



## MODELING OF SPENT DRILLING FLUIDS ON OIL FIELDS IN NIGER DELTA

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### ABSTRACT

The environmental pollution hazards due to the use of drilling fluids in the oil and gas sector were studied. Grab samples of spent drilling fluids, water and soil were collected from 7 locations in the oil field when the depth of the well was 3658m, before the 3962m pay zone. Samples were analyzed to determine the concentrations of contaminants such as Barium (Ba), Cadmium (Cd), Chromium total (Cr), Copper (Cu), Iron III ( $Fe^{3+}$ ), Lead (Pb), Manganese (Mn), Vanadium (Vn) and Zinc (Zn) in the treated and untreated SDFs, water, soil, ash and sludge samples that might constitute environmental hazards, in accordance with the Department of Petroleum Resources and American Public Health Association's guidelines and methods. The concentrations and the spatial distributions of the pollutants released to the environment were established through modeling with Ogata-Banks model equation and the material balance equations. The results of the test showed that these substances have levels above the recommended limits in the environment. These contaminants which are deleterious, toxic and hazardous, have led to large-scale human health problems and environmental degradation in the sensitive wetlands of the Oil Fields in the Niger Delta.

**Keywords:** Ogata Banks, material balance, Oil field, Drilling Fluids, Heavy Metals, Modeling

### INTRODUCTION

The Exploration and Production (E&P) companies and their extractive activities are in three ecological areas in the Niger Delta Region; Land, Swamp and Offshore, each terrain having a different environmental sensitivity. Since 1956 when SPDC discovered the first commercial find, Well-1 located in OML-29 in Oloibiri, Bayelsa State (SIPM Report EP 5339/1/2/3) many Development, appraisals, and completion Wells have been drilled in Akwa Ibom, Bayelsa, Delta, Ondo and Rivers States, On-shore (45%), Swamp (21%) and Offshore (34%). All these discharge unavoidable spent drilling fluids (SDF) entrained with contaminants into the environment (Conner, 1990).

SDF is a by-product of DF generated during exploration and production activities from the oil fields in Bayelsa State and has been released into the sensitive wetlands of Niger Delta over 50years ago. It contains toxic, hazardous and some suspected carcinogens such as heavy metals notably

Barium (Ba), Cadmium (Cd), Chromium total (Cr), Copper (Cu) and Iron (Fe) which are non-biodegradable, while others cause soil leachate that are problematic to the ecosystem. For example, "SOLTEX" a drilling fluid additive has been identified and listed by Greenpeace (1995), as being toxic and hazardous. According to (Hu, 1998), these substances that show persistence in the environment can be detrimental to human health over time.

It is in the light of the facts stated above that the present study is important so as to unravel and document the potential hazards posed by exploration and production activities.

The main aim of this study is to determine the environmental pollution and hazards due to the disposal of spent drilling fluids and to determine the concentrations of contaminants such as; Barium (Ba), Cadmium(Cd), Chromium total (Cr), Copper (Cu), Iron III ( $Fe^{3+}$ ), Lead (Pb), Manganese (Mn), Vanadium (Vn) and Zinc (Zn) in the treated and untreated SDFs,

water, soil, ash and sludge samples that might constitute environmental hazards from the oil and gas sector in Nigeria (Zupan and Kapilla, 2000).

## MATERIALS AND METHODS

Table 1: Materials and Equipment Used for the Study

S/N	EQUIPMENT / INSTRUMENT	USAGE
1	Atomic Absorption Spectrophotometer (AAS), Unicam 100 Series	Determination of Heavy Metals analysis
2	COMPAQ 140 Computer Notebook	Recording, Data Management & Sample analysis
3	Heating Mantle	Digestion of samples for analysis
4	Weighing balance	Weighing of samples for analysis
5	Oven	Drying of samples for analysis
6	Water bath	Determination of total Hydrocarbon
7	Lamps	Determination of Heavy Metals
8	Scoop, Scissors	Miscellaneous function
9	Sample Field Cooler	Storage for Sample preservation
10	Polyethylene Plastic Sample Bottles	Sample collection for analysis
11	Makers / Masking Tapes, Labels	Sample Identification
12	Global Positioning System (GPS) device Garmin 12XL	Determination of location Coordinates
13	Personal Protective Equipment (PPE)-Safety Overall, Safety Boots, Safety Helmet, Disposable Hand gloves, Ear muff	Work Safety Protection Requirement
14	Auger	For Soil sampling

The materials and equipment listed in Table 1 were used for the study.

**Site Description:** The Oil Field drilling operation is located in Gbaran, Yenagoa, Bayelsa State about 80km away from Port-Harcourt with coordinates of Lat: N 04° 41.588' Long: E 007° 02.258' This is one of the major projects in the sensitive wetlands of the Niger Delta. The service contractor of the Commercial Waste Facility, Brandt Thermal Desorption Unit (TDU) site is located in Eyaa, Onne Industrial Free Zone about 29km from Port-Harcourt in Rivers State with coordinates of LAT: N 04° 43.989' LONG: E 007° 09.270' in the Niger Delta Region.

Figure 1 shows the site layout and the sampling points (SPs) at the Joint Venture Oil field in Bayelsa State which includes the Drilling Rig used for petroleum drilling consisting of Drilling Floor, Solid Control Area, Power Area, Pipe Rack and Pumps. Mobile Offices serve as temporary accommodation for the Rig Crew. There are holding pits lined with concrete used for temporal storage of the Spent Drilling Fluids and Cuttings before haulage for waste

management. Also at the site is the Service Contractors equipment for haulage (heavy trucks, skips and trackhoe loaders) to waste management site in Onne, Rivers State. The Drilling Rig Platform has also some heavy equipment such as power generating equipment, mud circulation system, shale shakers, as well as security personnel around the drilling rig of a conventional Drilling Rig Platform.

**Sample collection and analysis:** The field data sample collection, grab sampling and methods of laboratory analyses for the study were carried out in accordance with standard methods (APHA, 1995) and Department of Petroleum Resources regulations (DRR, 2000). The parameters analyzed are heavy metals Barium (Ba), Cadmium (Cd), Chromium (Cr), Copper (Cu) Iron III (Fe<sup>3+</sup>) and Lead (Pb) . These parameters were selected because of the global recommendation for monitoring them by the Helsinki and Paris Commissions and also because they exhibit hazardous, toxicity; while some of them are suspected or known carcinogens. They have negative impacts on the environment according to EU (1998) and

WHO (2003). Table 2 highlights the sample collection sites and the parameters analyzed Heavy metals in the samples were measured by means of Atomic Absorption

Spectrophotometer (AAS) – Unicam 100 Series. The instrument was calibrated for

**Table 2: Samples, Parameters and Sample collection site**

S/No	Sample description	Type of analysis	Sample location
1	Drilling Oil Based Fluid	Heavy metals	Drilling Rig Platform (DRPFRM) from the Mud Circulating System
2	Spent Drill Cuttings	Heavy metals	Drilling Rig Platform from the Shale Shaker separation processes
3	Spent Oil Based Mud	Heavy metals	Concrete lined Holding Pits beside the Drilling Rig Platform
4	Feed Stock SDF	Heavy metals	TDU Onne Site, from the Holding Pit lined with high density polythene material
5	Produced Ash from TDU treatment plant	Heavy metals	TDU Onne Site, from the Discharge Ash Pit
6	Produced Sludge Sample from TDU treatment plant	Heavy metals	TDU Onne Site, from the Deposition point
7	Receiving Waters Sample	Heavy metals	Receiving water from the NNPC JV Oil Field vicinity of the Drilling Rig
8	Soil Sample	Heavy metals	TDU Onne Site process deposition site
9	Produced Water sample from TDU treatment after absorbent separation	Heavy metals	TDU Onne Site process at the point of absorbent separation between oily sludge and water

every batch run of 100 samples and zeroed it in every run of 10 samples thus standardizing it for various standardized metals with specific lamps which are placed in a curvette and measured. The various absorbance were read off spectrophotometrically.

(a) Ogata-Banks Model Equation for Solute transport in the Soil (Vertical-axis)

Simulation of the Soil in the Vertical -axis using Ogata-Banks model equation:

The study uses the Ogata-Banks model equation (11), for solute transport was employed in this research work for the simulation of contaminant transport at the Thermal Desorption Unit Plant dumping site because it simple and less complex to manipulate. The average contaminant concentration was observed at the contaminated surface at the sludge dumping site. This technique is used to predict and investigate the solute transport and spatial trend of pollutants (Ba, Cd, Cr, Cu, Fe, Mn, Pb, Vn, PAHs, PCBs, NO<sub>3</sub>, SO<sub>4</sub>, PO<sub>4</sub>) impact of the soil as they pollute the subsurface water vertical-axis represented by x-distance and horizontal-axis represented by y-distance in the model equation below. The Linear Algebraic Model formula has the form of eqn. 1:

$$c(x, T) = \frac{c_0}{2} \left[ e^{\left\{x \left(\frac{y-a}{\sqrt{2D}}\right)\right\} \text{Erfc}\left\{\left(\frac{x-at}{2\sqrt{Dt}}\right)\right\}} + e^{\left\{x \left(\frac{x+a}{\sqrt{2D}}\right)\right\} \text{Erfc}\left\{\left(\frac{x+at}{2\sqrt{Dt}}\right)\right\}} \right] \quad (1)$$

where,

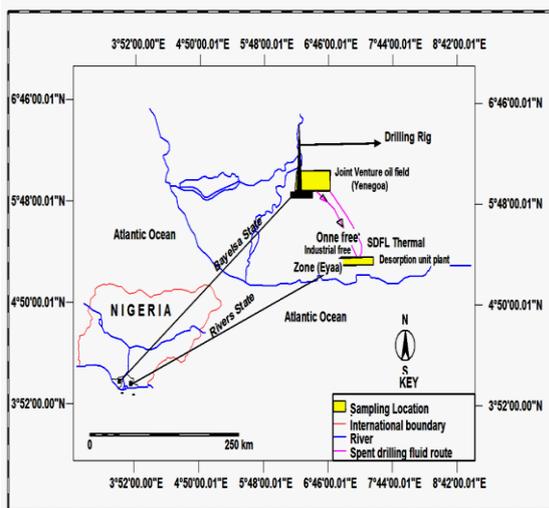


Figure 1: Cradle-to-grave of spent drilling fluid in the E&P oil field

Data Analysis were according to Ogata-Banks Model equation, and Material Balance Model Equation.

$A = (U^2 + 4D_x K_t)^{1/2}$ ,  $C_o$  = Concentration of Pollutant at the point of discharge,  $X$  = Distance from point of pollution application,  $U_x$  = Velocity of Solute transport, Erf C = Complementary error function,  $D_x$  = Dispersion coefficient,  $T$  = Time of flow,  $K_t$  = Decay constant and  $C(X, T)$  = Represents the equation with respect to distance and time. In most cases, the last term is usually neglected because ErfC is near zero when  $\sqrt{D_x}$  is large.

Ogata-Banks (1961) stated that omission of the second term results in a maximum error of 3 percent for the values of  $D/U_x$  less than 0.002.

Since solute is conservative (no decay),  $k=0$ , then  $a = \sqrt{u^2}$ ,  $a = u = v$ . Substituting in the equation above reduces to

$$C(x, t) = \frac{C_o}{2} \left[ \text{Erfc} \left\{ \left( \frac{x-at}{2\sqrt{Dt}} \right) \right\} \right] \quad (2)$$

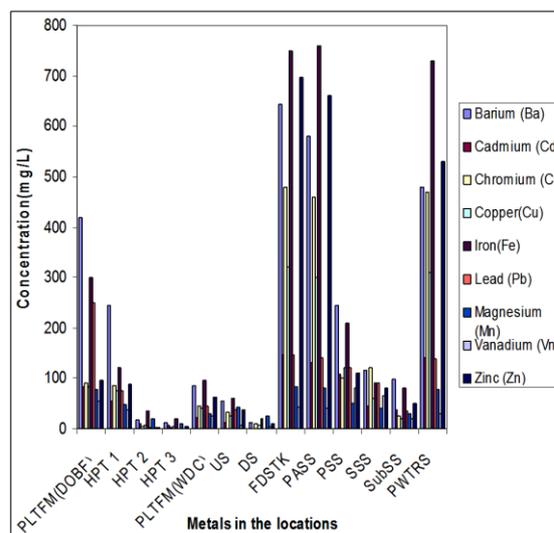
The Input Data for the Modeling processes are analyzed sample parameters from surface and subsurface (0.9m depth) of soil from the sludge dumping site.

(b) Material Balance Method: The material balance model flow for Brandt Thermal Desorption Unit (TDU) plant, one of the thermal treatment technologies at Onne Industrial free zone, Rivers State, assists to show the non-oxidizing process used to vaporize volatile and non-volatile wastes by heat application (700 - 800°F) thereby removing light hydrocarbons, aromatics, and other volatile organics, heavier Poly Aromatic Hydrocarbons are less easily removed. As a result, the process produces various secondary wastes stream, inert solids; oil base and water condensates which require further treatment. This reduction of the waste volume may lead to secondary environmental problem because the toxic components can still be a threat to the environment.

## RESULTS AND DISCUSSION

**Heavy metals in the spent drilling fluids (SDFs) and water samples:** From the Oil Field, it was detected and observed that Barium (420.18mg/kg) had the highest concentration in the DOBF/PLTFRM sample and RWTRS-DS sample (12.38mg/kg) the lowest. The RWTRS-US sample had 56.32mg/kg of Barium.

Figure 2 shows the concentrations of metals in the samples. Barium, Chromium, Copper, Iron III, Lead and Zinc were prominent in the samples from the Oil Field and Thermal Desorption Unit (TDU). From the TDU process, the highest concentration Barium (642.32mg/kg) was detected in the TDU/FDSTK sample, TDU/SubSS sample (97.48mg/kg) the lowest. The highest concentration of Cadmium (82.35mg/kg) was detected in the DOBF/PLTFRM sample while OBF/HPT 3 sample (8.41mg/kg) the lowest. The RWTRS-US sample had 12.38mg/kg of Cadmium. From the TDU process, TDU/FDSTK sample (146.78mg/kg) had the highest concentration of Cadmium; TDU/PWTRS sample (142.16mg/kg) the lowest.



**Figure 2:** Concentrations of Heavy Metals at Different Sites

Also shown in Figure 2, Chromium was detected in the samples, DOBF/PLTFRM sample (90.45mg/kg) recorded the highest concentration; SOBF/HPT 3 sample (2.38mg/kg) lowest. Also from the TDU

processes, TDU/FDSTK sample (480.52mg/kg) had the highest concentration, and TDU/PASS sample (460.15mg/kg) the lowest. For Copper concentration from the Oil field, DOBF/PLTFRM sample (82.4mg/kg) had the highest; SOBF/HPT 3 sample (5.28mg/L) lowest. From the TDU process, TDU/FDSTK sample (480.52mg/kg) as the highest; the lowest was TDU/SubSS sample (20.15mg/kg).

Also from Figure 2, DOBF/PLTFRM sample (300.16mg/kg) recorded the highest Iron III; the lowest from SOBF/HPT 3 sample (20.28mg/kg). RWTRS-DS sample had 20.18mg/kg. From the TDU process, the TDU/PASS sample had (760.52mg/kg) as the highest concentration, and TDU/SubSS sample (80.62mg/kg) the lowest. The WHO maximum permissible concentration for Iron is <0.30 mg/L, USEPA recommendation is 0.3 mg/L.

Lead was detected and identified in the samples. DOBF/PLTFRM sample (250.18mg/kg) had highest concentration; the lowest from SOBF/HPT 3 sample (0.95mg/kg). Others were RWTRS-DS sample (1.02mg/kg), RWTRS-US sample (38.9mg/kg). From the TDU process, the TDU/FDSTK sample (145.82mg/kg) had the highest concentration; and TDU/PWTRS sample (139.26mg/kg) lowest. However, WHO maximum concentration permissible levels recommendation for Lead is <0.05 mg/L, USEPA recommendation is mg/L. The WHO (1995) stated a legal limit of 50 ppb for Lead, which is decreased to 10 ppb by 2010.

Manganese was detected and identified. DOBF/PLTFRM sample (78.91mg/kg) the highest concentration, the lowest concentration from SOBF/HPT 3 sample (10.3mg/kg). RWTRS-US had 42.38mg/kg. Noted from the TDU process, the TDU/FDSTK sample (84.16mg/L) recorded the highest; TDU/PWTRS sample (30.44mg/kg) as the lowest. The WHO (2000) maximum concentration permissible

levels recommendation for Manganese is <0.05 mg/L.

Vanadium was also detected and identified. DOBF/PLTFRM sample (56.32mg/kg) had highest concentration detected; SOBF/HPT 3 sample (0.16mg/kg) lowest. RWTRS-US sample (6.72mg/kg) also noted. From the TDU process, TDU/PSS sample (80.3mg/L) the highest concentration, TDU/SubSS sample (20.75mg/L) the lowest. However, WHO (2000) maximum concentration permissible levels recommendation for Vanadium is <0.05 mg/L.

The results further revealed that the highest concentration of Zinc was detected from DOBF/PLTFRM sample (95.21mg/kg); SOBF/HPT 2 sample (3.56mg/kg) as the lowest and RWTRS-US sample (38.4mg/kg). From the TDU process, from TDU/FDSTK sample (695.38mg/kg) had the highest concentration; TDU/PWTRS sample (530.16mg/kg) the lowest. The maximum concentration permissible levels recommendation for Zinc is <5 mg/L (WHO, 2003).

### **Heavy Metals in the Secondary Wastes Stream Samples:**

In the secondary wastes stream samples from the TDU process, notable heavy metals were detected and identified in high concentrations. They were Barium (642.32mg/kg), Cadmium (146.78mg/kg), Chromium (480.52mg/kg), Copper (320.18mg/kg), Iron III (750.45mg/kg), Lead (145.82mg/kg), Manganese (84.16mg/kg), Vanadium (42.38mg/kg) and Zinc (695.38mg/kg). The iron III, Zinc and Barium were the highest concentrations of metals noted as contaminants.

In the ash samples, Zinc (660.38mg/kg) was noted as the highest concentration, while Manganese (81.2mg/kg) the lowest. Others were Barium (580.16mg/kg), Cadmium (132.45mg/kg), Chromium (460.15mg/kg), Copper (300.64mg/kg), Iron III (760.52mg/kg), Lead (141.31mg/kg), Vanadium (39.45mg/kg). The iron III, Zinc

and Barium were the highest concentrations of selected metals as contaminants in the ash sample (12).

In the sludge sample from the TDU process, high concentrations of heavy metals were detected especially in Barium (245.28mg/kg) recorded as the highest concentration; Manganese (50.45mg/kg) as the lowest. Others were Iron (210.30mg/kg), Copper (120.60mg/kg), Lead (120.40mg/kg), Zinc (110.60mg/kg), Cadmium (108.40mg/kg), and Chromium (100.88mg/kg).

**Heavy metals in soil samples:** At the top surface soil samples, the research study detected and identified high concentration of metals. Chromium (120.50mg/kg) was noted as the highest in concentration, while Manganese (40.26mg/kg) the lowest. Others were Barium (115.20mg/kg), Cadmium (45.50mg/kg), Copper (60.50mg/kg), Iron (90.50mg/kg), Lead (90.46mg/kg), Manganese (40.26mg/kg), Vanadium (80.30mg/kg) and Zinc 110.60mg/kg as pollutants. And from the Subsurface soil samples, Barium (97.48mg/L) was detected the highest in concentration and Copper (20.15mg/L) the lowest. Others were Cadmium (38.60mg/L), Chromium (25.62mg/L), Iron (80.62mg/L), Lead (35.80mg/L), Manganese (30.44mg/L), Vanadium (20.75mg/L) and Zinc (50.50mg/L).

### Heavy metals in Feedstock compared with HPT 1,2,3, Downstream and Upstream

**samples:** The data for the comparison between the feedstock (FDSTK) sample and the holding pits (HPT) 1,2,3, upstream (US) and downstream (DS). All the heavy metals detected in the feedstock (FDSTK) were found higher in concentrations than those found in the HPTs 1,2,3, US and DS samples. FDSTK sample has Barium (642.32mg/L), HPT1 has 245.28mg/L of barium, HPT2 has 245.28mg/L, HPT3 has 12.32mg/L. FDSTK has Iron (750.45mg/L), HPT1 has 120.13mg/L, HPT2 has

34.28mg/L, HPT3 has 20.28mg/L, US sample has 60.32mg/L and DS sample with 20.18mg/L. Chromium (480.52mg/L) was detected in the FDSTK while in the HPT1 (86.41mg/L), HPT2 (5.41mg/L), HPT3 (2.38mg/L), US (12.45mg/L) and DS (10.42mg/L).

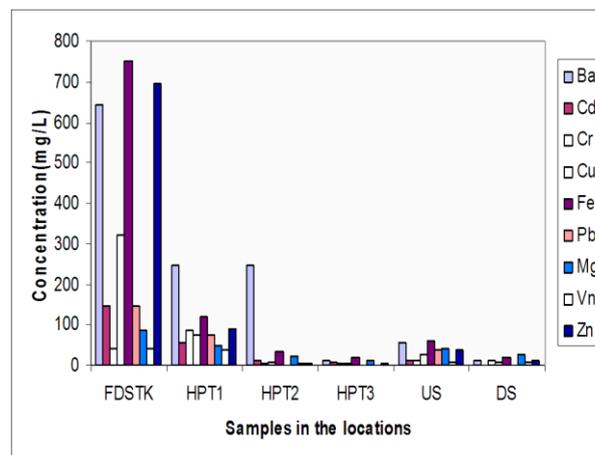


Figure 3: Feedstock compared with samples

Copper (320.18mg/L) were also found highest in concentration in the FDSTK than those in the HPTs 1(75.42mg/L), HPT2 (6.58mg/L), HPT3 (5.28mg/L), US(25.8mg/L) and DS (8.56mg/L) samples respectively. Same trend were applicable in other pollutants.

### Simulation of Solute transport into the Soil (Vertical x-axis):

A typical presentation of the results of the simulation processes of solute transport into the soil are shown in Figure 4 – 6 for Barium, Vanadium and Zinc. The results observed a progressive decrease in solute concentration with different pre-determined depths-20m, 40m...200m within a given period.

### Solutes Transport Velocity and Dispersion Coefficient:

The average solutes concentration was observed at the surface. Since Solutes were not decomposable, the rate constant (decay) were taken as zero. Determinations of Velocity and Dispersion Coefficient for Solutes were carried out indirectly. The

following results were obtained from the field.

Barium (Ba) Solute transport:

At the depth of 0.9m, it was observed that the Barium concentration was 95.85mg/kg on day 7 and 80.25 on day 21. Thus, with an initial concentration of 229.47mg/kg, the Velocity and Dispersion Coefficient may be determined as follows;

$$95.85_{(0.9m, 1week)} = \frac{227.49}{2} Erfc \left( \frac{0.9-v}{2\sqrt{D}} \right) \quad (3)$$

$$80.25_{(0.9m, 3weeks)} = \frac{227.49}{2} Erfc \left( \frac{0.9-v}{2\sqrt{3D}} \right) \quad (4)$$

$$0.8354 = Erfc \left( \frac{0.9-v}{2\sqrt{D}} \right) \quad (5)$$

$$0.6994 = Erfc \left( \frac{0.9-v}{2\sqrt{3D}} \right) \quad (6)$$

From Erf C Table (Ogata and Banks, 1961), the following were determined;

$$0.15 = \frac{0.9-v}{2\sqrt{D}} \quad (7)$$

$$0.275 = \frac{0.9-v}{2\sqrt{3D}} \quad (8)$$

Dividing Eqn 7 by Eqn 8

$$\frac{0.15}{0.275} = \left( \frac{0.9-v}{2\sqrt{D}} \right) \times \left( \frac{2\sqrt{3D}}{0.9-3v} \right) \quad (9)$$

Velocity = 11m/week or 1.59m/day or 0.066m/hr or 0.0011m/min ( $1.1 \times 10^{-3}$  m/min) is taken as the velocity of transport of the Barium solute pollutant. The Dispersion Coefficient thus may be determined from equation 4.5 by substituting for v = 11m/week

$$0.15 = \frac{0.9-11}{2\sqrt{D}} \quad (10)$$

D = 1133m<sup>2</sup>/week or 162m<sup>2</sup>/day or 6.75m<sup>2</sup>/hr or 0.11m<sup>2</sup>/min. Thus since Velocity of transport of Barium solute = 11.0m/week and Dispersion Coefficient = 1133m<sup>2</sup>/week, concentration of Barium for different depths can be determined, as follows for Depths between 0-200m for 1week – 4weeks using Excel. Similar determinations were made for other Solutes.

**Barium Solute transport for Vertical Movement:** The study presented the simulation of Barium solute transport for vertical movement at different depths in soil with initial concentration of 229.47mg/kg. In Week 1, it was observed that the Barium solute concentrations decreased progressively at different depths in soil 20m, 40m....200m with corresponding decrease in concentrations of 35.16mg/kg,

3.77mg/kg which finally decreased to zero concentration. Similar observations and trend were the same for Week 2 to Week 4.

Figure 4 depicted that there was a progressive increase of the Barium solute transport with corresponding different depths as the time of infringement increases from Week 1 to Week 4. In Weeks 1, 2, 3 and 4 at 20m depth.

The corresponding Barium solute transports were 35.16mg/kg, 58.38mg/kg, 71.73mg/kg and 80.87mg/kg. There were similar increases in concentrations at other depths. Also noted, at different periods there was also sharp decline in Barium concentrations 0.13mg/kg in Week 1, 0.29mg/kg in Week 2, 0.26mg/kg in Week 3, and 0.18mg/kg in Week 4 at the depths of 60m, 80m, 100m and 120m.

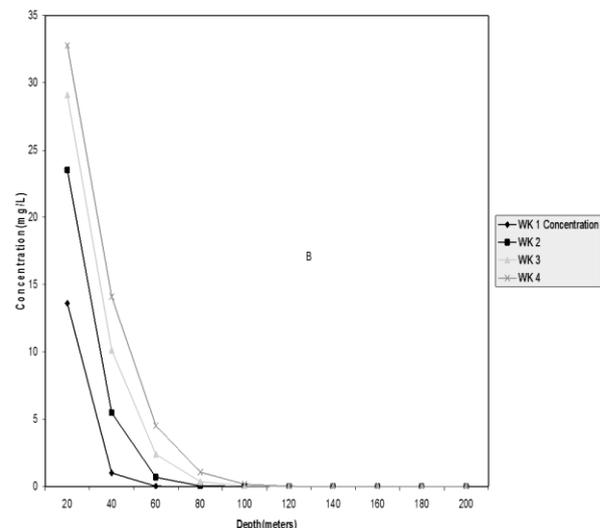


Figure 4: Concentration of Barium at Different Depths in Soil

**Cadmium Solute Ttransport for Vertical Movement:**

The study presented the simulation of Cadmium solute transport for vertical movement at different depths in soil with initial concentration of 101.4mg/kg. In Week 1, it was noted that there was a decrease in Cd solute concentration at different depths in soil 20m, 40m....200m with corresponding concentrations of 1.66mg/kg, 0.0005mg/kg decreasing to zero concentration. Week 2 to Week 4 showed similar trend.

In Weeks 1, 2, 3, and 4, at 20m depth, the corresponding Cd solute transports are 1.66mg/kg, 8.23mg/kg, 15.07mg/kg and

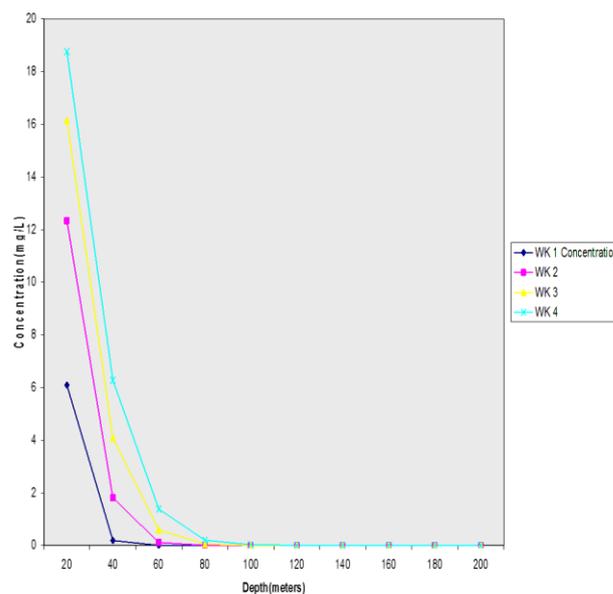
20.88mg/kg. Also noted in Week 1 to Week 4, there was a sharp decline in Cd solute concentration 0.0005mg/kg at 40m in Week 1, 0.0002mg/kg at 40m in Week 2, 0.011mg/kg at 60m in Week 3, 0.001mg/kg at 80m in Week 4.

**Chromium Solute transport for Vertical Movement:** The study presented the simulation of Chromium solute transport for vertical movement at different depths in soil with initial concentration of 91.98mg/kg. In Weeks 1, 2, 3, and 4, at 20m depth, the corresponding Cr solute transports were 0.85mg/kg, 4.96mg/kg, 9.45mg/kg and 13.42mg/kg. Also noted in Week 1 to Week 4 was a sharp decline in Cr solute concentration 1.61E-06mg/kg at 40m in Week 1, 0.04mg/kg at 40m in Week 2, 0.002mg/kg at 60m in Week 3, 0.0001mg/kg at 80m in Week 4 (Iselema, 2011).

**Lead Solute transport for Vertical Movement:** The simulation of Lead solute transport for vertical movement at different depths in the soil with initial concentration of 113.71mg/kg was undertaken. In Weeks 1, 2, 3, 4 at 20m depth, the corresponding Pb solute transport are 11.33mg/kg, 21.34mg/kg, 21.34mg/kg, 27.27mg/kg, and 31.28mg/kg. Also noteworthy is that in Week 1, 2, 3, 4 there was a sharp decline in Pb solute transport, 0.01mg/kg at 60m in Week 1, 0.01mg/kg at 80m in Week 2, 0.16mg/kg at 80m in Week3, 0.07mg/kg at 100m in Week 4.

**Manganese Solute transport for Vertical Movement:** The study presented the simulation of Manganese solute transport for vertical movement at different depths in soil with initial concentration of 44.8mg/kg (see appendix P7). In Week 1, 2, 3, and Week 4 at 20m depth, the corresponding solute transports were 4.91mg/kg, 8.82mg/kg, 11.07mg/kg, and 12.57mg/kg. Also observed was that in Weeks 1, 2, 3, 4 noticed a sharp decline in solute transport 0.004mg/kg at 60m in Week 1, 0.01mg/kg at 80m in Week2, 0.1mg/kg at 80m in Week 3, 0.05mg/kg at 100m in Week 4.

**Vanadium Solute transport for Vertical Movement:** The study showed the simulation of Vanadium solute transport for vertical movement at different depths in soil with initial concentration of 75.04mg/kg (Figure 5). In Week 1, it was noted that there was a decrease of Vanadium solute concentration with different depths in soil 20, 40m...200m with corresponding concentrations of 6.08mg/kg, 0.18mg/kg, 0.0001mg/kg which finally decreased to zero concentration.



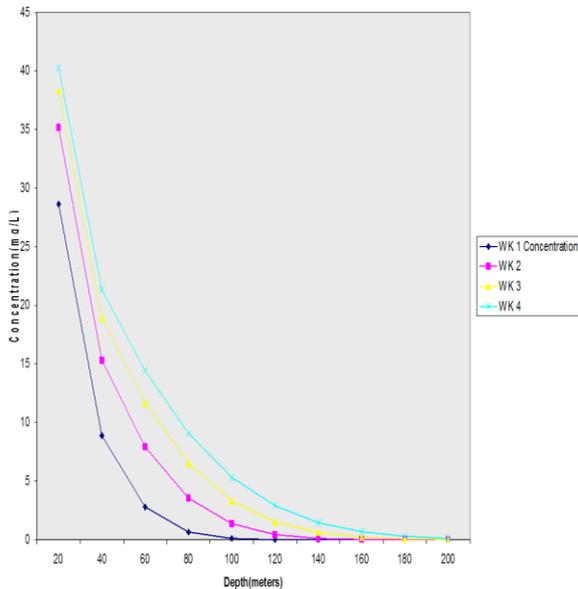
**Figure 5:** Concentration of Vanadium at Different Depths in Soil

In terms of vertical movements, for weeks 1, 2, 3, 4 at 20m depth, the corresponding solute transports were 6.08mg/kg, 12.33mg/kg, 16.15mg/kg, and 18.76mg/kg. Also observed was that in Weeks 1, 2, 3, 4, there was a sharp decline in solute concentration 0.0001mg/kg at 60m in Week 1, 0.003mg/kg at 80m in Week 2, 0.05mg/kg at 80m in Week 3, 0.02mg/kg at 100m in Week 4.

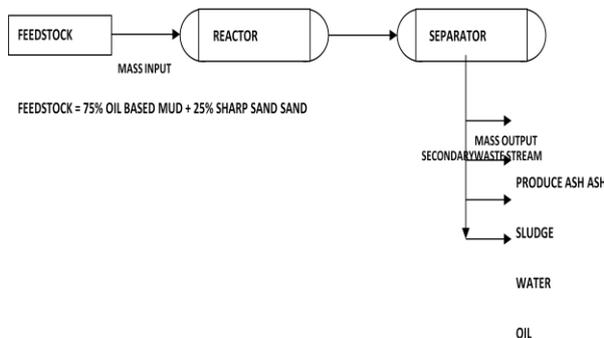
**Zinc Solute transport for Vertical Movement:** Zinc solute transport for vertical movement with had an initial concentration of 102.54mg/kg at different depths in soil (Figure 6). In weeks 1, 2, 3, 4 at 20m depth, the corresponding Zn solute transport were 28.65mg/kg, 35.19mg/kg, 38.32mg/kg, and 40.28mg/kg.

**Material Balance Model Equations for TDU Plant Processes**

Figure 5 shows the material balance model flow diagram for Brandt Thermal Desorption Unit (TDU) plant, one of the thermal treatment technologies at Onne Industrial free zone, Rivers State.



**Figure 6:** Concentration of Zinc at Different Depths in Soil



**Figure 7:** Material Balance Flow Chart for Thermal Desorption Unit Plant, Onne Rivers State

The MBME for the TDU Plant without a chemical reaction is governed by the following;

$$\text{Mass}_{(\text{input})} = \text{Mass}_{(\text{output})} \quad (11)$$

$$Y = M_1X_1 + M_2X_2 + M_3X_3 + C \quad (12)$$

Feedstock = Produced Ash + Produced Sludge + Produced Water.

The above equation was mathematically solved using LINEST function in Excel

For Barium Contaminant in the samples, the MBME is

$$Y = 0.5401X_1 + 2.6133X_2 - 0.3723X_3 - 42 \quad (13)$$

Feedstock =

$$0.5401\text{Ash} + 2.6133\text{Sludge} - 0.3723\text{Water} - 42 \quad (14)$$

The above showed a typical result of a Barium contaminant in the samples indicating that the Y are almost the same as the  $Y_{\text{est}}$ . The standard error of estimate 0.00054 depicted that there was a total correlation between the variables, the Feedstock and the produced Secondary Wastes Stream (Produced Ash, Sludge, Water) into the environment.

**CONCLUSION**

The studies found out the presence of high concentration levels of contaminants in the spent drilling fluids (SDFs), water, sludge, soil (surface and subsurface) and ash samples. These contain pollutants of primary concern capable of causing variety of adverse effects to human and the environment. The pollutants were heavy metals; Barium (Ba), Cadmium (Cd), Chromium total (Cr), Copper (Cu), Iron III ( $\text{Fe}^{3+}$ ), Lead (Pb), Manganese (Mn), Vanadium (Vn), and Zinc (Zn). High concentration levels of Barium, Chromium, Copper, Iron, Lead, Manganese and Zinc were found in the SDFs, water, Soil and the secondary waste streams samples. Though some of these metals are needed in small quantities by plants and animals but they are also hazardous in excess having exceeded the permissible threshold recommended by WHO standards. These contaminants were basically found in the drilling fluids/mud used for drilling oil and gas and detected during drilling activities at the JV Oil Field and also during the treatment of SDF at the TDU plant. They were found to contain myriads of contaminants which are toxic, hazardous; some are known to be carcinogenic, aesthetically insidious offensive (Bradl, 2004). These pollutants depending on their properties are sorbed into the soil. Also leaching into the porous and permeable soil then to groundwater was likely especially during the excessive

rainfall in the region. The concern is primarily from human health and ecosystem effects. The secondary reason is from contamination of water supplies. Their high presence and release to the environment where drilling operations take place are greatly due to human activities, their uses as chemical additives to the formulation of drilling fluids processes and also from the secondary wastes from the TDU processes. More importantly, the study had confirmed and established that chemicals of primary concern of the pollutants exceeded the threshold permissible level by World Health Organization, USEPA, and European Union Standards. These observed deleterious scenario will exhibit infringement, pose enormous and potential environmental pollution and degradation in the sensitive wetlands of Oil Field and the TDU sites in the Niger Delta.

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