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Research Article

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Darcy and Apparent Velocities of Groundwater in Phreatic Aquiferous Formations in Kumba – Cameroon: Determined by use of Trigger-Tube Tracer Test Method in Dug Wells

Akoachere Richard Ayuk* and Ngwese Yolande Mesode

Abstract

Kumba with a population of about 144,413 people is the capital of Meme Division, in the Southwest region is one of the largest cocoa cash crop producing areas in Cameroon. The inhabitants depend mostly on groundwater through dug wells. It has a hot and humid equatorial climate with annual rainfall 2298-3400 mm and annual temperature 27° C with a short dry season (December to March) and a long rainy season (April to November). There is a need for a good understanding of the hydraulic properties of the aquiferous formations for the planning and management of the groundwater resources of this area. Twenty-one hand-dug wells at different sites in Kumba were tested using sodium chloride (NaCl) as a conservative tracer, by use of the trigger-tube tracer test method. Field estimations of groundwater flow and groundwater velocities in the phreatic aquiferous formation in Kumba through by trigger tube tracer tests gave Darcy velocities ranging from 19.63 m/d at Krammar to 634.13 m/d at Dallas and apparent velocities ranging from 39.26 m/d at Krammar to 1268.27 m/d at Dallas.

The trigger tube tracer tests carried out in some dug wells in Kumba reveals significant spatial variations in groundwater velocities and groundwater flow velocities which are relatively poor at Krammar and good at Dallas. The huge spatial variations in groundwater flows and groundwater velocities imply that groundwater flows at different rates, directions, and at different rates in different sections of the phreatic aquiferous formation in Kumba, probably due to spatial variations in permeability and existence fractures acting as groundwater conduits. Areas with low groundwater velocities like Krammar have lower permeabilities compared to those around PS Kumba Town, Dallas and CCAS. This suggests spatial variations in formation types, facies changes (transgressive and regressive), thickness and layering.

Keywords

Hydraulic properties; Trigger-tube tracer tests; Darcy velocity; Apparent velocity; Kumba-Cameroon

***Corresponding author:** Akoachere Richard Ayuk II, Faculty of Science, Department of Geology, University of Buea, P.O. Box 63. Buea, South West Region, Cameroon, Tel: +2376 797 621 51; E-mail: r.akoachere@ubuea.cm

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Introduction

Kumba is the administrative headquarters of Meme Division and economic capital of Southwest Region of Cameroon. It is a center for one of the largest cash crop producing areas in the country with a population of about 144,413 people [1] mostly farmers and business people from almost every ethnic group in Cameroon and some from other countries. It has a hot and humid equatorial climate with annual rainfall 2298-3400 mm and annual temperature 27°C with a short dry season (December to March) and a long rainy season (April to November) [2].

Determination of hydraulic properties of the aquiferous formations in Kumba is froth with numerous problems as is in other parts of Cameroon.

Amongst these problems are:

a) Absence of hydraulic tests data. b) Scarcity of well-developed and maintained boreholes. c) Non implementation of government legislation on exploitation of groundwater resources. d) Lack of appropriate technology and equipment. e) Little or no funding attributed to research and development of groundwater resources.

This sums up for having few badly constructed and maintained public and private boreholes access to which is denied to researchers by cumbrous bureaucracy for public boreholes, ignorance and suspicion from private borehole owners.

The best option for any meaningful research in these auriferous formations is the accessible dug wells which are commonplace and owned by friendlier middle to lower class inhabitants.

Darcy velocity, Darcy flux, groundwater flux, seepage velocity, filtration velocity, fictitious velocity, discharge velocity or specific discharge is the volume of water flowing per unit time through a unit cross sectional area normal to the direction of flow. Division by an effective porosity yields an apparent velocity, actual groundwater velocity, seepage velocity or average (linear) groundwater velocity [3-6] which is the average flow rate of groundwater through the pores (voids) of the aquiferous formation.

Tracer testing

Point dilution is one of the most used tracer testing methods over the years [7-10]. It consists of monitoring the tracer concentration in a well from the time of injection until the tracer completely disappears. A tracer is injected into the isolated test section from a reservoir and is subjected to continual mixing in/out of the borehole by a submerged/surface pump as groundwater gradually replaces the tracer solution in the well. These tests require the creation of a homogeneous mix of solute in the test well using a pump making it difficult and costly to perform.

However, Akoachere and Van Tonder [11] used the trigger-tube apparatus to successfully mix solutes instantaneously, for injection tests in wells, while ensuring that solutes are injected as well mixed slugs. The introduction of solute by the trigger-tube apparatus does not increase the rate at which the tracer moves out of the well and the injection time is short compared to the overall length of time required to carry out the whole experiment. This method is cheap,

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rapid, and easy to perform and can be carried out in many wells over a large area to provide estimates of the Darcy and apparent velocities of groundwater in aquifers. The natural law of hydraulic head by Darcy [12] recognizes the fact that if you have a smaller open ended tube in a larger tube closed at one end and filled with water (piezometer in a borehole) piezometric levels in both tubes will be equal. If a well-mixed solute replaces the water in the smaller inner tube and has the same water level as the larger outer tube, it will instantaneously mix with the water in the larger tube if the inner tube is smoothly withdrawn without perturbations. This is the principle on which the trigger tube is based. This is the method used in mixing the conservative tracer (NaCl) in the dug-wells tested in this study.

Geology

Kumba is located in the Kumba Plain, a graben intercalated between the strato-volcanoes of Mt Cameroon and Mts Rumpi [13] at the northwestern edge of the Douala Basin.

The Cameroon Line (CL) is an alignment of Tertiary-to-Recent alkaline volcanoes, plutons and grabens extending over more than 1600 km stretching from the Atlantic oceanic island of Annobon through the Gulf of Guinea and within the African continent [14].

The Douala basin probably formed from a Precambrian cratonisation, granitisation and sedimentation phase followed by the Pan-African orogenesis, the Afro-Brazilian depression (the site of the future Cameroon Atlantic basin) with epi-continental sedimentation which may have begun during the lower Cretaceous, discordant Cretaceous to Pliocene sediments on the Precambrian Pan-African basement and covered in some areas by Miocene sedimentation and volcanism [15].

Although a detailed geological study of the Kumba Plain (Kumba Volcanic Field) is lacking, three main volcanic activities (which probably occurred between the Eocene and 1 Ma ago) have been identified. These include: old basaltic lavas covering the entire plain; cinder cones and phreatomagmatic units; and short vesicular basaltic lava flow [16].

There are 4 maars in the Kumba Plain. These include the BarombiMbo, Barombi Koto, Mbwadong and Dissoni Maars, in which the first two are occupied by Lakes BarombiMbo and Barombi Koto. Based on the composite fragments contained in the Barombi Mbo Maar (BMM) pyroclastic deposits, it is likely that the maar cuts through a geological succession composed by granite gneissic formation, sandstones, and basaltic lava flows; the same formations that make up the Kumba volcanic field [17].

Volcanic formations of the plain have been emplaced over Panafrican metamorphic formations intruded by granitoids and locally covered by Cretaceous continental sandstones (Figure 1). They commonly enclose mantle peridotite xenoliths [18].

Materials and Methods

Materials

All equipment used in the course of this work were calibrated according to manufacturer's instructions, where necessary, before starting (Table 1).

Twenty-one (21) hand-dug wells at different sites in Kumba (all of which were located in the phreatic aquiferous formations) were tested. These sites included: Mile 1, Kake 1, GBHS, Anglican, Krammar, Nkamlikum, 3Corners, Gar, St. Francis street, Akalestreet, Gentilstreet, Kossala, Dallas street, Buea Road Park, CCAS, Cow Fence, Mbongo street, Cassava Farms, Nnokostreet, PS Kumba Town and New Quarters (Figure 2).

At each point, the background EC of the well water, depth to well bottom, and well diameter and depth to static water level were measured. The Volume (V) of the water column in the well and volume of the trigger tube (V_T) were calculated:

$$V=2\pi r^2 h \tag{1}$$

Where: Height of water column, h= *(Depth of well bottom)* – *(Depth of water in well)*

$$ECV_w = EC_T V_T \tag{2}$$

Where γ_T=radius of the trigger tube; and h_T=height of water column in trigger tube

Considering that the Height of water column in the well and in the trigger tube was the same and that the EC of water was the same implied that:

$$h=h_T \tag{3}$$

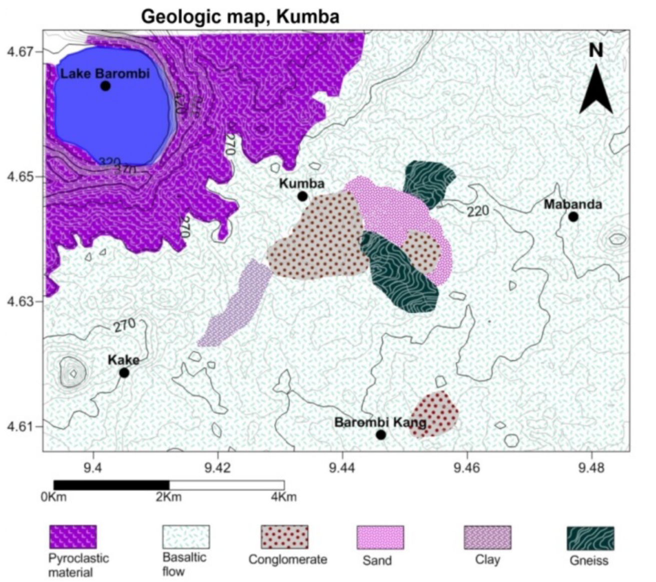


Figure 1: Geological map of Kumba with major lithologies.

Table 1: Equipment, Specifications and functions.

Equipment	Specifications	Functions
GPS	GARMIN GPSMAP 64	For mapping.
EC meter	HANNA HI 98304	To measure EC of water.
pH and temperature meter	HANNA HI 98127	To measure pH and temperature of water.
Water level indicator	Solinst Mini Model 102M	To indicate static water levels of water in wells
Weighted measuring tape	--	For measurement of well depth
Stop watch	Taksun TS-1809	Chronometry
Trigger tube	--	To mix water and tracer in well for tracer tests.
Water sample collector	--	To collect representative water sample.
Sodium chloride	--	Conservative tracer.

doi: 10.4172/2325-9647.1000149

$$ECV_w = EC_T V_T \quad (4)$$

Equations (1) and (2) in (4) imply that: $EC(2\pi r^2 h) = EC_T(2\pi r_T^2 h_T)$ (5)

Equation 3 in 5 gives: $EC(r^2) = EC_T(r_T^2)$ (6)

Rearranging equation 6 gives $EC = \frac{EC_T(r_T^2)}{r^2}$ (7)

A salt solution with EC 1.5 times the background EC was prepared and poured into the trigger tube. The trigger tube apparatus was inserted into the well with its lid closed. The tube was opened and withdrawn, mixing the solute instantaneously with the well water.

Changes of EC with time were measured until the EC of water in the well returned to over 90% of its background EC value.

Results

The depths from surface to well bottoms ranged from 2.63 m at Dallas to 11.80 m at Kake 1, depth from surface to static water level in each well ranged from 1.08 at Krammar to 11.41 m at Kake-1, water temperatures ranged from 26.80°C at Gar to 29.60°C at Kossala and background EC of the water samples ranged from 0.01 µS at CCAS and GBHS to 0.32 µS at Mbongo Street (Figure 3). The time taken for EC to fall to background EC ranged from 4 minutes at CCAS to 50 minutes at Kake 1 (Table 2).

Interpretation

From the trigger tube tracer test results, Darcy and apparent

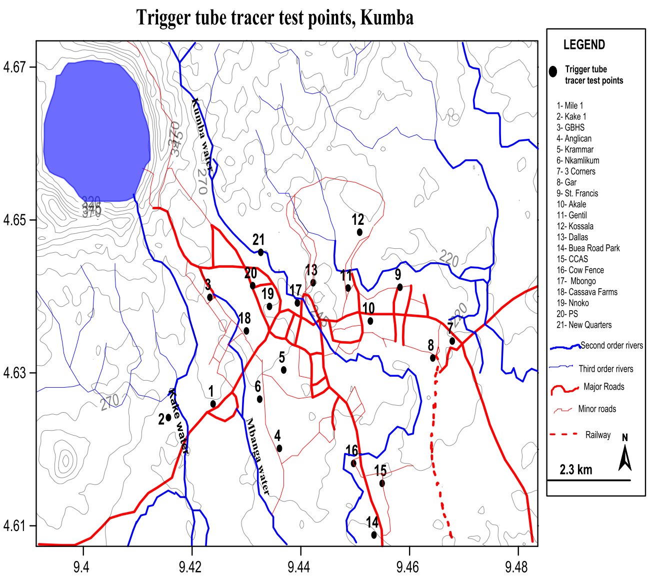
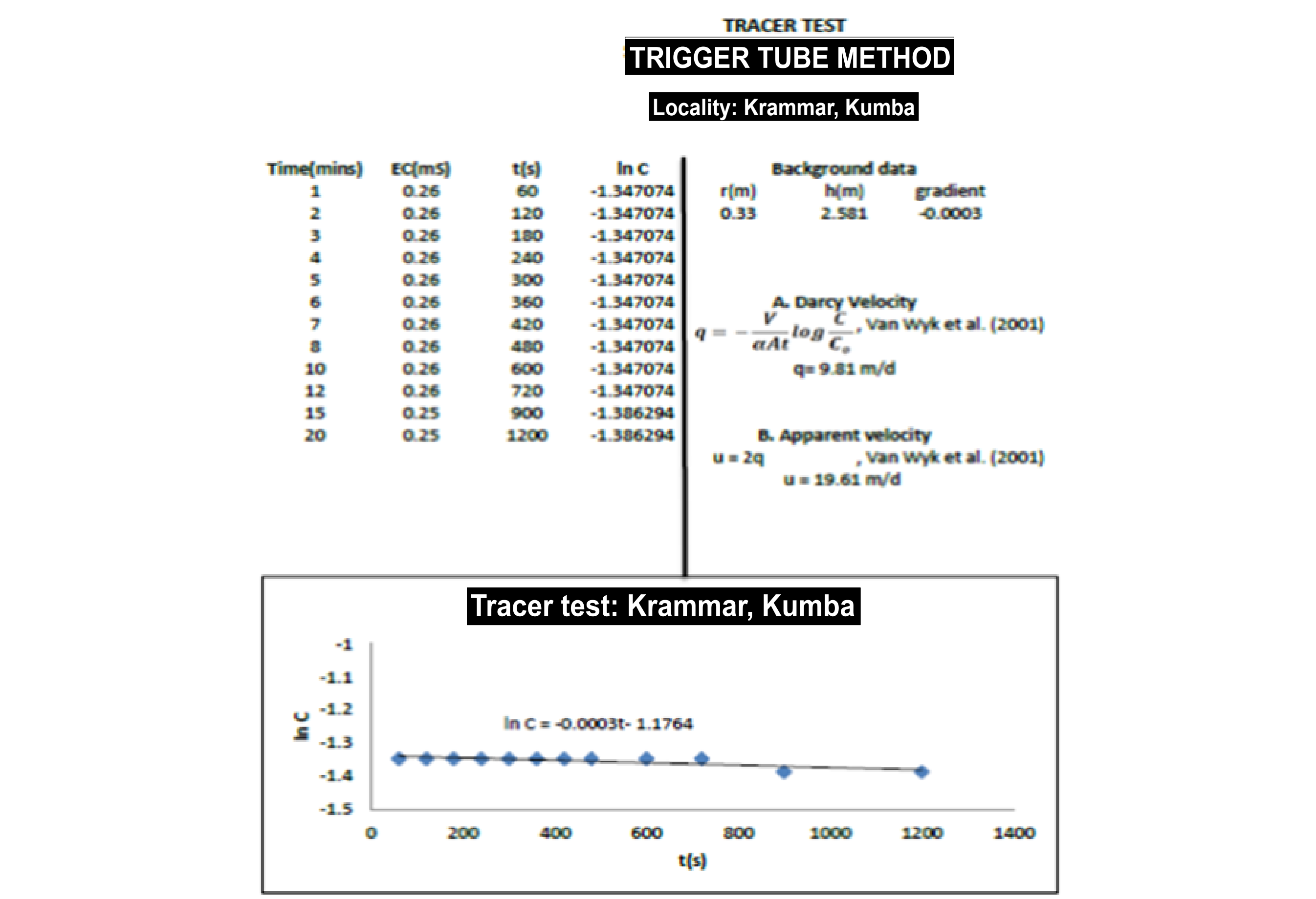


Figure 2: Locations of sites for point dilution tests carried out in Kumba.



Time(mins)	EC(mS)	t(s)	ln C
1	0.26	60	-1.347074
2	0.26	120	-1.347074
3	0.26	180	-1.347074
4	0.26	240	-1.347074
5	0.26	300	-1.347074
6	0.26	360	-1.347074
7	0.26	420	-1.347074
8	0.26	480	-1.347074
10	0.26	600	-1.347074
12	0.26	720	-1.347074
15	0.25	900	-1.386294
20	0.25	1200	-1.386294

Figure 3: Sample linear regression curve of Krammar tracer test result from which values of (q) Darcy and (u) Apparent velocities were determined.

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velocities of groundwater in the phreatic aquiferous formations in Kumba were estimated as described below (Table 3).

a. The Darcy velocities of groundwater were calculated using [19]

Darcy velocity, $q = -\dfrac{V}{\alpha At}\log\dfrac{c}{c_0}$ (8)

Where: V=volume of fluid contained in the test section; A=cross sectional area normal to the direction of flow; C_o= Tracer concentration at t=0; C=tracer concentration at time=t;

α= borehole distortion factor (between 0.5 and 4;=2 for an open well); t=time when the concentration is equal to C

$$q = -\frac{V}{\alpha At}\log\frac{c}{c_0} \quad (9)$$

$$q = -\frac{V}{\alpha At}\log\frac{c_0}{c} \quad (10)$$

$$q = -\frac{V}{\alpha At}\left(\frac{1}{t}\log\frac{c_0}{c}\right) \quad (11)$$

Converting the log in equation 3 to natural log gives:

$$q = 2.33\frac{V}{\alpha A}\left(\frac{1}{t}\ln\frac{c_0}{c}\right) \quad (12)$$

α= 2 for an open wells implies that equation 4 becomes

$$q = 2.33\frac{V}{2A}\left(\frac{1}{t}\ln\frac{c_0}{c}\right) \quad (13)$$

Assuming that water flows radially in the wells' cross sectional area normal to the direction of flow, $A = \pi r_w b$ (14)

Volume of fluid contained in test section, $V = 2\pi r_w^2 b$ (15)

Where: r_w=well radius; b=length of tested section in the borehole (length of water column) [20].

Equations (13) and (14) in (12) gives: $q = 2.33 r_w\left(\frac{1}{t}\ln\frac{c_o}{c}\right)$ (16)

A solution for the term $\left(\frac{1}{t}\ln\frac{c_o}{c}\right)$ in equation (16) is gotten from plotting a curve of ln C versus t. A line of best fit is obtained for this curve. This is a straight line with equation.

$$\ln C = mt + \ln C_o \quad (17)$$

Where; m = gradient of the line and $\ln C_o = y$, the intercept.

This implies that $\left(\frac{1}{t}\ln\frac{c_o}{c}\right) = -m$ (18)

Equation 18 in 16 gives: $q = -2.33 r_w m$ (19)

b. The apparent velocities of groundwater were calculated using

$q^{\alpha}=\gamma$ (20)

Where; γ=apparent velocity inside well; α=borehole distortion factor (between 0.5 and 4;=2 for an open well) [19]

This implies that for open well, γ=2q (21)

The apparent velocities in Kumba range from 39.26 m/d at Krammar to 1268.27 m/d at Dallas. With peaks at the Northeastern and Southeastern parts of Kumba at PS Kumba Town, Dallas and CCAS and the lowest values at St. Francis, Gentil, Mbongo and Krammar (Figure 4).

Discussion

The first step in groundwater flow modeling is to determine the flow velocity and direction at each point in the flow field. Darcy velocity and apparent velocity are useful in advection–dispersion modeling of constituents in groundwater. It is therefore important to determine these parameters in any given area (Figure 5).

Table 2: Tracer test results showing background EC, depth to well bottom, depth to static water level and temperature of water samples from some hand-dug wells in Kumba.

Location	Background EC (mS)	Depth to Well bottom (m)	Depth to static water level(m)	Temperature(C)
MILE 1	0.05	6.98	4.45	27.10
KAKE 1	0.03	11.80	11.41	26.50
GBHS	0.01	17.62	16.70	26.30
ANGICAN	0.08	8.87	4.95	28.20
KRAMMAR	0.22	3.66	1.08	28.20
NKAMLIKUM	0.12	8.65	2.86	28.10
3CORNERS	0.04	4.04	2.44	27.00
GAR	0.03	4.40	3.30	26.80
ST. FRANCIS	0.29	10.88	5.11	27.30
AKALE	0.30	9.25	2.22	27.30
GENTIL	0.39	7.18	6.07	28.00
KOSSALA	0.11	5.38	3.90	29.60
DALLAS	0.05	2.63	1.62	27.20
PARK	0.06	5.01	3.68	27.20
CCAS	0.01	10.06	7.54	27.30
COW FENCE	0.07	7.15	6.71	27.60
MBONGO	0.32	3.45	2.45	28.60
CASSAVA FARMS	0.18	6.63	4.89	27.70
NNOKO	0.18	3.70	1.68	27.60
PS	0.05	4.47	3.33	27.50
NEW QUARTERS	0.06	3.00	1.91	28.30

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Precise groundwater gradients can be used with Darcy velocities to calculate hydraulic conductivities in an area. Apparent velocities are used to calculate groundwater travel times of pollutants [10].

Field estimations of groundwater flow velocities in the phreatic aquiferous formation in Kumba through the trigger tube tracer tests gives darcy velocities ranging from 19.63 m/d at Krammar to 634.13 m/d at Dallas and apparent velocities ranging from 39.26 m/d at Krammar to 1268.27 m/d at Dallas.

Generally, groundwater velocity decreases with depth of the aquiferous formation from the surface. This is due to a fall in porosity and hence permeability with increasing distance from the surface due to a similar increase in overburden pressure. The huge spatial

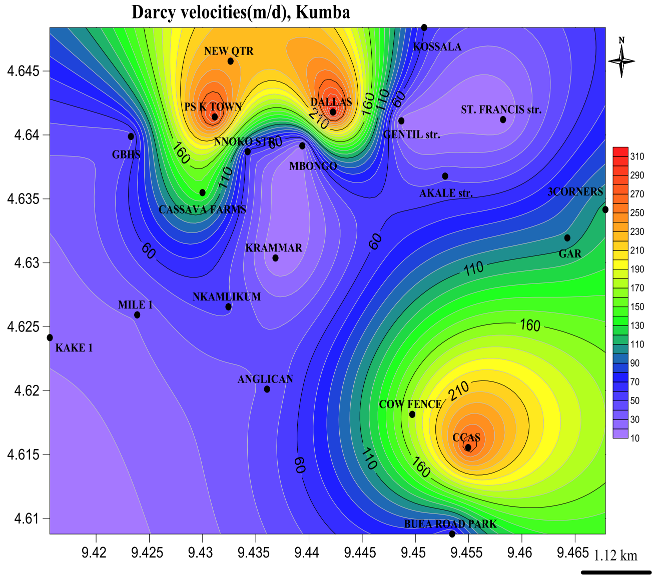

Figure 4: Tracer test results of Darcy velocities of groundwater in the phreatic aquiferous formations in Kumba. The highest values are at the Northeastern and Southeastern parts of Kumba at PS Kumba Town, Dallas and CCAS and the lowest values at St. Francis, Gentil, Mbongo and Krammar.

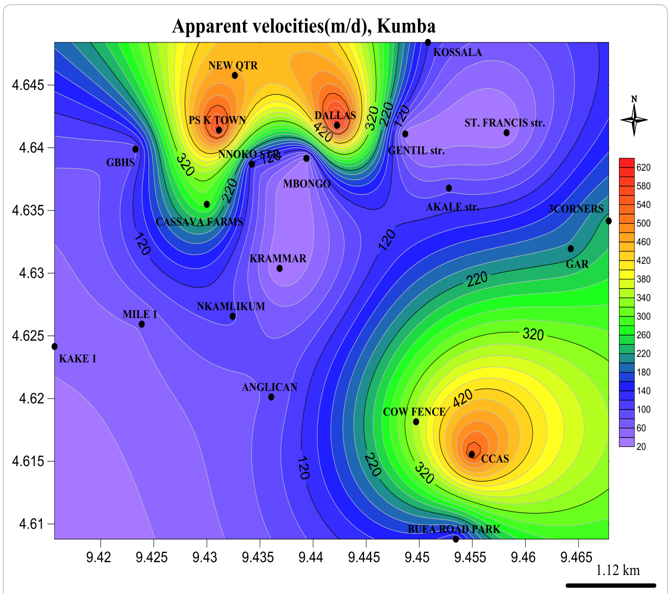

Figure 5: Tracer test results of apparent velocities of groundwater in the phreatic aquiferous formations in Kumba. The highest values are at the Northeastern and Southeastern parts of Kumba at PS Kumba Town, Dallas and CCAS and the lowest values at St. Francis, Gentil, Mbongo and Krammar.

Table 3: Measured and empirically determined parameters used in the derivation of Darcy and apparent velocities in Kumba. The q and u values were gotten from linear regression curves of the tracer tests.

Location	r(m)	h(m)	V(m³)	A(m²)	gradient	q(m/d)	u(m/d)
MILE 1	0.52	2.53	4.22	1.31	0.0006	62.21	124.41
KAKE	0.45	0.40	0.50	0.18	0.0005	45.30	90.59
GBHS	0.40	0.92	0.93	0.37	0.0011	88.58	177.15
ANGICAN	0.52	3.92	6.53	2.02	0.0008	82.94	165.88
KRAMMAR	0.33	2.58	1.71	0.84	0.0003	19.63	39.26
NKAMLIKUM	0.40	5.79	5.82	2.32	0.0013	104.68	209.36
3CORNERS	0.30	1.60	0.90	0.48	0.0038	229.50	458.99
GAR	0.43	1.10	1.25	0.47	0.0024	205.34	410.68
ST. FRANCIS	0.40	5.78	5.80	2.31	0.0003	24.16	48.31
AKALE	0.40	7.03	7.06	2.81	0.0012	96.63	193.26
GENTIL	0.44	1.11	1.35	0.49	0.0003	26.57	53.15
KOSSALA	0.43	1.49	1.68	0.63	0.0014	119.78	239.56
DALLAS	0.45	1.02	1.29	0.46	0.0070	634.13	1268.27
PARK	0.45	1.34	1.70	0.60	0.0013	117.77	235.54
CCAS	0.54	2.57	4.71	1.39	0.0050	543.54	1087.08
COW FENCE	0.35	0.44	0.34	0.15	0.0050	352.30	704.59
MBONGO	0.42	1.01	1.11	0.42	0.0004	33.82	67.64
CASSAVA FARMS	0.40	1.74	1.75	0.70	0.0036	289.89	579.78
NNOKO	0.45	2.02	2.57	0.91	0.0012	108.71	217.42
PS	0.40	1.14	1.14	0.46	0.0073	587.83	1175.66
NEW QUARTERS	0.45	1.09	1.39	0.49	0.0051	462.01	924.02

Note: r_n= Well radius; **h**=Height of water column in well; **V**=Volume of water in well; **A**=Cross sectional area of well; **q**=Darcy Velocity; **u**=Apparent velocity variations in groundwater flow velocities imply that groundwater flows at different rates and directions in different sections of the phreatic aquiferous formation in Kumba. This is probably due to spatial variations in permeability. Areas with low groundwater velocities like Krammar have lower permeabilities compared to those around PS Kumba Town, Dallas and CCAS. This could be an indication of layering in the aquiferous formation in Kumba.

Conclusion

The trigger-tube tracer tests carried out in some dug wells in Kumba reveals significant spatial variations in groundwater velocities and that groundwater flow velocities are relatively poor at Krammar and good at Dallas. The huge spatial variations in groundwater flows and groundwater velocities imply that groundwater flows at different rates, directions, and at different rates in different sections of the phreatic aquiferous formation in Kumba, probably due to spatial variations in permeability and existence fractures acting as groundwater conduits. Areas with low groundwater velocities like Krammar have lower permeabilities compared to those around PS Kumba Town, Dallas and CCAS. This suggests spatial variations in formation types, facies changes (transgressive and regressive), thickness and layering.

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Conflicts of interest

No conflict of interests.

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Author Affiliations

Top

Faculty of Science, Department of Geology, University of Buea, P.O. Box 63. Buea, South West Region, Cameroon