

Groundwater Quality Studies: A Case Study of the Densu Basin, Ghana

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Abstract

Groundwater samples from 68 communities within the Densu basin were sampled and analysed over a period of 1 year for various physico-chemical water quality parameters using appropriate certified and acceptable international procedures, in order to assess the water types as well as the suitability of groundwater within the basin for drinking and other domestic uses. The study showed that most of the physico-chemical parameters were within the World Health Organization limits recommended for drinking water. However, a few of the boreholes were slightly acidic. Some boreholes showed high level of mineralization. Borehole (GaD 6) at Pokuasi recorded the highest conductivity value of 7780.0 $\mu\text{S}/\text{cm}$. High levels of nitrates were also recorded in certain communities within the basin. These include Aponsahene (105.8 mg/l), Damang (66.0 mg/l), Adzen Kotoku (61.5 mg/l), Afabeng (50.8 mg/l), New Mangoase (48.3 mg/l), Asuoatwene (41.3 mg/l), Potrase (33.6 mg/l) and Maase (33.3 mg/l). Correlations between major ions showed expected process-based relationship between Ca^{2+} and Cl^- ($r = 0.86$); Mg^{2+} and Cl^- ($r = 0.84$); Na^+ and SO_4^{2-} ($r = 0.77$); Na^+ and Cl^- ($r = 0.75$); Mg^{2+} and SO_4^{2-} ($r = 0.74$); Mg^{2+} and Ca^{2+} ($r = 0.71$); Ca^{2+} and SO_4^{2-} ($r = 0.58$); and K^+ and SO_4^{2-} ($r = 0.51$), derived mainly from the geochemical and biochemical processes within the aquifer. Two major hydrochemical water types constituting 41% of groundwater sources within the basin have been delineated. These are Ca-Mg- HCO_3^- water (19%) and Na-Cl or Na-Cl- HCO_3^- -Cl water (22%) types. Fifty-nine per cent of groundwater sources are mixed waters with no particular cation predominating, and having either HCO_3^- or SO_4^{2-} ions as the main anion.

Introduction

Groundwater is globally important for human consumption, and changes in quality with subsequent contamination can, undoubtedly, affect human health. It is also important for the support of habitat and for maintaining the quality of baseflow to rivers. The chemical composition of groundwater is a measure of its suitability as a source of water for human consumption and for other purposes, and also influences ecosystem health and function (Appelo & Postma, 1993). It is, thus, important to detect change and early warnings of change both in natural systems and resulting from pollution. The chemistry (quality) of groundwater reflects

input from the atmosphere, soil and water-rock reactions as well as pollutant sources such as mining, land clearance, agriculture, acid precipitation, and domestic and industrial wastes (Appelo & Postma, 1993).

Groundwater pollution has become a major subject of public concern the world over. Despite the large volume of water that covers the surface of the earth, only 1% is inland or fresh and easily available for human use (Bockris, 1978). Only 30% of Ghanaians have access to safe drinking water. Over 50% of Ghanaians use "unprotected" source of water (Ministry of Health, 1999). Rural communities in Ghana, which form about 70% of the total population, rely heavily on

groundwater as the main source of drinking water. Groundwater quality is, therefore, critical to the quality of health of the people in these areas.

The Densu basin is a coastal river catchment in southern Ghana and a typical rural community like all other rural settlements in Ghana, in which the indigenous population uses groundwater, rivers, streams, ponds and springs as their sources of potable water. The qualities of these water resources vary naturally and widely depending on climate, season, and the geology of the bedrock, as well as anthropogenic activities. The effect of anthropogenic activities (primarily farming) within the Densu basin culminated in a public outcry over the quality of water supplied from the Weiya Reservoir (within the basin) which resulted in a ban on farming activities along the Densu river by the Government of Ghana (*Daily Graphic*, Friday, 14/09/2001), and a call to use water resources judiciously (*Daily Graphic*, Tuesday, 18/09/2001).

As a result of the growing public concern, the Government signed a Memorandum of Understanding (MOU) in 1999 with the United Nations Centre for Human Settlements-Habitat (UNCHS) to collaborate in a project on "Managing Water for African Cities". The primary aim of the project was to find solutions to the increasing water demand in the fast growing African cities, of which Accra and, subsequently, the Densu basin featured.

Natural geochemical and biochemical, as well as anthropogenic impact on groundwater do not only threaten the quality of human health but also poses a threat to sustainable development and management of groundwater resources. Groundwater

may, thus, be prone to chemical contamination. It is, therefore, imperative to carry out an extensive groundwater quality assessment of the basin, as well as water types of the different water sources, in order to understand the hydrochemistry of groundwater and, therefore, ensure its potable supply in the area. The paper seeks to assess and compare the chemical qualities and water types of groundwater in four districts within the basin to evaluate their suitability for domestic uses.

Materials and methods

Study area

The Densu basin is located in southern Ghana and lies between latitude 5° 30' N to 6° 20' N and longitude 0° 10' W to 0° 35' W. The basin lies within two distinct climate zones; the dry equatorial climate of the south-eastern coastal plains, and the wet semi-equatorial climate further north from the coast. Both climate zones are characterized by two rainfall regimes with different intensities (Dickson & Benneh, 1980). The major rainy season extends from May to July and the minor rainfall season occurs between September and November. The mean annual rainfall varies between 800 mm near the coast to about 1600 mm in the Densu river source area.

Temperatures are uniformly high throughout the year with a mean annual temperature of about 27 °C; March/April being the hottest (32 °C) while August is the coldest month (23 °C). The upper and middle sections of the basin are covered with semi-deciduous forest with a lush growth of thick and tall trees. In the low-lying areas along the coast, rainfall anomaly gives rise to savanna and scrub forest vegetation with

only few isolated trees. There are thickets of bush and grassland, as well as strands and mangrove swamps especially where brackish water prevails.

A complex of precambrian granite and granodiorite with associated gneiss underlie the larger part of the basin (about 90%). The other formations include rocks of the Upper Birimian that occur at the watershed of the Densu river in the northwest, which consist mainly of metamorphosed lava and tuff, and pyroclastic rocks (Junner, 1940); the rocks of the Togo series, which underlie the south-eastern part of the basin and the area south of Weija to the estuary. The rocks of Togo series were formed from eroded material deposited in the basin. The Togo series consists of sedimentary rocks and their metamorphosed versions (e.g. quartzite, schist, shale and phyllite), which were strongly folded to form what is now called the Akwapim Togo Ranges, extending from the coast near Accra to the Ghana-Togo border. Fig.1 shows the study area and the sampling communities.

Sampling and analysis

Sixty-eight water samples were collected from boreholes between February 2005 and December 2005. Sampling protocols described by Claasen (1982) and Barcelona *et al.* (1985) were strictly observed during sample collection. Samples were collected using 4-litre acid-washed polypropylene containers. For the determination of heavy metals, each sample was immediately filtered on site through 0.45- μ m filters on acetate cellulose. Filtrates for metal analysis were transferred into 100-cm³ polyethylene bottles and immediately acidified to $pH < 2$ by the addition of Merck™ ultra pure nitric

acid. Samples for anions analyses were collected into 250 cm³ polyethylene bottles without preservation. All samples were stored in an ice-chest and transported to the CSIR-Water Research Institute laboratory, stored in a refrigerator at a temperature of < 4 °C and analyzed within 1 week.

Temperature, pH and electrical conductivity were measured *in situ* using WTW-Multiline P4 Universal Meter. Chemical analyses of the samples were carried out using appropriate certified and acceptable international procedures outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 1998). Sodium (Na) and potassium (K) were analysed by flame photometric method, calcium (Ca) by EDTA titration, magnesium (Mg) by calculation after EDTA titration of calcium and total hardness, chloride (Cl) by argentometric titration. Nitrate-nitrogen was analysed by hydrazine reduction and spectrophotometric determination at 520 nm, and heavy metals were analysed using UNICAM 969 atomic absorption spectrophotometer. An ionic error balance was computed for each chemical sample and used as a basis for checking analytical results. In accordance with international standards, results with ionic balance error greater than 5% were rejected.

Results and discussion

The physical parameters of groundwater in the Densu basin are presented in Tables 1a-1d while the chemical parameters are presented in Tables 2a-2d. The water types within the basin are presented in Tables 3a-3d. Groundwater in the various districts of the Densu Basin showed variations in both physical and chemical parameters.

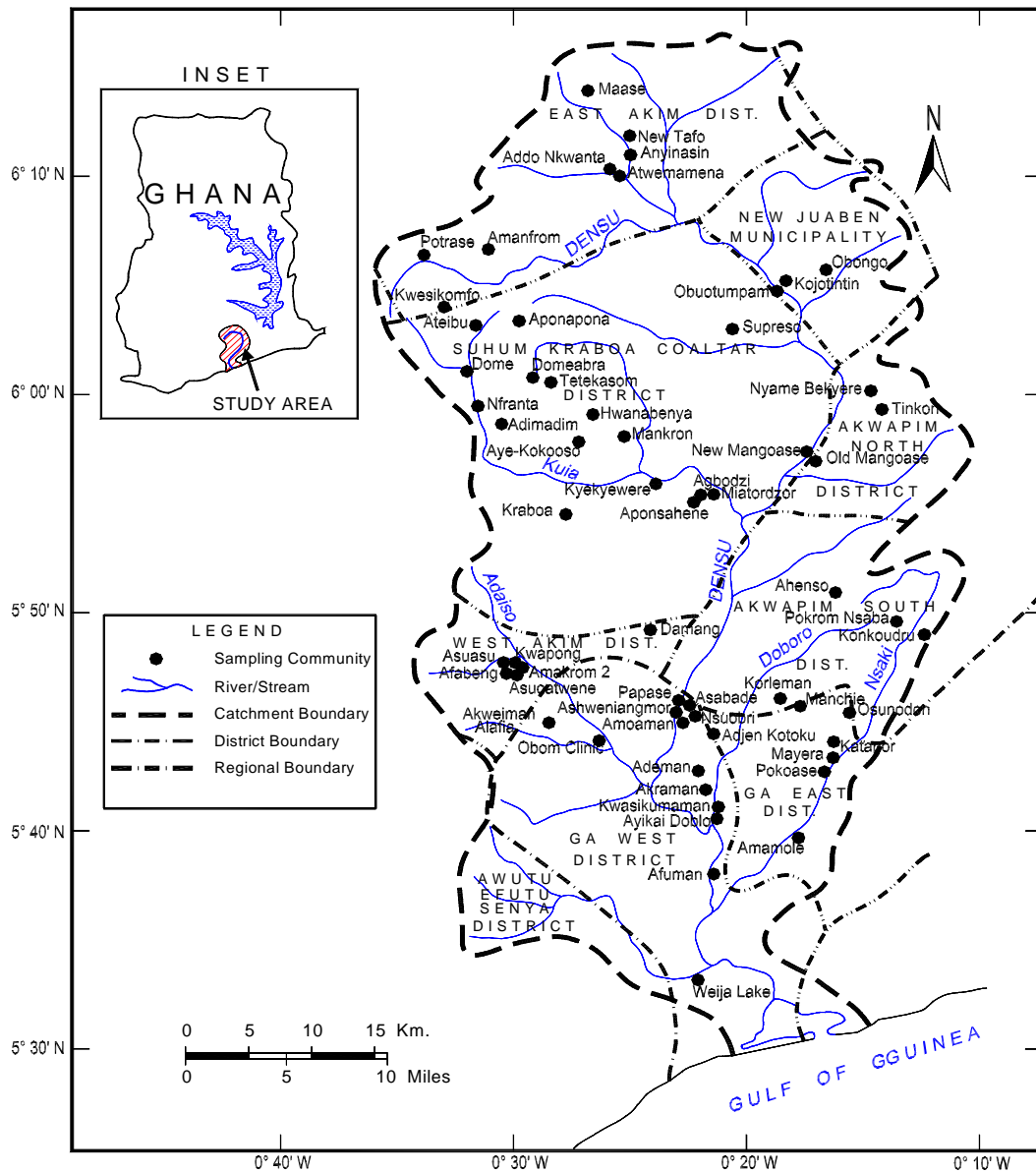


Fig. 1. The Densu basin and the sampling communities

TABLE 1a
Physical parameters of water samples from the Ga District of the Densu basin

<i>Location</i>	<i>Sample ID</i>	<i>pH</i>	<i>Temp. (°C)</i>	<i>EC (µS/cm)</i>
Amamole	GaD 1	6.60	29.5	480.0
Papase	GaD 2	7.03	29.1	1089.0
Ademan	GaD 3	6.18	30.6	1160.0
Ayikai Doblo	GaD 4	6.95	29.1	2211.0
Pokuasi	GaD 5	6.63	27.1	4450.0
Pokuasi	GaD 6	6.71	28.7	7780.0
Kwasikuma	GaD 7	6.92	29.3	2980.0
Papase	GaD 8	6.41	29.2	471.0
Akramam	GaD 9	6.90	26.6	533.0
Akweiman	GaD 10	6.77	27.8	1401.0
Obom Clinic	GaD 11	6.40	28.0	964.0
Pokuasi	GaD 12	6.69	26.8	3760.0
Mayara Fiase	GaD 13	6.10	28.6	1633.0
Katapor	GaD 14	5.90	26.1	371.0
Korleman	GaD 15	5.99	26.7	644.0
Manchie	GaD 16	5.87	28.9	354.0
Amoaman	GaD 17	6.70	30.0	1385.0
Nsuobri	GaD 18	7.17	30.2	987.0
Ashweniangmor	GaD 19	6.79	27.5	1099.0
Asabade	GaD 20	6.80	28.0	2310.0
Aden Kotoku	GaD 21	6.67	30.5	1160.0
Akramam	GaD 22	6.70	30.0	2880.0
Osunodonpe	GaD 23	6.19	28.7	213.0
Amamole	GaD 24	6.73	29.0	809.0
Median		6.70	28.9	1129.5

GaD = Ga District

TABLE 1b
Physical parameters of water samples from the Suhum District of the Densu basin

<i>Location</i>	<i>Sample ID</i>	<i>pH</i>	<i>Temp. (°C)</i>	<i>EC (μS/cm)</i>
Mankron	SuD 1	7.40	28.3	1080.0
Kyekyewere	SuD 2	6.86	28.5	1000.0
Krabo	SuD 3	6.95	27.9	478.0
Tetekasom	SuD 4	6.11	27.2	134.0
Tetekasom	SuD 5	6.60	26.7	328.0
Adimadim	SuD 6	6.57	26.3	301.0
Adimadim spring	SuD 7	6.33	25.4	217.0
Nfranta	SuD 8	6.88	27.1	603.0
Dome 1	SuD 9	6.78	27.0	408.0
Dome 2	SuD 10	6.46	27.9	493.0
Aponapona	SuD 11	6.63	27.0	317.0
Ateibu 1	SuD 12	6.35	27.6	417.0
Ateibu 2	SuD 13	6.03	27.9	403.0
Supreso	SuD 14	5.89	27.1	267.0
Obuotumpam	SuD 15	6.80	27.3	532.0
Obongo	SuD 16	5.75	27.2	438.0
Miatorzor	SuD 17	6.30	28.4	585.0
Agbodzi	SuD 18	6.80	28.4	2340.0
Aponsahene	SuD 19	6.47	29.9	1180.0
Aye-Kokooso	SuD 20	6.73	28.3	719.0
Hwanabenya	SuD 21	6.80	27.5	816.0
Damang	SuD 22	6.62	28.7	1029.0
Median		6.61	27.6	485.5

SuD = Suhum District

TABLE 1c
Physical parameters of water samples from the Akwapim District of the Densu basin

<i>Location</i>	<i>Sample ID</i>	<i>pH</i>	<i>Temp. (°C)</i>	<i>EC (μS/cm)</i>
Kojotintin	AkD 1	6.11	28.0	256.0
New Mangoase	AkD 2	6.36	28.2	920.0
Old Mangoase	AkD 3	6.52	28.4	683.2
Nyame Bekyere	AkD 4	6.74	28.0	628.0
Tinkon	AkD 5	6.51	29.2	443.0
Ahenso	AkD 6	6.62	28.0	397.0
Konkourou	AkD 7	4.49	27.1	107.0
Median		6.51	28.0	443.0

AkD = Akwapim District

TABLE 1d
Physical parameters of water samples from the Akim District of the Densu basin

Location	Sample ID	pH	Temp. (°C)	EC (µS/cm)
Addo Nkwata 1	Ea D1	4.37	27.3	446.0
Atwemamena	EaD 2	6.40	26.6	180.0
Anyinasin	EaD 3	5.50	27.4	524.0
Maase 1	EaD 4	5.80	28.0	396.0
Maase 2	EaD 5	5.70	27.8	532.0
Potrase	EaD 6	6.60	26.7	612.0
Kwesikomfo	EaD 7	6.81	26.3	576.0
Wirenkyem Amanfrom	EaD 8	6.51	27.2	653.0
Amakrom	EaD9	7.08	27.7	1183.0
Amakrom 2	EaD 10	7.20	27.1	1026.0
Asuoatwene	EaD 11	6.38	28.5	922.0
Asuasu	EaD 12	6.10	26.5	651.0
Afabeng	EaD 13	6.60	26.5	1053.0
Kwapong	EaD 14	6.55	27.4	648.0
Ntronso	EaD15	6.30	26.2	179.0
Median		6.40	27.2	612.0

EaD = East Akim District

TABLE 2a
Major ions, nutrients and trace metal levels of water samples from the Ga District of the Densu basin

	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃	SiO ₂	Fe	Mn
Amamole	24.0	15.5	28.0	5.0	116.0	29.6	49.9	0.2	37.7	0.02	<0.01
Papase	9.2	53.9	64.0	1.5	68.0	41.1	199.0	0.4	35.9	0.05	<0.01
Ademan	83.6	73.7	27.8	7.1	250.0	26.4	199.5	20.2	15.3	0.01	0.10
Ayikai Doblo	68.6	52.4	358.0	3.6	384.0	175.0	399.5	3.3	35.6	0.38	0.50
Pokuasi	80.2	83.0	620.0	8.6	120.0	220.0	1226.0	0.6	19.8	0.01	1.01
Pokuasi	537.0	306.0	410.0	9.2	88.0	270.0	2382.0	0.1	29.6	0.17	0.41
Kwasikuma	64.1	293.7	59.0	2.8	208.0	202.0	745.0	0.6	24.2	0.01	0.05
Papase	21.5	12.6	59.0	1.6	146.0	27.6	56.9	0.3	41.0	0.06	0.02
Akramam	41.7	7.7	39.0	6.0	84.0	52.4	66.7	5.8	15.3	1.76	0.21
Akweiman	30.5	73.8	64.0	6.9	178.0	103.0	181.0	0.7	34.2	0.01	0.01
Obom Clinic	56.1	37.8	81.2	2.8	154.0	98.6	204.0	0.3	39.9	0.03	0.02
Pokuasi	56.1	115.0	490.0	6.5	110.0	170.0	963.0	0.7	26.6	0.07	0.05
Mayara Fiase	96.4	51.1	156.6	6.7	124.0	39.5	481.4	0.2	28.8	0.17	0.01
Katapor	21.2	12.3	27.6	3.6	36.0	11.4	81.8	0.1	9.6	0.18	0.03
Korleman	46.5	17.4	32.0	5.4	160.0	10.4	99.3	0.6	41.3	0.04	0.01
Manchie	18.2	11.3	32.9	6.3	88.0	5.9	60.9	0.1	28.6	0.17	0.41
Amoaman	20.9	36.9	185.4	2.0	142.0	51.0	344.0	0.3	26.2	0.02	0.02
Nsuobri	37.5	16.6	88.9	1.0	74.0	25.8	208.0	0.1	8.4	0.09	0.01
Ashweniangmor	28.9	74.8	55.0	7.3	196.0	86.4	184.0	0.2	27.4	0.01	0.42
Asabade	100.0	54.5	216.7	5.4	90.0	51.7	557.0	0.6	31.5	0.02	0.05
Aden Kotoku	44.0	18.4	166.0	3.5	240.0	51.1	170.7	61.5	8.9	0.01	0.10
Akramam	68.9	10.1	23.3	3.8	244.0	14.8	33.7	0.4	29.8	0.01	0.02
Osunodonpe	15.6	11.2	6.1	2.6	66.0	18.0	16.9	0.2	8.4	0.90	<0.01
Amamole	68.2	24.0	98.7	4.6	248.0	108.0	101.0	0.9	35.7	0.01	0.04
Median	45.3	37.4	64.0	4.8	133.0	51.0	191.5	0.4	28.7	0.04	0.04

All values in mg/l.

TABLE 2b
Major ions, nutrients and trace metal levels of water samples from the Suhum District of the Densu basin

	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃	SiO ₂	Fe	Mn
Mankron	35.2	75.4	197.3	1.7	360.0	52.7	288.0	7.8	13.0	0.01	0.02
Kyekyewere	44.4	49.8	175.2	5.7	390.0	89.4	155.9	21.2	15.0	0.01	0.30
Krabo	29.0	6.9	66.5	5.7	104.0	72.9	62.2	5.6	10.0	0.01	0.30
Tetekasom	5.9	1.9	19.5	1.5	62.0	6.0	5.6	3.6	8.0	0.01	0.01
Tetekasom	36.8	5.6	31.5	2.2	112.0	32.9	35.6	5.5	9.0	0.10	0.30
Adimadim	23.7	10.2	26.2	2.0	86.0	37.3	32.0	0.8	10.0	0.04	0.20
Adimadim spring	10.4	7.2	26.8	2.0	84.0	11.7	21.0	4.2	7.5	0.40	0.01
Nfranta	59.8	10.5	48.1	1.2	156.0	66.7	58.6	6.6	12.0	0.10	0.60
Dome 1	46.4	13.3	20.2	6.5	144.0	46.9	26.1	4.7	11.0	0.01	0.40
Dome 2	34.0	13.8	19.8	2.1	126.0	12.7	60.3	0.2	10.5	0.01	0.50
Aponapona	26.5	8.6	65.8	3.5	108.0	65.6	57.8	0.1	14.0	0.10	0.30
Ateibu 1	27.8	3.8	54.7	3.4	180.0	15.4	31.5	14.3	9.3	0.02	0.10
Ateibu 2	12.6	9.9	24.1	2.5	99.8	5.4	28.9	2.7	11.0	0.02	0.01
Supreso	12.9	1.4	42.1	2.4	68.1	14.7	36.1	5.3	8.9	0.01	0.02
Obuotumpam	21.4	3.8	84.1	4.3	204.0	32.5	38.5	30.6	14.0	0.01	0.20
Obongo	34.4	13.9	56.6	4.0	88.2	15.7	119.2	12.8	15.0	0.01	0.01
Miordzor	36.8	13.2	118.9	3.4	220.0	48.8	103.1	11.5	15.0	0.01	0.02
Agbodzi	117.4	132.9	304.1	6.3	372.0	281.7	702.6	18.1	11.9	0.01	0.10
Aponsahene	66.0	17.2	219.6	3.4	400.0	87.8	142.0	105.8	13.6	0.02	0.04
Aye-Kokooso	30.3	17.9	195.3	3.2	450.0	35.0	90.2	27.2	15.0	0.02	0.10
Hwanabenya	44.3	32.8	201.0	3.1	378.0	74.3	174.7	3.0	15.0	0.02	0.10
Damang	69.2	15.7	220.8	10.5	272.0	181.3	157.5	66.0	14.0	0.01	0.10
Median	34.2	11.9	61.2	3.3	150.0	42.1	59.5	6.1	12.0	0.01	0.10

All values in mg/l

TABLE 2c
Major ions, nutrients and trace metal levels of water samples from the Akwapim District of the Densu basin

	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃	SiO ₂	Fe	Mn
Kojotintin	10.8	2.7	19.3	0.6	82.0	3.6	3.4	3.2	7.0	0.04	0.01
New Mangoase	48.2	20.8	105.5	5.2	140.0	45.7	152.2	48.3	12.7	0.05	0.01
Old Mangoase	36.5	26.7	68.6	6.0	220.0	29.2	86.9	15.9	15.0	0.04	0.02
Nyame Bekyere	28.7	23.1	98.7	2.4	296.0	32.6	44.1	19.1	11.0	0.01	0.01
Tinkon	15.1	5.7	85.8	1.9	178.0	41.6	26.4	10.8	10.0	0.01	0.10
Ahenso	31.3	25.8	7.6	3.6	178.0	12.7	46.6	0.8	13.0	0.10	0.20
Konkoudru	3.9	2.4	10.9	3.6	12.0	8.5	20.4	5.4	8.0	0.01	0.02
Median	28.7	20.8	68.8	3.6	178.0	29.2	44.1	10.8	11.0	0.04	0.02

All values in mg/l

TABLE 2d
Major ions, nutrients and trace metal levels of water samples from the Akim District of the Densu basin

	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃	SiO ₂	Fe	Mn
Addo Nkwata 1	21.2	2.9	29.3	3.4	9.2	16.0	65.0	26.4	13.1	0.03	0.04
Atwemamena	18.7	6.3	8.7	1.6	91.8	1.1	10.5	0.5	15.0	0.12	0.07
Anyinasin	32.7	2.4	37.3	5.2	65.0	10.4	91.9	0.1	8.0	0.12	0.07
Maase 1	23.7	1.1	13.3	3.9	22.0	14.7	40.6	18.2	15.0	0.12	0.01
Maase 2	36.9	1.5	17.3	4.3	22.0	0.0	64.3	33.3	15.0	0.01	0.32
Potrase	50.6	4.2	24.3	1.2	100.0	0.1	55.3	33.6	9.0	0.06	0.35
Kwesikomfo	29.9	13.5	22.0	3.7	164.0	0.0	24.5	0.1	14.0	0.10	0.10
Wirenkyem Amanfrom	43.0	28.3	53.1	1.7	280.0	40.4	40.7	0.3	15.0	0.01	0.14
Amakrom	14.5	28.2	171.3	3.3	35.0	114.5	60.3	10.3	15.0	0.50	0.01
Amakrom 2	12.0	42.4	93.8	2.2	116.0	115.0	113.2	10.3	14.0	0.04	0.02
Asuoatwene	21.5	20.2	122.3	3.3	120.0	57.8	145.3	41.3	15.0	0.10	0.20
Asuasu	15.1	12.2	100.6	3.3	130.0	57.6	95.7	4.1	13.0	0.02	0.10
Afabeng	41.2	24.2	77.3	5.3	96.0	75.0	108.6	50.8	12.0	0.04	0.50
Kwapong	22.9	17.7	82.2	2.2	190.0	60.2	71.7	4.1	15.0	0.04	0.05
Ntronso	23.2	3.9	15.7	0.6	120.0	3.2	5.7	7.8	17.0	0.02	0.05
Median	23.2	12.2	37.3	3.3	116.0	16.0	64.3	10.3	15.0	0.04	0.07

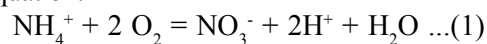
All values in mg/l

Physical characteristics

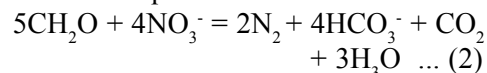
The median values of the water temperature ranged from 27.2 °C in the Akim District to 28.9 °C in the Ga District. These values are within the natural background levels of 22–29 °C for waters in the tropics (Stumm & Morgan, 1981). The water pH varied slightly, with median values ranging from 6.40 in the Akim District to 6.7 in the Ga District. The pH levels of groundwater in the Densu basin are within the natural background levels of 6.5–9.0 (Stumm & Morgan, 1981) although Korleman (5.99), Katapor (5.9), Manchie (5.87) in the Ga District (Table 1a), Supreso (5.89) and Obongo (5.75) in the Suhum District (Table 1b), Konkourou (4.49) in the Akwapim District (Table 1c) and Addo Nkwanta (4.37), Anyinasin (5.50), Maase (5.7 and 5.80) in the Akim District (Table 1d) had pH levels outside the natural background levels.

Groundwater acidification in these areas could originate from different anthropogenic processes such as excessive use of ammonia and manure as fertilizers in farming activities.

The oxidation of ammonia by oxygen can be described by the following reaction equation:



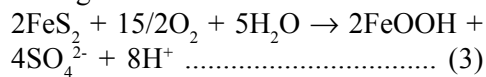
This reaction is the main acidifying process in the soil. When plants consume all the nitrate (NO₃⁻) produced in equation 1, the proton production due to the oxidation process is balanced by the HCO₃⁻ production of the denitrification process as presented in equation 2.



However, the ubiquitous presence of nitrate in aquifers is ample proof of the opposite, and nitrification of ammonia must

be considered as an important acidifying process. The net effect of nitrification on the pH of recharge water is largely determined by the amount of lime, which is applied together with fertilizers to the soil.

Oxidation of pyrite (FeS₂). Pyrite is found at least in small quantities in most reducing sediments and a lowering of the groundwater table, caused by production wells, may result in the oxidation of pyrite. This reaction can be described by the following overall reaction:



This reaction is one of the most strongly acid-producing reactions in nature. Thus, anthropogenic processes have significant effect on the acidification of groundwater. The box plots (Fig. 2) show that groundwater in the Ga District recorded the highest median pH, while the Akim District recorded the lowest median pH.

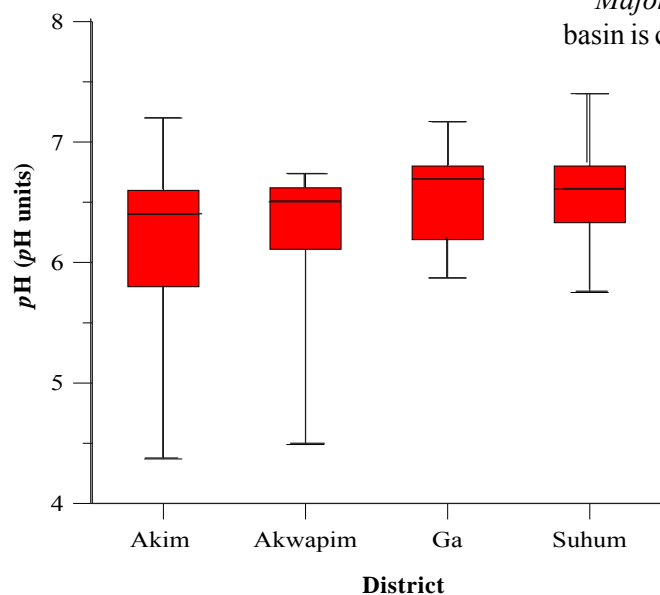


Fig. 2. pH levels in the groundwater of the Densu basin.

The median conductivity levels varied between 443.0 μS/cm in the Akwapim District and 1129.5 μS/cm in the Ga District. Generally, groundwater in the Densu basin recorded relatively low conductivity values, except for Ayikai Doblo (2211.0 μS/cm), Pokuasi (3760.0, 4450.0 and 7780.0 μS/cm), Kwamikuma (2980.0 μS/cm), Mayara Fiase (1633.0 μS/cm), Asabade (2310.0 μS/cm) and Akramam (2880.0 μS/cm) in the Ga District, and Agbodzi (2340.0 μS/cm) in the Suhum District. This is an indication of the extent of mineralization, which is dependent on pH, and, therefore, suggestive of heavy impact of human or natural geochemical and biochemical activities in these areas. As can be seen in the box plots (Fig. 3), the Ga District recorded elevated conductivity values, with Pokuasi (7780.0 μS/cm) recording the highest (Table 1a).

Chemical characteristics

Major ions. Groundwater in the Densu basin is characterized by low chloride levels with median values ranging from 44.1 mg/l in the Akwapim District to 191.5 mg/l in the Ga District. These values are within the acceptable WHO limits of 250 mg/l for drinking water. However, a few communities recorded elevated chloride values. These include Mankrong (288.0 mg/l) and Agbodzi (702.6 mg/l) in the Suhum District, and Ayikai Doblo (399.5 mg/l), Pokuasi (963 mg/l, 1226.0 mg/l and 2382 mg/l), Kwamikuma (745 mg/l), Mayira Fiase (481.4 mg/l), Amoaman (344.0 mg/l) and Asabade (557.0 mg/l) in the Ga District.

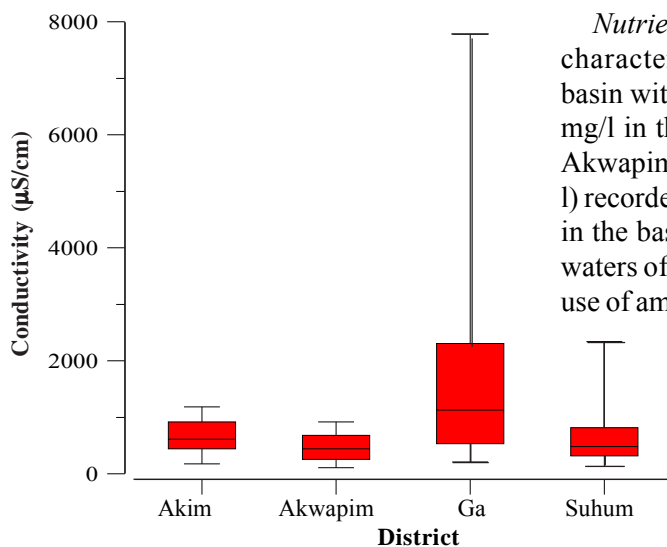


Fig. 3. Conductivity levels in the groundwater of the Densu basin.

Nutrients. Low to medium nitrate levels characterize groundwater in the Densu basin with median values ranging from 0.4 mg/l in the Ga District to 10.8 mg/l in the Akwapim District. Aponsahene (105.8 mg/l) recorded the highest nitrate concentration in the basin. The high nitrate values in the waters of the basin could originate from the use of ammonia and manure as fertilizers in farming activities and/or human and animal wastes. The amounts of nitrate, nitrite and ammonia present in natural waters in the form of nitrogen are of great interest because of their nutrient levels. $\text{NH}_3\text{-N}$,

$\text{NO}_3\text{-N}$ and $\text{NO}_2\text{-N}$ are considered to be non-cumulative toxins (Dallas & Day, 1993). When present in high concentrations, $\text{NO}_3\text{-N}$ may give rise to potential health risks particularly in pregnant women and bottle-fed infants (Kempster *et*

According to the classification of Dallas & Day (1993), chloride ions are non-cumulative toxins; however, excessive amounts of it, if taken over a long period of time, can constitute a health hazard. As can be seen in the box plots (Fig. 4), the Ga District recorded relatively higher chloride levels compared to the other districts. This could originate from natural sources such as the intrusion of sea-water, because of the nearness of the Ga District to the coast. It may also be due to anthropogenic activities such as the intrusion of sewage effluent. The high chloride values in the waters of the Ga District may increase the corrosive ability of the waters in these areas, particularly in low alkalinity waters.

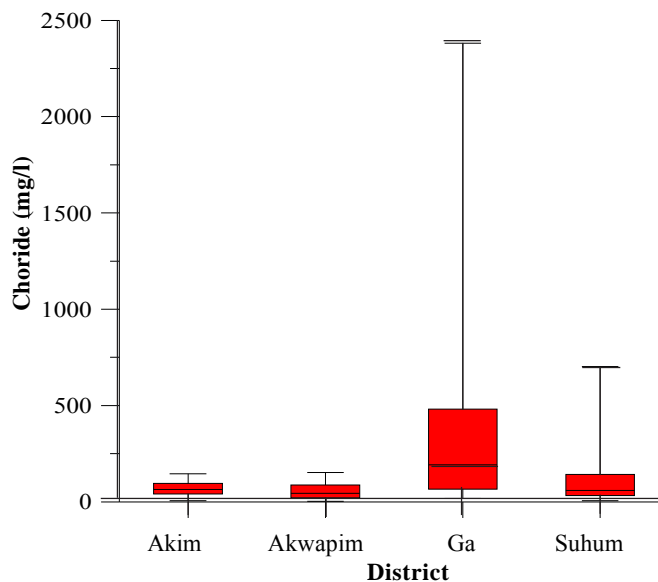


Fig. 4. Chloride levels in the groundwater of the Densu basin.

al., 1997; Kelter *et al.*, 1997; Cotruvo, 1988; Bush & Mayer, 1982). At elevated concentrations, $\text{NO}_3\text{-N}$ is also known to result in cyanosis in infants (Comly, 1945). Above 10 mg/l, appreciable amounts of $\text{NO}_3\text{-N}$ may be produced from $\text{NH}_3\text{-N}$ under suitable anaerobic conditions (WHO, 1993; Kempster *et al.*, 1997).

The nitrate levels in the groundwater at Ademan (20.2 mg/l), Adzen Kotoku (61.5 mg/l) in the Ga District; Kyekyewere (21.2 mg/l), Ateibu (34.3 mg/l), Obuotumpan (30.6 mg/l), Agbodzi (18.1 mg/l), Aponsahene (105.8 mg/l), Aye Kokoosu (27.2 mg/l), and Damang (66.0 mg/l) in the Suhum District; New Mangoase (48.3 mg/l), Old Mangoase (15.9 mg/l), and Nyame Bekyere (19.9 mg/l), in the Akwapim District; Addo Nkwanta (26.4 mg/l), Maase (18.2 and 33.3 mg/l), Potrase (33.6 mg/l), Asuoatwene (41.3 mg/l), and Afabeng (50.8 mg/l) in the Akwapim District are at such levels capable of causing

methemoglobin 'blue baby syndrome' in infants and a suspect for stomach cancer in adults (Baird, 1995). As can be seen in the box plots (Fig. 5), the Akim District recorded the highest median nitrate level. The levels of nitrates in these areas may be attributed to extensive use of ammonia and manure in farming activities.

Heavy metals. Heavy metal (iron and manganese) levels in the groundwater of the basin are relatively low. Nevertheless, significant iron (Fe) levels were recorded at Akraman (1.76 mg/l) and Osunodompe (0.9 mg/l) in the Ga District, and Amakrom (0.5 mg/l) in the Akim District, which were all above the WHO limit of 0.3 mg/l for drinking water. The high Fe levels in these waters could be attributed to natural sources such as the geochemical and biochemical processes within their aquifers. Fig. 6 presents the box plots of Fe in the basin. As shown in Fig. 6, the Akim District recorded the highest median Fe value.

Manganese (Mn) is one of the more biogeochemical and active transition metals in aquatic environment (Evans *et al.*, 1977) and often occurs with iron (Fe). Its concentrations in some communities were also significantly above the WHO limit of 0.1 mg/l for drinking water. These communities included Pokuasi (0.41 and 1.01 mg/l), Ayikai Doblo (0.5 mg/l), Akraman (0.21 mg/l), Manchie (0.4 mg/l), Ashwenangmor (0.42 mg/l) in the Ga District; Kyekyewere (0.3 mg/l), Krabon (0.3 mg/l), Tetekasom (0.3 mg/l), Adimadin (0.2 mg/l), Nfranta (0.6 mg/l), Dome (0.4 and 0.5

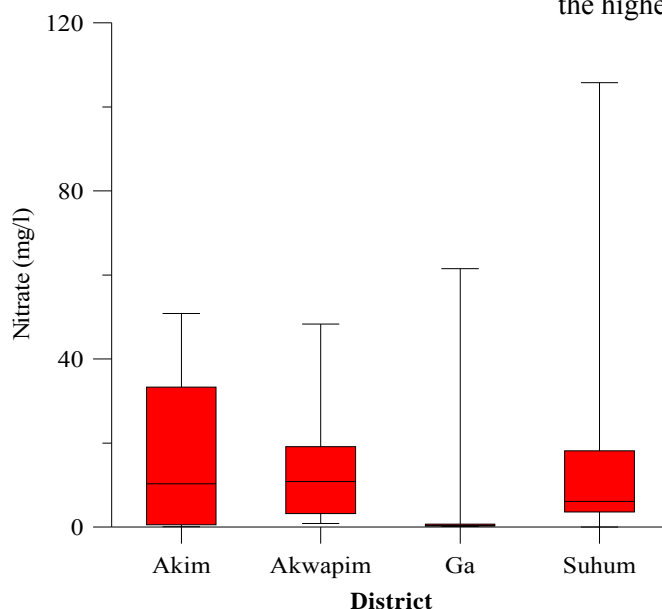


Fig.5. Nitrate levels in the groundwater of the Densu basin

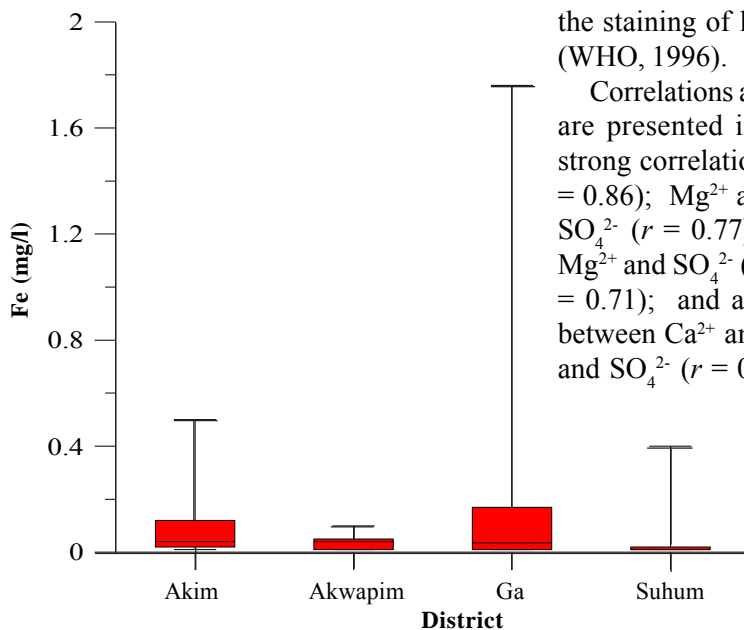


Fig. 6. Fe levels in the groundwater of the Densu basin

mg/l) and Aponapona (0.3 mg/l) in the Suhum District; Ahenso (0.2 mg/l) in the Akwapim District and Maase (0.32 mg/l), Potrase (0.35 mg/l), Asuoatwene (0.2 mg/l) and Afaben (0.5 mg/l) in the Akim District.

Fig. 7 presents the box plots of Mn in the basin. As shown in Fig 7, the Suhum District recorded the highest median Mn value. Though the presence of high Fe and Mn concentrations in water does not pose human health problems, these concentrations have the ability of discoloring water, i.e. high Fe concentrations results in reddish brown coloration, while high Mn concentrations results in black coloration, which both result to

the staining of laundry and sanitary wares (WHO, 1996).

Correlations among chemical parameters are presented in Table 3. The positively strong correlation between Ca^{2+} and Cl^- ($r = 0.86$); Mg^{2+} and Cl^- ($r = 0.84$); Na^+ and SO_4^{2-} ($r = 0.77$); Na^+ and Cl^- ($r = 0.75$); Mg^{2+} and SO_4^{2-} ($r = 0.74$); Mg^{2+} and Ca^{2+} ($r = 0.71$); and a weak positive correlation between Ca^{2+} and SO_4^{2-} ($r = 0.58$); and K^+ and SO_4^{2-} ($r = 0.51$), derived mainly from the geochemical and biochemical processes within the aquifer, suggest that these pair of ions have a common origin. Additionally, the strong correlation between conductivity (EC) and Cl^- ($r = 0.95$), Ca^{2+} ($r = 0.83$), Mg^{2+} ($r =$

0.82), Na^+ ($r = 0.76$), and SO_4^{2-} ($r = 0.76$), is suggestive of the contribution of these ions to the salinity of groundwater in the Densu basin.

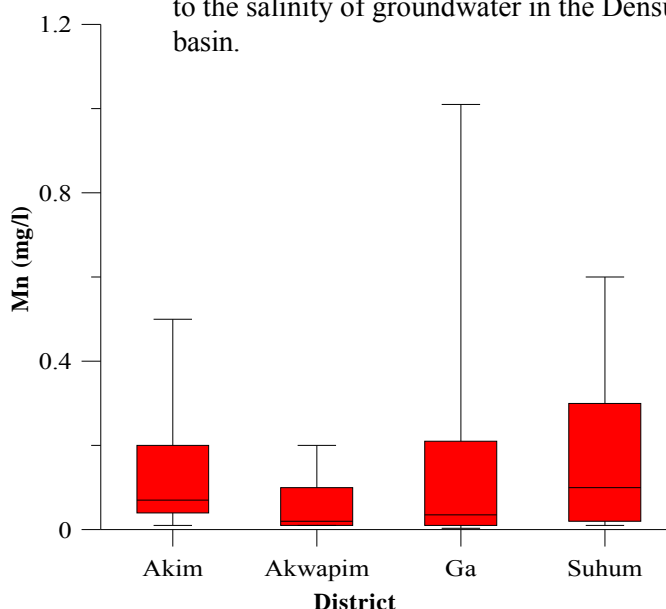


Fig. 7. Mn levels in the groundwater of the Densu basin

TABLE 3a
Groundwater sources and their water types in the East Akim District

<i>Location</i>	<i>Sample ID</i>	<i>Water Type</i>
Addo Nkwata 1	EaD1	Na-Ca-Cl
Atwemamena	EaD 2	Ca-Mg-Na-HCO ₃
Anyinasin	EaD 3	Ca-Na-Cl-HCO ₃
Maase 1	EaD 4	Ca-Na-Cl
Maase 2	EaD 5	Ca-Na-Cl
Potrase	EaD 6	Ca-Na-HCO ₃ -Cl
Kwesikomfo	EaD 7	Ca-Mg-Na-HCO ₃
Wirenkyem Amanfrom	EaD 8	Mg-Na-Ca-HCO ₃
Amakrom	EaD 9	Na-Mg-HCO ₃ -SO ₄
Amakrom 2	EaD 10	Na-Mg-Cl-SO ₄ -HCO ₃
Asuoatwene	EaD 11	Na-Mg-Cl-HCO ₃
Asuasu	EaD 12	Na-Cl-HCO ₃
Afabeng	EaD 13	Na-Ca-Mg-Cl-HCO ₃ -SO ₄
Kwapong	EaD 14	Na-Mg-HCO ₃ -Cl
Ntronso	EaD 15	Ca-Na-HCO ₃

EaD = East Akim Dsistrict

TABLE 3b
Groundwater sources and their water types in the Akwapim District

<i>Location</i>	<i>Sample ID</i>	<i>Water Type</i>
Kojotintin	AkD 1	Na-Ca-HCO ₃
New Mangoase	AkD 2	Na-Ca-Mg-Cl-HCO ₃
Old Mangoase	AkD 3	Na-Mg-Ca-HCO ₃ -Cl
Nyame Bekyere	AkD 4	Na-Mg-HCO ₃
Tinkon	AkD 5	Na-HCO ₃
Ahenso	AkD 6	Mg-Ca-HCO ₃ -Cl
Konkourou	AkD 7	Na-Cl

AkD = Akwapim District

TABLE 3c
Groundwater sources and their water types in the Ga District

<i>Location</i>	<i>Sample ID</i>	<i>Water Type</i>
Amamole	GaD 1	Mg-Na-Ca-HCO ₃ -Cl
Papase	GaD 2	Mg-Na-Cl
Ademan	GaD 3	Mg-Ca-Cl-HCO ₃
Ayikai Doblo	GaD 4	Na-Cl-HCO ₃
Pokuasi	GaD 5	Na-Cl
Pokuasi	GaD 6	Ca-Mg-Na-Cl
Kwasikuma	GaD 7	Mg-Cl
Papase	GaD 8	Na-Ca-Mg-HCO ₃ -Cl
Akramam	GaD 9	Ca-Na-Cl-HCO ₃ -SO ₄
Akweiman	GaD 10	Mg-Na-Cl-HCO ₃ -SO ₄
Obom Clinic	GaD 11	Na-Mg-Ca-Cl-HCO ₃ -SO ₄
Pokuasi	GaD 12	Na-Mg-Cl
Mayara Fiase	GaD 13	Na-Ca-Mg-Cl
Katapor	GaD 14	Na-Ca-Mg-Cl
Korleman	GaD 15	Ca-Mg-Na-Cl-HCO ₃
Manchie	GaD 16	Na-Mg-Ca-Cl-HCO ₃
Amoaman	GaD 17	Na-Mg-Cl
Nsuobri	GaD 18	Na-Ca-Cl
Ashweniangmor	GaD 19	Mg-Na-Cl-HCO ₃
Asabade	GaD 20	Na-Ca-Mg-Cl
Adzen Kotoku	GaD 21	Na-Ca-Cl-HCO ₃
Akramam	GaD 22	Ca-HCO ₃
Osunodonpe	GaD 23	Mg-Ca-HCO ₃ -Cl
Amamole	GaD 24	Na-Ca-Mg-HCO ₃ -Cl-SO ₄

GaD = Ga District

TABLE 3d
Groundwater sources and their water types in the Suhum District.

Location	Sample ID	Water Type
Mankron	SuD 1	Na-Mg-Cl-HCO ₃
Kyekyewere	SuD 2	Na-Mg-HCO ₃ -Cl
Kraboa	SuD 3	Na-Ca-Cl-HCO ₃ -SO ₄
Tetekasom	SuD 4	Na-Ca-HCO ₃
Domeabra	SuD 5	Ca-Na-HCO ₃ -Cl
Adimadim	SuD 6	Ca-Na-Mg-HCO ₃ -Cl-SO ₄
Adimadim spring	SuD 7	Na-Mg-Ca-HCO ₃ -Cl
Nfranta	SuD 8	Ca-Na-HCO ₃ -Cl-SO ₄
Dome 1	SuD 9	Ca-Mg-Na-HCO ₃ -SO ₄
Dome 2	SuD 10	Ca-Mg-Na-HCO ₃ -Cl
Aponapona	SuD 11	Na-Ca-HCO ₃ -Cl-SO ₄
Ateibu 1	SuD 12	Na-Ca-HCO ₃ -Cl
Ateibu 2	SuD 13	Na-Mg-Ca-HCO ₃ -Cl
Supreso	SuD 14	Na-Ca-HCO ₃ -Cl
Obuotumpam	SuD 15	Na-Ca-HCO ₃ -Cl
Obongo	SuD 16	Na-Ca-Mg-Cl-HCO ₃
Miatordzor	SuD 17	Na-Ca-HCO ₃ -Cl
Agbodzi	SuD 18	Na-Mg-Cl
Aponsahene	SuD 19	Na-Ca-HCO ₃ -Cl
Aye-Kokooso	SuD 20	Na-HCO ₃ -Cl
Hwanabenya	SuD 21	Na-Mg-HCO ₃ -Cl
Damang	SuD 22	Na-Ca-HCO ₃ -Cl-SO ₄

SuD = Suhum District

Water samples. Fig. 8 shows Piper Trilinear Plot (Piper, 1994) of major ions concentrations of water samples in the Densu basin. Two major hydrochemical water types have been delineated. These are Ca-Mg-HCO₃ water where the chemical properties of the water are dominated by alkaline earths and weak acids (Karanth, 1987). This water type occupies the section of the diamond shape designated as II and represents 19% of groundwater in the Densu basin. This percentage is made up of

7%, 3%, 3%, and 6% contributions from the East Akim, Akwapim, Ga and the Suhum districts, respectively. Their sources may comprise either dolomite (Ca Mg (CO₃)₂) or calcite (CaCO₃) in the rock matrix, and, therefore, characterized by temporary hardness.

The Na –Cl or Na –Cl –HCO₃–Cl water type has saline characteristics. This water type occupies the section of the diamond shape designated as V and represents 22% of groundwater in the basin. This percentage

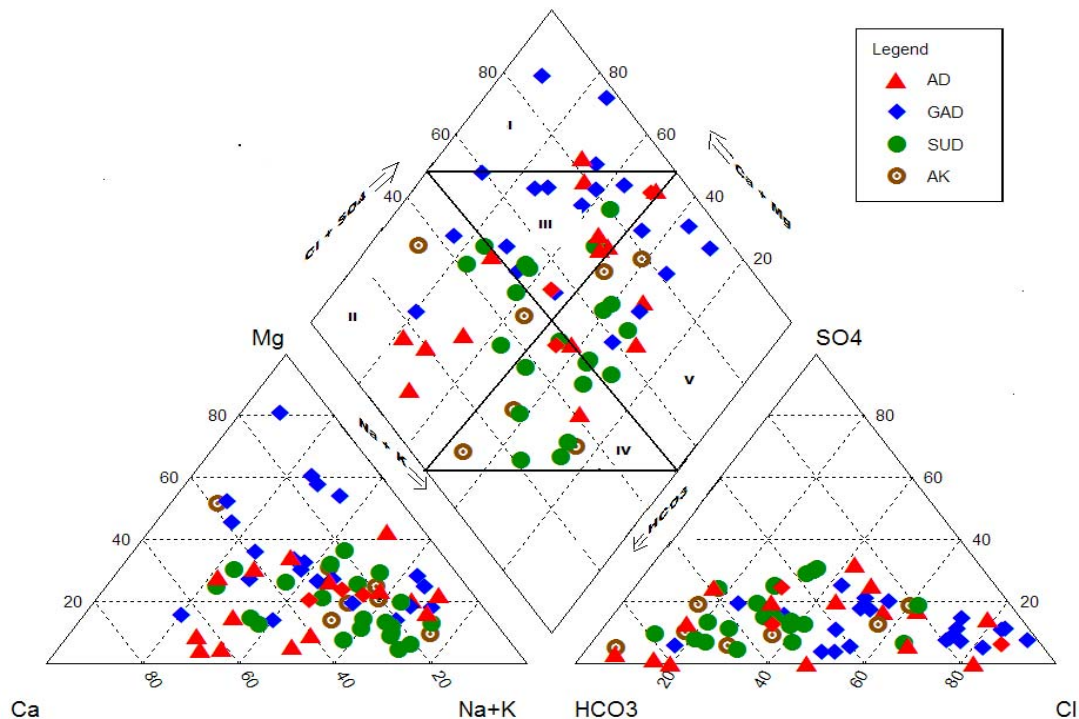


Fig. 8. Piper plot showing the chemical types of groundwater sources in the Densu basin

is made up of 3%, 3%, 9% and 7% contributions from the East Akim, Akwapim, Ga and the Suhum districts, respectively. Their sources may comprise either of sea- or rain- water. Other water types that are of major importance in the explicit understanding of the water chemistry of groundwater in the Densu basin can be characterized as mixed waters. This include the Na-Mg-Ca-HCO₃ water. In this type, no particular cation predominates while HCO₃⁻ is the main anion. This water type occupies the section designated as IV and constitutes 21% of groundwater within the basin.

The Na⁺ - Cl⁻ -SO₄²⁻ water type has no particular cation which predominates, while

SO₄²⁻ is the main anion. This water type occupies the section designated as III and forms 34% of groundwater within the basin. A minor water type, Ca-Mg-SO₄ water (I field) of the diamond shape, have also been delineated within the basin. The source aquifers contain gypsum (CaSO₄·2H₂O) or anhydrite (CaSO₄) that may have undergone dissolution and, therefore, characterized by permanent hardness. About 4% of groundwater within the basin consists of these aquifers.

The major water types and Na⁺ - Cl⁻ - SO₄²⁻ water type depict rock-water interactions involving the dissolution of carbonates and rain- or sea-water by the recharging groundwater within the relatively

permeable weathered zone above the underlying rocks. The rock types of the study area, as stated earlier, consist mainly of a complex of precambrian granite and granodiorite with associated gneiss underlying the larger part of the basin and the Togo series, which consists of sedimentary rocks and their metamorphosed versions (e.g. quartzite, schist, shale and phyllite). The rocks of the Togo series contain carbonates either in the form of impure limestone or as cement in the matrices of the sandstone (Kortatsi, 2005). These carbonates are the soluble type within the Togo series and, thus, constitute the source of Ca-Mg-HCO₃.

Conclusion

The study showed that most of the chemical parameters in the waters of the Densu basin are within the WHO limits for drinking water, posing no health threat to consumers. However, the levels of nutrients, especially in the waters at Aponsahene (105.8 mg/l), Damang (66.6 mg/l), Mangoase (48.0 mg/l), Potrase (33.6 mg/l), Asuatwene (41.3 mg/l) and Afabeng (50.8 mg.l), and, possibly, all the other areas, where nitrate levels exceeded the critical value of 10 mg/l, should be closely monitored. Human activities such as farming, washing and sewage disposal within the basin, perhaps, have great impact on the quality of groundwater. Groundwaters in the Ga and Suhum districts were found to be more mineralized, suggestive of heavy impact of human activities and existence of old waters.

Correlations between major ions showed expected process-based relationship between Ca²⁺ and Cl⁻ ($r = 0.86$); Mg²⁺ and Cl⁻ ($r = 0.84$); Na⁺ and SO₄²⁻ ($r = 0.77$); Na⁺

and Cl⁻ ($r = 0.75$); Mg²⁺ and SO₄²⁻ ($r = 0.74$); Mg²⁺ and Ca²⁺ ($r = 0.71$); Ca²⁺ and SO₄²⁻ ($r = 0.58$); and K⁺ and SO₄²⁻ ($r = 0.51$), derived mainly from the geochemical and biochemical processes within the aquifer. Two major hydrochemical water types constituting about 41% of groundwater sources within the basin have been delineated. These are Ca-Mg-HCO₃ water (19%) and Na –Cl or Na –Cl –HCO₃–Cl water (22%) types. Fifty-nine per cent of groundwater sources are mixed waters with no particular cation predominating, and having either HCO₃⁻ or SO₄²⁻ ions as the main anion.

Acknowledgement

The study forms part of the comprehensive study of application of isotope techniques in groundwater assessment in the Densu basin by International Atomic Energy Agency (IAEA) and the Government of Ghana. Facilities provided are gratefully acknowledged. The authors also acknowledge the efforts of Ms Grace Dartey, a technician, of the Environmental Chemistry Division, CSIR-Water Research Institute, for assisting in the collection and analysis of samples, and Mr Harrison Komladjei, Principal Draughtsman, CSIR-Water Research Institute, for producing the map of the study area.

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