Mathematically Aided Risk Assessment of Crude Oil Contamination in Ogoni, Nigeria

Part 3. Spatial Model of the Multiple Contamination

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Abstract

Mathematical modeling can support environmental risk assessment and decision making processes. Soil contamination caused by crude oil in the Ogoni region, Nigeria, is described in detail in part 1 [10] to understand expected mathematical results. A mathematical-statistical analysis following in part 2 [11] characterizes 33 contaminated sites as entire ecological complex. The sites are studied in part 3 by multivariate classifying models to derive precise information about kind and degree of contamination at every studied location.

The 33 sites were studied by multivariate heuristic classifying methods (cluster analyses). Resulting classes or groups include all samples which are similar with respect to their pollution. The amount of 665 analyzed samples was reduced to 28 classes distinguishable by kind and degree of pollution. Mutual relationships between the classes were visualized by dendrograms. The calculated averaged properties of each class have been attached to any sample belonging to a class. Additionally, the geographic origin and depth of each sample was introduced to localize the pollution.

The cluster membership of any sample can be marked by symbolic colors and visualized in mini-profiles which were drawn into geographic layers. Four sites in Ogoni have been selected to show and to discuss the result.

Introduction

Object of the case study is the ecologically extremely sensible Ogoni region within the Rivers State, Republic of Nigeria, where crude oil was produced, handled and transported for 50 years. The United Nations Environmental Program (UNEP) was invited to survey the Ogoni area to assess possible ecological damage due to these activities. NZIDEE reported recently that fieldwork and laboratory analyses are now completed to develop an "independent assessment of the environment and public health impacts in oil contamination" in Ogoni [7].

The application of suitable mathematical models within the frame of these activities shall open new approaches to define locations and extension for necessary clean-up measures.

Altogether 33 polluted sites in Ogoni were investigated by shallow bore holes. The generalizing statistical analysis of about 660 subsoil samples shows a wide range of contamination caused by aliphatic and aromatic hydrocarbons [10, 11].

Statistical descriptions are outlining an investigated data set as an entire "random sample". More detailed results regarding single sites, points or samples can be expected by the application of multivariate classifying models.

Primary Determination of Classes of Contamination

Topic. It was shown that crude oil contaminations in subsoil have a very complex composition [10]. They are varying at every location by quality and quantity depending on the oil-type, on soil properties, on the distance to surface or to the groundwater level, on the time since the impact happened and other factors. An evaluation of the obtained data is difficult especially in cases where several oil compounds are chemically analyzed, e. g. short and long chain aliphatic hydrocarbons, benzene, ethylbenzene, cresols, xylols, phenols or more constituents in several hundreds of samples. It might become complicated to consider all samples with their special character of pollution adequately just by a view onto the data file. This problem increases if more than two describing attributes have to be considered.

Heuristic mathematical methods are helpful and suitable to group (to classify) the manifold of information before decisions about the further treatment of a contaminated site have to be made.

In Ogoni, full chemical analyses were available for two crude oil compounds only: for the sum of aliphatic and the sum of aromatic hydrocarbons. The restriction to only two attributes facilitates the modeling. The multivariability is reduced to two dimensions but it can be extended to any higher number.

Methods. Mathematical multivariate classification models are suitable to recognize patterns within multivariately described sets of objects. Such a pattern can be built up by groups of samples from extremely high and complex contaminated sites, samples that are intolerably polluted by aromatic hydrocarbons only, samples showing no pollution whatsoever and so on. A cluster analytical model has to fragment the entity of involved objects (samples) by all their involved properties into quasi homogenous groups without any prior knowledge of the interior structure of the investigated entirety of objects. At the same time, it has to define the class to which any sample is belonging and to characterize the average parameters of such a class. (A discriminant analytical model has to be applied instead of a cluster analysis if there is a certain prior knowledge about the class membership of investigated objects or samples, e. g. due to its geological age or to a certain geological sequence.)

Multivariate classifications without prior knowledge belong to heuristic models. They are based on heuristic experience and act as an expert would do. For example, they take a first sample and their data (the concentration values of pollutants) and have a look to all other samples and their data to recognize similarly composed cases. Similarly composed samples will be merged into one class. Less or not similar samples form a (maybe: new) second class etc.

Classes are growing whilst the ongoing classification process. Their average properties can slightly change in this course until the classification process is finished.

Several factors are influencing the result of multivariate classifications, first of all, number and kind of the involved attributes (here: contaminants). The expert is responsible to determine a qualified selection of attributes to be involved: thus, he can control the result. Parameters having small measuring values cannot influence the result as much as such with great values: a value transformation is useful to avoid undesired effects. Furthermore, attributes that are strongly correlated jointly influence the result more than not correlated parameters. The expert has to consider this effect and eliminate some attributes if necessary. Finally, the mode of unification of similarly

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composed samples, of determination of their common properties and of the definition of distances to other classes can influence the final result. In one word: there is no "the classification"!

Quick cluster analyses implemented in computer software packages are suitable to process great numbers (n > 100) of samples. They operate as mentioned above. The involved attributes regarding the subsoil contamination in Ogoni were not standardized to mean = 0 and stddev = 1 before because the range of values is nearly the same for the attributes aliphatic and aromatic hydrocarbons (where mean denotes the arithmetical mean value, stddev – the standard deviation). Both parameters influence the result therefore in an equivalent scale. Quick cluster analyses result in a certain number of (before given by the expert) classes. The membership of each sample to one of the classes will be registered. Arithmetically averaged properties of each attribute will be displayed for each class (cluster centers). Mutual relations between the groups, however, cannot be calculated because quick clustering belongs to the non-hierarchical models.

The cluster centers of primary quick clustered classes can be used as input for a following hierarchical cluster analysis. These models are suitable for smaller numbers of objects to be classified. They calculate multivariate distances between each pair of objects (here: the obtained cluster centers) and arrange the objects by their distance measures in a dendrogram. The primary cluster center values shall be first normalized to mean = 0 and stddev = 1 regarding their wide-spread value ranges. A quadratic Euclidean distance measure and average linkage method may be applied but it is possible to test other entries and to choose the best interpretable one. The dendrogram visualizes the connection between the primary cluster centers. Two classes are relatively similar to each other if their distance on the vertical axis is low and vice versa. The distance itself is without any environmental meaning.

Table 1 **Characteristics of primary step cluster centers for 665 samples**

Cluster no.	Mean content aliphatics	Mean content aromatics	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	a 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.

Result. Ten resulting clusters (primary classes) had been set by the authors. This is a reasonable number based on experience. The quick cluster analysis grouped all 665 involved samples with respect to the two attributes "aliphatic pollution" and "aromatic pollution". Table 1 shows the identification of classes (here: no. 01 to 10), number of involved samples, and averaged attributes for the contamination. It even can be expanded by the sample ID's of every involved sample if necessary. The averaged characteristics of each class allow describing and derivation of recommendations for the future handling of the sites or layers represented by the samples.

Already a first overview shows that the amount of hundreds of more or less polluted samples can be subdivided into well distinguishable classes. This result is not self-evident: there are cases where all classified objects are very similar to each other.

The mutual relation – similarity ore dissimilarity – between the obtained 10 primary classes can be seen in Figure 1.

The four samples contained in cluster no. 01 show very high aromatic pollutions combined with negligible aliphatic concentrations. Clusters no. 04 to 10 include samples that are extremely high contaminated with both parameters. Land use at these places seems to be at least temporarily impossible and problems due to hazardous groundwater abstraction are foreseeable. Table 2 is reduced to the group membership of all samples representing extremely contaminated sites and locations; this applies to class no. 01 and 04 to 10. They include altogether 40 (of 665 studied) samples – a relatively agreeable amount. The Table also informs about location and sampling depth. This information has to be added to the mathematical result manually.

Cluster classes no. 02 and 03 unite 96 and 529 samples respectively. This is the bulk volume of analytical data. The majority – 529 out of 665 samples – is only moderate or not contaminated! This is valuable information regarding the environment in Ogoni. Furthermore, it shows that ad-hoc clean-up programs were already successful in many parts of the region.

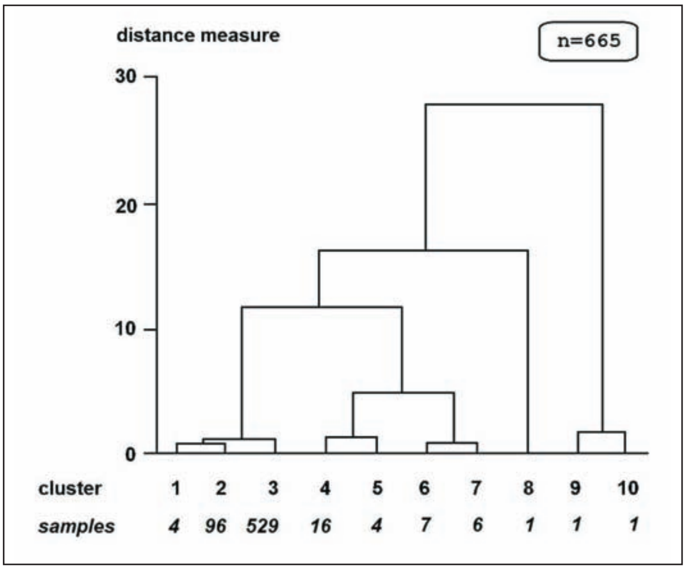

Fig. 1 Primary cluster analysis of 665 samples

Samples within each of the groups no. 02 and 03 are relatively similar to each other. A new modeling approach would be required to handle such a great amount of similarly contaminated samples.

Dissection of Undifferentiated Cluster Classes

Topic. The samples not yet differentiated by their chemical composition show a high similarity. Figure 1 illustrates this fact by short distances along the vertical axis. It is nearly impossible to subdivide these compacted classes e. g. by choosing more than 10 primary classes. Preliminary tests have shown that an approach using more than 10 classes leads to a preferred splitting of classes which are less occupied by objects (dissimilarly contaminated samples). But this effect is not wanted.

Experience made at the vertical stratification of lithological profiles composed of several hundreds of specimen by multivariate cluster analysis resulted in the creation of two-step cluster analyses as a new methodological approach. It was tested with mineralogical and geochemical parameters and led to interesting results [4, 9]. A refinement of results will be obtained by such splitting the entire data pool into subgroups.

Method. The basic idea is to continue a primary cluster analysis – carried out by quick cluster or hierarchical cluster analysis – by a more sophisticated secondary cluster analysis. Mutual distances between the attributes of multivariately determined samples within the multivariate parameter space will be diminished if single primary cluster classes are classified again but without “disturbing” dissimilar samples.

The computing procedure is the same as at primary cluster analyses. The second step can be carried out for any primary cluster class but it is recommended to apply it especially for classes characterized by a large number of similarly polluted samples. Thus, more detailed structures of the studied project can be recognized.

Table 2 **Samples belonging to exposed primary cluster classes**

Primary step cluster **no.**	Site	Sample no.	Sampling depth cm from	to	mean	Aliphatics mg/kg	Aromatics mg/kg
01	Kpite S	401	50	100	75	2060	2830
	Wiikayako	300	0	30	15	510	2710
		501	0	70	35	1180	5010
	Kegbara	530	0	50	25	3720	4130
04	Ejama	211	80	280	180	6400	1550
		220	0	20	10	8670	2310
		222	140	220	180	10,700	4080
		302	240	300	270	8610	1870
		321	140	300	220	7790	2090
		402	200	300	250	11,000	3200
		503	200	300	250	7420	3340
		511	0	113	57	7080	4440
		531	0	30	15	7910	4160
	Obolo N	220	0	40	20	6120	4310
	Nsisioken	402	200	300	250	6380	2160
	Dere	210	0	20	10	7160	1820
	Wiibusuu	421	50	100	75	8860	4380
	Bela S	222	220	250	235	6410	3990
	Bela N	322	120	200	160	7520	3160
	Kpor	502	20	40	30	6240	3390
05	Ejama	311	15	60	38	8490	5550
		532	30	300	165	7080	6560
	Kpor	300	0	40	20	8940	6520
	Kegbara	531	50	200	125	10,100	8420
06	Ejama	210	20	80	50	12,900	3980
		310	0	15	8	11,300	3160
		320	0	140	70	14,400	5820
		420	0	100	50	12,400	2870
		501	0	40	20	14,000	3760
	Wiibusuu	422	100	250	175	15,200	5210
	Kpor	302	200	260	230	14,200	4460
07	Ejama	221	0	140	70	13,200	7660
		400	0	100	50	16,400	6390
		401	100	200	150	15,400	5510
		421	100	200	150	17,600	6790
		422	200	300	250	14,100	6740
	Kpor	501	0	20	10	16,000	7270
08	Ejama	300	0	140	70	28,200	8390
09	Ejama	502	40	75	58	19,400	9870
10	Ejama	301	140	240	190	23,100	8390

Results. A two-step cluster analysis was made for cluster no. 02. Its samples as a whole show yet acceptable concentrations of aliphatics but inacceptable high concentration of aromatic hydrocarbons (averaged 1500 ppm). All 96 highly aliphatic polluted samples belonging to this group have been classified again to subdivide the relatively great amount of samples. Such, new sub- cluster centers at a second (lower) level were created and described (Table 3) and a new secondary dendrogram (Figure 2: left side below) was generated. The ten sub-classes are described as no. 20 to 29. They completely replace the former cluster class no. 02.

The detailed analysis made by the second-step cluster analysis explains that there are different types of crude oil caused pollution in the studied soil. These different types maybe occur due to their different sources of production or due to their different age and stage of degradation etc. Nevertheless, amount and kind of pollution are high, very high or extremely high at these locations. At least, detailed investigation and temporarily restricted land use are recommended but it is foreseeable that intensive remediation measures have to be planned for these sites.

All 529 moderately or not polluted samples forming the primary cluster no. 03 were also classified in a second step to sub-classify the great amount of individual samples. New sub-cluster centers at the second (lower) level were created, described (Table 4) and illustrated in a new dendrogram (Figure 2: right side below). The ten sub-classes are described as no. 30 to 39. They completely replace the former cluster class no. 03.

It is obvious that these samples do not represent

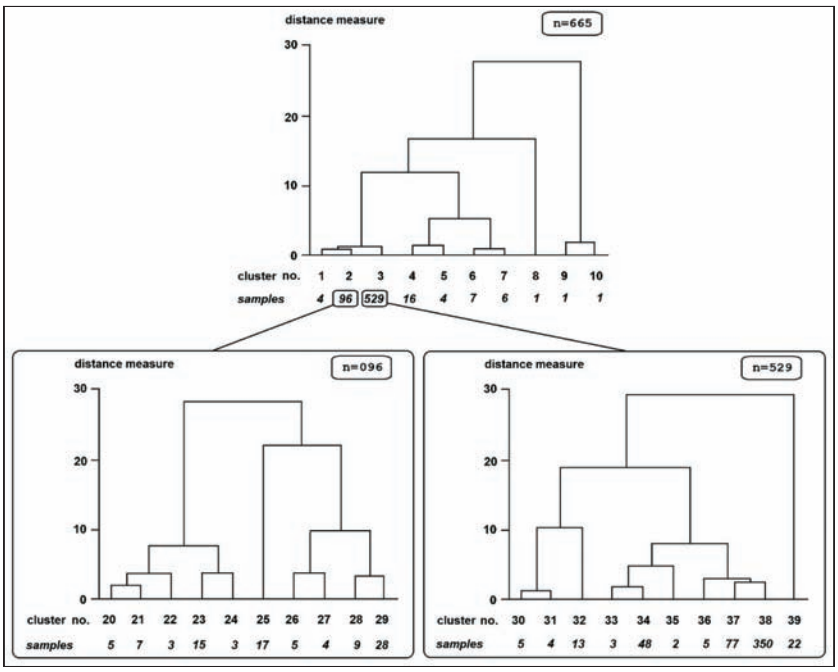

Fig. 2 **Two-step-cluster analysis of 665 samples taken at Ogoni**

Table 3 **Characteristics of second-step-cluster center for 96 highly by aliphatics polluted samples (first-step-cluster no. 02)**

Cluster no.	Mean content aliphatics	Mean content aromatics	Number of samples	Description and recommendations
20	5410	1080	5	high aromatic pollution; detailed exploration is recommended.
21	2070	1640	7	high aromatic pollution; remediation seems to be required.
22	4420	2860	3	very high aromatic pollution; remediation seems to be required.
23	2150	630	15	polluted by aromatics; detailed exploration and restricted land use only is recom mended.
24	5390	4310	3	extreme aromatic pollution; remediation seems to be required.
25	4050	1420	17	high aromatic pollution; remediation seems to be required.
26	3230	2120	5	very high aromatic pollution; remediation seems to be required.
27	5610	1930	4	very high aromatic pollution; remediation seems to be required.
28	5620	2850	9	very high aromatic pollution; increased aliphatic pollution; remediation seems to be required.
29	2770	1070	28	high aromatic pollution; detailed exploration is recommended.

Table 4 **Characteristics of second-step-cluster center for 529 mostly moderately contaminated samples (first-step-cluster no. 03)**

Cluster no.	Mean content aliphatics	Mean content aromatics	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.

the maximum contaminated subareas but their content of aromatics seems to require further activities before land and groundwater can be used without any restrictions.
The studied sites in Ogoni as a whole show a main amount of samples – 529 soil samples or 4/5 of involved samples (cluster no. 03) – with relatively low concentrations of aliphatics (270 ppm) but distinctly higher concentrations of aromatics (140 ppm).
Their secondary subdivision results in the very important class no. 38. All 350 samples united in this group are nearly clean: the average content of contaminants is 54 ppm and 33 ppm respectively. These samples represent subareas in which further cleaning up or monitoring activities can be excluded. Marking them on the map, these parts of Ogoni can be assigned for future land use without any restrictions. It is interesting that about 53% of all investigated samples belong to this quasi "clean" class!
Cluster class no. 37 is occupied by 77 samples (about 12% of the studied material) showing moderate pollution. The concentration of aromatic hydrocarbons in soil exceeds the recommended intervention value slightly, whereas the aliphatics can be neglected. It may be recommended to monitor these spots, sites and subareas represented by these samples over a certain period for effects of natural attenuation. Physical remediation measures are not necessary here.

Geographical Extension of Cluster Classes

Topic. Contamination caused by crude oil impacts is inseparably connected with the place and depth of sampling of the corresponding site. Next step in the mathematically aided risk assessment is an analysis of the geographical location of obtained cluster classes. There are two approaches: First, it is possible to show the geographical location and distribution of all members of any obtained cluster class – it documents where the samples of this class occur. The second and more important way is to isolate each involved site and to assign it to the class of samples belonging to it – this shows where and at which degree the site is contaminated.
Methods. Best way to solve this problem is the application of a Geographical Information System (GIS). Computerized results of heuristic classification can be transferred directly into this system and displayed in scaled maps. Helpful tools are distinguishable and meaningful symbols to mark the different classes of pollution. GIS applications in environmental studies are state of the art. For instance, Twumasi & Merem [12] studied changes of the coastal environment in the Niger Delta region by applying GIS, and Obinna [8] tries to use GIS to model the impact of gas flaring on the ecosystem.
Another well known model is the construction of isoline maps. It does not require preceding cluster analyses because every attribute characterizing the complex soil pollution is processed independent of other constituents. Isolines have been used for instance to define subareas showing <50 mg/kg, 50 to 5000 mg/kg and >5000 mg/kg TPH (total petroleum hydrocarbons) for the selected case studies at K-Dere (Gokana LGA), Nsisioken-Ogale (Eleme LGA) or Korokoro (Tai LGA) in the UNEP report [13]. The application of such contour mapping is a proper approach because only one common parameter is to be shown. GIS can also be applied to create scaled isoline maps. A set of isoline maps is yet less clear if several chemical pollutants are analyzed. Furthermore, the construction of isoline maps requires more or less equally distributed observation points within the investigated region. This is not given for the Ogoni sites: isolated sites exist in form of elongated structures (following the pipelines) or nests (according to former production sites). Between these

sites vast areas without observation points are located.

Result. It was found that the samples of the primary cluster classes no. 07, 08, 09 and 10 and the half amount of samples classified into cluster no. 04 and 05 – altogether 27 samples – are exclusively situated in the site Ejama-Ebubu. This location represents the maximum pollution of all investigated Ogoni areas and the main contamination is concentrated in a square of about 300 m by 150 m. This area south of the village Ejama-Ebubu has been subject of extensive clean-up measures in the past which have been suspended not completed [2].

The geographical localization of the remaining cluster classes and sub-classes shows a differentiated pattern. Low and high impacted points can be found at nearly all sites close together. As an example, Table 5 informs about the clusters determined for the bore holes in Ejama-Ebubu. Preliminary recommendations are added by applying the international intervention values for soil contamination [11].

The four selected sites show different ecological scenarios. The site Ochanni-Ebubu is close to a village and nearly not polluted. The site Okenta-Alode demonstrates moderate contaminations caused by a pipeline. Impacted sampling points are arranged parallel to the pipeline. The site Okuluebu-Ogale is situated within a forest and shows high and less contaminated points next to each other – a typical punctual pollution with sharp boundaries. Residents are not directly exposed but the site represents a severe impact on nature.

The present or absent dependencies of concentrations on the sampling depth can be learnt also from Table 5. The evaluation confirms that there is not any systematical decreasing or increasing of pollution at changing depths.

A compilation of such information for every studied site may be useful if decisions with respect to the further treatment of sites will be made.

Table 5 comprises all available information that characterizes an investigated site. But 33 equivalent tables could have to be developed and interpreted in the present case study. A new approach is required to develop spatial or quasi spatial models of contamination.

Table 5 **Cluster membership of samples taken at Ejama-Ebubu, LGA Eleme**

Borehole no.	Cluster no. Top		Bottom	Description and recommendations
20	38	38	–	not significantly contaminated.
21	06	02	27	top extreme contents of aliphatics and aromatics; deeper parts: high aromatic pollution; bottom: very high aromatic pollution – remediation seems to be required.
22	02	07	02	top: high aromatic pollution; deeper parts: extreme contents of aliphatics and aromatics; bottom: high aromatic pollution – remediation seems to be required.
30	10	09	02	top to deeper parts: extreme contents of aliphatics and aromatics; bottom: high aromatic pollution. Remediation seems to be required.
30a	38	38	–	not significantly contaminated (?)
31	06	04	23	top: extreme contents of aliphatics and aromatics; deeper parts: high aliphatic and very high aromatic pollution; bottom: polluted by aromatics – detailed exploration is recommended combined with restricted land use.
31a	38	38	–	not significantly contaminated (?)
32	06	02	–	top: extreme contents of aliphatics and aromatics; bottom: high aromatic pollution.
32a	38	–	–	not significantly contaminated (?)
33	37	–	–	negligibly contaminated; monitoring is recommended.
40	07	07	02	top to deeper parts: extreme contents of aliphatics and aromatics; bottom: high aromatic pollution. Remediation seems to be required.
40a	38	–	–	not significantly contaminated (?)
41	25	34	30	top: high aromatic pollution – remediation is required; deeper parts moderately polluted by aromatics and detailed exploration recommended; bottom polluted by aromatics and detailed exploration is recommended combined with restricted land use.
41a	38	–	–	not significantly contaminated (?)
42	06	07	07	top: extreme contents of aliphatics and aromatics; deeper parts to bottom: extreme contents of aliphatics and aromatics.
43	37	29	–	top negligibly contaminated: monitoring recommended; bottom: high aromatic pollution – a detailed exploration is recommended.
50	06	08	02	top: extreme contents of aliphatics and aromatics; deeper parts: maximum contents of aliphatics and aromatics; bottom: high aromatic pollution. Remediation seems to be required.
51	02	39	—-	top: high aromatic pollution; bottom moderately polluted by aromatics: detailed exploration is recommended.
52	30	37	—-	top polluted by aromatics: detailed exploration recommended and restricted land use; bottom negligibly contaminated but monitoring is recommended.
53	02	04	—-	top: high aromatic pollution; bottom: high aliphatic and very high aromatic pollution. Remediation seems to be required.

Spatial Model of Contamination

Topic. The geographical extension of cluster classes can be displayed commercially based on GIS. The product is a multivariate map showing a two-dimensional distribution of several classes each characterized by degree and kind of contamination. It is also possible but costly in terms of labor to design such a map manually by drawing symbols into usual surface maps.

A spatial model, however, will enlarge the two-dimensional representation. Thus, it will be tried to introduce the third space dimension into the geographic map and to generate quasi 3D maps.

Method. Instructive satellite images put into the World Wide Web by the Google Inc. [6] have been used as basic layers in the present study due to the lack of any cartographic documents. The quality of the Google maps is excellent and allows a localization of the sampling points with a sufficient accuracy.

The sampling depth as third dimension could be introduced going back to an early concept realized at the representation of German lignite deposits or lithological constitution of sedimentary sequences (e. g. [1, 5]): vertical mini-profiles were designed and put to the geographical bore hole location. They inform about essential qualitative and quantitative properties of the strata series drawn to scale and can be surveyed quick and easy within a cartographic map.

This suggestion has been modified in the present application: small profiles which are not to scale were introduced into the mapped basic layer. They are built up by one to four sampled horizons corresponding to the sampling scheme. Each horizon is represented by a small square independent of the thickness of the sampling interval. Every square will be marked by the corresponding cluster number which is representative for the character (kind and degree) of contamination and for first risk assessments as registered in Table 5 as an example. Colored boxes have been applied according to a graded scale of colors instead of the cluster numbers. They

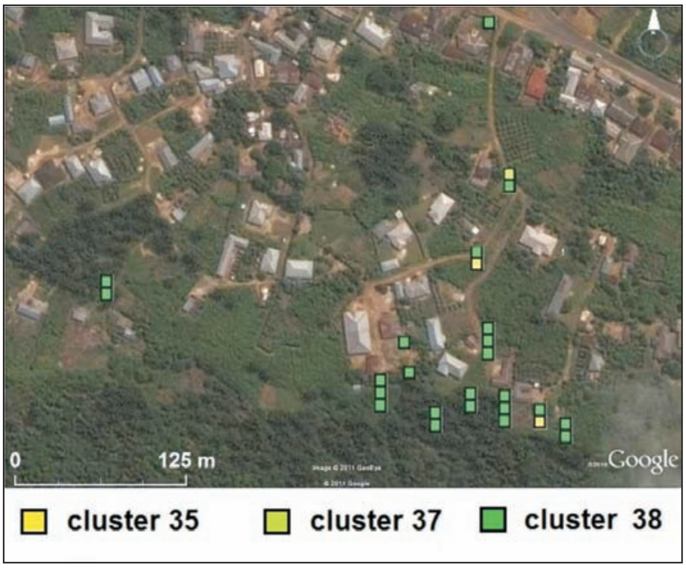

Fig. 3 Contamination pattern Ochanni-Ebubu, LGA Eleme. – Basic layer from Google maps (2011). Image ©2011 GeoEye; ©2011 Google

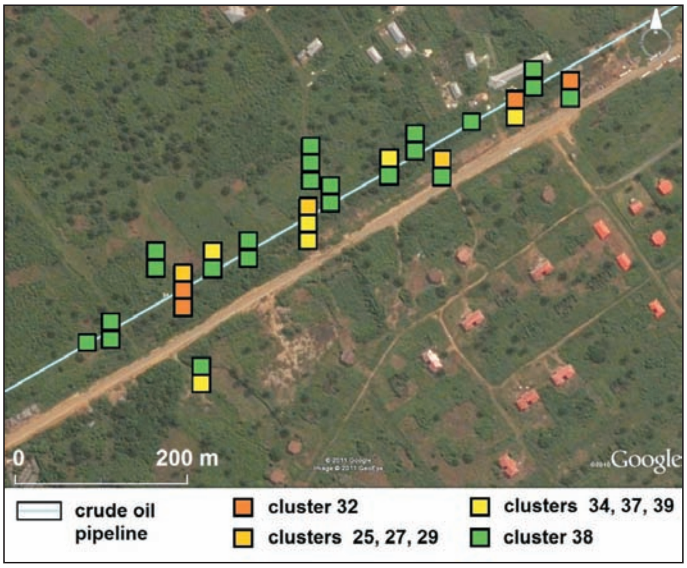

Fig. 4 Contamination pattern Okenta-Alode, LGA Eleme. – Basic layer from Google maps (2011). Image ©2011 GeoEye; ©Google 2011

allow distinguishing between cluster classes of pollution as mentioned above, e. g. green boxes for clean or nearly unpolluted points, yellow ones for moderately contaminated, orange and red marks for high degree contamination.

Maps no. 12 to no. 16 issued at pages 113 to 134 in the UNEP report [13] show also light and dark yellowish colored squares. These signs, however, are not identical with the small boxes introduced in this contribution. They simply mark the position of different sampling locations in contaminated Ogoni sites whereas the squares presented here include a lot of information about position, depth, kind and degree of pollution obtained by mathematical cluster analyses.

This approach reduces considerably the amount of different contamination patterns: At the beginning, there were more than 600 different samples and each of it has its own multiple environmental characteristic, defined by the specific spectrum of contaminants and level of their concentration. Consequently, more than 600 specifiable signs had to be drawn into the basic cartographic layers. It is impossible to recognize any contamination pattern by this way. Next, the cluster analysis has reduced the number of distinguishable pollutions to an amount of 28. It may be possible to differentiate between 28 kinds of contamination using colors and supplementing symbols. A quick interpretation, however, is still difficult. The final step was to merge similar classes of soil pollution and ecological recommendations to that groups represented in Figures 3 to 6 and marked by green, yellowish green, light yellow, dark yellow, orange, and red colors.

Results. Figures 3 to 6 visualize the environmental situation in the four selected sites. It is easy to recognize the location of investigated points, the association with former or recent facilities of the crude oil extraction and transport, and the adjacencies like villages, surface waters, sensible environmental subareas etc. At the same time, the vertical distribution of cluster classes regarding contaminating aliphatic and aromatic hydrocarbons can be detected and evaluated. The general impression and all details open up at a glance. A risk assessment of crude oil contamination can be supported and made easier not only in Ogoni but also at any other region in the Niger Delta and worldwide.

Figure 3 shows 13 shallow boreholes drilled in the middle of the residential area Ochanni-Ebubu in the LGA Eleme. The location is about 20 km ESE of Port Harcourt and covers an area of 150 m by 150 m. The analytical results proof that there is no or only little contamination present from the surface to the final depths of the drillings. Private hand-dug water wells in that area are not endangered by impacts of hydrocarbons. The site can be "discharged" from the stock of contaminated sites.

Seventeen drillings have been arranged over 650 m along a pipeline which runs parallel

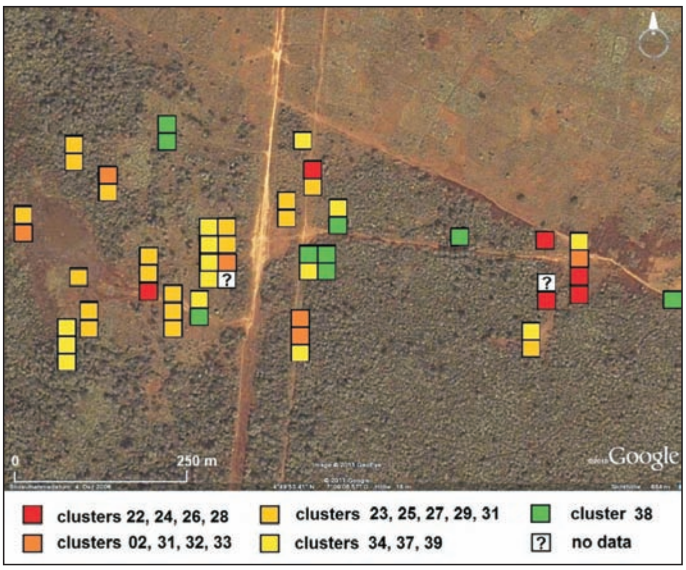

Fig. 5 Contamination pattern Okuluebu-Ogale, LGA Eleme. – Basic layer from Google maps (2011). Image ©2011 GeoEye; ©Google 2011

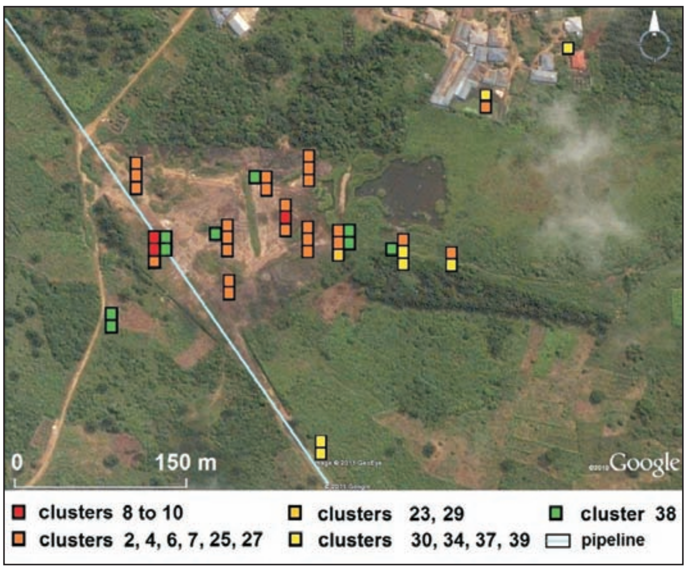

Fig. 6 Contamination pattern Ejama-Ebubu, LGA Eleme. – Basic layer from Google maps (2011). Image ©2011 GeoEye; ©2011 Google

to a road connecting the highway to Port Harcourt with a refinery (Fig. 4). The site Okenta-Alode is located nearly 12 km east of Port Harcourt and is close to residential buildings in a distance of about 200 m. The contamination is generally moderate. Isolated samples with higher concentrations occur in various depths. The isolated ("punctual") character of the contamination and the absence of vulnerable goods of private or public interest nearby makes remediation activities not necessary. The next area with strong groundwater contamination is about 1.5 km away from the site close to the refinery.

25 drillings have been located close to the pipeline next to Okuluebu-Ogale shown in Figure 5. This site is located 11 km ESE of the Eleme Junction or 6 km N of Ejama-Ebubu respectively. The center of the figure shows an area of 400 m by 200 m with no vegetation and degraded growth of plants which indicates a former oil spill. The contamination in the upper soil is generally moderate, but isolated samples with high concentrations in various depths indicate an incomplete remediation of the oil spill. In the eastern part seems to be another oil spill with high concentrations throughout the entire profile. Remediation is recommended because an influence of the contamination on the groundwater has been proven by installed water wells in May 2010, when 7 out of 10 boreholes showed a very strong presence of hydrocarbons exceeding the depth of 12 m. The seven highly contaminated boreholes are situated adjacent to the pipeline or 100 to 200 m west of it, where the vegetation is degraded. Figure 5 nevertheless shows relatively clean soil conditions there. On the contrary to the impression Figure 5 gives, the logs of three water wells installed in May 2010 close to the highly impacted area about 400 to 500 m east of the pipeline recorded no or only slight hydrocarbon odor. One major oil spill obviously happened west of the pipeline, where the shallow boreholes for soil sampling did not reach the still present contaminated underground. This causes a false impression of the real situation. An isolated, relatively shallow and not remediated contamination is situated east of the pipeline. It has been detected by the shallow drillings. However, this spill did affect deeper strata only slightly. The site is also characterized by dangerous soil contamination deeper than three meters below surface. A sufficient ecological risk assessment cannot be made if these deeper parts of subsoil are not sampled and analyzed. It was already stated that only 16% of all samples taken in the UNEP project are covering a depth below 1.5 m and that it is impossible to evaluate the general pollution of Ogoni subsoil in greater depths [10, 11]. It can be recommended to extend forthcoming drilling campaigns to significantly deeper horizons to detect residual dangerous contamination which might impact the upper groundwater level.

The contaminated site Ejama-Ebubu shown in Figure 6 is situated 20 km east of Port Harcourt. It covers an area of about 150 m by 150 m. Hydrocarbon bearing sludge analyzed by Ayotamuno, Akor & Daka [3] showed a total hydrocarbon content of 98,000 ± 150 mg/kg within the top soil down to a depth of 24 cm. This site was partially decontaminated yet in 2006 by re-enhanced natural attenuation (RENA). RENA was described by the authors as an "integrated biological and physic-chemical process" using water, sunlight, aerial oxygen and nutrients under tropical conditions in the Niger Delta. The initiated clean-up measures, however, were suddenly stopped. Ayotamuno [2] noticed: "This did not achieve much result as the work was stopped midway during the excavation and segregation of heavily contaminated soil from relatively clean soils." He reasons that now deeper excavation is necessary to explore yet existing hot spots covered by already remediated material. The Ejama-Ebubu site is distinctly contaminated due to several oil spills in the past. The situation is sensible due to directly exposed goods of private or public interest in a village only 200 m to the north and a university campus about 400 m to the SE An area with no vegetation and degraded growth of plants in the center of the site mark the incomplete remediation that took place by soil excavation, soil tilling and soil translocation. Figure 6 shows the presence of some of the highest contaminated clusters (clusters no. 8 to 10 and 2 to 7) close to the pipeline and in the center of the site. The area is still extremely contaminated although the contamination seems to diminish towards the residential areas in the north. A shallow pond in the center functions as a pathway for mobilized hydrocarbons especially in the rainy season carrying hydrocarbons to a swampy area about 1 km in the east. Negligible polluted points are adjacent to remarkable contaminated sampling points (green marked squares next to orange or red ones). The presented mathematical model fully confirms the statement made by Ayotamuno [2]. It verifies also previous general statistical results [11]: the possibly contaminated soil samples taken at Ogoni as a whole area do not show any dependency of hydrocarbon contents on the sampling depth.

Especially Figures 5 and 6 show the direct vicinity of very high and moderately contaminated samples and sampling locations. Contaminated boreholes and boreholes without dangerous concentrations of hydrocarbons in soil are sometimes only few meters away from each other.

Conclusions

Application of cluster analyses. Cluster analyses can be valuable tools to support decision making processes in environmental risk assessment. A splitting of the large data set into quasi homogenous groups was obtained by a two-step cluster analysis. This approach reduces the number of objects which are to distinguish remarkably. Two main classes containing the main part of low to moderate polluted samples are accompanied by eight classes with distinct pollution that should be investigated in detail. The two main classes it selves were grouped again and they generated two important subgroups of samples which are only moderately or not polluted by aliphatic and aromatic hydrocarbons. These mathematical models facilitate the interpretation of great data files. They are available in several software packages.

Localization of clustered samples. The interpretation of location and sampling depth of contaminated and unpolluted samples as well and the design of a corresponding geographical map allow a correlation between geographical position, geological milieu and environment and kind and degree of soil contamination. This step should be made by applying GIS.

3D modeling of areal contamination. A clear impression of lateral extension, depth distribution, kind and degree of contamination within an extended area consisting of numerous sites gives a 3D or quasi 3D model. It can be created by drawing short vertical profiles on a geographical surface using cluster classes. This presentation concentrates all information contained in a large data set. It is easy understandable and instructive and can serve at decision making after an environmental risk assessment.

Recommendation. It is recommended to combine usual statistical evaluations regarding partly contaminated regions with calculation and graphical representation of classes of similarly polluted samples, spots, or sites. Input and expense of this approach are agreeable if existing computer software and GIS will be applied.

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