Modeling and preliminary assessment of crude oil contaminated soil in Ogoni (Nigeria)

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Abstract

In 2010, a severe contamination of soil and groundwater caused by the production and transportation of crude oil were detected in the Ogoni area, Federal Republic of Nigeria. A linear correlation between aliphatics and aromatics and the missing link between the degree of contamination and the depth of the soil samples indicate incomplete earlier remediation activities. 665 analyzed samples were mathematically reduced to 28 contamination patterns that can be distinguished by type and degree of pollution, environmentally assessed and visualized by a quasi 3-D model. Case studies taken from the Local Government Areas Eleme, Gokana, Khana, and Tai show the methodology and results.

Keywords: crude oil; hydrocarbons; soil; Africa; environmental protection; large scale survey; mathematical method; contamination pattern.

Zusammenfassung

2010 wurden im Gebiet Ogoni, Bundesrepublik Nigeria, signifikante Kontaminationen von Boden und Grundwasser erkannt, die durch Produktion und Transport von Rohöl verursacht worden sind. Eine lineare Korrelation zwischen Aliphaten und Aromaten und das Fehlen eines Zusammenhangs zwischen dem Grad der Kontamination und der Teufe der Bodenproben deuten auf unvollständige Dekontaminationsmaßnahmen in der Vergangenheit hin. 665 untersuchte Proben wurden mathematisch 28 Belastungstypen zugeordnet, die sich sicher nach Typ und Stärke der Verunreinigung unterscheiden, beschreiben, bewerten und in einem quasi 3-D Modell visualisieren lassen. Fallstudien aus den Lokalen Regierungsgebieten Eleme, Gokana, Khana und Tai verdeutlichen Methodik und Resultate.

Keywords: Rohöl; Kohlenwasserstoffe; Boden; Afrika; Umweltschutz; Großprojekt; mathematische Methode; Kontaminationsmuster.

1 Introduction

Nigeria is situated in the tropics of West Africa between latitudes 04°N and 14°N and longitudes 02°02'E and 14°30'E and has an area of 923,770 km^2. Ogoni in the Niger Delta is part of Rivers State in the Federal Republic of Nigeria with a size of about 900 km^2. It is subdivided into the four Local Government Areas (LGA) Eleme, Gokana, Khana, and Tai (Figure 1). Vegetation in Nigeria ranges from thick mangrove forests and dense rain forests in the south to a near-desert condition in the north-eastern corner of the country. The river Niger opens to the Atlantic Ocean. Ogoni is characterized by the oil industry, by small industrial businesses close to Port Harcourt, and agriculture and farming in the countryside. Other important branches as sources of livelihood of the Ogoni people are fishery, fresh water and marine.

Figure 1: Contaminated sites investigated by UNEP (modified from [1]).

Oil exploration and production in Ogoni have been ongoing since the 1950s. Crude oil exploration, production, transportation, and handling of refined products, have effected the environment and resulted in the pollution of soil and groundwater. Important goods of public interest such as the health of residents, agriculture and farming, fishing and the natural habitats are endangered.

In July 2006, the United Nations Environment Program (UNEP) received a formal request from the Government of Nigeria for a comprehensive environmental assessment of oil-impacted sites in the Ogoni region of the Niger delta. The following survey resulted in an Environmental Impact Assessment of Ogoni involving several scientific disciplines, including a survey of the soil and groundwater situation. The respective report was released in August 2011 [1]. The German journal "altlasten spektrum" specialized in brownfields referred to this project in 2012 [2].

This contribution is meant to support the UNEP report and to derive a methodology for large scale surveys, where huge amounts of multiple data have to be processed and interpreted. Mathematically obtained results will be preliminary assessed applying experience in the environmental risk assessment of contaminated soil at former industrial sites in Germany.

2 Hydrology, Hydrogeology, Soil

The Niger delta comprises an estuary of about 70,000 km^2. All upper groundwater horizons in the Niger delta are constituents of the Benin formation. The Pleistocene Benin formation is made up of friable sandstones, gravels and intercalations of shale, which comprises the region's main aquifers [3].

The upper groundwater level in northern parts of the project area is located about 12 m below ground getting closer to the surface in southern direction to the mouth of the river Niger. This upper groundwater level is commonly semi-confined and is developed in fine to medium grained, grey to yellow sands. The general direction of groundwater flow in the delta is towards south bending easterly or westerly respectively close to the inlets of the Niger. The velocity of the groundwater flow can be estimated as low to medium.

The soil in the delta is influenced by tropical rainfalls and a relatively high groundwater table which leads to physical and chemical alterations of its composition. It is sometimes described as hydromorphous [4]. This soil type can be classified as gleysol according to the Food and Agriculture Organization of the United Nations (FAO) taxonomy, as fluvisol or as entisols with its suborder fluvents according to the taxonomy used by the US Department of Agriculture [5]. The soil horizons are weakly developed [6].

About 960 boreholes were drilled mainly up to a depth of 5 m. UNEP stated in [1] that three observations are evident: "(1) the shallow geology of Ogoniland is highly variable with wide variations within short distances; (2) the shallow formations range from gravelly sand to clay and everything in between; and (3) there is no continuous clay layer across Ogoniland". It is quite difficult to correlate the results of a specific borehole with those of other ones, even if they are situated within relatively close proximity.

Vertical lithological profiles show a sequence of unconsolidated clayey, silty and sandy sediments up to a minimum depth of about 5 m. All these layers are, in most cases, yellowish or brownish, although other colors like red also occur. Horizons deeper than 5 m have been surveyed in the area of Nsisioken-Agbe. They consist of coarse sand up to 50 m below surface. The groundwater level varies from about 1 m below surface to more than 10 m depending on the distance of the borehole to the nearest inlet and to the mouth of the river Niger respectively.

The organoleptic assessment of the cores resulted in dense clayish or loamy sediments with high silt content and relatively little coarser fractions (Figure 2). The transmissivity of the clayey and silty top soil can be estimated by $k_f \approx 10^{-5}\ ms^{-1}$ and less.

Penetrated hydrocarbons (HC) originated by oil spills form a thin film around the grains of the sediment. Such a two-phase flow system leads to stagnant hydrodynamic conditions and a reduced mobility of hydrocarbons in the aquifer. Lateral migration of non-halogenated hydrocarbons therefore rarely exceeds a few meters unless the soil has been loosened earlier due to digging activities, for instance along the course of pipelines.

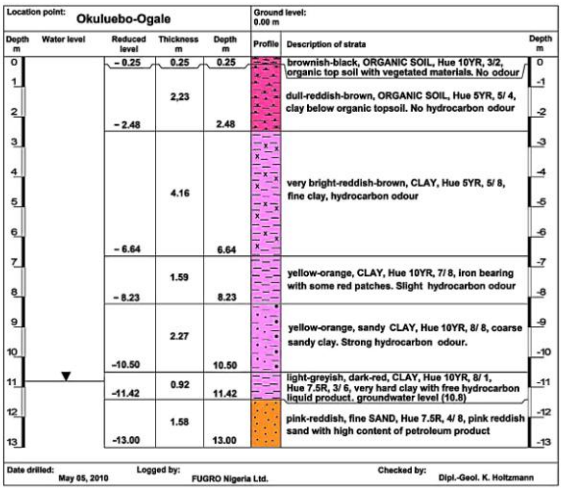

Figure 2: Log 005-001-06 at Okuluebu-Ogale drilled 2010-05-05 by FUGRO Nigeria Ltd.

The degradation rate of hydrocarbons might be diminished within the existing reducing milieu. These results however do not comply with estuarine microcosm experiments published by Amund & Akangbou [7] and applications in Nigerian terrestrial ecosystems [8] where bacterial stems lead to distinct degradation rates for Bonny Light Crude Oil under laboratory conditions.

3 Vulnerable Goods of Private and Public Interest

Crude oil polluting soil in Ogoni is hazardous for the biosphere due to its toxic, mutagenic or carcinogenic ingredients (Table 1).

For a balanced ecological evaluation analytical results indicating remarkable contamination of certain locations were related to exposed vulnerable goods of public or private interest near to them, such as the human health of the residents in the nearby settlements, groundwater used for consumption or irrigation, fresh water and marine fisheries or agricultural sites. Other vulnerable goods of public interest are sensitive uses as for instance schools, playgrounds and hospitals, or in legal terms, the unrestricted use of private property. Soil, the upper groundwater level and open water bodies are the main receptors of contamination in Ogoni. All examined sites are close to the oil infrastructure (cf. Figure 1). In Ogoni, some people are sometimes living very close to or literally on the oil infrastructure, which is marked by an approximately 25 m wide “right of way” (ROW) of the oil company operating the respective pipeline.

Table 1: Compounds of soil pollution in Obolo-Ebubu.

Compound	Conc. ppb	Chemical formula	Attributes
nonane and decane	128	C_9H_{20} and $C_{10}H_{22}$	aliphatic HC; liquid; toxic.
undecane and dodecane	747	$C_{11}H_{24}$ and $C_{12}H_{26}$	aliphatic HC; liquid; toxic, irritant.
2-methoxy-2-methyl-propan (MTBE)	< 5	$C(OCH_3)(CH_3)_3$	aliphatic HC; liquid, slightly soluble in water; water endangering.
benzene	< 10	C_6H_6	aromatic HC; liquid; slightly soluble in water; carcinogen.
xylenes	< 140	$C_6H_4(CH_3)_2$	aromatic HCs; liquid; soluble in benzene; toxic.
benzene, toluene, ethyl-benzene, xylenes (BTEX)	no data	mixture	see single compounds!
1,2,4-trimethylbenzene	< 90	$C_6H_3(CH_3)_3$	aromatic HC; liquid; harmful, causes dermatitis etc.
phenylethene (styrene)	< 100	$C_6H_5(C_2H_3)$	aromatic HC; liquid; toxic.
acenaphylene	34.6	$C_{12}H_8$ (3 rings)	PAHC*; solid but soluble in benzene;

			mutagen, irritant.
acenaphthene	57.5	$C_{12}H_{10}$ (3 rings)	PAHC*; solid but soluble in benzene; water endangering.
fluorene	88.1	$C_{13}H_{10}$ (3 rings)	PAHC*; solid but soluble in benzene; mitogen.
anthracene	66.4	$C_{14}H_{10}$ (3 rings)	PAHC*; in traces soluble in water; water endangering.
pyrene	47.3	$C_{16}H_{10}$ (4 rings)	PAHC*; solid but soluble in organic solvents; harmful.
fluoranthene	24.7	$C_{16}H_{10}$ (4 rings)	PAHC*; in traces soluble in water; toxic, mutagen, carcinogen.
chrysene	12.6	$C_{18}H_{12}$ (4 rings)	PAHC*; solid but soluble in benzene; carcinogen.
benzo(b)fluoranthene	36.8	$C_{20}H_{12}$ (5 rings)	PAHC*; solid; harmful, irritant.
benzo(k)fluoranthene	40.8	$C_{20}H_{12}$ (5 rings)	PAHC*; solid; harmful, irritant.
dibenzo(a, h)anthracene	< 23	$C_{22}H_{14}$ (5 rings)	PAHC*; solid; irritant, toxic.
			* polycyclic aromatic hydrocarbon

4 Data Acquisition

The studied sites are located close to the oil infrastructure in the four LGA Eleme, Tai, Gokana and Khana (Figure 1). To assess the degree of soil contamination more than 200 shallow boreholes most of them not exceeding 2 m and rarely deeper than 2.5 m have been drilled close to spill sites which have been identified before by a database provided by the oil company Shell. This database described the exact location of the spills, their approximate size, the date of the incident, the affected type of land etc. More than 600 soil samples have been taken from the cores of the shallow drillings.

A sampling scheme has been developed using so called transects to survey the identified locations of oil spills [2]. The contaminated site has been intersected by randomly positioned sampling lines for the allocation of the drillings. The plan was to start the sampling in clean areas, then crossing the contaminated area and reaching clean land again, in order to achieve a realistic image of the contamination.

In an ideal case, the sampling pattern should also consider a subsequent computerized mathematical interpretation to ensure an appropriate distribution of sampling points and at least a minimum number of sampling points at any contaminated site. In the present case the sampling regime has not been adjusted to a following mathematical analysis.

Only the parameters “sum of aliphatic hydrocarbons” (abbreviated by “aliphatics”) and “sum of aromatic hydrocarbons” (“aromatics”) have been used in the mathematical processing. This limited the potential of the mathematical models but made it easier to demonstrate and to explain the methodology.

The chemical analyses were carried out in a certificated laboratory in the UK. There was no information available about the applied analytical methods including accuracy and precision of the data. It is well known that information about these parameters is frequently neither ordered by the customer nor delivered by the laboratory. Thus, it was assumed (1) that systematic errors – if occurring at all – are significantly fewer than internationally applied threshold levels to evaluate ecological hazards and (2) that possible random errors are significantly fewer than differences between various classes of contamination to be calculated.

The sum of aliphatics includes all short- and long-chain (non-halogenated) hydrocarbons which occur in Nigerian crude oil. In general, it is a mixture consisting of small amounts of short-chain constituents such as methane, ethane, propane, butane and mainly liquid parts mixed by pentane, hexane, heptane, octane up to hexadecane. The sum of aromatics includes mainly benzene, naphthalene, phenanthrene, ethylbenzene, toluene and xylenes. UNEP classifies the carcinogenic benzene and the skin irritant methyl tertiary butyl ether (MTBE) as the most critical parameters.

5 Mathematical Modeling

Available data (chemical analyses of soil samples) has been processed mathematically (1) to characterize the general ecological situation and (2) to visualize type and degree of the contamination in a spatial or quasi-spatial multivariate model.

The generalizing statistical description consists of a thorough selection of all important chemical pollutants; the determination of the type of frequency distribution $f(x)$ and the statistical estimation of the mean value m and standard deviation s of every involved chemical compound; the determination of mutual associations between the contaminants by statistical correlation and regression analyses; an analysis of the dependency of the concentration of every studied pollutant from the sampling depth applying correlation and regression analyses.

The observed sum of aliphatic and aromatic hydrocarbons varies between zero ppm and 42,000 ppm and can exceed this value without a limit, only depending of the crude oil supply and limited by the capacity of the soil. The concentration values of every studied attribute can have a range which is a priori free and absolutely independent of the concentration of other pollutants. They do not form so-called compositional data and an application of traditional correlation and regression analyses is possible without fault.

A statistical analysis leads to unbiased and reproducible results independent of individual conceptions of experts and characterizes the contaminated sites and samples as an entity but not single cases (samples).

The multivariate modeling by means of a cluster analysis considers all parameters at the same time and groups the manifold of 665 samples into some classes which contain samples similar to each other regarding a specific contamination and dissimilar to other classes and their specific contamination. This method reduces the number of samples distinctly, systematizes sites, locations and samples and generates distinctly distinguishable contamination patterns. Every resulting class can be described by the number of enclosed samples, their profile, their location and sampling depth and the average composition of all enclosed samples. The relation between the cluster classes can be visualized by a dendrogram. For example, this tool was successfully applied by Deekae & Henrion [9] in an adjacent area of the Niger delta to group observation stations based on the occurrence or absence of about 40 mollusk species in inlets of the Niger river water depending on its salinity and pH value.

A non-hierarchical cluster analysis was applied due to the great amount of samples. The relationship between the resulting ten classes of contaminated samples was analyzed and visualized by a hierarchical cluster analysis – now of the classes and not of the single samples – based on the Euclidean distance measure and Ward's strategy. The authors reactivated the idea of a two-step cluster analysis to refine the results and classified those pre-classes occupied by many samples again.

The preliminary risk assessment will be made more instructive especially for decision makers if contamination type, location and depth of each sample are drawn into a scaled cartographic base to design a quasi 3-D model. Each cluster class can be marked in the map by an obvious sign, hatching or color, e. g. green color for not or slightly contaminated, yellow for medium or red for highly polluted samples.

6 Environmental Risk Assessment

The mathematically obtained results can be interpreted environmentally to derive recommendations regarding the handling of crude oil contamination in subsoil.

The criteria for the official evaluation of soil contamination in Nigeria are published in the guideline "Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN)" [10]. Because of the high relevance of environmental impacts due to activities of the oil industry and the dominant role of the Dutch company Shell in the oil producing area the intervention values of the "Dutch list" have been adopted by EGASPIN, although not strictly. In the New Dutch list [11] and EGASPIN the “intervention value” for “mineral oil” and aliphatic hydrocarbons respectively in soil is identically 5000 ppm. EGASPIN defines “intervention values” as those that indicate “the quality for which the functionality of the soil for human, animal and plant life are, or threatened with being seriously impaired. Concentrations in excess of the intervention values correspond to serious contamination” [10].

Regardless of the orienting values of EGASPIN, any soil contamination and any contaminated site are to be evaluated individually considering the concentration of hazardous substances, the ability of pollutants to migrate under specific environmental conditions, the nature of soil, the water saturation in soil and the depth of the upper aquifer, possible adjacent groundwater use, land use, a possible exposure of residents, life stock and natural or agricultural vegetation, climate, and other specific conditions. The human-toxicological aspect, however, has the highest priority. A consistent ecological risk assessment will finally meet international best practices if the resulting positive effects bring about maximum benefits for the environment with a minimum of costs, e. g. they have a positive cost-benefit ratio. A final risk assessment of the crude oil contamination in soil of Ogoni is solely the responsibility of the public administration of Nigeria.

7 Results

General statistical description. Both aliphatics and aromatics show an asymmetric distribution function skewed to the left: the majority of samples is slightly or not significantly polluted whereas high and extreme concentration values also occur. 91.4% of all samples are contaminated by aliphatic hydrocarbons below the frequently cited “intervention value” 5000 ppm. However, nearly one half of all samples are polluted by more than 70 ppm aromatics, an “intervention value” for aromatic hydrocarbons (Figure 3).

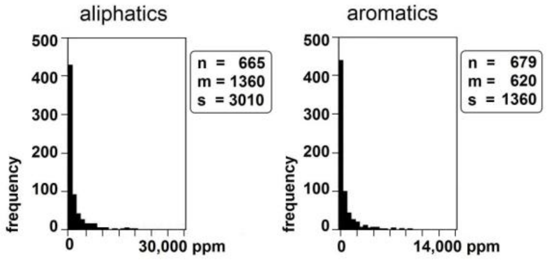

Figure 3: Histograms of aliphatic and aromatic hydrocarbons.

The commonly used arithmetic mean value for the contaminants (here: 1360 ppm aliphatics and 620 ppm aromatics) must not be calculated for left-skewed or lognormally distributed data. The statistically correct estimation with respect to the actual distribution function is 3510 ppm aliphatics and 1690 ppm aromatics. The average concentration of aromatic hydrocarbons is the main problem in terms of soil contamination in Ogoni.

The lognormal distribution matches with the empirical distribution at a significance level of 95%.

A statistically significant correlative relation exists between the sum of aliphatic and aromatic hydrocarbons. The correlation coefficient $r = +0.92$ shows that there is a high aromatic pollution generally connected with a high aliphatic pollution and vice versa. A suitable regression function is $aromatics = 0.422 * aliphatics + 48$ (all terms in ppm) where aliphatics and aromatics denote the concentration in dry soil. Figure 4 shows the strong mutual dependency.

The correlation coefficient is statistically significant at a significance level of α = *95%*. The sum of aliphatic and the sum of aromatic hydrocarbons are *in general* significantly correlated. It is a statistical conclusion valid for the data set as a whole but not necessarily for every involved single sample.

The correlation analysis between the concentration of a pollutant and the sampling depth indicates that there is no connection at all. High degree pollution can be observed both at low and at greater depths. The expected decrease of contamination with increasing sampling depths cannot be confirmed. This result is illustrated by the correlogram shown in Figure 5. It seems to be caused by previous clean-up measures carried out after an oil spill: contaminated soil has been excavated, treated by land-farming and backfilled. The original stratification of the subsoil was lost and sometimes insufficiently decontaminated material has been placed onto still polluted soil. This complies with the findings published in the UNEP report [1].

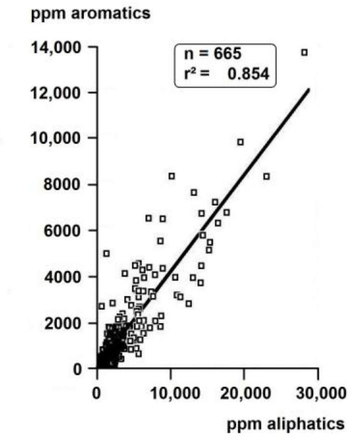

Figure 4: Association between aliphatics and aromatics.

The correlation coefficients $r = +0.110$ and $r = +0.069$ for aliphatic hydrocarbons and aromatics versus sampling depth respectively are – due to the great amount of samples – only in a statistical sense significant at $\alpha = 95\%$. However, only 1.2% and 4.8% respectively of the dispersion in the scatterplot (Figure 5) can be explained by mutual dependencies which is insufficient for serving as a basis for discussion.

Multivariate contamination patterns. The multivariate classification of all 665 samples representing 33 polluted sites in Ogoni leads to ten well distinguishable cluster classes representing different contamination patterns. Eight of them show high or extremely high contaminated samples (Table 2). Although spectrum and degree of pollution are different, the contamination represented by these classes is unacceptably high. One of the first working steps in the future revitalization of the sites should be to continue the remediation at all sites represented by these 40 samples.

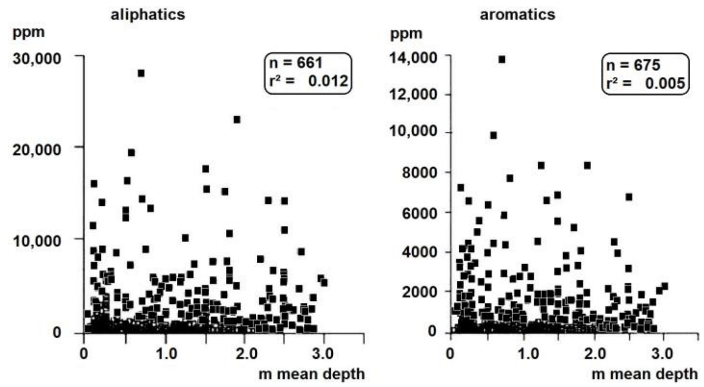

Figure 5: Missing dependency of the aliphatic and aromatic pollution on the sampling depth.

Table 2: Contamination patterns obtained by first step cluster analysis involving 665 samples.

Cluster no.	Mean content aliphatics (ppm)	Mean content aromatics (ppm)	Number of samples	Description and recommendations
01	1900	3700	4	very high aromatic pollution – an immediate remediation seems to be necessary.
02	3500	1500	96	high aromatic pollution; cluster class must be subdivided due to the number of included samples.
03	270	140	529	mostly moderate or no contamination; cluster class must be subdivided due to the number of included samples.
04	7800	3100	16	high aliphatic and very high aromatic pollution, an immediate remediation seems to be necessary.

05	8700	6800	4	high aliphatic and extreme aromatic pollution, an immediate remediation seems to be necessary.
06	13,500	4200	7	extreme contents of aliphatics and aromatics, 1st type: immediate remediation seems to be indicated.
07	15,500	6700	6	extreme contents of aliphatics and aromatics, 2nd type: immediate remediation seems to be indicated.
08	28,200	13,800	1	maximum contents of aliphatics and aromatics: immediate remediation seems to be indicated.
09	19,400	9900	1	extreme contents of aliphatics and aromatics, 3rd type: immediate remediation seems to be indicated.
10	23,100	8400	1	extreme contents of aliphatics and aromatics, 4th type: immediate remediation seems to be indicated.

96 samples are assembled within cluster class no. 02. A second-step clustering subdivided them into ten sub-cluster classes which replace the former pre-class no. 02. They include different types of crude oil contamination at the studied sites but nevertheless they all represent unacceptably highly contaminated samples. Detailed surveys, temporary restrictions of land use or further technical remediation measures seem to be appropriate actions.

Cluster class no. 03 contains 529 samples, most of which are moderately polluted. The average soil contamination of them is 270 ppm aliphatics and 140 ppm aromatics. The second-step clustering of these samples results also in ten new cluster subclasses replacing the former pre-class no. 03. Table 3 shows the sub-classes and their attributes. 350 samples are found in the new sub-cluster no. 38 which represents nearly clean samples: the averaged concentrations are 54 ppm aliphatics and 33 ppm aromatics and are therefore acceptable. All of these samples and the corresponding sites or locations do not require any remediation. Sub-cluster no. 37 contains 77 samples (more than 10% of all samples) which are also nearly clean. Thus, clean-up measures in the future can be limited to selected locations.

Figure 6 shows the result of the complete two-step cluster analysis.

Table 3: Contamination patterns obtained as sub-classes of the second step of cluster analysis.

Cluster no.	Mean content aliphatics (ppm)	Mean content aromatics (ppm)	Number of samples	Description and recommendations
30	940	650	5	polluted by aromatics; detailed exploration and restricted land use only is recommended.
31	1740	510	4	polluted by aromatics; detailed exploration and restricted land use only is recommended.
32	1310	860	13	polluted by aromatics; remediation seems to be recommended.
33	1570	1400	3	highly polluted by aromatics; remediation seems to be required.
34	650	360	48	moderately polluted by aromatics; detailed exploration is recommended.
35	60	730	2	polluted by aromatics; detailed exploration and restricted land use only is recommended.
36	1700	910	5	polluted by aromatics; detailed exploration and restricted land use only is recommended.

37	340	160	77	negligibly contaminated; monitoring is recommended.
38	54	33	350	not significantly contaminated.
39	1180	380	22	moderately polluted by aromatics; detailed exploration is recommended.

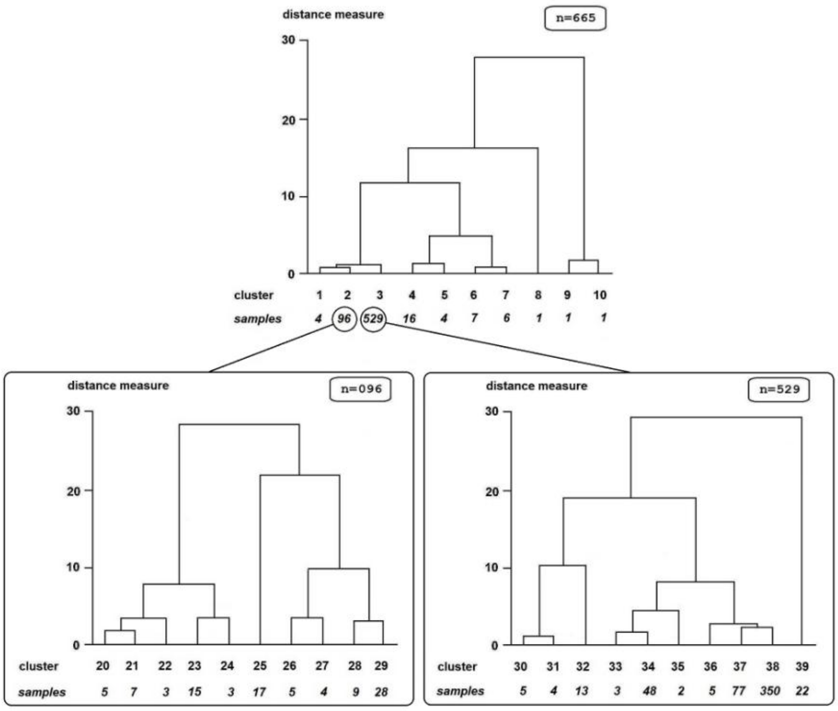

Figure 6: Two step cluster dendrogram.

The description and recommendations given in the tables are based on the ideas and assumptions discussed in chapter 6. They may support the decision about monitoring, natural attenuation, restriction of land use, excavation, clean-up of soil etc. but should not be understood as any final decision.

The geographical occurrence of not, moderately or highly contaminated locations and depths are shown on maps. Different degrees and types of pollution are indicated by different colors. Green colors mark not or negligible contaminated points, orange and red – highly polluted ones. The respective relation between a certain color and the cluster class or its average concentration of toxic hydrocarbons can be seen in the legends of the maps. The mini-profiles are not true to scale and were drawn into Google maps® images of Ogoni due to the lack of scaled geographical maps of the Ogoni sites. The basic layers for Figures 7 to 13 are taken from Google maps (2011): Image © 2011 GeoEye; © 2011 Google.

8 Examples

Ochanni-Ebubu. Thirteen shallow boreholes drilled in the middle of the residential area Ochanni-Ebubu in the LGA Eleme (Figure 7). The location is about 20 km ESE of Port Harcourt and covers an area of about 200 m by 200 m.

The mathematically processed analytical results prove that there is no or only little contamination present from the surface to the final depths of the drillings. Contamination at greater depths is not likely and also water samples taken in July 2010 resulted in clean conditions. Although the environmental situation is sensitive due to residential buildings nearby, the site can be removed from the list of contaminated sites and no further action seems to be necessary.

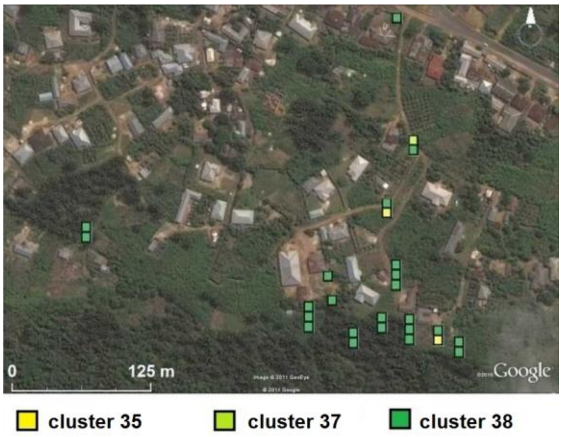

Figure 7: Contamination pattern Ochanni-Ebubu, LGA Eleme. Basic layer from Google maps (2011). Image © 2011 GeoEye; © 2011 Google.

Bera South. Another way to interpret and visualize polluted samples of surveyed sites after a cluster analysis is to use the table form (Table 4) without mapping by mini-profiles. Four distinguishable cluster classes can be found at this site. The averaged properties of the cluster class no. 34, 37, and 38 are described in Table 3. Parts of the site seem to be nearly uncontaminated due to previous clean-up measures.

Cluster class no. 04 was observed in one sample. The arithmetic mean values of this class are approximately 7770 ppm aliphatics and 3140 ppm aromatics. Both values require remediation measures mainly at greater depths in the area of drilling no. Bera-220. It is likely that unacceptably high pollution can be found also at other deeper parts of the site. The site close to two parallel pipelines running north is situated in the middle of farm land. Eight sampling locations cover a length of the course of the pipeline of about 200 m. All the logs of the shallow drillings record “strong hydrocarbon smell” which seems to be a contradiction to the results listed in Table 4 where a mostly “moderate” contamination is described by the clusters no. 34, 37 and 38.

Table 4: Cluster results (contamination patterns) for Bera, LGA Gokana.

Bore-hole no.	Mean depth m	Observed aliphatics ppm	Observed aromatics ppm	Cluster no.	Properties of cluster class and recommendations
200	0.25	10	10	38	not significantly contaminated.
	0.75	260	130	37	negligibly contaminated; monitoring is recommended.
	1.55	310	120	37	negligibly contaminated; monitoring is recommended.
210	0.20	0	10	38	not significantly contaminated.
	0.95	180	120	38	not significantly contaminated.
	1.85	350	200	37	negligibly contaminated; monitoring is recommended.
220	0.45	0	0	38	not significantly contaminated.
	1.55	70	50	38	not significantly contaminated.
	2.35	6410	3990	04	high aliphatic and very high aromatic pollution, an immediate remediation seems to be necessary.
230	0.25	230	130	37	negligibly contaminated; monitoring is recommended.
	1.15	780	330	34	moderately polluted by aromatics; detailed exploration is recommended.
300	0.20	150	40	38	not significantly contaminated.
	1.20	40	10	38	not significantly contaminated.
310	0.50	150	60	38	not significantly contaminated.
	1.50	900	340	34	moderately polluted by aromatics; detailed exploration is recommended.
320	1.00	40	0	38	not significantly contaminated.
330	0.20	40	410	38	not significantly contaminated.

1.20	0	0	38	not significantly contaminated.

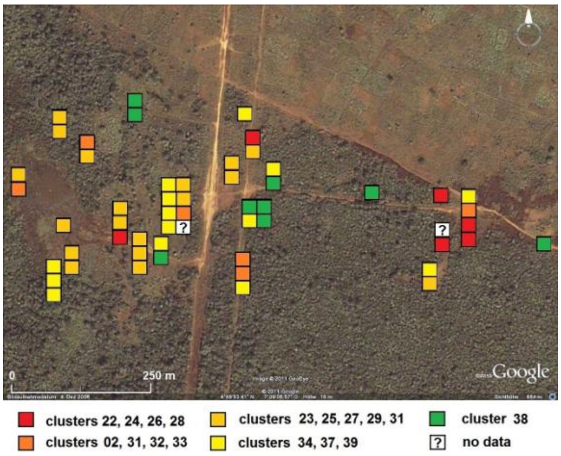

Figure 8: Okuluebu-Ogale, LGA Eleme.

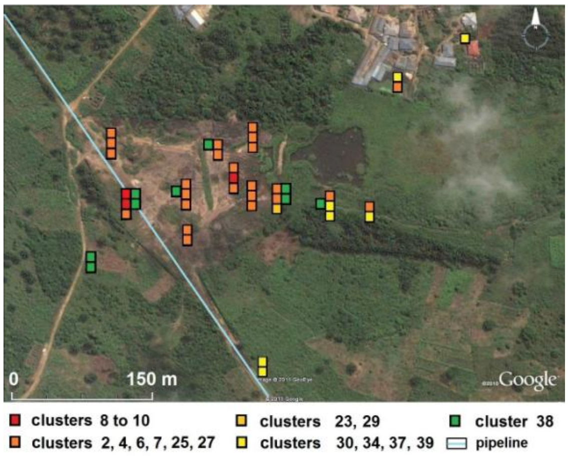

Figure 9: Ebubu-Ejama, LGA Eleme.

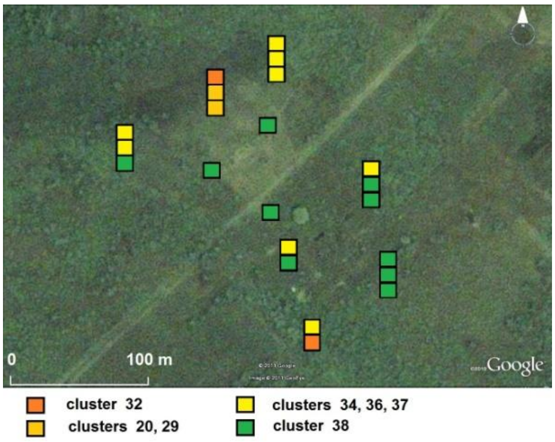

Figure 10: Kwawa, LGA Khana.

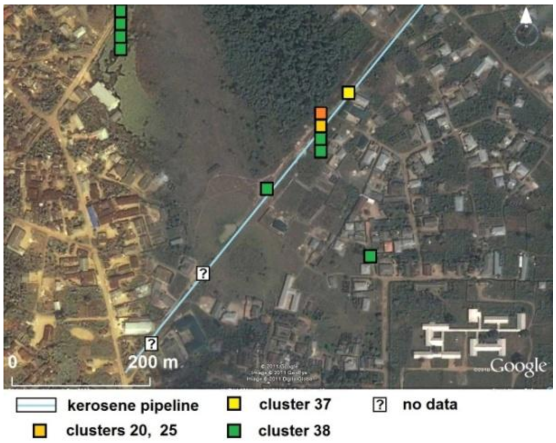

Figure 11: Nsisioken-Agbi, LGA Eleme.

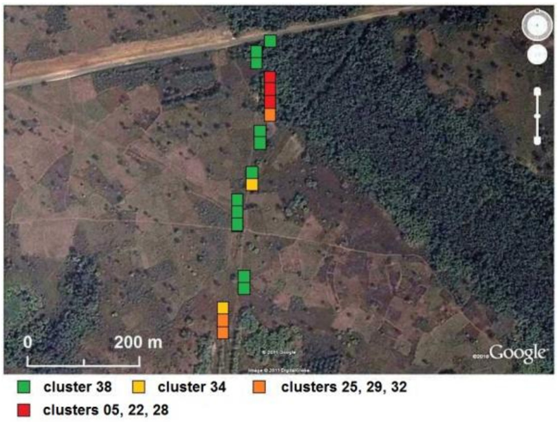

Figure 12: Kpite, LGA Tai.

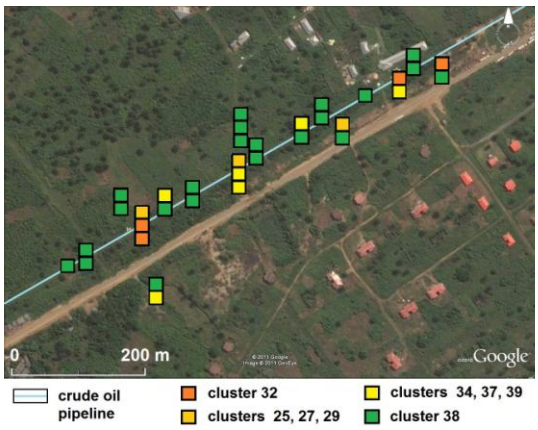

Figure 13: Okenta-Alode, LGA Eleme.

The shallow groundwater table is important for the evaluation of the ecological damage. The oil spill could impinge upon groundwater immediately after passing only 0.8 m of sediment or backfilled material. The loosened material along the bedding of the pipelines functions as a primary pathway. Location Bera-220, situated between the two pipelines, can serve as an example of what has happened. The maximum drilling depth is only 2.35 m. The oil spill has been only superficially remediated. This is indicated by the relatively small concentrations (and corresponding heuristic clusters) close to the surface and the stronger contamination still found in greater depths. The nearest buildings are situated less than 200 m away. The presence of hand dug wells there is likely and the environmental situation is sensitive. Only the presence of one member of cluster no. 04 has indicated that the site has not yet been cleaned completely.

Okuluebu-Ogale, LGA Eleme. Located 11 km ESE of Eleme Junction or 6 km N of Ejama-Ebubu. 25 drillings. An area of 400 m by 300 m with degraded vegetation indicates a former oil spill. Isolated samples with high concentrations in various depths indicate an incomplete remediation (Figure 8). The environmental situation is not sensitive but further remediation is recommended because an influence of the contamination on the groundwater has been proven by installation of water wells in 2010.

Ebubu-Ejama, LGA Eleme. Location 20 km east of Port Harcourt. A site of 400 m by 400 m vulnerable due to a village with many hand dug wells nearby. Polluted by oil spills some of them happened about 40 years ago. Hydrocarbon bearing sludge analyzed by Ayotamuno, Akor & Daka (quoted in [12]) showed a total hydrocarbon content of 98,000 ppm within the top soil. This site was partially decontaminated in 2006 by re-enhanced natural attenuation (Figure 9).

Kwawa, LGA Khana. Situated about 65 km SE of Port Harcourt. A crossing "right of way" in the middle of farmland with an area of degraded growth of vegetation (Figure 10). Hydrocarbon pollution is absent or low. Groundwater level is close to the surface (0.5 m) but clean water samples taken July 2010 confirm the impression of a relative clean site.

Nsisioken-Agbi, LGA Eleme. Located about 17 km west of Port Harcourt. Spills occurred along a pipeline carrying refined product (Figure 11). Sensitive situation due to residential areas, hand dug wells and a nearby hospital. The Figure gives an incorrect impression of relatively clean conditions: Groundwater survey in 2010 revealed a strong contamination of deeper, here not analyzed strata along the pipeline and groundwater in adjacent areas within a size of about 15 ha.

Kpite, LGA Tai. Located about 15 km east of Ejama-Ebubu. 8 drillings parallel to a pipeline. A water level of about 2.5 m below ground in the middle of agricultural sites, Kpite nearby, and a stadium 600 m away suggests sensitive conditions (Figure 12). Further remediation seems to be the adequate action although the middle part is relatively clean.

Okenta-Alode, LGA Eleme. 17 shallow drillings surrounding a pipeline parallel to the road and scattered buildings close to the survey sites (Figure 13). Predominant cluster no. 38 in the mini-profiles indicates no or only negligible contamination. But the erratic occurrence of clusters representing stronger contamination (e. g. cluster no. 25, 29, and 32) in different depths indicates incomplete remediation of oil spills.

9 Conclusions and Recommendations

(1) Soil in the surveyed sites in Ogoni is less contaminated with aliphatic hydrocarbons from oil spills but mainly polluted by toxic aromatics. Residents and the environment are directly exposed to the contamination. Harmful effects of the ever present contamination of aromatic hydrocarbons on the health condition of the residents are likely but not proven epidemiologically.

(2) Previous remediation measures carried out in Ogoni have cleaned-up many sites which were contaminated by crude oil but there are still sites where the measures are incomplete and unacceptably high contamination is still prevalent. This statement was confirmed by the detailed multivariate mathematical analysis of aliphatic and aromatic hydrocarbons in subsoil samples. Therefore, the regimes of re-enhanced natural attenuation, excavation, land farming, and backfilling should be revised and improved in order to ensure a sufficient degradation of hydrocarbons. This postulation complies with conclusions of UNEP that "procedures for oil spill clean-up and remediation need to be fully reviewed and

overhauled" [1]. An increase of the survey for soil contamination to greater depths would be also necessary.

(3) The application of computerized mathematical models is a valuable tool if hundreds of samples with several different properties are to be evaluated simultaneously. A statistical analysis characterizes the entire studied area as a whole. This is an important preparation to assess the volume of remediation work to be done in the future. Cluster analyses generate a smaller number of classes of contamination which are well distinguishable by type and degree of pollution and which can be shown easily.

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References

[1] UNEP (2011): Environmental assessment of Ogoniland. Abuja, Nigeria; 246 pp.

[2] Kallnischkies, T. (2012): Altlasten im Niger-Delta nach 60 Jahren Erdölförderung [Soil and groundwater contamination after 60 years of oil production in Niger Delta]: altlasten spectrum, vol. 2012 (1), 19 – 27 [in German language]

[3] Amajor, L. C. (1991): Aquifers in the Benin formation (Miocene – recent), eastern Niger delta, Nigeria. Lithostratigraphy, hydraulics, and water quality: Environ. Geol. Water Sciences, vol. 17 (2), 85 – 101.

[4] Obinna, F. C. (2010): Data on the Hydrogeology of the Niger Delta with special Reference to Ogoni Communities: UNEP study, Port Harcourt, Nigeria, 16 pp.

[5] USDA (2002): Soil taxonomy – A basic system of soil classification for making and interpreting soil surveys: NRCS, US Dept. Agriculture, Soil Survey Staff, Washington, 2nd ed., 871 pp.

[6] FAO (1974): Soil taxonomy (World soil classification): Soil map of the world: Food and Agriculture Organization of the United Nations, Rome, Italy, vol. 1, 59 pp.

[7] Amund, O. O.; Akangbou, T. S. (1993): Microbial degradation of four Nigerian crude oils in an estuarine microcosm: Letters Appl. Microbiol., vol. 16 (3), 118 – 121.

[8] Antai, S. P. (1990): Biodegradation of Bonny light crude oil by *Bacillus sp.* and *Pseudomonas sp.*: Waste management, vol. 10 (1), 61 – 64.

[9] Deekae, S. N.; Henrion, R. (1993): Multivariate analysis of species distribution: A survey on occurrence of mangrove mollusks in the Bonny and New Calabar rivers of the Niger delta: Acta hydrochim. hydrobiol, vol. 21 (5), 273 – 279.

[10] Department of Petroleum Resources (DPR) (1991): Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN): Lagos, revised edition 2002, 451 pp.

[11] Ministerie van VROM (2000): Dutch Target and Intervention Values 2000 (the New Dutch List): Staatssuitgeverij, Den Haag, NL, 51 pp.

[12] Ayotamuno, J. M. (2010): Desk Top Study of the Ejama-Ebubu Contaminated Lands: Fac. Engineering, Rivers State Univ. of Science & Technology, Port Harcourt, Nigeria; 21 pp.

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