The Hydrogeological Regimen and Saltwater Intrusion in Parts of Bonny Island, Rivers State.

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Saltwater intrusion is a common form water pollution in coastal areas. Bonny Island situates in the tidal zone of the Niger River Delta and has a very limited supply of potable water. Chloride, a prevalent ion in seawater, indicates intrusion when found in significant amounts in groundwater. The concentration of chlorides in groundwater on the Island ranged between 247mg/l to 20501mg/l, which exceeds the saline intrusion threshold value of 250mg/l. Chloride/bicarbonate ratio ranged between 35.55 in August to 106.39 in January, far in excess of the threshold value of 2.0 indicating intrusion. Aquifer recharge is entirely through rainfall which is highest in October and lowest in February and is reflected in a sinusoidal curve of static water levels that characterises the hydrogeological regimen on the island. Electrical conductivity ranged between 162µs/cm to 7190µs/cm, where 800µs/cm is described as brackish. Inferring from the Chloride/bicarbonate ratio, only few wells in Abalamabie and Oguede, situate towards the centre of Bonny Island were moderately saline. Thus, of the wells sampled, 33.33% were classified as moderately saline, 54.41% were saline and 9.26% were highly saline.

Keywords: Intrusion, Facies, Hydrogeological, Regimen, Saltwater, Up-coning.

1.0 Introduction

Water has the peculiar quality of being an inexhaustible natural resource, but water of usable quantity and quality present in the right place and at the right time is not inexhaustible. Although it is a renewable resource, demand is often greater than supply with the attendant water shortage becoming an increasing global problem [9].

Saltwater intrusion is one of the most common forms of groundwater contamination because about 70% of the world's population live in coastal areas [2]. Saltwater intrusion is the movement of seawater into freshwater aquifers as a result of groundwater development. When groundwater is pumped from aquifers that are in hydraulic connection with the sea, and the piezometric surface of the freshwater is lowered, the balance between the seawater/freshwater interface is disturbed, the hydraulic gradient so created induce seawater to encroach the freshwater aquifer [4]; [17].

Saltwater intrusion is a threat to many islands in the World that have a thin freshwater lens of groundwater lying above saline groundwater. The freshwater development in these small islands is one of the most challenging problems facing hydrogeologists today [4]. Bonny Island where this study was carried out exists in the tidal zone of the Niger Delta, which predisposes it to saltwater intrusion. The growth of industrial development on the island and the attendant population explosion places a very heavy demand on the lean supply of freshwater. Over the years "indiscriminate abstraction of groundwater from the top aquifer has resulted in saltwater intrusion in several coastal wells especially in Bonny…" [7]. This limits the supply of potable drinking water on the island, which can have detrimental effects on human health, wild life habitat as well as increasing the cost of water treatment [4]. This paper attempts a critical evaluation of the hydrogeologic and hydrogeochemical characteristics of Bonny as a framework for the management of groundwater resources on the island and elsewhere having similar challenges.

2.0 Geology and Hydrogeology of the Island.

Bonny Island situates on a sandy beach ridge delta front environment of the Nigeria Atlantic coastal setting. It seats within the transitional environment of the Quaternary Niger River Delta and is characterised by beaches, mangrove swamps and barrier bars. The surrounding Bonny River is characterised by a fairly strong wave activity, with a diurnal rhythm of tides that inundates an anastomosing network of creeks which drains the entire island. Lying between Longitudes 7.131^o and 7.323^o East and Latitudes 4.374^o and 4.540^o North, it is located at about 50 nautical miles South East of Port Harcourt, Rivers State.

Bonny Island is comprised of sediments of Pleistocene to Holocene in age deposited by fluvial and shallow continental shelf hydrodynamic processes. The lithofacies includes the delta tip; mainly evenly laminated clean greyish fine to medium sand, very fine sand, silts, silty clays and chicoco muds. These surficial deposits mask the Benin Formation, which is Miocene to Holocene in age and comprises of alluvial coastal plain sands, about 2000m thick. Underlying this is the Agbada Formation deposited in fluvio-deltaic environments during the Eocene to Recent times, consists of over 3,700m of siliciclastic interbeds of sands and shales. Underneath the Agbada Formation is the Akata Formation (7000m thick), Paleocene to Holocene in age and composed of marine shale sequence, turbidite sands and minor amounts of clay and silt [15], [1], [5].

Both confined and unconfined aquifers are encountered at varying depths and they contain highly saline groundwater. The water table in the area generally fluctuates around 2.0m inland from the coast. The maximum elevation of the Island ranges between 2.0m-4.5m above mean sea level. There is a subsection of clay at the top, preceding a column of coarse and pebbly sands [6], [12].

Data on aquifer hydraulic parameters for groundwater resource evaluation in the area are generally scanty. Typical average porosity values range from 28%-32%, while permeability values range between 5-7 Darcy [7]. [10] identified 3 aquiferous zones in the Niger Delta viz:

1. An upper unconfined aquifer extending throughout the Benin Formation with its thickness ranging between 15-80m, while the static water level (SWL) varies between 4m-21m.
2. A middle aquifer system, semi-confined and consisting of thick medium to coarse grained sometimes pebbly sands with thin clay lenses. Its thickness varies between 30m-60m.
3. A lower system that extends 220m-300m and consists of coarse-grained sands and gravels with some interlayer clay.

The majority of groundwater wells abstract water from the first and second aquifers (<100m deep). Whilst very few industrial and municipal groundwater supply wells tap deeper aquifers. Over abstraction of the first aquifer have induced the intrusion of sea water into the freshwater aquifers on the island.

Figure 1: Bonny Island showing sample stations (blue pins), black ellipse shows study area inset in NGSA Geological Map of Southern Nigeria.

2.0 The Ghyben-Hergzberg's Model

The Dutch and German hydrogeologists Badon Ghyben (1888), and Herzberg (1901) respectively; working independently of each other derived models that tried to elucidate the freshwater/saltwater relationship in coastal aquifers. This class of problems treats a biconvex lens of freshwater floating on seawater at rest, the edges of the lens being fixed by the coast; for example, an idealised Island (circular symmetry). With the assumption of a constant lateral diffusion (dispersion) coefficient in a steady boundary layer model, the thickness of the mixing zone in a two dimensional Ghyben-Herzberg system is approximately proportional to the square root of the radius of curvature of the interface. Thus, the thickness should tend to decrease towards the coast, [18].

For the fact that seawater is heavier than freshwater, it will form a saltwater wedge in coastal aquifers that drain into the ocean. Assuming that freshwater move horizontally to the ocean and that the saltwater-freshwater interface is abrupt and originates at the shoreline, the freshwater pressure at any point of the interface can be expressed as (h+z) ρ_f, where h is the height of the water table above sea level, z is the distance of the interface below sea level, and ρ_f is the density of freshwater. This pressure must be the same as the saltwater on the other side of the interface, which is Zρ_s where ρ_s is the density of saltwater. Equating the two expressions and solving for z, yields:

$$Z = \rho_f / (\rho_s - \rho_f)\, h \qquad \text{(Ghyben-Herzberg formular)} \;....2.1$$

Since ρ_f = 1.0 g/cm3 and ρ_s = 1.025g/cm3 for seawater, the Ghyben-Herzberg equation shows that for coastal aquifers Z = 40 h. Thus for every meter that the water table is above sea level, freshwater will extend below sea level for 40m before saltwater occurs. However, if groundwater withdrawal from coastal aquifer exceeds safe yield and water levels decline, the saltwater will rise 40m for every meter drop in water table [3]. This concept is illustrated in fig.2

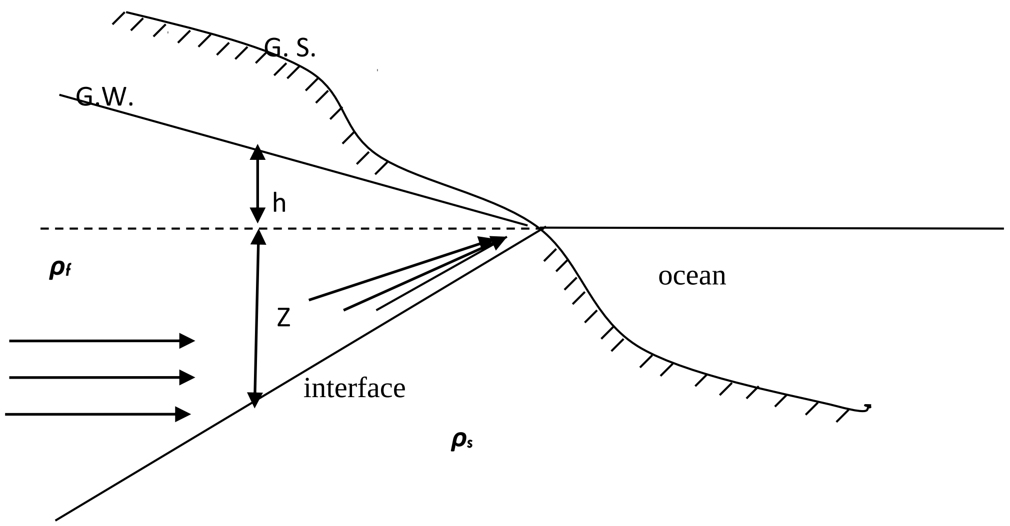

Fig. 2 Freshwater-Saltwater interface in coastal aquifer draining into the ocean (modified after Bouwer,1978).

Models such as the one above allow engineers and hydrogeologists to test hypotheses in a manner that is removed from and non-destructive to the problem at hand [16]. In reality the conditions are not as simple as those assumed by Ghyben-Herzberg, for example water drains into the ocean over a certain area rather than at a point as assumed by Ghyben-Herzberg.

2.1 UPCONING

When freshwater groundwater is underlain by saline water, pumping a well in the freshwater zone causes the freshwater/saltwater interface to rise below the well (Fig 4). This "upconing" is in response to the pressure reduction on the interface due to the saline water or the well discharge is relatively high, the saltwater cone may reach into the well, causing the well discharge to be a mixture of fresh and saline groundwater.

Assuming steady, horizontal flow of freshwater to the well, no lateral movement of saltwater and a sharp interface, the height Z of the cone below the well centre can be calculated in the same manner as the Ghyben -Herzberg lens, yielding:

$$Z = \rho_f Sw/(\rho s - \rho_f) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.2$$

Where Sw is drawdown of water table at well [3].

Thus, where fresh groundwater is underlain by saline water prediction of upconing is important for determining safe depths and pumping rates of wells (including "skimming" wells) that prevent the entry of saline water into well [3]. See fig.4

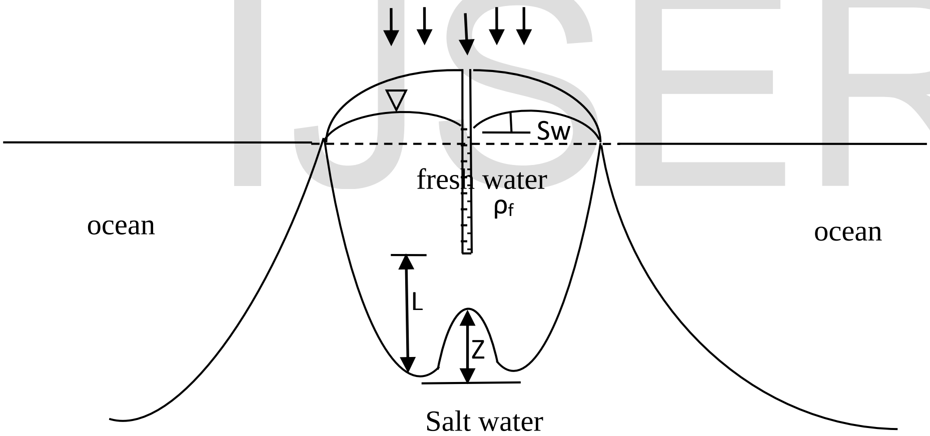

Fig.4 Geometry and symbols for the upconing of saltwater beneath a pumped well, on an island(dashed lines represent static positions of water table and interface; modified after Raghunath, 1990).

3.0 Materials and Methods.

Analysing saltwater intrusion in Bonny Island involved hydrogeological and geochemical at various locations (see fig 1) around the island. Water samples were collected once every month (August to January) and analysed for (i) pH, (ii) Electrical Conductivity, (iii) Chlorides, (iv) Bicarbonates, (v) Calcium, (vi) Sodium, (vii) Magnesium, (viii) Sulphates, (ix) Total Hardness and (x) Total Dissolved Solids, using standard water quality assessment (APHA, 1989) methods. Depth to water table was measured every time water wells were sampled.

4.0 Results and Discussions

Field observations and data gathering reveal an interplay of complex scenarios of saline water intrusion into aquifers on the island. There is the observed lateral migration of saline water into aquifers as the island is surrounded on all sides by the brackish waters of the Bonny River on the western side, the Andoni River on the east and the Atlantic Ocean on the southern face. The aquifer materials deposited on the shallow continental shelf contained saline connate water which is released during abstraction. Up-coning due to industrial abstraction of deeper aquifers on the island further accentuates the saline intrusion. Furthermore, the decreasing pressures in the underlying aquifers occasioned industrial abstraction described above induces saline waters to migrate downwards to further contaminate the aquifers.

The geochemical potentials of groundwater on the island engenders complex ion exchange, with increasing chloride and sodium concentrations. The saline intrusion is further evidenced by the high concentrations total dissolved solids observed.

4.1 Hydrogeological Regimen in Bonny Island.

The aquifers in Bonny are relatively very permeable; as the Island is located on a sandy beach ridge [12]. Seawater is in contact with groundwater on all sides. The surface aquifers are recharged entirely by rainfall. Rainwater percolates easily into the sediments, forming a freshwater lens which drains towards the coast. This movement displaces saline water, which is expected to reach approximately 70m during the wet season [11]. The high permeability of the aquifers leads to a loss of a significant volume of freshwater to the sea.

A graphical plot of static water levels from August to July show a double high and a trough curve with it's peak in October. The mean annual rainfall value in Bonny Island evaluated over a twenty year period (1980-1999) is 4,682mm [11]. Ninety-two percent of the mean rainfall amount is spread between March and November. The driest months are December, January and February. While the wettest months are June/July and September/October [8]. In this study, the January samples were considered to be representative of the peak dry season and the October results taken as representative of peak wet season.

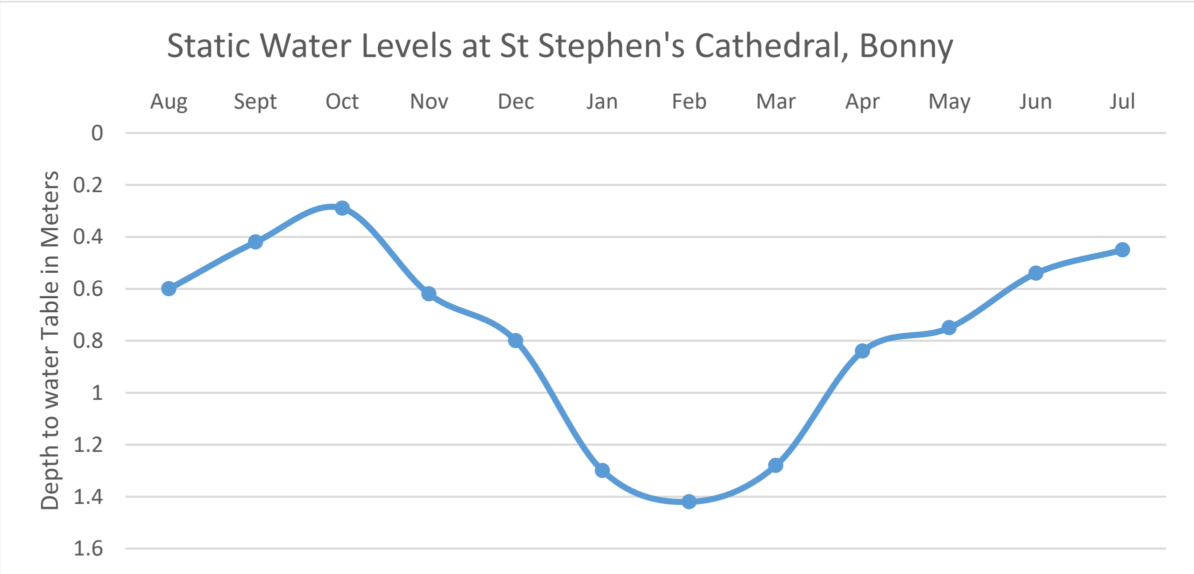

Figure 4.1: Depth to Water Table Curve from August to July.

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4.2 Geochemical Analyses of Groundwater

Geochemical studies provide a complete knowledge of the water resources of a Hydrological regimen; and are of great value with respect to water use [13]. The results of geochemical analyses conducted in Bonny Island during a six-month period (August to January) reveal a trend which indicates maximum intrusion during the peak dry season (January-February). This can be attributable to the fact that recharge of the surface aquifers sampled is entirely by rainfall.

Table 4.1: Six-month Aggregate Physico-Chemical Values of Parameters at Individual Stations.

Parameters	Min	Max	Stations										
			1	2	3	4	5	6	7	8	9	10	11
pH	6.7	7.3	7.3	7.3	7.1	7.1	6.7	6.9	7.0	7.1	6.9	7.2	7
EC (µs/cm)	221	2524	2524	761	399	533	221	525	537	552	960	402	1248
Cl^- (mg/l)	513	6167	6153	3699	3700	3604	3088	4579	513	587	6167	2256	5351
HCO_3^-(mg/l)	19	229	229	208	107	103	35	95	74	73	156	19	132
Na^+(mg/l)	7.8	14.5	8.04	10.2	12.08	10.8	7.8	8.6	7.8	12.4	12.8	13.4	14.5
Mg^{2+}(mg/l)	10.4	16.02	12.04	16.02	15.06	13.05	10.04	11.02	12.8	14.02	13.8	12.67	14.8
Ca^{2+}(mg/l)	0.18	2.44	2.02	1.74	2.0	1.3	0.18	2.44	0.19	0.19	0.24	0.3	2.17
SO_4^{2-}(mg/l)	2	21	15.1	13.7	8.1	13.1	6.25	13.6	9.91	7.02	9.74	2	21
TH (mg/l)	4.7	184	184	135	104	75	4.7	46	23	30	55	15	58
TDS (mg/l)	154	1393	1393	533	279	373	154	370	376	563	1185	316	581

Table 4.1 above presents aggregate values of each of the parameters in all eleven stations in Bonny Island. TH represents Total Hardness

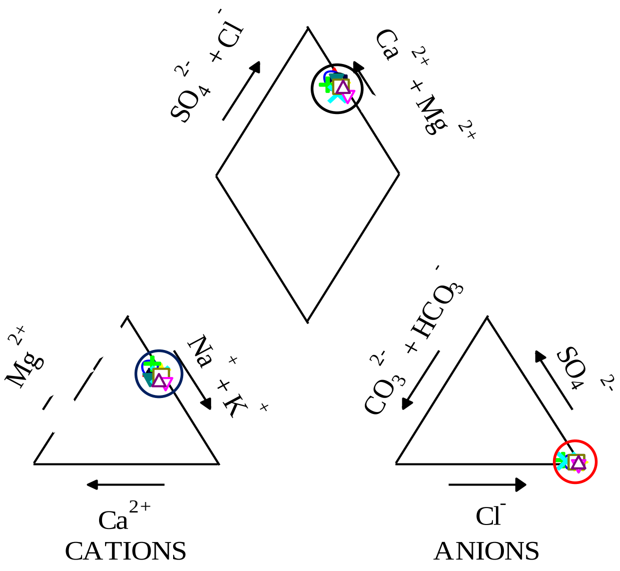

Figure 4.1. Piper diagram above displays the bulk chemical composition of groundwater from the eleven sampling stations at various locations in Bonny Island. Note the extreme plots of chloride ions indicative of severe salinization.

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Table 4.2: Chloride and Bicarbonate Concentrations in mg/l at the study locations

Months	Stations																					
	1		2		3		4		5		6		7		8		9		10		11	
	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-	Cl^-	HCO_3^-
August	1432	134	743	92	1235	84	872	98	327	62	843	112	247	76	323	74	5681	128	4941	08	6532	152
September	1634	114	1347	108	1547	96	1432	98	723	34	764	108	526	82	468	78	5562	142	823	10	4520	164
October	3894	164	2072	122	2470	140	3262	158	1827	10	3247	162	988	88	1020	64	5434	160	1976	12	6321	172
November	3064	287	4670	232	4464	120	2604	106	3247	26	2840	102	632	68	814	72	6342	100	1897	16	6687	134
December	6395	236	6480	284	5820	110	1846	87	5243	32	2244	64	436	72	403	68	6820	164	1925	44	6823	92
January	20501	440	5880	412	6669	92	11609	68	7163	44	17537	20	247	56	494	80	7163	244	1976	24	6916	80

4.1 GEOCHEMICAL INTERPRETATION OF SALTWATER INTRUSION ON BONNY ISLAND.

Chloride is the dominant ion in seawater and it is only available in small quantities in groundwater. While Bicarbonate which is available in large quantities in groundwater occurs only in very small quantities in seawater [13]. It has been found that a chloride/bicarbonate ratio greater than 2 is indicative of saltwater intrusion [14].

The following equation is used to evaluate the degree of salinization:

$$\frac{x/35.46}{y/61.02} > 2 \quad \text{indicates intrusion}$$

Where x is chloride concentration in mg/l

y is bicarbonate concentration in mg/l

35.46 molecular mass of chlorine

61.02 molecular mass of bicarbonate

Table 4.3 Showing location of monitoring wells, Chloride/Bicarbonate Ratio and Distance from Shoreline.

Station ID & Coordinates		Distance from Shoreline (m)	Chloride/Bicarbonate Ratio
1. Usiah Gilbert	(7^o10.452', 4^o27.388')	400	38
2. Chief Ezekiel Hart	(7^o10.404', 4^o27.035')	550	27
3. St Stephen's Cathedral	(7^o09.994', 4^o26.595')	300	61
4. Praise-Be-to-God	(7^o10.211', 4^o26.834')	400	75
5. Wamina Opubo	(7^o10.080', 4^o26.109')	1000	190
6. Dynamite Praise Church	(7^o10.340', 4^o23.736')	1700	280
7. Chief LongJohn, Abalamabie	(7^o12.886', 4^o25.449')	5000	12
8. Chief Manila Pepple, Oguede	(7^o12.702', 4^o26.110')	6000	14
9. Plot 150, Finima	(7^o09.393', 4^o23.801')	1500	72
10. Christ Army Church, Lighthouse	(7^o08.347', 4^o24.124')	500	318
11. Mr Bernard Cosmas	(7^o08.185', 4^o24.209')	200	91

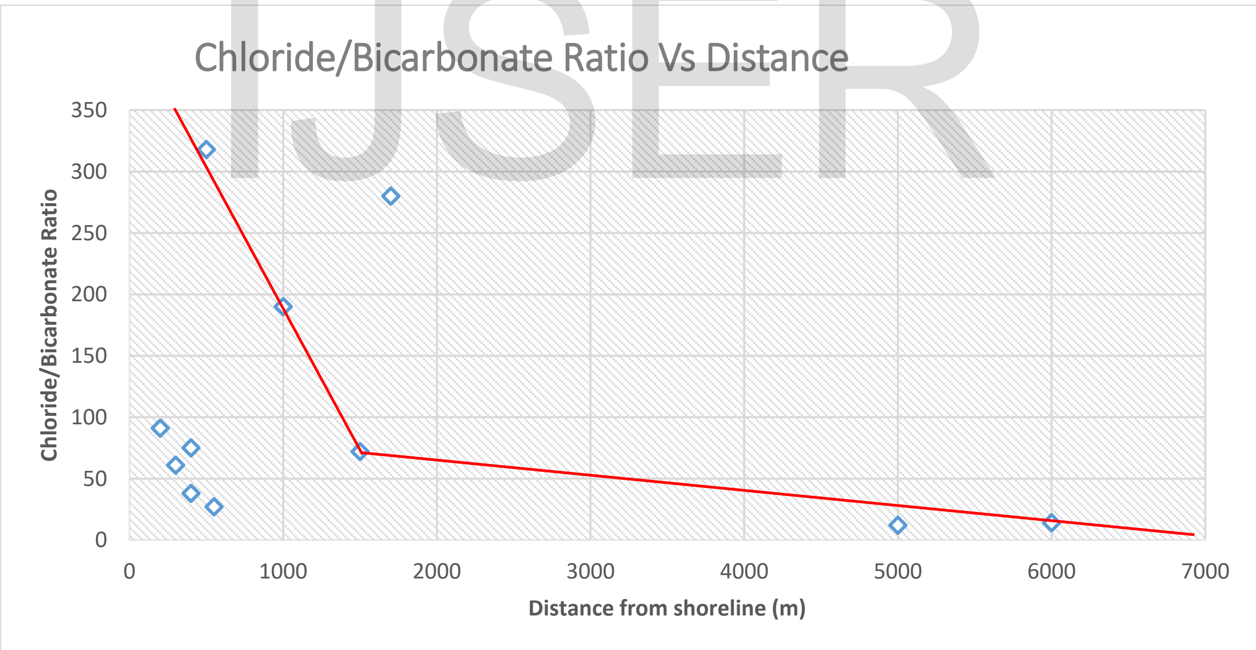

Figure 4.2 Shows decreasing Chloride-Bicarbonate ratio with increasing distance from shoreline indicating high salinization near the shore.

4.2 General Parameters Depicting Groundwater Quality on the Island.

The concentration of various parameters in sampled water around the Island revealed the pH ranging between 6.7 and 7.3, with a near neutral mean value of 7.05; while the mean electrical conductivity was 787.46µs/cm. Chloride values ranged from 513 to 6167mg/l with a mean value 3608.82mg/l. Bicarbonate range was 19 to 229mg/l with an average value of 111.91mg/l. Sodium had a mean value of 10.77mg/l; while calcium averaged at 1.16mg/l. Sulphates ranged between 2 to 21mg/l with a mean value of 10.87mg/l. Total hardness ranged between 4.7 to 184mg/l with a mean value of 66.34mg/l. Total Dissolved Solids showed a minimum value of 154mg/l and a maximum value of 1393, averaging at about 556.64mg/l.

From the foregoing, water wells located close to the shoreline (St. Stephen's Cathedral, Light House areas) indicated high chloride concentrations when contrasted with wells at the centre of the island at Abalamabie and Oguede (see figure 1). This depicts that the freshwater lense being thickest at the centre of the island would have moderated the diffusive influx of seawater.

Again, the geochemical data as processed by the Piper diagram in figure 4.1 shows samples that plot in a range of geochemical facies; with the chloride type being the most predominant. The other facies, beginning from the Ca-Mg-SO_4-Cl to the Mg-Na-K and CO_3-HCO_3-SO_4 facies indicate the mixing and ion exchange taking place during the migration of saline and freshwater types induced by recharge and influenced by the diurnal tidal cycles.

The chloride-bicarbonate ratios in Abalamabie and Oguede were the lowest (12 and 14 respectively). This is very apparent in figure 4.2 where the chloride-bicarbonate ratios were also lowest at the farthest distance from the shoreline. However, high values obtained from samples collected from other parts of the Bonny island, especially around the Light House area indicate saline water circulation induced by the diffusion of brines from the sea influenced by tidal action.

Conclusion

The composition of seawater is very distinct from freshwater resources; therefore, whenever seawater diffuses into freshwater aquifers, the effects of this mixing could be very impactful. Groundwater quality in Bonny island is generally poor, as indicated by the extreme plot of chlorides on the Piper diagram in relation to other geochemical facies. This is caused by an interplay of factors ranging from the diurnal flux of the tides to low pressure head and an anastomosing network of creeks within the island through which seawater flows during flood and ebb tides. Recharge of the aquifers is entirely by rainfall, which is limited to the rainy seasons, ultimately influencing the circulating patterns of flow towards the shorelines.

Furthermore, industrial developments and the attendant rapid population growth on the island places a heavy demand on the groundwater resources. Over-abstraction of water from the top aquifer creates and a disequilibrium between the freshwater/saltwater interface, with the underlying saline water being induced into the islands aquifers. Hence, electrical conductivity and total dissolved solids indicate a significant mixing of saline waters within the surface freshwater aquifers.

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