 μS/cm), which is located less than 1½ km downgradient from the city´s sewage oxidation lagoons.

Table 1: Inorganic chemistry of the Granada Aquifer, Laguna Apoyo, and Lake Nicaragua

Sample Number	Well Name	Depth (m)	Temp-erature (°C)	Electrical Conduct. (mS/cm)	SDT (mg/L) (calculated)	PH	EPM error (%)
0	Laguna Apoyo	----	31.0	5840	4056	8.40	-15.0
1	Intercasa	45	31.6	433	137	7.74	+10.0
2	Malga Rossa	25	30.9	557	90	7.32	-9.0
3	Escudo I	54	31.2	397	---- [a]	7.15	---- [a]
4	Escudo II	54	31.8	381	130	7.24	-7.0
5	Quinta Ena I	32	30.5	365	---- [a]	6.97	---- [a]
6	Quinta Ena II	35	30.2	457	140	6.95	-0.7
7	Quinta Ena III	36	30.7	327	94	6.95	+4.0
8	El Charco	36	25.0	224	240	7.73	+16.3
9	Hotel Granada	29	30.0	511	151	7.05	+2.1
10	Gabriel Lopéz	17.5	28.5	1680	708	7.01	-6.6
11	Antonio Flores	3	28.1	599	234	6.87	+3.6
12	HaciendaObregón	15	25.0	1245	404	6.98	-11.0
13	Hda.S.José Viuda	29	28.2	697	245	6.90	+5.4
14	Hda. San Ignacio	31	27.5	561	225	7.44	+16.0
15	Hda. San José	5	27.0	1044	512	7.11	-14.0
16	Santiago Murillo	2	28.7	3410	2125	6.08	+17.6
17	Jabonería Prego	37	31.3	1420	630	7.36	-7.2
18	Antonio Alvarado	63.5	29.6	1314	511	7.70	+28.4
19	Hotel Serramonte	62	27.9	346	223	7.76	+18.5
20	Textiles D´Lago	95	28.3	2100	1284	7.85	+10.9
21	FUMOSA	36	29.8	651	250	8.31	+16.4
22	Valle Laguna	103	28.3	344	143	8.03	+16.0
23	Lake Nicaragua	----	30.0	503	399	7.50	-16.7

Table 1: Inorganic chemistry of the Granada Aquifer, Laguna Apoyo, and Lake Nicaragua (continued)

Sample Number	Ca^{++} (mg/L)	Mg^{++} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Fe_{total} (mg/L)	HCO_3^{-} (mg/L)	SO_4^{2-} (mg/L)	Cl^{-} (mg/L)	NO_3^{-} [b] (mg/L)
0	67	30	1046.0	12.0	< 0.10	163	1366.0	1369	2.7
1	11	2	26.9	11.4	0.81	22	10.5	38	14.1
2	8	1	16.4	1.4	0.50	16	< 2.0	40	6.4
3	---- [a]	---- [a]	---- [a]	---- [a]	---- [a]	---- [a]	---- [a]	---- [a]	5.1
4	8	1	25.5	7.0	0.28	20	13.4	48	6.1
5	---- [a]	---- [a]	---- [a]	---- [a]	---- [a]	---- [a]	---- [a]	---- [a]	14.7 [c]
6	10	2	28.5	7.1	1.58	19	14.0	44	25.1
7	9	1	18.1	6.1	0.24	17	11.4	24	7.7
8	18	2	30.3	63.0	0.41	55	7.6	64	< 1.0
9	9	7	27.4	8.9	0.63	19	16.2	44	18.9
10	29	7	139.5	47.1	0.50	20	74.2	200	191.2
11	10	2	66.8	7.4	0.93	15	21.6	84	26.9
12	29	7	65.6	10.4	0.55	16	25.0	132	118.5
13	11	3	66.8	7.4	0.33	21	15.9	74	45.6
14	8	3	72.7	14.7	0.70	20	14.4	76	15.9
15	19	3	118.9	10.4	0.50	22	20.6	240	77.2
16	72	24	789.8	58.9	0.99	39	499.9	640	< 1.0
17	10	2	183.3	25.1	0.58	19	52.4	320	18.0
18	7	1	228.9	28.2	0.46	22	58.1	160	6.3
19	3	1	89.5	13.4	0.26	19	13.2	80	14.0
20	8	2	518.0	36.9	0.41	22	93.2	600	3.7
21	7	1	99.9	1.4	0.26	19	24.2	90	7.0
22	8	1	38.2	13.9	1.46	29	6.4	40	5.2
23	12	4	62.5	9.5	2.25	255	20.9	30	2.2

[a] Only nitrate was measured for Samples 4 and 5.

[b] Nitrate concentrations of 78 mg/L were measured in Quinta Ena IV, which was subsequently shut down, and therefore not measured in this sampling campaign.

[c] Replicate samples were in reasonable agreement from CIA-UCR: Sample 5, 17.2 mg/L (compared to 14.7 mg/L); Sample 6, 29.8 (25.1); Sample 3, 5.9 (5.1); and Sample 21, 8.4 (7.0).

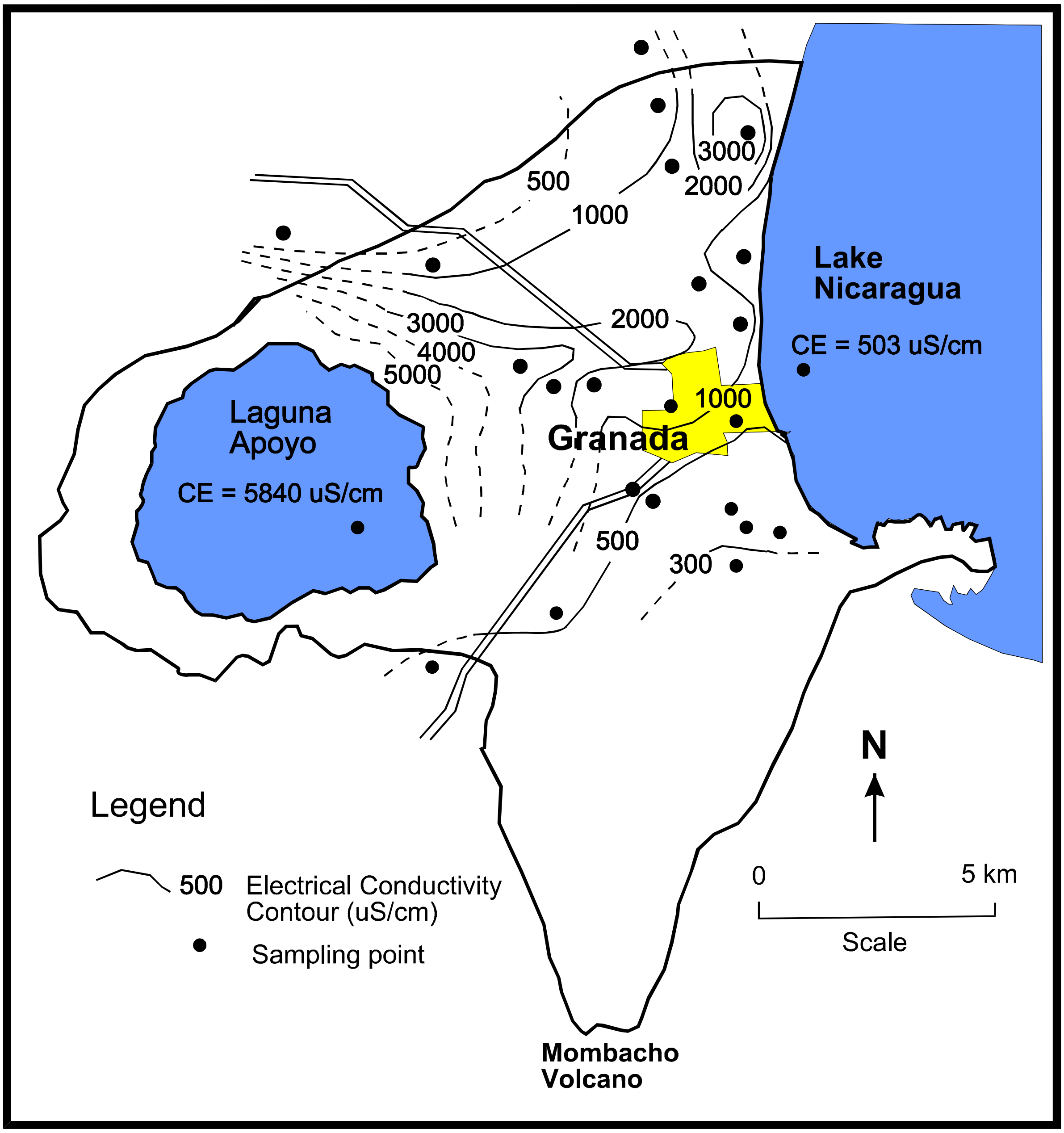

Figure 5: Electrical Conductivity of Groundwaters
in the Granada Aquifer

On the other hand, the southern portion of the aquifer exhibits lower values of EC, ranging from 300 to 500 μS/cm. This area is recharged from Mombacho Volcano, and thus does not have saline recharge. These EC measurements were in good agreement with calculated total dissolved solids (TDS) values determined from major ion chemistry (Table 1), with a linear regression of $r^2 = 0.95$ between EC and TDS.

In general, the groundwater is a sodium-chloride type water. In the Piper diagram (Figure 6), groundwaters plot along a clear mixing line in the cation ternary plot. A less clear tendency also occurs in the anion portion of the diagrama. Those wells in the northeast portion of the study area, near Laguna Apoyo (**Group 1**, Figure 6; Samples 20, 18, 19, 17 and 21, *in order of decreasing relative sodium content*), are the most sodic (98-95% Na^+) and are similar to the composition of Laguna Apoyo (Sample 0; 90% Na^+). The anionic composition of this group of samples is also the most chloride-rich (>85% Cl^-), in contrast with the relatively sulfate-rich Laguna Apoyo (57% Cl^-, 41% SO_4^{2-}). Samples 21 and 22, given the fact that they are not located in the flow path between Laguna Apoyo and Lake Nicaragua, are less sodium- and chloride-rich.

A second group of samples, collected from those wells located to the north of Granada (**Group 2**, Samples 16, 14, 11, 15, 13 and 10, *in order of decreasing relative sodium content*), are less sodium- (95-75% Na^+) and chloride- (95-75 Cl^-) rich. Again sulfate is a minor ion (<20%) in these samples, except in the aforementioned well impacted by oxidation lagoons (Sample 16; 39% SO_4^{2-}). Only one well north of Granada (Sample 12) has a different relative sodium content (58% Na^+), although its chloride composition is similar (82% Cl^-) to this group of samples.

Those samples from wells south of the city of Granada (**Group 3**), where EC and TDS values are much lower, also have a distinct cationic and anionic chemistry. Samples 3, 6, 1, 7, 8 and 9 (*in order of decreasing relative sodium content*) have much less sodium (75-55% Na^+) and chloride (54-67% Cl^- with the exception of Sample 2 with 81% Cl^-), and are the most similar in composition to Lake Nicaragua (Sample 23).

The diminishing TDS concentrations and the decreasing importance of sodium and chloride as major ions towards Lake Nicaragua in the northern portion of the aquifer can be explained by the dilution of the plume by calcium-magnesium-bicarbonate type waters recharging the aquifer between Laguna Apoyo and Lake Nicaragua. However, many wells are still above the drinking water standards for sodium (200 mg/L), potassium (10 mg/L), sulfate (250 mg/L) and chloride (250 mg/L) (CAPRE, 1994), making groundwater in large areas of the northern portion of the aquifer unpotable (Table 1).

The pH of groundwater, where the high-pH waters from Laguna Apoyo (pH = 8.4) recharge the aquifer to the east, delineates a plume that decreases from near 8 in Samples 20, 21 and 22 to values below 6.5 near Lake Nicaragua (Figure 7). The pH of groundwaters in the southern portion of the aquifer are near 7.

The pH of Laguna Apoyo is not anomalous for saline volcanic lakes. Laguna Apoyo can be classified in terms of its salinity as a Class II Lake (600 to 6000 μS/cm), which are generally closed-basin lakes, where evaporation has a significant role in

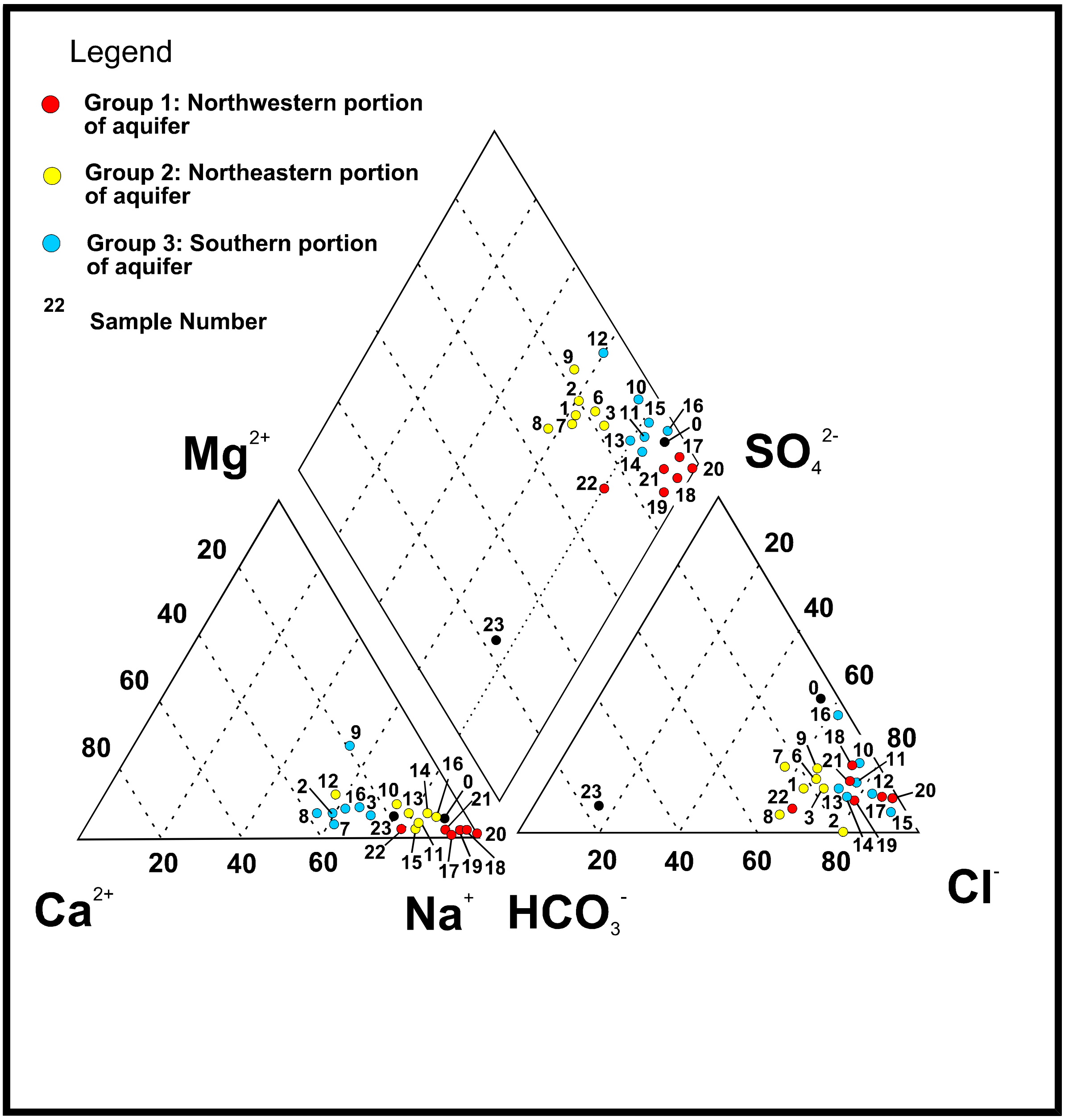

Figure 6: Piper Diagram of Major Ion Composition of Groundwaters in the Granada Aquifer

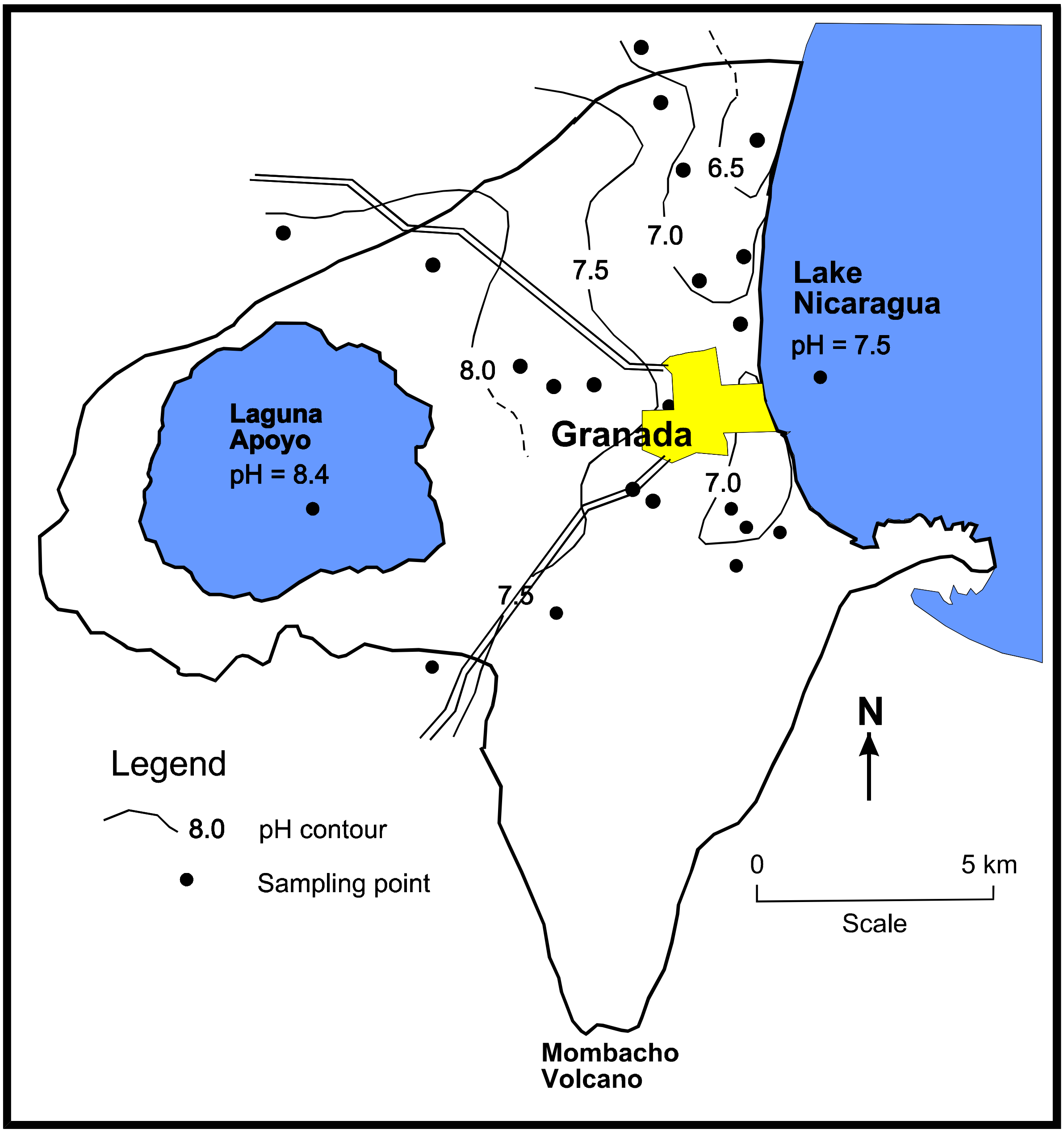

Figure 7: Groundwater pH in the Granada Aquifer

concentrating ions in solution, or open-basin lakes with significant inflow from alkaline volcanic areas (for example, Lakes Tanganyika and Kivu in East Africa) (Payne, 1986). Class II Lakes are calcium- and magnesium-poor given that these ions tend to precipitate at mdoerate concentrations and with increasing pH, allowing other ions to predominate in solution. Most Class II Lakes are generally bicarbonate-rich and more alkaline (8.8 to 9.5) than Laguna Apoyo, although some examples of chloride-rich lakes with a pH range of 7.5-8.5 exist in the Andes and the Sahara, which are often accopanied by high sulfate concentrations (Payne, 1986).

Nitrate analyses indicate that the northwestern portion of the aquifer is strongly impacted, with concentrations above or near the drinking water limit (50 mg/L) in for of seven wells (Samples 10, 12, 13 and 15) (Figure 8). This area is outside the urban area and is intensively used for animal husbandry, which could explain the strong nitrate contamination. Nitrate diminishes to less than 10 mg/L toward Laguna Apoyo, whose nitrate concentration is very low (2.7 mg/L), and around which few agricultural or urban sources of nitrate exist.

As mentioned earlier, nitrate concentrations as high as 78 mg/L have been measured in the municipal wells in the souther portion of the study area to date, and in this study, 25 mg/L was discovered in Sample 5. The sources of nitrate in this area include septic wells, open sewage canals and latrines of the urbanized area that has been constructed around the municipal wells in recent years, and the La Joya Landfill, also located upgradient. Agricultural activities in this area are less concentrated than in the north. Nitrate concentrations decrease toward Mombacho Volcano, and are below detection in Sample 8.

CONCLUSIONS

The city of Granada is faced with a serious threat to their scarce groundwater resource, both from natural and anthropogenic sources. Recharge from Laguna Apoyo is creating a plume of high-TDS, high-pH groundwater that is severely impacting the groundwater quality of most of the northern portion of the aquifer. Inicial data also indicate that nitrate, porbably from animal husbandry, has contaminated many areas of the northeastern portion of the aquifer. Thus future groundwater development will have to occur in the southern portions of the aquifer.

However, nitrate contamination has appeared in municipal water wells in this area, which are probably due to urban and not agricultural activities. Thus, the continued growth of Granada must be planned to keep the recharge area and sites for future well development free from contaminating activities. More importantly, the site for further development of water wells suggested by Vázquez (1995) is not advisable, considering the upgradient proximity of the La Joya Landfill.

In Figure 1, an area for future wellfields has been identified, which is located far from most urban and agricultural activities, yet where water levels are not so deep that pumping groundwater would not be uneconomical. A groundwater protection area should be defined immediately for these future wellfields, which would impose controls on development upgradient on the flanks of Mombacho Volcano, so that these groundwaters can be exploited in the future.

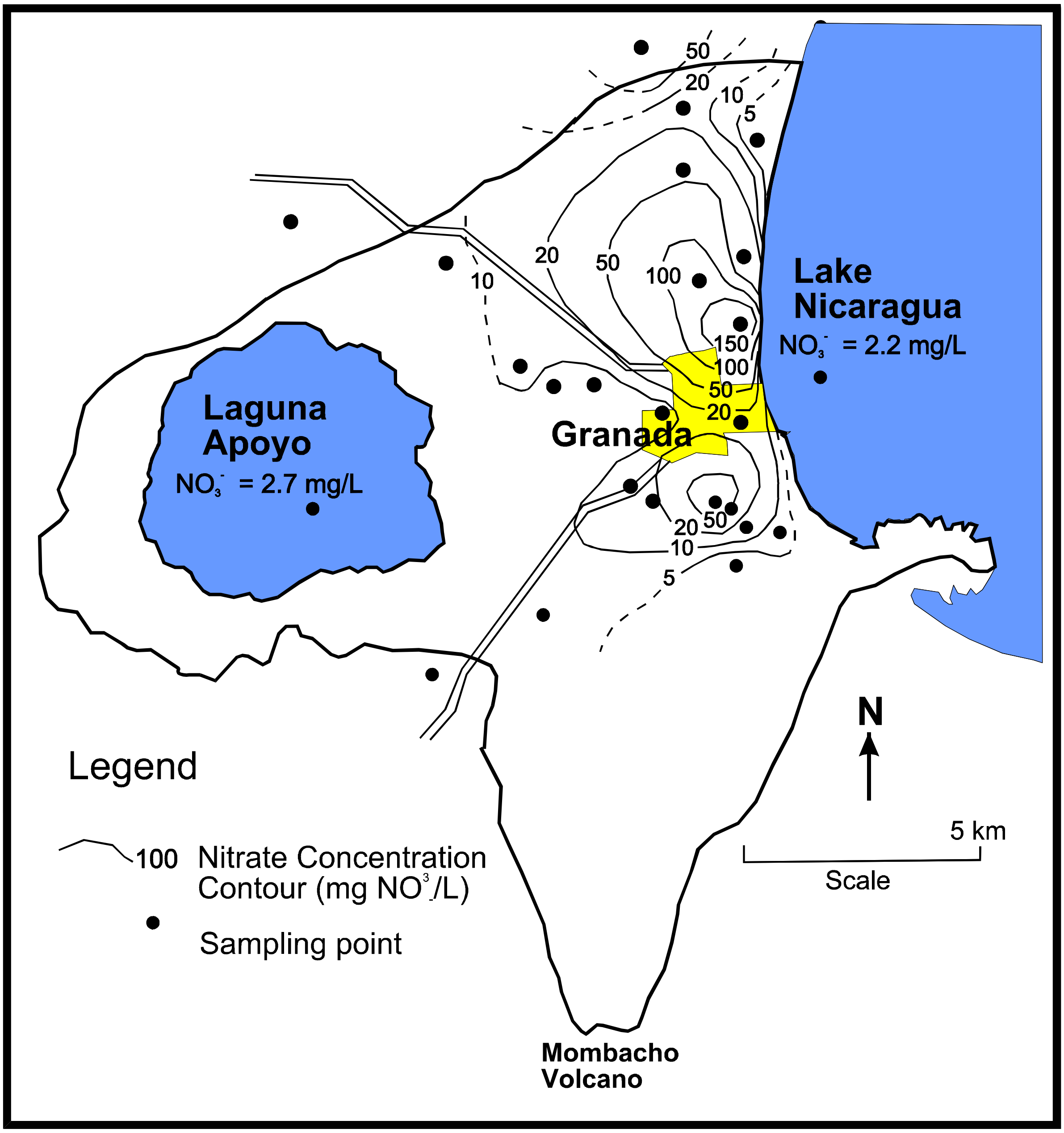

Figure 8: Nitrate Concentrations of Groundwater in the Granada Aquifer

Furthermore, a further study of the aquifer could include the development of a numerical model to help optimize well locations and pumping rates, and assure that wells do not draw in waters from either Laguna Apoyo or from known sources of nitrate, similar to the modeling study completed by Cruz (1997) in defining groundwater protection areas for the municipal wells of Managua.

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