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Proportionate Risk-Based Approach to Groundwater Quality Sustainability in the Nigerian Niger Delta

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Abstract
The vulnerability of groundwater was assessed with the aim of evaluating how susceptible groundwater resources were to pollution from various unsafe acts in the study area. Therefore, fourteen (14) VES were taken using Schlumberger electrodes configuration and the field data was modelled using Res2DINV to obtain the final geolayer parameters. This was used to compute the longitudinal conductance (S) for the overburdens in the studied area; the values for the longitudinal conductance obtained were less than one (1) for the entire subsurface investigated. This suggested that groundwater resources in the studied area are vulnerable to pollution hazards. Because of the large area of the groundwater resources exposed to pollution hazards from unsafe conditions, the study area was designated safeguards zone. The risk based approach towards protecting the designated area is the enforcement of good land use practices, controlling of high risk activities as well as drilling of monitoring wells especially within VES 10 - VES 14.
Keywords: Unsafe act, Groundwater, Safeguard zone, Vulnerability, Unsafe conditions and Risk.

1.0 Introduction

The pollution of most surface water in the Nigerian Niger Delta has caused the increasing dependency of the populace on groundwater. Therefore, presently groundwater is the largest available source of potable water supply in the Niger Delta. However, the proportion of potable water supply by groundwater varies from place to place depending on the local geology (Evans etal., 2010).

In addition to private domestic use of groundwater, many farms, schools, hospitals, bottling companies, government establishment, churches, mosque and food processing plants rely on their own groundwater supplies as do major manufacturing industries. When compared to surface water, groundwater is of relatively high quality and usually requires less treatment prior to use (Mitchell, 2013; Evans & George, 2007; AARD, 2000; Ekanem, 2013a), even for use as drinking water for both man and livestock. Despite these important uses, groundwater in the Nigerian Niger Delta is under risk of pollution from companies (especially oil companies), domestic waste as in-stream sand gravel mining. Some of the environmental poor practices that render groundwater vulnerable are agriculture, in-situ sanitation, gas line filling stations, pipeline network, metal industries, solid waste disposal, painting and enamel work, timber, industry, dry cleaning, pesticide manufacturing, sewage sludge disposal, leather tanneries and red earth mining.

The vulnerability of aquifer is essentially fixed by the natural hydrogeological setting (Foster etal., 2000). Therefore, the intrinsic characteristics of the geological strata forming the overlying vadose zone plays vital role in groundwater quality sustainability. Keely etal. (1986) noted that geological setting controls the transportation of plume into groundwater. Groundwater once polluted becomes very difficult to restore. This paper therefore, presents risk-based approach as the most cost effective method of groundwater quality sustainability rather than clean up method as commonly practiced in the Niger Delta.

2.0 Groundwater Pollution

The pollution of groundwater can occur through direct or indirect contamination. The direct contamination of groundwater is possible through wells dug on the earth surface. These wells are direct conduit that links the surface of the earth to aquifers (Sophocieous, 2002; AARD, 2000). Hence, unsafe acts or conditions around the well mouth become threats to the aquifers. Such acts or conditions include spills beside wells, poor blow out protection, flooded well pits, back-siphoning from pesticide mixing tanks and buried fuel tanks (AARD, 2000; Kirsch,2009; Okiwelu etal., 2012; Evans etal., 2012a). The indirect contamination can come from leaking sewage, fertilizer or manure spreading, pesticide spraying and spillages on land. Groundwater pollution occurs if the subsurface contaminant load is inadequately controlled and exceeds the natural attenuation capacity of the underlying rock strata. The risk to groundwater pollution increases as the vadose zone become thinner, and may becomes very high where the aquifers are unconfined (Guetala etal., 2009; Ekanem, 2013a). While acknowledging that groundwater can also be polluted by naturally occurring substances (such as iron, sulfates and radon), unsafe acts and conditions remain the primary source of groundwater pollution. The speed at which the contaminations get to the receptor (groundwater) is a function of the permeability of the pathway. This is because organic materials can be effectively filtered by pathway (soil). However, many chemicals are resistant to dilution and degradation and can persist along the pathway for a long time.

3.0 Some common Groundwater Pollutants

Groundwater pollutants are substance liable to cause pollution. A number of groundwater pollution exists, but this paper only reviewed a few of them.

3.1 Nitrate:

This is the soluble compound of nitrogen and oxygen. It occurs naturally in soil and it is the main form of nitrogen taken up by plants. Farmers, in an attempt to maximize yields, introduce artificial nitrogen into the soil in the form of chemical fertilizer or livestock manure. The natural sources of nitrogen in the soil are from the breakdown of organic matter from crops (such as legumes) and the plough of grassland (AARD, 2000). Any nitrate not used by plants is particularly vulnerable to leaching from soil to aquifers. However, the transportation of plume from soil to aquifers takes a long time. Foster and Gardufio (2004) noted that it takes decades before the impact of a pollution episode by a persistent contaminant becomes fully apparent in groundwater supplied abstracted from deeper wells. Researchers had shown that, nitrate is non-hazardous pollutant, but its high concentration (above 50m/liter) in potable water can cause serious blood condition in babies (USEPA, 2010; Mitchell, 2013). Besides, high concentration of nitrogen in water can lead to eutrophication of surface water- a situation that promotes proliferation of algae and reduction of dissolved oxygen content in water. This generally leads to extinction of marine life.

3.2 Ammonia

This is a compound of nitrogen and hydrogen. It is water soluble and toxic to fishes. Ammonia becomes toxic in drinking water as the concentration is above the safety limit of 0.5mg/liter of drinking water. However, ammonia concentration of 0.1mg/litre can be harmful to fishes. Therefore, the fresh water directive guideline specifies 0.005mg/litre of un-ionised ammonia. Ammonia also reduces metabolic processes in animals, plants and bacteria. It is present in sewage, manure, farm slurries, silage liquers and in leachates. Mitchell (2013) observed that land fill leachate can have ammonia concentration of 2000mg/liter.

3.3 Hydrocarbons

The Nigerian Niger Delta is one of the world's largest producers of hydrocarbon products. These include benzene, petrol, paraffin, diesel, lubricating oil, greases, naphthalene and asphalt. Hydrocarbons are hazardous substances and have posed high risk of groundwater contamination in the Nigerian Niger Delta. For instance, it is common to have leakages from buried pipelines tanks, pipelines which are points sources threat to groundwater quality (Evans, etal, 2012; Okiwelu, etal 2011; Okiwelu etal, 2012). Also, Mitchell (2013) reported that, fuel additives (such as tert-amylmethylether, (TAME) and ethyl-butyl ether (ETBE)) developed to enhance the performance characteristics of unleaded petrol, turn out to present significant threat to groundwater quality. The potency of the threat depends on the nature of the additives' solubility, mobility in soil pathways, poor biodegradability and low taste threshold.

3.4 Solvents as Contaminants

Solvents are liquid chemicals that are good for dissolving other substances. They are commonly used in the extraction and purification of other chemicals, for degreasing metal components and as fluid for dry cleaning. Also they are used in paints, varnishes and adhesives. Four chlorinated solvents common in groundwater have been identified by Moran etal. (2007) to include methylene chloride, perchloroethene, 1,1,1-trichoroethane and trichloroethene. The knowledge of the redox conditions of aquifers and the hydraulic properties of the saturated and vadose zones are necessary in determining the intrinsic susceptibility of groundwater to contamination by solvents. Recently, the use of edible oil in
cleaning up contaminated groundwater has proved to be cost effective, environmental friendly and most efficient method. Aiken (2013) noted that switching to biodegradable treatment of groundwater is expected to meet environmental clean-up objectives in one-third the time of traditional techniques, saving millions of dollars of the United States clean-up funds.

3.5 Microbiological Contaminants

Most land based microbiological pollutants are filtered or die off as groundwater infiltrates through the pathway. However, viruses, because of their relatively small sizes are not readily filtered out but persist through considerable distance in groundwater unlike bacteria. Mitchell (2013) observed that cryptosporidium is relatively common in natural environment and represents a routine risk to groundwater quality. The risk can be very high in geology characterized by fissured strata since microbes travels faster in cracks. Some identified sources of microbes pollution of groundwater are septic tanks, disposal of farm waste, sewage sludge handling, leaking sewers and recharge of aquifers from surface water bodies (rivers) containing sewage effluent as well as cemeteries and animal burials (ASTM, 1985; USEPA, 2004; Ekanem, 2013b; Evans etal., 2012).

3.6 Mining of Earth Resources

Mining activities ranging from sands to metal mines generally result in aquifer pollution. Sand mines for different purposes remove the protective cover of aquifers usually impervious rocks (Braga etal., 2006, Aris etal., 2007, Okiwelu etal., 2012) and expose the water table to contaminants. Metal mines contaminate water from rebound of groundwater depressed by pumping. During groundwater rebound at mine sites, rock piles find their way into aquifers through leaching. Also groundwater rebound has the potential to cause flooding of the site. The major pollutants from mining are heavy metal such as iron, lead, zinc, cadmium, manganese, copper and acid (Aris etal., 2007).

4.0 Soil – Groundwater Migration Pathway

Contaminants leaching from soil to groundwater may pose a significant threat to groundwater quality. The protection of groundwater can be determined by the vulnerability of the aquifers in an area which can be determined by the thickness of the overlaying rock strata. However, Braga etal. (2006) noted that the combinations of overburdens thickness and resistivity into single variables can be a better determinant of aquifer vulnerability. For a sequence of horizontal, homogeneous and isotropic layers, the combinations of resistivity ρ_i and thickness h_i are defined as:

$$S = \sum_{i=1}^{n} s_i = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad \text{(Siemens)} \qquad (1)$$

and

$$T = \sum_{i=1}^{n} T_i = \sum_{i=1}^{n} \rho_i . h_i \quad (\text{Ohm.m}^2) \qquad (2)$$

where s_i is the longitudinal conductance and T_i is the transverse resistance of ith subsurface layer overlying the aquifer. These single variables defined the protection of groundwater and transmissivity respectively.

In risk-based method of groundwater quality sustainability, the transverse unit resistance is used to determine where to install monitoring wells, while the longitudinal conduction is used to identify zones of probable risks of contamination. The soil- groundwater migration pathway for contaminates can be computed according to KDHE (2010) as

$$c_t = c_w[(k_d) + \frac{\theta_w + \theta_a H^I}{\rho_b}] \qquad (3)$$

where c_t is screening level in soil (mg/kg), c_w is groundwater-soil leachate concentration (mg/L), k_d is soil water partition coefficient (L/kg), θ_w is water-filled soil porosity (L_{water}/L_{soil}), θ_a is the air-filled soil porosity (L_{air}/L_{soil}), ρ_b is the dry soil bulk density (kg/L) and H^I is Henry's constant. The level of conductivity of contaminants along the pathway, also known as volatilization factor (VF) is given by

$$VF(m^3/kg) = \frac{\theta}{c} x \frac{[\pi D_a T]^{1/2}}{2 D_a \rho_b} x10^{-4} (m^2/cm^2) \qquad (4)$$

D_a is apparent diffusivity (cm^2/s), T is exposure interval (seconds) n is total soil porosity (L pore/L soil), D_i diffusivity in air (cm^3/s) and $\frac{\theta}{c}$ is inverse of the mean concentration at the centre of square source (gm^2s per kg/m^3).

5.0 Hazards and Effect Management Process (HEMP)

Hazards and effect management process is the heart of health, safety and environment management system. The application of the concept of HEMP to groundwater quantity sustenance is a risk-based approach to groundwater quality protection. HEMP involves four basic tools namely: identification, evaluation (assessment), control and recovery.

The first and most important step in reducing the likelihood of contaminants getting into groundwater is hazard identification. It involves geophysical mapping of the near surface sediments to investigate the presence of groundwater hazard. The information obtained can be used for determining the vulnerability of aquifer, predicting the presence of contaminant and for control purposes. Generally, real-time geophysical method (particularly, electrical methods) is employed for studying aquifer vulnerability. Also in some cases monitory wells could be used for monitoring of contaminants in the subsurface.

6.0 Study Location and Geology

The study area is located in the southern end of the Nigeria extending from about latitude $5^{o}00^{/}$ and 5^{o} $05^{/}$ and longitude $7^{o}50^{/}$ and $7^{o}75^{/}$ and geologically belongs to the Benin Formation. This Formation is the uppermost stratigraphic unit of the Nigerian Niger Delta Atlantic coastal plain with its mixture (poorly sorted), loose (porous, highly permeable and unconsolidated), fine – medium coarse grained continental sediments. The sediments are predominantly sands with minor clay, silts, gravel, sandstone and shale intercalations. This is typical of most continental deltaic depositional environment. The study area is generally masked by sandy deposits with an occurrence of large quantity of groundwater underlying it (Evans etal., 2012b; Ekanem, 2013a&b).

6.1 Methodology

Geoelectrical resistivity method employing Schlumberger array in vertical electrical sounding mode was used to map contamination prone area in parts of the Nigerian Niger Delta. A total of fourteen (14) VES were obtained within the environs of the Akwa Ibom State international stadium; the choice of this location was informed by the influx of population into villages (Atan Offot, Obio Etio and Obio Offot) surrounding the international stadium. This rise in population is expected to mount pressure on the resources (including groundwater) within the studied area.

The field data obtained was converted to field curves and manually smoothened for computer modeling using Res2DINV. The computer model yielded the subsurface geoelectrical parameters contained in Table1. The geoelectrical data was validated by correlating it with ground truthing using available bore hole lithology log close to VES 8 (Fig. 1). The longitudinal unit conductance for the overburden was computed. The result shows that the longitudinal unit conductance was generally less than one (1). This is an indication that, the overburden geomaterials path way is highly porous. Braga etal. (2006) in their work on resistivity method applied to aquifer protection studies stated that, when the longitudinal conductance of the overburden is less than one (1), the underlying aquifer is not protected. For locations where the values is one (1) and above, the aquifer is said to be adequately protected. In protected areas, the overburden has the potential to attenuate exodus mass, toxicity, volume or concentration of organic and inorganic contaminants to the vadose zone.

The geologic information from borehole was combined with the geoelectrical parameters to produce the geoelectrical section (Fig. 2). Based on the geoelectrical section and the values of the longitudinal conductance obtained for the study site, as well as the known problems with the deteriorating water quality, this work designate the study area as safeguards zone.

6.2 Results and Discussion

The results shows that, the longitudinal unit conductance computed varied from 0.001S around VES 14 to 0.03S around VES 2, and the longitudinal unit conductance was generally less than one (1). This is an indication that, the overburden (geomaterials) which constitute the contaminants' pathway is thin and highly porous. This overburden geomaterials are disproportionately distributed throughout the subsurface of the area studied. Braga etal., (2006) in their work on resistivity method applied to aquifer protection stated that, when longitudinal unit conductance of the overburden geomaterials is less than 1, the underlying aquifer is unprotected; but for locations where the values are one (1) and above, the aquifer is deemed to be adequately protected naturally. Foster & Gardufio (2004) corroborate that, in protected areas the overburden has the potential to attenuate exodus mass, toxicity, volume/concentration of organic and inorganic contaminants through the vadose zone.

The results of this study thus revealed that, aquifers in the study area are unconfined and its contained groundwater naturally unprotected due the prevailing thin and porous overburden condition. This makes its groundwater resources susceptible pollution by unsafe activities in the environment; especially around VES 12 – VES 14 within the overburden thins out, thereby increasing the risk to contamination. VES stations 6,7,12 and 14 are most vulnerable areas due to the excessively low longitudinal conductance obtained around these locations based on the interpreted model parameter, the values of the longitudinal conductance obtained for this site as well as the known problems of the deteriorating water quality in this area, this work designates the study area as safeguards zone.

7.0 Conclusion

The study revealed that, groundwater resources in the study area are unconfined and unprotected naturally due to the porous overburden. This makes groundwater resources susceptible to pollution by unsafe conditions in the environment. The porous overburden very low longitudinal unit conductance (less than 1) with is disproportionately distributed throughout the subsurface. The overburden thins out within VES 10, thereby increasing the risk to contamination. The entire study area was designated safeguard zone. Consequent upon this, the proportionate risk-based approach to protect groundwater resources in the study area from contamination are:

enforcement of good land use practices, controlling of high risk activities to address potential problem of groundwater resources pollution, drilling of monitoring well within VES10 and periodic investigation of the subsurface for the existence of groundwater quality threat.

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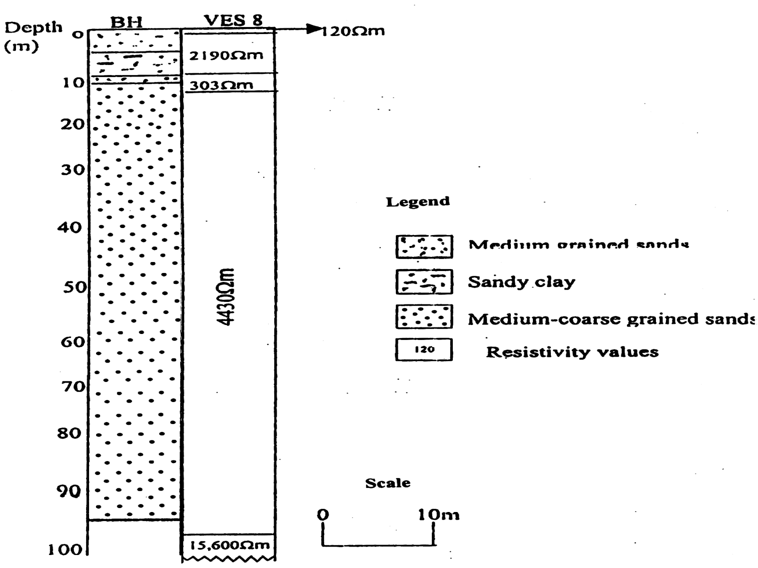

Fig. 1: Correlation of VES 8 with ground truthing using borehole lithology log 10m away

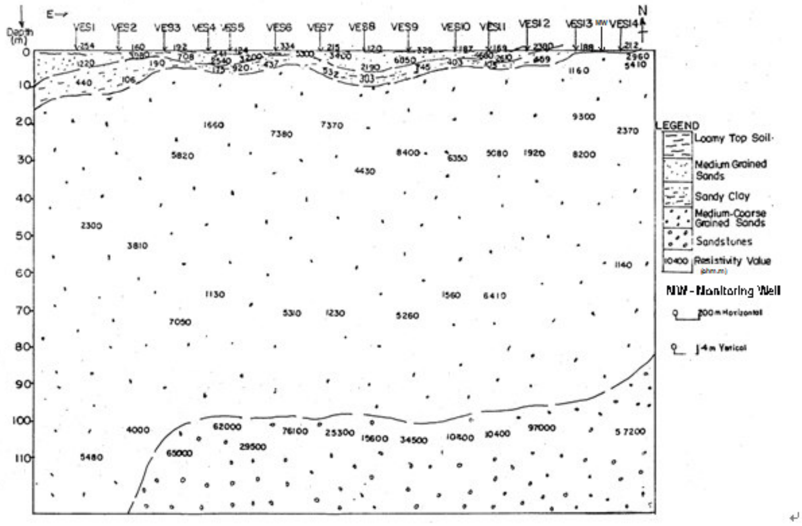

Fig.2: Geoelectrical section for the study area

Table 1: Subsurface layer parameters from geoelectrical survey of the study area

			Resistivity of layer (ohm. m)						Depth to bottom of layers (m)					Thickness of layers (m)					Longitudinal conductance of overburden (Siemens)			
Ves Station	Location	No of layer	P_1	P_2	P_3	P_4	P_5	P_6	D_1	D_2	D_3	D_4	D_5	h_1	h_2	h_3	h_4	h_5	S_1	S_2	S_3	$\sum S$
1	Atan Offot	5	254	1220	490	2300	5480	-	0.56	5.1	11.4	103.0	-	0.35	4.54	6.30	91.60	-	0.002	0.004	0.01	0.016
2.	Atan Offot	5	160	3980	106	3810	400	-	0.80	3.2	10.8	98.1	-	0.80	2.40	7.6	87.3	-	0.005	0.023	0.002	0.03
3.	Atan Offot	6	192	708	190	5820	7050	6500	0.45	1.3	2.9	39.2	102.0	0.45	0.85	1.60	36.30	62.8	0.002	0.001	0.008	0.011
4.	Atan Offot	6	341	2540	175	1660	1130	8200	0.44	3.9	5.6	14.6	98.0	0.44	3.46	1.7	3.6	56.4	0.001	0.001	0.001	0.012
5.	Obio Etoi	6	124	3200	920	1700	1610	29500	0.87	2.1	5.6	47.5	102.0	0.87	1.23	3.2	42.2	54.5	0.007	0.0003	0.003	0.010
6.	Obio Etoi	6	344	5300	437	7380	5310	76100	0.3	1.5	3.9	37.5	99.0	0.3	1.20	2.4	33.36	61.5	0.001	0.000	0.005	0.006
7	Obio Etoi	6	215	3400	532	737	1270	28300	0.46	1.6	3.7	36.5	99.4	0.46	1.14	2.10	32.8	6.30	0.000	0.000	0.005	0.004
8.	Obio Etoi	5	120	2190	303	4480	15600	-	0.52	8.9	14.6	98.5	-	0.52	8.38	5.70	83.9	-	0.004	0.004	0.019	0.027
9.	Obio Etoi	6	329	6850	745	8300	5260	34500	1.1	3.4	6.5	35.2	100.1	1.1	2.3	3.1	28.9	64.9	0.003	0.000	0.009	0.012
10.	Obio Etoi	6	187	4680	403	6350	1500	10,400	1.o	1.7	4.1	31.3	99.3	1.0	0.70	2.40	27.2	68.0	0.005	0.000	0.006	0.011
11.	Obio Etoi	6.	169	2610	105	5080	6410	10,400	0.76	2.6	2.6	4.4	29.9	97.0	0.76	1.84	1.8	15.9	67.1	0.001	0.017	0.022
12	Obio Etoi	5	2380	459	8200	1920	9700	-	048	3.2	16.8	96.1	-	0.48	2.72	12.6	79.3	-	0.000	0.006	0.002	0.008
13.	Obio Offot	5	188	1160	9300	8200	59800	-	0.38	9.9	25.1	95.1	-	0.38	9.52	15.2	90.0	-	0.002	0.008	0.002	0.012
14.	Obio Offot	6	212	2960	5410	2370	1140	57200	0.29	1.2	3.2	32.6	91.0	0.29	0.91	2.30	29.4	58.4	0.001	0.000	0.000	0.001