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# Oil facility operations: a multivariate analyses of water pollution parameters

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## Abstract

This paper provides some new insights into the variability and severity of petroleum hydrocarbon contaminants from the first ever environmental audit of Nigeria's downstream oil facilities commissioned by the National Council on Privatization and the Bureau of Public Enterprises. Petroleum facility operation is the backbone of energy supply all over the world but this process is not without potentially avoidable water pollution incidents. Meanwhile, past studies tend to ignore patterns of pollution parameters at the national scale and are often limited in scope and coverage. To address this research gap, Principal Component Analysis and Kruskal-Wallis test were applied for evaluation of the variability in 'national' pollution data to tease-out novel patterns that best discriminate between groups of pipeline facility network across Nigeria's downstream sector. The key results are (a) a mix of strong and weak statistically significant ($p$-value < 0.001) and positive correlation between pollutants across three pipeline regions; (b) the main eigenvector statistically explains 71.5% of the variance found in the 'national' pollution parameters; (c) the hierarchical cluster analyses show incoherent pattern from the group data and a rather weak association which suggest that the type of oil facility systems in operation or their products have no effect on the severity of hydrocarbon pollution parameters found in water samples across the three regions. The possible implication of these results is the potential application of a uniform approach in responding to subsequent petroleum contamination depending on site specific hazards posed by toxicity level, temporal nature of detected chemicals and human exposure. Future study should consider the use of carbon stable isotope ratios to assess variances in hydrocarbon contamination in water bodies, and tailor this for cost-effective national response given the aforementioned caveats. This can guarantee a more sustainable downstream operations and enhance response to water pollution incidents.

**Keywords**: oil facility operation, water pollution, petroleum hydrocarbons, Principal Component Analysis (PCA), Kruskal-Wallis test; Nigeria.

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## 1. Introduction

### 1.1 Importance of the Problem

The demand and supply of crude oil and natural gas are a function of exploration, production, processing, liquefaction, transportation, gasification / regasification and venting facility operations. This has been demonstrated by some authors including Jeong et al. (2014) in California's emissions inventory of $CH_4$; Anifowose and Odubela (2015) in the study of pipeline systems in Nigeria; and Ahmad et al. (2017) in the study of sustainable supply chain management. Oil industry facility operations are a focus of recent calls for sustainable practices (George et al. 2016). Each stage of these operations has a propensity to impact ecosystems in a similar or unique manner (Brittingham et al. 2014), specific to impact quality review (Anifowose et al. 2016) and water resource is most often affected (Xiang et al. 2016). Arguably, the environmental impacts and risks of these activities are poorly understood (Akob et al. 2016). Nevertheless, the environmental impacts of both onshore and offshore oil and gas facility operations have received significant international attention dating back to the 1950s. Even in recent times, the advancement in technology and expansion into more difficult terrains have escalated potential impacts such as increased volume of oil and gas wastewater discharge in the U.S., for example (Harkness et al. 2015).

In Australia, an environmental impact study of the 2009 Montara oil blowout found low concentrations of hydrocarbon in the sampled sediments – suggesting that the concentrations were orders of magnitude lower than expected for biological impacts to occur (Burns and Jones 2016). Also, there are significant environmental issues relating to unconventional hydrocarbon exploitation (e.g. coal-bed methane) just like conventional petrochemical activities (Maretto et al. 2014), with impacts on groundwater and surface water systems such as high levels of water consumption (Li et al. 2016) and water quality issues (Dahm et al. 2014).

Despite the innovative coupling of Enhanced Oil Recovery and sequestration as a cost-effective and environmentally safe approach (Su et al. 2013), freshwater scarcity and unequal access to water remain significant challenges for sustainable energy production in China (Cai et al. 2014). In fact, oil and gas production and other energy-related facility operations are projected to yield an estimated 77% rise in water withdrawal by 2030 (Cai et al. 2014). Also, the removal of oil compounds released into the environment as oilfield wastewater poses a challenge for remediation and is mainly influenced by temperature e.g. in North China (Wang et al. 2015). Apart from water-based pollutants, gaseous releases into the atmosphere from oil and gas operations are not uncommon globally (Jeong et al. 2014). Generally, petroleum facilities pose significant problems to freshwater resources and ecosystem services (Kelly et al. 2010) particularly in developing nations like Nigeria (UNEP 2011).

In Nigeria – the focus of this paper, less globally widespread but not unusual cases of deliberate oil facility interdiction (Anifowose et al. 2012) and infrastructure-related incidents often lead to the pollution of freshwater resources. Yet, existing toxicological data can not sufficiently estimate the impacts of spilled oil on aquatic communities (Bejarano and Barron 2014). This is a severe problem for Nigeria and other similar nations as there are many poor households without treated piped water thereby leading to greater inequality and lack of access to safe drinking water (Yang et al. 2013).

### *1.2 Research Gap*

There have been many studies focusing on water pollution incidents from oil and gas facilities in Nigeria and other oil producing nations (section 1.1) but these are often limited in scope and coverage. For example, Agbalagba et al. (2013) evaluated the concentrations of Naturally Occurring Radioactive Materials (NORM) substances such as $^{226}$Ra, $^{228}$Ra and $^{40}$K in drinking water samples from three oil and gas producing communities, and found that concentrations are well above the WHO permissible limits. In a 96-hour lab bioassay conducted on brackish water shrimps, Amaeze et al. (2015) assessed the toxicity of de-oiling effluents from a decommissioned oil pipeline facility in the Niger Delta while Asagbra et al. (2015) found polycyclic aromatic hydrocarbons (PAHs) in water, sediment and tissue of tilapia fish in the Warri River at Ubeji. Interestingly, surface and groundwater pollution from oil pipelines and other facilities including leaks from aging, dilapidated and abandoned infrastructure; and those from transport and localised refining of stolen oil in Ogoniland was the focus of Linden and Palsson (2013). From the Calabar municipality, Nganje et al. (2012) analysed PAHs concentration in water and soil samples from a tank farm distribution facility. The study by Nriagu et al. (2016) suggests that people’s risk perception in five local government areas of Akwa Ibom is influenced by oil and gas facility hazards e.g. fears of pipeline explosions and fire; visible gas flares and smoke stacks; and chemosensory cues like off-flavour in drinking water. Obinaju et al. (2015) investigated PAHs pollution around open gas flare site and petroleum exploration facility in the Ovia River axis of Edo state. Despite these and many other publications, there has been no study assessing whether groups of water pollution incidents differ on a national scale and why, based on a combination of variables from downstream oil facilities. The Pipelines and Products

Marketing Company (PPMC) oversees downstream activities such as acquisition, storage, transportation and distribution of petroleum products and has operated refined and crude oil pipeline network and related facilities since 1988 on behalf of the Federal Government of Nigeria (NCP/BPE 2008). Like other oil and gas facilities, the PPMC infrastructures have been a target of interdiction and source of significant environmental impacts (Aroh et al. 2010) including fatalities and burns (Jasper 2009).

Therefore, this study aims to evaluate water pollution incidents associated with downstream oil facility operation by assessing their regional variation along a combination of variables for optimum mitigation. To achieve this aim, the set objectives are to:

a. Collate hydrocarbon pollution data (i.e. TPH, TAH, PAH and BTEX) from the National Council on Privatization (NCP)/ Bureau of Public Enterprises (BPE) archived water samples across selected downstream oil facilities;
b. Analyse the variation in these data across different regions and tease out novel patterns that best discriminate between the groups of pollution data; and,
c. Evaluate the study outputs from a. and b. above and recommend efficient management approach that may be applicable in similar conditions elsewhere.

## 2. Materials and Methods

### *2.1 The Study Area*

Nigeria's PPMC manages and operates downstream oil facilities comprising of > 5,000 kilometres of integrated network of refined products (~4,300 km) and crude oil (~700 km) pipeline systems and the associated Right of Way in Nigeria (NCP/BPE 2008). Other supporting facilities include 22 product storage depots; 20 pump /

booster stations; nine Liquefied Petroleum Gas storage depots, five terminals / Jetties and a number of retail outlets. Some of these are shown in Figure 1. Further details on the five operational divisions or regions used by the Nigeria National Petroleum Corporation (NNPC)/PPMC to manage these facilities and their bases can be found in Anifowose et al. (2012).

The depots and pump stations utilise water mainly for firefighting purposes and each has, at least, a borehole with water pumps and water storage tanks while the pipelines crisscross wetlands and many major rivers and streams (NCP/BPE 2008). In fact, a recent study found that the downstream pipeline network has about 115 river crossings, viz: 27 in hydrological area II, 15 in hydrological area III, six in hydrological area IV, ten in hydrological area V, 40 in hydrological area VI, nine in hydrological area VII and eight in hydrological area VIII (Anifowose et al. 2014). Figure 2 illustrates a schema of a typical downstream oil facility and its operations including the routine for emitting and treating gaseous and water-based substances.

### *2.2. Data and Data Sources*

For the first time since the 1970s when the installation of downstream oil facilities began, the Federal Government of Nigeria through the NCP/BPE commissioned a comprehensive environmental audit of the PPMC facilities between 2006 and 2008. Environmental consultancy firms like Environmental Resources Management Southern Africa (Pty) Limited and AWML International Limited with support from SEEMS Nigeria Limited undertook laboratory and field studies in selected PPMC facility locations. The Federal Ministry of Environment played a prominent role in the audit exercise. The audit addressed all the key environmental receptors such as surface and groundwater, air quality, land and soil, socioeconomics and demographics. The data utilised in this present article were retrieved from the data archive and report submitted to the government.

### *2.2.1 Samples and Sampling Procedure*

The environmental audit exercise assessed surface and groundwater bodies including wastewaters and effluents from impacted areas and communities within 2 km of the depots and pipelines. The audit broadly identified and sampled ten categories of water as follows (NCP/BPE 2008):

- raw/untreated intake borehole water
- well/underground water
- treated borehole/tap water
- undischarged/retention wastewater at oil-water separator sumps
- wastewater at discharge outfalls
- wastewater from generator house
- water (mixed with rainwater) in tank farm
- receiving surface bodies of water, namely:
  - Streams
  - Pond
  - Rivers
  - Channel water
- water from pipeline right of way
- water from area of previous burst pipeline

The parameters of interest for this paper (i.e. BTEX, PAH, TPH and TAH) were not always present in treated borehole water/tap water (NCP/BPE 2008). Therefore, the analyses herein focus mainly on water samples from receiving rivers/streams, pipeline right of way or areas of burst pipeline, fuel-mixed wastewater and oily water bodies at tank farms, sumps and pump stations. The analysed data are based on samples taken from the Systems 2A/2B, 2C/2CX and 2D/2DX pipeline facility network (Figure 1) – no coherent data were available for system 2E/2EX and are therefore exempted from our analyses. According to NCP/BPE (2008): Part 7, the systems are as follows:

(i) **Systems 2A/2B**: Warri-Benin-Ore-Mosimi
Atlas Cove-Mosimi-Satellite; Mosimi-Ibadan-Ilorin

(ii) **Systems 2C/2CX**: Escravos-Warri-Kaduna, via Abudu, Auchi, Lokoja, Abaji, Izom & Sarkin Pawa Pumpstations, Benin-Suleja via Auchi pumpstation; Auchi-Suleja-Kaduna; Suleja-Minna

(iii)**Systems 2D/2DX**: Kaduna-Gusau via Zaria Pumpstation; Kaduna-Kano via Zaria Pumpstation; Kaduna-Maiduguri via Biu Pumpstation; Jos-Gombe.

There were about 112 sampling stations across the three Systems viz: 2A/2B, 2C/2CX and 2D/2DX pipeline network but only 59 sampled locations had complete data on Total Petroleum Hydrocarbons (TPH); Total Aliphatic Hydrocarbons (TAH); PAHs; and Benzene, Toluene, Ethylbenzene & Xylene (BTEX). These petroleum hydrocarbons were undetectable in 39 (of the 112) sampled locations which are mainly boreholes and had zeros input against them in the data archive, hence the study exempted them from the analyses. Outliers from 14 other stations were also left out.

### *2.2.2 Quality Assurance, Quality Control (QA/QC) and Analytical Procedures*

The NCP/BPE (2008) contains a robust detail of the QA/QC framework and analytical procedures for the sampling and data collection processes. Extant guidelines by government agencies, including the Department of Petroleum Resources and the Federal Ministry of Environment, guided the data collection from sites. Pre-sterilized plastic bucket was used to collect water samples and from each collection, sub-samples were collected in 2-litre capacity plastic bottles. In line with FEPA (1991), preservation methods for assessing hydrocarbon and other physicochemical parameters were deployed. Sample deterioration was avoided by pre-sterilizing the tools while sample preservation enroute to the laboratory was done at $4^oC$ using ice-cooled chests and samples were refrigerated at the same temperature prior to analysis. In-situ field analysis of parameters with short holding-time like water profile temperature was done using WPW pH/mV-Temperature Meter Type 91 and also for electrical conductivity, pH (using a temperature/pH/EC meter), Dissolved Oxygen (using a Dissolved Oxygen meter) and Biological Oxygen Demand ($BOD_5$). For general water chemistry, samples for delayed analyses were preserved through refrigeration while in the case of heavy metals, total hydrocarbon and Dissolved Oxygen (DO), either pH adjustment or chemical pre-treatment was used (NCP/BPE 2008). To preserve samples like DO, they were acidified to a pH 2 with concentrated sulfuric acid ($H_2SO_4$) and nitric acid ($NHO_3$). Details of field sample handling and preservation procedures are provided in supplementary folder_1.

For lab-based analyses, these commenced upon arrival at the laboratory and were completed within three weeks of sample collection and the ASTM D3921 (infrared spec.)/GC, a standard test method for oil, grease and petroleum hydrocarbons in water, was used to analyse BTEX, TPH, PAH and Total Hydrocarbon contents of the various water samples. The handling of samples and their preservation, treatment and preparation were done according to APHA et al. (1980); Golterman et al. (1978) and US EPA (1979) – as cited in NCP /BPE (2008). The details of recommended test methods for physicochemical parameter analyses as used in this study are provided in supplementary folder_2.

### *2.3 Method of Data Analysis*

The complete data from the 59 remaining sampled locations were grouped according to the pipeline network they belong, viz: systems 2A/2B (Group 3), 2C/2CX (Group 1) and 2D/2DX (Group 2), each with 20, 19 and 20 sets of TPH, TAH, PAHs and BTEX data – a total of 236 data points. The raw datasets are provided in supplementary folder_3. This work utilised Principal Component Analysis and the Kruskal-Wallis test to interrogate the data.

#### *2.3.1 Principal Component Analysis*

Principal Component Analysis (PCA) is a robust mathematical technique especially for cases where the multivariate normal assumption has been violated (Wang and Du 2000; Bersimis and Georgakellos 2013) unlike its Factor Analysis (FA) counterpart. The PCA procedure uses ‘an orthogonal transformation to convert a number of observations of correlated variables into a reduced number of linearly uncorrelated variables (this is the main advantage of this procedure) called principal components (PCs)’ (Bersimis and Georgakellos 2013, p.107). These PCs are arranged such that the first sets are representative of the highest variation in the original variable thereby reducing the possible impacts of multicollinearity between the different variables and maintaining most of the variation that exists in the dataset (Destefanis et al. 2000; Park et al. 2015).

Multivariate Analysis of Variance (MANOVA) would have been a useful alternative to PCA in this study but for the stringent statistical assumptions expected of the multivariate datasets (Finch and French 2013) with specific examples in ecological data by Anderson (2001). In addition, MANOVA has four popular test statistics (i.e. Roy's, Hotelling's trace, Wilks's lambda and Pillai's trace) designed for specific cases which may yield conflicting outcomes, although this could be seen as an advantage given the flexibility. Nevertheless, the preliminary hypothesis testing to determine the suitability of MANOVA in this study yielded negative results. For example, the Kolmogorov-Smirnov test was used to examine a null hypothesis that the datasets do not differ from a normal distribution while the Levene's homogeneity of variance test was used to test the null hypothesis that the difference between group variances is zero. The Levene's test was statistically significant ($p < 0.05$) in all the groups apart from the BTEX where $p = 0.217$. Therefore, the group variances are significantly different hence violating the homogeneity of variance assumption for MANOVA. The Box's test of equality of covariance matrices was also statistically significant ($p < 0.0001$) which further suggests that the homogeneity assumption is violated.

The foregoing were the main reasons PCA was considered the most appropriate tool for addressing the study's main objective (section 1.2). There are existing mathematical frameworks for PCA's linear combination of variables but that of Park et al. (2015) is expressed here by assuming that the random vector $X$ has covariance matrix $K$ with eigenvalues $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n \geq 0$, and eigenvectors $a_1$, $a_2$,…$a_n$. Assume

$X$ is an n by p matrix, given a set of n observation on a vector of p variable, Park et al. (2015) show that the $X$ matrix's linear combination can evolve with variance and covariance as follows:

$$Z_1 = a_1^t = a_{11}X_1 + a_{12}X_2 + \ldots a_{p1}X_n \qquad (1)$$

$$Z_2 = a_2^t = a_{21}X_1 + a_{22}X_2 + \ldots a_{p2}X_n \qquad (2)$$

$$\vdots$$

$$Z_p = a_p^t = a_{p1}X_1 + a_{p2}X_2 + \ldots a_{pn}X_n \qquad (3)$$

$$Var\,[Z_i] = a_i^t k a_i, \qquad i = 1, 2, \ldots n \qquad (4)$$

$$Cov\,[Z_i, Z_j] = a_i^t k a_j, \quad i = 1, 2, \ldots n, \; j = 1, 2, \ldots n \qquad (5)$$

where $i$ represents number of PC and $t$ represents the transpose operator;

$Z_1$, $Z_2 \ldots Z_p$, $Z_i$, are the PCs which are uncorrelated linear combination;

k is the covariance of the random vector X.

For reliability, the study ran PCA's Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy test and Bartlett's Test of Sphericity on the hydrocarbon pollution data to assess partial correlation and dependence which could affect the PCA results (Gu et al. 2016). Despite the robustness of PCA as a mathematical technique, Karamizadeh et al. (2013) have detailed some of its shortcomings.

### *2.3.2 Kruskal-Wallis test*

The non-parametric version of one-way independent ANOVA is the Kruskal-Wallis test and it is mainly assumption free. To further ensure analytical rigour, it is appropriate to utilise an alternative (Alrumman et al. 2015). The Kruskal-Wallis test is herein useful as it compares the mean ranks instead of the population means (Field 2009), thereby enabling the direct processing of the raw datasets (Santis et al. 2016;

Gao et al. 2017). Hence, this work tests the null hypothesis that the mean ranks of petroleum hydrocarbon data in the water samples from the three systems are all equal. The test statistic for Kruskal-Wallis (*H*) can be expressed as follows:

$$H = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_{i\cdot} - \bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}(r_{ij} - \bar{r})^2} \qquad (6)$$

where,

$n_i$ is the sample size in group *i*
$r_{ij}$ is the rank of data j from group *i* (as ranked from lowest-highest for all data)
$N$ is the total sample size (i.e. 59 in this case)
$\bar{r}_{i\cdot} = \frac{\sum_{j=1}^{n_i} r_{ij}}{n_i}$ is the mean rank of all data in group *i*
$\bar{r} = \frac{1}{2}(N+1)$ is the average of all the $r_{ij}$

## 3. Results and Discussion

### *3.1 Applicability, Sample Size Adequacy and Correlations*

First, this paper assessed PCA's applicability and sample size adequacy using KMO Measure of Sampling Adequacy and Bartlett's *p*-value Test of Sphericity. Table 1 shows the KMO result as 0.604 while the Bartlett's Test is $p < 0.001$ and for PCA to be adjudged applicable, the KMO should be > 0.6 and the Bartlett's test of sphericity should be statistically significant i.e. $p < 0.05$ (Gu et al. 2016; Marzouk and Elkadi 2016). Therefore, as our KMO value is closer to 1 than 0 (Table 1), there is indication that patterns of correlations in the hydrocarbon data are relatively compact and so PCA should yield reliable results (Marzouk and Elkadi 2016). Also, Bartlett's $p < 0.001$ suggests the data '…had some internal dependences and overlappings, is middling acceptable for PCA application and suitable for PCA application' (Gu et al. 2016, p.350).

Table 2 shows the correlation matrix while the principal components, the corresponding Eigenvalues and cumulative Eigenvalues are presented on Table 3. Of particular interest is the strong, statistically significant ($p$-value $< 0.001$) and positive correlation coefficients between some hydrocarbon parameters on Table 1. The positive correlation, $r = 0.533$, between BTEX and TPH is not surprising (though not as strong as those found by other studies [e.g. $R^2 = 0.955$ in sediment samples by Rauckyte et al. (2010)]) partly because TPH itself is the gross quantity of petroleum-based hydrocarbon mixture without any identification of its constituents.

Another exception to the strong correlation is seen between TAH and BTEX ($r = 0.421$) and PAH and BTEX ($r = 0.319$). These rather weak correlation coefficients is not unconnected with the nature of BTEX group of chemicals which are highly mobile Volatile Organic Compounds (VOCs) that can evaporate easily from water. Studies have found relatively weak correlation between aromatic compounds such as BTEX and dispersed oil in water (Ekins et al. 2007). Also, BTEX compounds and PAH were found to have no strong relationship with certain workpiece properties in a study by Gamage et al. (2016). BTEX is carcinogenic, hence a public health concern for governments, institutions and communities globally (Ekins et al. 2007; Jovanovic et al. 2010). Though it is slightly more soluble in water while PAHs are considerably less soluble in water and are relatively present in dispersed oils (Ekins et al. 2007).

### *3.2 Results of Principal Component Analysis*

From the main PCA results (Table 3), the eigenvalues show the variances of the principal components i.e. the level of variability in hydrocarbon parameters as captured by the newly derived principal components. The principal components with eigenvalues > 1 are retained and all the others typically accounting for less variance are ignored (Park et al. 2015). Hence, Principal Component (PC) 1 is retained amongst the four since its eigenvalue is > 1 and this why a bigger extraction sums of squared loadings is shown against PC1 (Table 3). The main eigenvector (i.e. PC1) statistically explains 71.5% of the variance found in the regional hydrocarbon pollution parameters in water samples. But about 90% of the total variance in the four variables can be reduced into two new variables i.e. components 1 and 2 (Table 3). Furthermore, the scree plot presents the eigenvalues against the four components and after the first component, it is obvious from the almost flattened line that each successive component accounts for less and less variance (Figure 3). It is not uncommon to assume the ‘inflexion point of scree plot curve’ as cut-off point for selecting the PCs to be retained (Marzouk and Elkadi 2016, p. 4546; Park et al. 2015).

The loaded component matrix shows a positively strong correlation and all the four variables are loaded well on PC 1 but there is generally a weak negative correlation for PC 2 except for BTEX that loaded well on both PCs (Table 4). This confirms that PC 1 contains the most information on water pollution samples across the three regions. The ‘odd’ performance of BTEX in Table 4 is likely due to its peculiar nature as discussed in section 3.1.

A cluster analysis of the score plot is shown in Fig. 4 where each subject in our data (by group) has been plotted on the basis of its first and second component values. Majority of the data in group 3 (i.e. system 2A/2B) and group 2 (i.e. system 2D/2DX) are on the left hand side in the loading plot, therefore negatively correlated, with just a few group 1 (i.e. system 2C/2CX) data (Fig. 4). Conversely, most of the group 1 data are placed on the far right of the loading plot and are quite dispersed. Furthermore, the hierarchical cluster analysis explores the relationship between all the pollution data; and the resulting dendrogram (Fig. 5A) shows the data are set apart along the x-axis with no 100% similarity. Similar to the correlation results (section 3.1), TPH, TAH and PAH all show high degree of similarity above 89% while BTEX does not show any significant similarity, hence only one cluster is conspicuous in the dendrogram (Fig. 5A). Figure 5B shows the result of hierarchical cluster analysis between observations (i.e. per the three regional pipeline networks: systems 2A/2B, 2C/2CX and 2D/2DX) using squared Euclidean distance measure (Currell 2015). The dendrogram used correlations to identify similarity and split the individual data into three uneven clusters separated by about 57% similarity (Fig. 5B). Fifteen individual data in Group 1 (system 2C/2CX) were assigned to cluster 1 in the analysis and the remaining four were misclassified into clusters 2 and 3. Surprisingly, none of the 20 individual data in Group 2 (system 2D/2DX) was assigned to either cluster 2 or 3 but only four were assigned to cluster 1. Similar pattern was observed in Group 3 (System 2A/2B) where only two individual data were assigned to cluster 3 and only one in cluster 2.

This lack of clear coherent pattern emerging in the group-based data cluster analysis and the weak association indicate that the type of oil facility systems in operation or their products have no effect on the severity of hydrocarbon parameters found in water samples across the three groups. In order words, the potential impact of water pollution incidents is not dependent on the pipeline system nor the various product types transported through these systems. The implications and inferences thereof are further discussed in section 3.3.

The principal components of the four variables (i.e. TPH, TAH, PAH and BTEX), PC1 to PC4, derived through a linear combination with the relevant coefficients agree with the cluster analysis. Minitab calculates the value of each principal component (vPC1 to vPC4) starting with PC1 by multiplying the PC1 coefficient with variable 1 (i.e. TPH), then add the coefficient of variable 2 (TAH) multiplied by variable 2; and this is done for all the 59 data points from PC1 to PC4 (Currell 2015). The outcome of vPC1 to vPC4 is shown in Fig. 6 and TPH vs. vPC1 is the best aligned across the three pipeline operating regions (Fig. 6A) unlike Figs. 6B to D.

### *3.3 Output from the Kruskal-Wallis test*

No statistically significant evidence that the level of hydrocarbon pollutants (i.e. PAH, TPH, TAH and BTEX) found in the 59 water samples is different throughout the three systems. All the Kruskal-Wallis test statistic for each hydrocarbon parameter yielded $p > 0.05$. Just like the results in section 3.2, this is intriguing given that (a) these three systems handle different petroleum products based on the state of refining and in varying quantities (Anifowose et al. 2012); (b) each ‘petroleum product has its own mix of constituents’ with the variation often reflected in the finished products (ATSDR 1999); (c) the chemical compounds in these products are bound to react differently with ambient environmental conditions (ATSDR 1999; Wang et al. 2015) and do undergo spatiotemporal transformation (Gomez et al. 2012; Xiong et al. 2017) and (d) the natural environment in each of the three systems are not exactly the same and the level of dissolved chemical concentrations can be influenced by seasonality (Kelly et al. 2009; Xiong et al. 2017).

More interesting is the fact that past studies have suggested that oil pollution incidents are more rampant in the southern part of Nigeria (Aroh et al. 2010; Anifowose et al. 2012)  which predominantly covers the system 2A/2B and part of 2C/2CX (e.g. Escravos-Warri via the Abudu and Auchi axis) as studied herein. Although the present study focuses mainly on the downstream oil pipeline facilities (Anifowose et al. 2014). For reasons stated earlier, amongst others, it could be expected that these oil pollution compounds would vary in composition as well as level of contamination across the three regional systems. For instance, the geographic extent and concentrations of TPH, PAHs and other chemical compounds in the surrounding areas of the BP/Deep-water Horizon oil spill in the Gulf of Mexico revealed spikes and patchiness in contaminant levels across different states (Sammarco et al. 2013) – though unlike our present study, this focused solely on unrefined crude oil. A recent study of oil and gas wastewater discharge also found no differences in certain chemical concentrations in samples from the unconventional Marcellus and Fayetteville plays versus the Appalachian conventional oilfield (Harkness et al. 2015) which may be due to similar geological formations. Other sources of hydrocarbon contaminants contiguous to the downstream of oil facilities in Figure 1 could have influenced the data used in our analyses. For instance, PAH and other pollutants are known to emanate from fires, vehicular traffic, urban road debris and other anthropogenic sources (Andersson et al. 2014) and could readily be incorporated into water bodies (Clément et al. 2015).

In addition, the system 2E/2EX (which mainly supplies the southern part of the country) did not have a complete set of data and was therefore exempted from our analyses (Leorri et al. 2014), and this could probably explain the non-statistically significant results obtained, and of course, the cluster analyses results (section 3.2). The system 2E/2EX captures the Port Harcourt-Aba-Enugu and Enugu-Auchi pipeline routes including the associated facilities; and remains one of the most interdicted of all the downstream systems (Aroh et al. 2010; Anifowose et al. 2012). It is also possible that the slight difference in group size for system 2C/2CX, which has 19 samples as against 20 each for the two others, played a role. But it is fair to assume that the robustness of PCA and Kruskal-Wallis test's assumption-free nature would suffice (Field 2009). Alrumman et al. (2015) found numerous non-statistically significant results in hydrocarbon contamination levels in soil samples collected from Fresh Boyndie, Insch and Brechin in Aberdeenshire UK. Also, no significant difference in the concentrations of PAH was found across three different land-use types in the Pearl River Delta area of four geographic regions in South China (Wei et al. 2014).

According to ATSDR (1999), TPH is mainly associated with environmental sampling analyses and it describes a broad range of several other chemical compounds representing a mixture of petroleum-based components originally emanating from crude oil. The analysis of TPH, BTEX, PAH and TAH in soil and water samples is not uncommon (Gomez et al. 2012; Kim et al. 2014) but the product of crude oil distillation classified by boiling points can be expected to differ over time and in space, especially when spilled into environmental media. This is why some of our results is intriguing. On the other hand, the results from our analyses may not be surprising as pollutants and flowing water interactions with suspended sediments can be complex (Liu et al. 2015).

Based on the above results, it is suggested that future response to petroleum hydrocarbon contamination from downstream oil facilities should take a cost-effective uniform approach while considering the site-specific hazards posed by toxicity level, temporal nature of detected chemicals and human exposure (Harkness et al. 2015). This appears to be a more efficient management approach and could be applicable in other nations of the world with similar developmental and climatic characteristics as Nigeria.

### *3.4 Limitations of Study*

It is not uncommon to find uneven geographical distribution of records of pollutants and where they exist, the data are often limited in temporal extent (Leorri et al. 2014), and this study is not an exception. The outliers in the archive meant some data point had to be exempted (section 2.2.1). Also, of the five regions of facility operations, only the Systems 2A/2B, 2C/2CX and 2D/2DX had petroleum pollution data available and accessible, hence making it impossible to have a complete nation-wide view of the problem. Nevertheless, Norman and Streiner (2008) have suggested against having more than six or seven in/dependent variables in any one analysis. The procedures followed in this article should most likely make it possible to infer beyond the three systems.

## 4. Conclusions and Future Research

For the first time, this paper has assessed discriminants and evaluated the variability of selected petroleum hydrocarbon contaminants from the first ever environmental audit of Nigeria's downstream oil facilities. It combined PCA mathematical technique and statistical models, found some similarities but no statistically significant evidence that the severity level of hydrocarbon pollutants (i.e. PAH, TPH, TAH and BTEX) in 59 water samples is different across the three regional systems. This is intriguing because, amongst other reasons, the three systems handle different petroleum products based on their state of refining and throughput volumes while each ‘petroleum product has its own mix of constituents’ with the variation often reflected in the finished products. Also, the frequency of facility interdiction and intensity of pollution incidents are markedly different across the three systems. The key implication of this finding is that a uniform approach may be utilised in responding to subsequent petroleum hydrocarbon contamination in water from downstream oil facilities. Although this would need to be cautiously applied given the site specific hazards posed by toxicity level and temporal nature of detected chemicals as well as human exposure, especially where access to treated pipe-borne water is limited. The study approach and, possibly outcome, could be a useful starting point for nations with new oil and gas discoveries such as Ghana, Kenya, Tanzania, Mozambique, Uganda, The Gambia, Liberia and so on.

Other studies have assessed variances in hydrocarbon contamination in water not only by multivariate statistical analyses of concentration (as done here) but also through carbon stable isotope ratios. The latter is an area of future study.

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