Sediment Hydrocarbons in Former Mangrove Areas, Southern Ogoniland, Eastern Niger Delta, Nigeria

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Abstract

The sediments and former mangrove areas near the town of Bodo in the Niger Delta are highly contaminated in the upper 20 cm by oil residues. The oil pollution resulting from two spills of approximately 10,000 t of Bonny Light crude oil in 2008 from the Trans-Niger Pipeline (TNP) killed mangroves in more than 1000 ha of local creeks. The impact of pollution in 2008 was exacerbated from late 2009 by increased transport and artisanal refining of crude oil stolen from tapped pipelines. It has been controversial which source of impact is the more relevant. Areas still contaminated include traditional fishing resources used by local communities. After years of preliminary engagement to build trust among stakeholders, the Bodo Mediation Initiative (BMI) was constituted formally in October 2013 to conduct cleanup of sediments in the impacted mangrove areas in an act of community self-management. This was to be accomplished with assistance from Shell Petroleum Development Company (SPDC) and mediation by the Dutch mission, federal and local government agencies, with advice from the United Nations Environment Programme (UNEP). The BMI then planned and undertook a preliminary Shoreline Cleanup Assessment Technique (SCAT) survey of the residual oil. SCAT is an internationally accepted visual survey method using standardized field

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procedures, photography and qualitative record-keeping. SCAT was calibrated using quantitative sediment sampling. These parallel activities were to investigate the degree of contamination, to help plan the cleanup, and to compare the situation before and after cleanup.

Total, aliphatic and aromatic hydrocarbon concentrations were determined using Gas Chromatography with Flame Ionization Detector (GC-FID). The results show the highly contaminated status of the sediments near Bodo in August 2015. Only one (1) of thirty-two (32) surface sediment samples (0–5 cm) showed a concentration of Total Petroleum Hydrocarbons (TPH in the C_5–C_{44} hydrocarbon range) below the Nigerian regulatory limit of 5000 mg/kg. Six (6) samples showed concentrations between 5000 and 10,000 mg/kg, seven (7) samples ranged between 10,000 and 20,000 mg/kg, fifteen (15) between 20,000 and 100,000 mg/kg, and three (3) were contaminated at levels above 100,000 mg/kg. Fifty-five (55) samples were taken at two different depths (0–5 cm and 15–20 cm), including the surface dataset. Although concentrations of TPH, aliphatic and aromatic hydrocarbons in the equivalent C_{12}–C_{44} range (EC_{12}–EC_{44}) were elevated in surface and subsurface samples, thirteen (13) of the subsurface samples had TPH concentrations below the Nigerian regulatory limit of 5000 mg/kg. TPH concentrations in three (3) subsurface samples showed concentrations between 5000 and 10,000 mg/kg, ten (10) samples ranged between 10,000 and 20,000 mg/kg, and six (6) between 20,000 and 100,000 mg/kg. The differences between surface and subsurface mean concentrations of TPH, aliphatic and aromatics fraction were each statistically significant ($p < 0.01$). The decreased concentrations from the surface towards deeper strata within the fine-grained sediments were as expected in the absence of significant deposition of new sediment above the oil spill layer. For the lower molecular weight fraction of aromatics (EC_5–EC_{12}) the trends were different. This fraction was detected in fifty-

five (55) samples in much lower concentrations overall, and with only twenty (20) samples exceeding 1 mg/kg, and seven (7) exceeding 5 mg/kg of which six (6) were subsurface samples. Also, in the case of lighter aromatics, the mean concentrations increased significantly with depth ($p < 0.01$) due to their higher volatility and potential for penetrating fine-grained sediments compared to the heavier hydrocarbons.

The Polycyclic Aromatic Hydrocarbons (PAH) concentrations determined by Gas Chromatography-Mass Spectrometry (GC-MS) in 55 samples ranged widely with no significant difference with depth. Although none exceeded the Nigerian regulatory limit of 40 mg/kg, fifteen (15) samples of which seven (7) were in the subsurface, exceeded Environment Canada sediment quality guidelines for the sum of sixteen PAHs (ΣPAH_{16}). A forensics evaluation of the available PAH data suggests the following sources of PAHs: petroleum, combustion of petroleum, and combustion products from wood and grass. This mixture illustrates inputs from both oil industry and illegal refinery activities, overprinted on a baseline of traditional biomass fuels. The SCAT and hydrocarbons results can be used to design practical cleanup and monitoring actions and to assess health risks for people ingesting or exposed to oil above an acceptable daily intake. Recommendations include preparing for the mangrove restoration, addressing possible human health impacts, better law enforcement, and improving employment opportunities in Bodo.

Keywords

Bodo · Contaminated sediments · Intervention values · Oil spill cleanup · PAH isomer fingerprinting · Potential health risk · UNEP environmental assessment

14.1   Introduction

14.1.1   Background

Bodo is a town located in Rivers State, Nigeria with a population total of about 69,000 inhabitants including outlying settlements (Pegg and Zabbey 2013). The study area is in south Ogoniland, near Port Harcourt on the Bonny River in the eastern Niger Delta and bordering the Atlantic Ocean. Bodo is in Gokana Local Government Area (LGA) which has a population of 228,828 (2006 census). Figure 14.1 shows the location of Bodo.

Environmental reviews and surveys of the Niger Delta were carried out in 1983 for SPDC by Baker (1983), in 1983–1985 for the Nigerian National Petroleum Corporation

(NNPC) by RPI (1985), and in 1996 by the Niger Delta Environmental Survey (1997), an industry-funded non-government organisation (NGO). In 2007, UNEP was asked by the federal government of Nigeria to conduct a detailed survey of oil industry environmental and potential health impacts in Ogoniland (LGAs Gokana, Eleme, Tai and Khana). The UNEP findings were published (UNEP 2011) and an overview of conditions on higher land and groundwater as well as intertidal mangrove areas is given below:

Box 14.1. UNEP Environmental Assessment of Ogoniland

– Sediment and groundwater were found to be contaminated by aliphatic and aromatic hydrocarbons mostly within and adjacent to the Right-of-Way (RoW) of onshore pipelines. During construction, the foundation bedding of the pipelines was composed of loosened and/or made ground (usually coarse sandy material). This bedding forms a hydraulic high compared to the ambient undisturbed sediment, which has a lower permeability. Due to this hydraulic gradient the RoW bed often functions as a trap for spilled oil.

– Regression modeling, correlation and non-hierarchical cluster analyses of the analytical data revealed that contamination with aromatic hydrocarbons was locally still very high in samples taken from both recent and years-old spill sites. Contamination was influenced by the intensity and age of the impact, and by the depth of the groundwater table (Thiergärtner and Holtzmann 2014).

– UNEP criticised the remediation procedures typically being used in Ogoniland. Remediation is carried out mostly by contractors which are not instructed to apply state-of-the-art techniques and have often not been supervised adequately. One of the most frequent remediation techniques applied by SPDC in Ogoniland is Remediation by Natural Attenuation (RENA). This is a form of land-farming, involving the excavation and/or aeration of polluted material and the degradation of the hydrocarbons within the sediment under atmospheric conditions, sometimes enhanced by nutrient fluids (bioremediation). In many cases, RENA has failed because insufficiently degraded hydrocarbons in backfilled material led to additional contamination hazards for the population (UNEP 2011; Thiergärtner and Holtzmann 2014).

Box 14.1 (continued)

– Groundwater of the upper aquifer was found to be highly contaminated locally. However, a fully representative analytical screening of the water quality in hand dug wells, the main source for potable water in Ogoniland, was not performed.

– Although systematic health questionnaires were conducted and sources of health risk were correctly identified, no epidemiological effects of the contamination on the health of the population were proven. This was not achievable mainly because a comprehensive physical and medical examination of the local population was not included in the survey.

– Analytical investigation of the tissue of fish and shellfish from local markets showed that hydrocarbon concentrations were compliant with current environmental quality standards and generally lower than 1983 levels in samples collected in the field (Baker 1983). In contrast, the most contaminated fishing areas in 2010 were being avoided by fishermen.

– Plants and agricultural products were not analysed chemically. However, plants showed symptoms of stress, for instance degraded growth, which might be ascribed to contaminated sediment and soils close to the roots.

– UNEP recommended the establishment of an Environmental Restoration Fund for Ogoniland, with estimated costs for the first 5 years of 1 billion US $. This included implementation of: emergency measures (*e.g.*, alternative drinking water sources for those communities with a contaminated water supply); clean-up of contaminated land and intertidal sediments; mangrove transplants and restoration; and accompanying monitoring measures.

The studies described above were not baseline surveys designed to show before-after and control-impact (BACI) effects, because oil had already been discovered in 1956 at Oloibiri-1, and the TNP from Bomu to Bonny was constructed in 1965. Soon after, oil was a central cause of the disastrous Biafran war, and oil pollution and social problems were among its legacies. Eighty-nine (89) producing oil wells were completed in Ogoniland by 1993 when SPDC production was halted by civil unrest. There have been many false starts to the cleanup of oil spills in the Niger Delta, in particular in Ogoniland due to a history of protest against SPDC. Nevertheless, UNEP successfully prepared

the way for the Bodo Mediation Initiative (BMI) during its intensive survey of Ogoniland, including the Bodo area (UNEP 2011). Implementation of the wider UNEP recommendations was announced on 2 June 2016, and on 4 August 2016 the President of Nigeria established a Governing Council and Trust Fund.

Major sources of oil contamination in the area include two operational spills in 2008 prior to the UNEP field work. These spills were caused by pipeline corrosion and resulted in mangrove losses along the TNP crossing Bodo (Gundlach 2013). The mangrove losses in the area of the present chemistry sampling are shown in Fig. 14.1 (Gundlach 2017 this volume). From 2012, the Embassy of The Netherlands in Abuja in conjunction with leading NGOs began the BMI to facilitate cleanup and restoration of sediments in former mangroves near Bodo instead of waiting for an unpredictable outcome from a legal process in a United Kingdom court. Supported by the Nigerian and Dutch governments, in October 2013 the BMI started the formal process for planning and implementation of cleanup. An out-of-court settlement was reached in December 2014 between the Bodo community and SPDC that led to payment of compensation for the entire affected area of the creek, including 1000 ha of mangroves. A remediation project team was established by the BMI with local, national and international experts, regulators, church leaders, NGOs and a UNEP observer, together with employees of SPDC. A primary objective of remediation is to reduce sediment contamination to a level that facilitates recovery of the mangrove habitat and local livelihoods, either naturally or by transplanting mangrove seedlings cultivated in nurseries.

The project area in the Niger Delta consists of intertidal sediments dominated by silts and clays, and bisected by tidal channels mostly accessible only by boat (Figs. 14.2, 14.3 and 14.4). To prepare for the cleanup, the BMI decided to investigate the difficult ground conditions using a visual survey methodology, consistent with the internationally-accepted Shoreline Cleanup Assessment Technique (SCAT; Owens and Sergy 1994; Owens and Sergy 2003). The BMI has successfully brought together the stakeholders and in 2015 conducted preliminary surveys using a multi-disciplinary SCAT approach. It also engaged international cleanup contractors supported by experienced national companies. Despite all field operations being stopped by violent agitation in October 2015, the BMI has maintained the technical and logistical capability to plan and implement the cleanup and restoration of the degraded Bodo mangrove ecosystem. SCAT fieldwork resumed in September 2017.

The BMI decided to verify and calibrate the SCAT findings by commissioning analyses of samples for hydrocarbons in sediments taken from the areas of affected mangroves near Bodo. The aim of this contribution is to
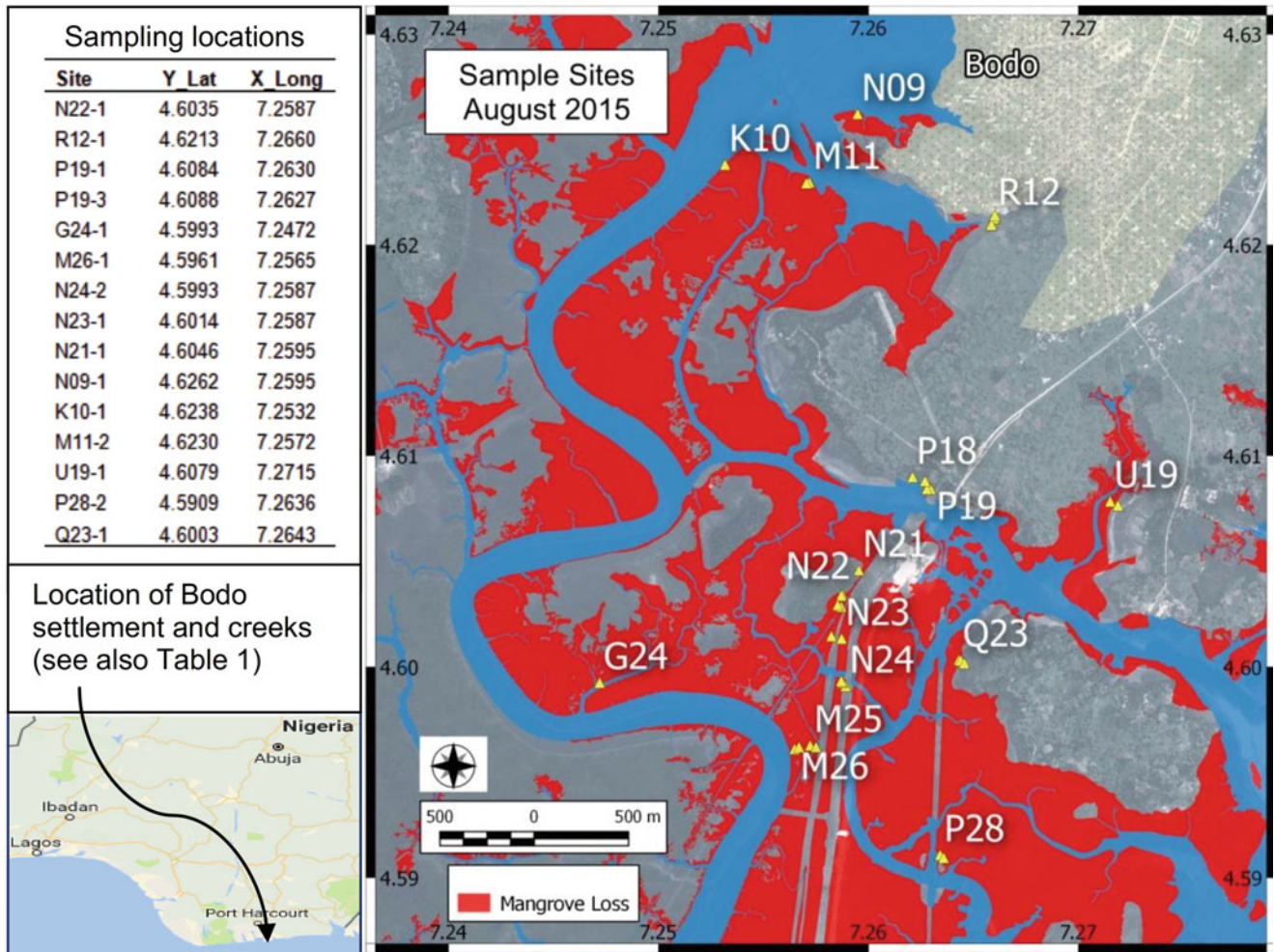
Sampling locations

Location of Bodo settlement and creeks (see also Table 1)

Site	Y_Lat	X_Long
N22-1	4.6035	7.2587
R12-1	4.6213	7.2660
P19-1	4.6084	7.2630
P19-3	4.6088	7.2627
G24-1	4.5993	7.2472
M26-1	4.5961	7.2565
N24-2	4.5993	7.2587
N23-1	4.6014	7.2587
N21-1	4.6046	7.2595
N09-1	4.6262	7.2595
K10-1	4.6238	7.2532
M11-2	4.6230	7.2572
U19-1	4.6079	7.2715
P28-2	4.5909	7.2636
Q23-1	4.6003	7.2643

Fig. 14.1 August 2015 sampling sites near Bodo; mangrove loss defined by Gundlach (this volume)

Fig. 14.2 Typical views of oil-killed mangroves in the Bodo study area, 1 May 2015 (Credit: D. Little)

Fig. 14.3 Difficult working area on fine-grained and low shear-strength mudflats among dead mangroves, 7 May 2015 (Credit: M. Bonte)

Fig. 14.4 Oiled mangroves indicate tidal range; Nipa palms *Nypa fruticans* (Asian invasive species) and terrestrial vegetation visible (Credit: D. Little)

present and discuss the analytical results of the first sampling campaign in August 2015.

14.1.2 Natural Environment Baseline

In January–February 1983 an environmental study of five SPDC-operated areas in the Niger Delta was conducted by Baker (1983). This included the area of the present chemistry sampling on the intertidal mudflats near Bodo. The sediments were described as consisting of accretional poorly-sorted medium to very fine silts (59–99% <63 µm particle diameter). The Bodo area is part of the interconnected Bonny and Andoni rivers system, that are in fact tidal embayments unconnected to the Niger Delta distributary system (NDES 1997). Tidal range is 1.4 m at Bonny town and 1.8 m at Port Harcourt (RPI 1985). Water circulation is driven by flood-tide dominated tidal currents, and salinity is dominated by seasonal rainfall. Steep salinity gradients lead to clay flocculation in the channels, bringing nutrients and suspended muds of mainly marine origin to the intertidal flats and mangrove forest. Salinity is also a primary environmental gradient affecting the local biota, ranging during the early 1983 dry season from 13 to 30 parts per thousand (ppt) from the north of Bodo southwards to the confluence of the Kpador channel with Bonny River (Baker 1983). In the rainy season salinity decreases across all the estuary system (Dublin-Green 1990). For example in April 2013 salinity ranged between 19.5 and 23.5 ppt from Bodo to Bonny River (Gundlach this volume).

Before development of the oil industry in Bodo, the natural vegetation was dense mangrove forest. This formed a self-sustaining coastal defence against Atlantic storms, and supported diverse natural habitats supplying sustainable environmental services to the Ogoni people. In 1983, creeks and mangroves provided nutrient filtration, fish nursery and bird staging areas, and local transport corridors for human access to vital natural resources such as food and wood for building, fuel and making cultural artifacts (Fentiman and Zabbey 2015). For all these reasons mangrove habitats are ranked by the Environmental Sensitivity Index (ESI) as the type of marine shoreline most sensitive to persistent oil pollution world-wide (Gundlach and Hayes 1978), and in particular Nigeria (Gundlach et al. 1981; RPI 1985).

During the 1983 survey across five SPDC-operated areas, the red mangrove *Rhizophora racemosa* was the dominant baseline species along almost the entire forest shoreline of the Bodo West area, with the subordinate species *R. harrisonii* and black mangrove *Avicennia germinas* also found respectively at 14% and 27% of the twenty-two (22) rapid assessment sites. A further species of *Rhizophora* (presumably *R. mangle*) was found at 18% of sites. The intertidal mangrove community was complemented at 45% of sites by low shrubs of *Laguncularia racemosa,* occasionally dense near

creek confluences towards the Bonny River in the south. In 1983, the invasive Nipa palm *Nypa fruticans* was observed mainly in the Forcados area, and only at one of a total of twenty-seven (27) sites in the Bodo area, where it is now more common. Since 1983 these and other ecologically important aspects of the Bodo area have been subject to habitat scale and cascading impacts intensifying after 2008 (Figs. 14.1, 14.2, 14.3 and 14.4). The mangroves formerly provided a firm substrate and shelter for a rich community of invertebrates such as the oyster *Crassostrea gasar*, the fiddler crab *Uca tangeri* and other crabs at 86–90% of sites. Additionally, the isopod *Sphaeroma terebrans* and snail *Littorina angulifera* were found at 33% of the sites, providing a traditional food resource for the community (Baker 1983).

In January–February 1983 surficial (0–5 cm) sediment samples (n = 36) were taken across all five SPDC-operated areas for determination of hydrocarbon concentrations. In the Bodo West area, the arithmetic mean TPH concentration in five (5) composite samples from six (6) intertidal sites in the locality was relatively low at 2690 mg/kg; well below the threshold (intervention) concentration of 5000 mg/kg set more recently by the Nigerian Department of Petroleum Resources (DPR 1991). The Bodo samples were found to range from 110 mg/kg of weathered and partly biogenic hydrocarbons, up to 6750 and 8100 mg/kg of degraded crude oil at two sites respectively near the Bodo wellhead and the confluence with the Bonny River. The first of these two samples that exceeded the current DPR limit had been affected by a spill from the Bodo West flow station in the year prior to the survey by Baker (1983).

Sediment samples (n = 37) in Ogoniland were taken from the 0 to 10 cm depth by UNEP teams in April–November 2010 (UNEP 2011; Lindén and Pålsson 2013; Pålsson and Lindén 2014). The range in TPH concentrations found at the nine (9) intertidal sites in Bodo and the surrounding Gokana LGA was from a minimum of 279 mg/kg (twice that found almost three decades earlier) up to 17,900 mg/kg. This maximum value was also twice that measured in Bodo in 1983, using comparable methods. Six (6) samples exceeded the DPR limit of 5000 mg/kg TPH. The mean value was 7500 mg/kg, almost three times the 1983 mean. Deeper sediment layers at five (5) sites were also sampled in 2010 (UNEP, unpublished). Four (4) of these sites were in the impacted mangrove areas near Bodo. Although the mean TPH concentration of 11,918 mg/kg (n = 4) in the surface 0-10 cm exceeded the DPR limit, the concentrations of TPH, aliphatic and aromatic hydrocarbons were much lower in the 20–30 cm and 40–50 cm layers than in the surface 0-10 cm. The same was true for PAH, except at one site (Bodo West) where the ΣPAH_{16} concentration was 8.09 mg/kg in the 40–50 cm layer. Unpublished data from two independent sampling events in 2014 show high TPH concentrations at 20–40 cm sediment depths. However, these 2014 data were

obtained using different methods to the 1983 and 2010 data that better represent the baseline conditions for comparison with the August 2015 survey, albeit at a different set of sampling sites (see Discussion).

14.2 Methodology

14.2.1 Shoreline Cleanup Assessment Technique (SCAT)

The methodology for the May–August 2015 survey campaign was based on two multi-discipline SCAT surveys and an analytical chemistry investigation in parallel with SCAT. Initially used in 1988 in the 'Nestucca' spill and developed fully during the 1989 'Exxon Valdez' spill, SCAT is now an accepted, codified and internationally established survey methodology (Owens and Sergy 1994; Owens and Sergy 2003). Areas contaminated by oil spills are investigated by multi-disciplinary teams visually assessing factors such as colour, form and degree of oiling, depths of sediment penetration, and obvious biological impacts, but without necessarily taking numerous sediment samples for analyses. SCAT surveys provide a characterization of the severity of oil contamination and build consensus on a recommended cleanup methodology. In this case, the SCAT surveys utilized a 200×200 m grid pattern. The sediment sampling followed this plan in order to link the analytical chemistry results to the field oiling conditions, character and severity, and to justify the proposed cleanup strategy. Before and after cleanup SCAT surveys will be the primary line of evidence to document project success. It was proposed to select a number of sites representing the variability in severity of contamination (e.g., 'heavily oiled' sites to 'rainbow sheen only').

In May 2015, a preliminary ('pre-SCAT') campaign was conducted during 1 week in the Bodo area to plan the main campaign for August 2015 (Gundlach 2015a). SCAT was chosen to prepare the cleanup contractors for the field conditions in the project area and to enable them to apply the appropriate remediation technologies for different site conditions. It was thus the first attempt to develop a broad cleanup plan, including the segmentation and prioritisation of the affected area. SCAT also should enable the contractors to apply the optimal safety and precautionary measures for the work force, including personal protective equipment (PPE).

The aims of the survey undertaken in August 2015 "were to (a) define areas that can be cleaned during the first phase of cleanup, (b) provide an overview of different habitats and levels of oiling, and (c) continue SCAT field training of participants" (Gundlach 2015b). The data collected in both surveys were noted in the field on the 'Shoreline Oiling

Summary Form', and transferred onto maps. In total, fifty-two (52) SCAT sites were surveyed in twenty-nine (29) grid cells during 2015.

14.2.2 Chemistry Sampling and Analyses

The BMI determined that sampling and chemical analysis should not be carried out for each SCAT location surveyed. Instead, samples were collected from a selection of sixteen (16) grid cells to establish representative pre- and post-remediation hydrocarbon concentrations. The BMI advised the project team to conduct the sampling of the designated 1000 ha remediation area in order to calibrate and verify the SCAT data, using multiple samples taken within the same grid pattern as used in the SCAT surveys. Another primary rationale for the chemistry survey was to assess the hydrocarbon concentration in the sediment below which mangroves can survive, regenerate or recolonize.

The 'Bodo Creek Chemical Sampling and Analysis Protocol' was prepared by a Shell employee with input and support from a technical sub-group drawn from the BMI (Bonte 2015). The aim of this exercise was to organize the operations according to international best practices and to be consistent with SPDC's 'Oil Spill Response and Remediation Management System' (SPDC 2013). The samples were collected by a Nigerian company (Geoterrain Nigeria Limited) according to a plan agreed by the BMI. Figure 14.1 and Table 14.1 show the sample site coordinates and dates, arranged primarily along the TNP. The total number of samples was 57, with less data being reported for some parameters due to 'non-detect' values in the laboratory. Samples were sent under chain-of-custody to ALcontrol an ISO 17025 accredited laboratory in the United Kingdom. Key analytical parameters included:

– Methyl tert-Butyl Ether (MTBE), Benzene, Toluene, Ethylbenzene, Xylenes (BTEX);
– Low molecular weight aromatics fraction (C_5–C_{12});
– Total Aliphatics (C_{12}–C_{44}) and aliphatics within specified carbon number ranges;
– Total Aromatics (EC_{12}–EC_{44}) and aromatics within equivalent carbon number ranges;
– Total Petroleum Hydrocarbons (TPH C_5–C_{44}); and
– Polycyclic Aromatic Hydrocarbons (PAH) as individual and total concentrations of the 16 parent PAHs from the US Environmental Protection Agency (USEPA) Priority Pollutant List (Naphthalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benz(a)anthracene, Chrysene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Benzo(a)

Table 14.1 Surface (0–5 cm) sediment sampling locations, dates, contaminants (mg/kg) and SCAT data

Grid	Coordinates		Date	Laboratory data		SCAT fieldwork data		
Site	Lat	Long	2015	TPH	ΣPAH_{16}	Surface	Subsurface	Sediment type
N22-1	4.6035	7.2587	13/08	60,000	16.7	TB	BO, PFP	Chikoko mud
N22-2	4.6034	7.2587	13/08	99,500	16.7	TB	BO, PFP	Chikoko mud
N22-3	4.6029	7.2587	13/08	24,400	1.6	AP, FR	BO, PFP	Chikoko mud
N22-4	4.6029	7.2585	13/08	25,500	5.7	NO	BO, PFP	Chikoko mud
R12-1	4.6213	7.2660	14/08	7700	1.0	SS	SS, PFP	Mud + algal mat
R12-2	4.6210	7.2659	14/08	27,700	0.8	BO	BO, PFP	Soft mud over chikoko
R12-3	4.6214	7.2660	14/08	81,100	12.6	BO	BO, PFP	Soft mud + algal mat
P19-1	4.6084	7.2630	17/08	54,900	10.0	AP	BO, SS, PFP	Chikoko mud
P19-2	4.6084	7.2628	17/08	6410	1.0	TB	BO, PFP	Mud + dead organics
P19-3	4.6088	7.2627	17/08	75,000	9.0	BO	BRO, PFP	Mud mixed with leaves
P18-2	4.6089	7.2621	17/08	88,500	24.2	BO	BO, PFP	Chikoko mud + algal mat
G24-1	4.5993	7.2472	18/08	26,700	n/d	NO	BO, SS, PFP	Chikoko mud
M26-1	4.5961	7.2565	18/08	7110	n/d	NO	BO, SS, PFP	Chikoko mud
M26-2	4.5962	7.2567	18/08	17,700	0.6	NO	BO, SS, PFP	Chikoko mud
M25-3	4.5963	7.2572	18/08	16,400	4.6	NO	BO, SS, PFP	Chikoko mud
M26-4	4.5962	7.2575	18/08	15,000	5.7	NO	BO, OP	Chikoko mud
N24-2	4.5993	7.2587	20/08	111,000	19.9	TB	BO, OP	Mud + algal mat
N24-3	4.5993	7.2587	20/08	17,200	0.9	NO	BO, PFP	Chikoko mud + algal mat
N23-1	4.6014	7.2587	20/08	9570	0.2	SS	BRO, PFP	Silty sand, chikoko, algal mat
N23-2	4.6015	7.2582	20/08	66,600	n/d	TB, SS	BRO, OP	Chikoko mud + algal mat
N21-1	4.6046	7.2595	20/08	8720	7.0	FR	BO, OP	Sand + roots
N09-1	4.6262	7.2595	21/08	135,000	1.2	SS	BO, OP	Chikoko mud + algal mat
K10-1	4.6238	7.2532	21/08	22,500	0.6	SS	BO, PFP	Chikoko mud + algal mat
M11-1	4.6290	7.2571	21/08	117,000	0.6	TB, AP	BO, PFP	Clay
M11-2	4.6230	7.2572	21/08	96,400	19.8	NO	BO, BRO, PFP	Chikoko mud + algal mat
U19-1	4.6079	7.2715	25/08	12,800	0.6	SS	SS, PFP	Chikoko
U19-2	4.6077	7.2719	25/08	3650	n/d	NO	BO, PFP	Chikoko mud + algal mat
P28-1	4.5911	7.2634	25/08	80,700	1.2	AP	BO, OP	Clay + Chikoko + asphalt
P28-2	4.5909	7.2636	25/08	6130	0.6	NO	BO, SS, PFP	Chikoko mud + algal mat
Q23-1	4.6003	7.2643	25/08	16,300	1.3	SS	BRO, OP	Sand + chikoko
Q23-2	4.6003	7.2644	25/08	25,800	3.3	TB	BO, PFP	Sand, chikoko, asphalt, algal mat
Q23-3	4.6002	7.2646	25/08	12,600	3.8	FR	BO, OP	Brown silty sand

SCAT oiling codes: *TB* tar or tarballs, *AP* asphalt pavement, *FR* fresh oil, *OP* oil-filled pores, *PFP* partially-filled pores, *BO* black oil, *BRO* brown oil, *SS* silver/rainbow sheen, *NO* no oil, *Chikoko* mangrove peat, *n/d* not detected; sampling site grid locations corrected to those plotted by SPDC Geomatics Department

pyrene, Indeno(*1,2,3-cd*)pyrene, Dibenzo(*a,h*)anthracene, and Benzo(*g,h,i*)perylene).

The above scope was specified by the technical sub-group convened by BMI. The selected laboratory had been used by UNEP in 2010 for TPH determinations. Their methods were also comparable to those used by Baker (1983): pooling of five (5) composite surficial samples, storage at −20 °C, solvent extraction, separation, and analysis by GC-FID. Petroleum hydrocarbons were extracted using a microwave-assisted solvent extraction method (EPA 3546). The analysis of extractable total petroleum hydrocarbons (TPH, in the C_5–C_{44} range) was using GC-FID (EPA Method 8015 modified) and PAH was analyzed using GC-MS (EPA Method 8270

modified). The volatile petroleum hydrocarbons (C_5–C_{12} gasoline range) and BTEX were analyzed using static head space extraction (EPA Methods 8020 and 8260 modified). In addition, the laboratory reported TPH results in the risk-based specified carbon number ranges for aliphatic and aromatic hydrocarbons (TPHCWG 1997). Quality assurance/quality control (QA/QC) was in terms of percentage recovery of compounds from analytical QC samples run with the field samples: surrogate recoveries were between 81% and 111% and generally well inside the statistical lower and upper control limits.

The laboratory work also included some analytes typically used in petroleum fingerprinting studies. However, it was assumed that most of the pollution detected would be Bonny Light crude oil, and so standard USEPA-type

procedures were followed, rather than specialised hydrocarbon fingerprinting methodology (Stout and Wang 2016). The data obtained did not allow for a detailed environmental forensics level of interpretation. For example, chromatographic resolution by carbon range numbers did not identify individual alkane peaks, preventing reliable evaluation of the petroleum type(s) in the samples analysed. In addition, since the gas chromatograms were presented in a format normalised to the highest peak, the chromatograms were often too small scale to be useful for fingerprinting by visual comparison. In some cases the only identifiable peaks were the added internal standards, and contaminant peaks characteristic of the sample were hard to discern.

The individual PAH concentrations in some of the samples were below the laboratory detection limits, and eleven (11) total PAH values were below the detection limits. In addition, the PAH analytes did not include alkylated homologues. This selection was based on the correct assumption that, apart from the alkylated naphthalene and dibenzothiophene, these compounds are present at very low levels in the non-weathered crude oil. However, illegal refineries exist in many parts of the Niger Delta, including 87 sites in Bodo West and 60 in Bodo East (Gundlach this volume). When the light ends of crude oil are distilled off then the residual materials contain elevated levels of alkylated homologues. Without the alkylated homologues, only parent high molecular weight PAHs are reported, which limits the fingerprinting value of the analytical data. In future, high resolution GC-FID chromatograms and GC-MS outputs with selected ion chromatograms of representative samples should be included, as has been done recently in Owaza, Niger Delta by Faboya et al. (2016). This would provide fingerprinting tools even for samples where most *n*-alkanes are biodegraded.

14.3 Results

14.3.1 Summary of SCAT Survey Results

During the pre-SCAT survey in May 2015 teams visited seventeen (17) impacted sites, documenting the variability of surface and subsurface oil occurrence and behaviour (Fig. 14.5). Observations included: "dead mangrove plants, hydrocarbon impacted sediments to varying degrees from oil sheen to weathered crude in form of asphaltic tar, burnt carbonized residue and free-phase oil, and evidence of regeneration of dead mangrove vegetation where re-oiling has been minimised" (Gundlach 2015a).

The August SCAT survey provided an inventory of phenotypes of contaminated mangroves in the area: "The very large extent of oiling and required cleanup was again noted by survey participants. All sites surveyed during August 2015 need some level of cleanup, particularly related to reducing the level of oiling in soft muddy sediment" (Gundlach 2015b). SCAT observations of oiling and sediment types in August 2015 are given in Table 14.1 for those sites sampled in parallel for chemistry (Fig. 14.1). Additionally, mangrove loss was observed in each of the thirteen (13) scat grid cells that were not yet sampled. All but two of these were within the designated 1000 ha remediation area.
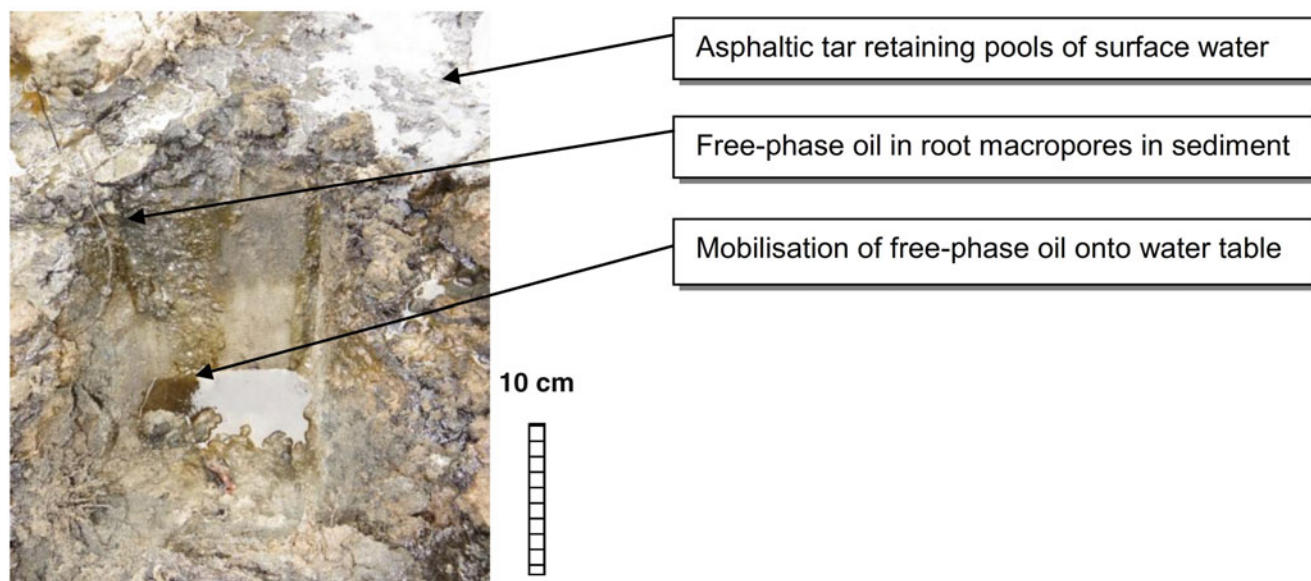

Fig. 14.5 SCAT pit showing surface asphaltic tar, mobilisation of free-phase oil into sediment macropores and onto the water table (Credit: M. Bonte)

Full results of the SCAT surveys carried out by the BMI in 2015 are given by Gundlach (2017).

14.3.2 Chemistry Results

14.3.2.1 Surface Samples

Site locations sampled from 13 to 25 August 2015 are shown in Fig. 14.1 and analytical results are given in Table 14.1 along with field information from SCAT.

Thirty two (32) sediment samples were taken from fifteen (15) grid locations at a depth interval of 0–5 cm. At these sites only one (1) of the 32 surface sediment samples showed a TPH (C_5–C_{44} range) concentration below the Nigerian regulatory limit value of 5000 mg/kg (see Discussion). Six (6) samples had concentrations between 5000 and 10,000 mg/kg; seven (7) samples ranged between 10,000 and 20,000 mg/kg; fifteen (15) between 20,000 and 100,000 mg/kg; and three (3) samples exceeded 100,000 mg/kg (Table 14.1).

There was general agreement between visual SCAT observations and chemistry data. However, due to oil weathering and the presence of algal mats, the sediment surface often appeared cleaner than when pits were dug to reveal fresh oil in the subsurface (e.g., especially all sites in grid cell M26, but also N22-4, G24 and P28-2). Table 14.1 shows that in the subsurface 15–20 cm layer, of thirty (30) observations that were made of 'black oil' or 'brown oil' (SCAT oiling codes BO and BRO), twenty-four (24) of them corresponded with TPH concentrations >10,000 mg/kg in the surface layer. This fully confirmed the SCAT finding of severe oiling.

14.3.2.2 Surface and Subsurface Samples Compared

Because TPH (as well as aliphatic, aromatic fractions and PAH) concentrations were also high in the deeper sampling interval, at thirteen (13) grid locations 55 samples were taken in two different depths (0–5 cm and 15–20 cm). These data from surface and subsurface are given in Tables 14.2 and 14.3 respectively. Data for TPH and the sum of PAH_{16} correspond with the above surface dataset (Table 14.1), but for N23 and N24 data were not available for aromatic and aliphatic fractions.

Of the subsurface total of 32 samples, thirteen (13) samples had TPH concentrations below the regulatory limit of 5000 mg/kg. TPH concentrations in three (3) subsurface samples were between 5000 and 10,000 mg/kg, ten (10) samples were between 10,000 and 20,000 mg/kg, and six (6) between 20,000 and 100,000 mg/kg (Table 14.3). In summary:

– *In the surface 0–5 cm the mean concentrations were*: TPH 43,208 mg/kg; Aliphatics 25,045 mg/kg; Aromatics 17,015 mg/kg; EC_5–EC_{12} aromatics fraction 3.26 mg/kg; and PAH_{16} 6.11 mg/kg (n = 28, except TPH n = 32, and PAH n = 27).

– *In the subsurface 15–20 cm the mean concentrations were*: TPH 14,601 mg/kg; Aliphatics 7702 mg/kg; Aromatics 4288 mg/kg; EC_5–EC_{12} aromatics fraction 9.28 mg/kg; and PAH_{16} 5.09 mg/kg (n = 27, except TPH n = 32, and PAH n = 23).

– *In both depth strata combined the mean concentrations were*: TPH 28,904 mg/kg; Aliphatics 16,531 mg/kg; Aromatics 10,767 mg/kg; EC_5–EC_{12} aromatics fraction 6.16 mg/kg; and PAH_{16} 5.65 mg/kg (n = 55, except TPH n = 64, and PAH n = 50).

The TPH concentrations in the sediments of the Bodo area ranged over almost three (3) orders of magnitude; from 163 mg/kg at R12 (subsurface sample) to 135,000 mg/kg at N09 (surface sample). Although the low end of the present range in TPH concentrations is similar to the background concentrations found in 1983 and slightly less than in 2010, the high end of the range in oil content (13.5% of the sediment mass) is not an outlier, and indeed only one surface sample was below the regulatory limit of 5000 mg/kg. This emphasizes the severity and persistence of the 2008 Bodo pipeline oil spills, and the subsequent spills due to other illegal activity.

14.3.2.3 Further Data Evaluation

With such a wide range of data, it is difficult to express meaningful measures of central tendency, such as arithmetic means. Under these circumstances, to make valid comparisons between the surface and subsurface layers, samples need to be compared at the same locations and the variability of the TPH data needs further evaluation. The ratio of the standard deviation (SD) to the mean of samples in each depth layer at each site was calculated (where n = 2 or more, noting that sites P18, G24, K10, N09 and N21 had only one sample per depth).

When expressed as a percentage, each of these ratios represents a dimensionless coefficient of variation (CV) where CV = SD × 100/mean. For surface 0–5 cm samples the CV ranged from 13.7% (M11) to 122% (P28) and the mean was 67%. In the subsurface 15–20 cm samples the CV ranged from 20% (U19) to 132% (N23), with a similar mean of 58%. The overall similarity of the CVs in terms of depth in the sediment was encouraging, but the size and range of CVs underlined the intense patchiness of oil distribution in the mangrove sediments of the Bodo area. Although reduced by taking composite samples, this patchiness is normal in coastal sedimentary systems, due to the unpredictable oil distribution at the time of the spill and subsequently to variable oil penetration down macropores

Table 14.2 TPH, Aliphatics (C_{12}–C_{44}), Aromatics (EC_{12}–EC_{44}), Aromatics (EC_5–EC_{12}) fraction and ΣPAH_{16} data for surface (0–5 cm) sediment samples taken from 15 grids in August 2015

Surface sample	mg/kg				µg/kg
	TPH	Aliphatics	Aromatics	Aromatics EC_5–EC_{12}	ΣPAH_{16}
N22-1	**60,000**	35,400	24,600	0.14	**16,700**
N22-2	**99,500**	68,900	30,600	0.18	**16,700**
N22-3	**24,400**	12,500	11,900	0.59	1570
N22-4	**25,500**	17,000	8460	0.27	5660
R12-1	**7770**	4310	3460	0.62	1030
R12-2	**27,700**	16,000	11,700	1.68	794
R12-3	**88,100**	70,100	18,100	1.86	**12,600**
P19-1	**54,900**	36,400	18,400	0.19	**10,000**
P19-2	**6410**	4430	1990	0.32	962
P19-3	**75,000**	36,400	38,600	0.39	**8980**
P18-2	**88,500**	48,700	39,700	0.13	**24,200**
G24-1	**26,700**	14,900	11,800	0.06	n/d
M26-1	**7110**	4730	2380	0.12	n/d
M26-2	**17,700**	11,100	6590	0.07	590
M26-3	**16,400**	9310	7060	0.3	4600
M26-4	**15,000**	10,400	4590	0.87	5710
N24-2	**111,000**	n/a	n/a	n/a	**19,900**
N24-3	**17,200**	n/a	n/a	n/a	875
N23-1	**9570**	n/a	n/a	n/a	236
N23-2	**66,600**	n/a	n/a	n/a	n/d
N21-1	**8720**	5780	2660	73.54	6980
N09-1	**135,000**	73,200	61,900	0.82	1180
K10-1	**22,500**	13,400	9090	0.33	590
M11-1	**117,000**	61,200	55,500	0.12	590
M11-2	**96,400**	42,100	54,300	4.44	**19,800**
U19-1	**12,800**	8710	4080	0.03	590
U19-2	3650	2330	1320	0.02	n/d
P28-1	**80,700**	54,500	26,200	2.06	1180
P28-2	**6130**	3510	2620	0.95	590
Q23-1	**16,300**	10,300	6070	0.57	1340
Q23-2	**25,800**	17,900	7860	0.39	3330
Q23-3	**12,600**	7750	4890	0.11	3820
Means	**43,208**	25,045	17,015	3.26	6111

In bold: TPH concentration >5000 mg/kg limit value (EGASPIN) and PAH_{16} concentration >7070 µg/kg Probable Effects Level (Environment Canada; note that the EGASPIN limit value of 40,000 µg/kg was not exceeded)

n/d not detected, *n/a* data not available

such as plant root channels and infaunal burrows (Howard and Little 1987; Kingston et al. 2000).

To compare the widely-ranging contaminant concentrations in relation to the sample depth it was thus necessary to $\log_{10}$-transform the data. This was done to reduce the samples' variances in relation to their means, and helps to approach the normal distribution permitting use of a parametric t-test. Tables 14.2 and 14.3 respectively show the surface and subsurface data. Note that the individual data points were rounded by the laboratory to three significant figures, and so in Tables 14.2 and 14.3 the data for separated fractions of aliphatics and aromatics do not always sum exactly to the respective values for TPH (C_5–C_{44}).

14.3.2.4 TPH, Aliphatic and Aromatic Hydrocarbons Statistical Results

Although aromatic hydrocarbons concentrations were significantly higher in the surface than subsurface using the parametric t-test, the similar vertical differences in mean TPH and aliphatic hydrocarbons could not be tested because of the high variance ratios (shown by the F-test) of the samples even after $\log_{10}$-transformation. Nor could non-parametric alternatives to the t-test be used (e.g., Wilcoxon's test for matched pairs and Mann-Whitney U-test), because the frequency distributions differed in skewness between the surface and subsurface samples (see "Discussion"). However, when measurements constitute a matched pair, the matched pairs t-test can be used. Despite the necessary omission of the few

Table 14.3 TPH, aliphatics (C_{12}–C_{44}), aromatics (EC_{12}–EC_{44}), aromatics (EC_5–EC_{12}) fraction and ΣPAH_{16} data for subsurface (15–20 cm) sediment samples (n = 27) taken from 13 grids in August 2015

Subsurface sample	mg/kg				µg/kg
	TPH	Aliphatics	Aromatics	Aromatics EC_5-EC_{12}	ΣPAH_{16}
N22-2	2430	1610	815	0.48	539
N22-3	3070	1980	1090	3.31	976
N22-4	1610	1030	576	0.18	2890
R12-1	163	76.2	86.6	0.03	n/d
R12-2	4880	3150	1720	2.6	1020
R12-3	**19,600**	14,500	5140	2.64	2320
P19-1	**21,900**	16,500	5390	0.89	**7700**
P19-2	4710	2860	1840	0.74	2070
P19-3	**13,600**	8780	4820	0.51	1630
P18-2	2500	1590	910	0.2	320
G24-1	**17,100**	10,200	6890	2.89	2200
M26-1	**17,100**	10,600	6470	9.42	3880
M26-2	**23,300**	13,900	9310	9.99	2020
M26-3	**7820**	5530	2200	32.31	**8500**
M26-4	**6520**	3590	2910	8.02	521
N24-1	**17,000**	n/a	n/a	n/a	**10,300**
N24-2	**19,800**	n/a	n/a	n/a	**20,500**
N24-3	**89,500**	n/a	n/a	n/a	**22,800**
N23-1	531	n/a	n/a	n/a	590
N23-2	**16,000**	n/a	n/a	n/a	n/d
N21-1	**5070**	3010	1590	150.9	**7850**
N09-1	**71,700**	45,000	26,700	1.07	1180
K10-1	**14,200**	9320	4860	1.64	n/d
M11-1	**12,600**	8640	4000	1.16	1560
M11-2	**29,500**	17,900	11,600	3.96	n/d
U19-1	215	107	108	0.11	n/d
U19-2	287	174	113	n/d	n/d
P28-1	2050	1270	768	1.27	n/d
P28-2	1290	662	630	0.22	n/d
Q23-1	**25,300**	15,200	10,100	0.64	**14,200**
Q23-2	**11,700**	8380	3370	0.12	1540
Q23-3	4180	2390	1770	5.93	n/d
Means	**14,601**	7702	4288	9.28	5092

In bold: TPH concentration >5000 mg/kg limit value (EGASPIN) and PAH_{16} concentration >7070 µg/kg Probable Effects Level (Environment Canada; note that EGASPIN limit value of 40,000 µg/kg was not exceeded)

n/d not detected, *n/a* data not available

unpaired samples, this is a more sensitive test, and for consistency it was used on all the hydrocarbons data.

The t-test for matched pairs of log_{10}-transformed data indicated that the difference between the mean TPH (C_5–C_{44}) concentrations of the surface 0–5 cm layer and the subsurface 15–20 cm layer was statistically significant at $p < 0.01$ (t = 5.73 at 30 degrees of freedom, d.f.). The difference between the two sediment layers in terms of mean C_{12}–C_{44} aliphatic hydrocarbons was statistically significant at $p < 0.01$ (t = 5.57, 26 d.f.). The vertical difference in mean EC_{12}–EC_{44} aromatic hydrocarbons was also statistically significant at $p < 0.01$ (t = 5.92, 26 d.f.).

14.3.2.5 Light Aromatics Fraction Statistical Result

Using the matched pairs t-test the difference between the two sediment layers in terms of mean aromatic hydrocarbons in the carbon number range between EC_5 and EC_{12} was found to be statistically significant at $p < 0.01$ (t = 3.01, 25 d.f.). However, in contrast to the TPH, aliphatic and higher molecular weight aromatic hydrocarbons, in the case of the EC_5–EC_{12} aromatics the subsurface layer was significantly more contaminated than the surface layer.

This is a function of the volatility of light aromatic compounds that would have evaporated quickly from the sediment surface after spillage, and partly due to the ability of lighter aromatics to penetrate fine-grained sediments more

easily than heavier hydrocarbons. Recent rapid sediment deposition could also bury lighter hydrocarbons, but is not a likely factor because deposition rates since the spill would have had to be very high.

14.3.2.6 PAHs Results and Sources

In the surface layers of six sampling sites, the PAH_{16} concentrations were 24.2 mg/kg (P18), 19.9 mg/kg (N24), 19.8 mg/kg (M11), 16.7 mg/kg (two samples at N22), 12.6 mg/kg (R12), 10.0 and 8.98 mg/kg (P19). These PAH_{16} levels are very high and exceed international sediment quality guidelines (Environment Canada 7.07 mg/kg Probable Effects Level; PEL). Although sample variances of total PAH_{16} were sufficiently close to proceed with the t-test, the difference in mean concentrations between the surface and subsurface layers was found not to be statistically significant (t = 0.98). The matched pairs t-test also was not significant (t = 0.64). Indeed, subsurface PAHs concentrations were also found in excess of PEL as follows: 22.8, 20.5 and 10.3 mg/kg (N24), 14.2 mg/kg (Q23), 8.5 mg/kg (M26), 7.85 mg/kg (N21), and 7.7 mg/kg (P19). In contrast to these high values, there had been no PAH_{16} concentrations exceeding PEL measured in Bodo 0–10 cm sediments in 2010 (Lindén and Pålsson 2013).

The probable source types of the PAHs are shown in Fig. 14.6. The sectors of the graph pertaining to each potential source type such as petroleum, combustion products of petroleum and biomass burning are each marked according to the work of Yunker et al. (2002), as modified by Oros and Ross (2004), Costa and Sauer (2005), Stout and Wang (2016), and Little and Galperin (2017).

Despite many samples being at or below detection limits for individual PAHs, the double ratio cross-plots in Fig. 14.6 clearly show that in about half the samples the PAH was petroleum-derived, as would be expected near the SPDC pipeline spills of 2008 and oil theft and spillage of Bonny Light crude oil at Bodo. In addition, the geochemical influence of petroleum combustion at illegal refinery sites was seen at Q23 and at N22 (surface and subsurface at both sites). At Q23 the total PAHs concentration reached 14.2 mg/kg in one subsurface sample. In the surface sample at N22 (surface) and also at R12 (subsurface) near Bodo waterfont, isomer ratios transitional between petroleum and petroleum combustion were observed.

However, acute atmospheric fallout across the region is also produced by oil industry flaring and well tests, tyre burning (pers. com. Pålsson) and chronic emissions from vehicles and industries in Port Harcourt and Eleme such as oil refining and petrochemicals (UNEP 2011) and cement, paint and fertiliser (NDES 1997). Although all these are partly responsible for petroleum combustion as a secondary

source of PAHs, their input is outweighed by oil spills from several pipeline tappings and at new illegal refineries causing further mangrove impacts documented in cumulative losses mapped using satellite imagery and aerial photography from late 2009 (Gundlach this volume).

A third PAHs source was biomass combustion from both natural and anthropogenic forest fires, and domestic fires. Although of minor interest to the problem of cleanup, biomass combustion was sub-dominant at N09, N21, Q23, M26, P18, P19 and U19, usually in surface samples, but at N09 and P18 in both surface and subsurface samples. This suggests that in addition to oil fires, the burning of wood and grass (and coal, although most unlikely in Bodo) has contributed to the PAHs geochemical signature for some considerable time. This is typical of rural areas undergoing forest clearance for agriculture, and with the use of wood fuel in domestic cooking. UNEP (2011) showed the health risk of indoor cooking fuels in Ogoniland.

14.3.2.7 Additional Contaminant Source Indicators

Many of the above site-by-site patterns agreed well with other source indicators such as MTBE and volatile aromatic hydrocarbons (BTEX). Although reported as being below the limit of detection at most sites, where they were detectable, these contaminants often occurred at much higher concentrations in the subsurface sediment layer.

For BTEX at N21 the subsurface concentration (0.052 mg/kg) was five times more than at the surface. Examples of MTBE enrichment include N21 (surface and subsurface) and M26 (subsurface, as high as 0.96 mg/kg). MTBE is a refined fuel blending component and therefore a precise indicator of contamination by spilled petrol. It was introduced to replace the lead additives in petrol that were banned in Nigeria in 2005. It is likely that the MTBE indicates the increasing use of petrol in the creeks since then by small vessels, including security craft, and perhaps those servicing illegal refineries.

For light aromatic EC_5–EC_{12} fractions at M26 the subsurface mean concentration (14.94 mg/kg, n = 4) was over forty (40) times more than in the surface. In both the surface and subsurface of M26 the gas chromatograms showed fresh petrogenic inputs in the range C_{12}–C_{16}. In addition, the range of relatively fresh oil input up to C_{21} was seen in chromatograms of samples from N21, G24, N22, M26, P19 and R12 (subsurface), and less obviously from N22, M26, P19 and R12 (surface).

Over time, all these lighter hydrocarbons not only evaporate, but they can also penetrate the sediment and could mobilise heavier molecules including PAHs into deeper sediment layers, further reducing their biodegradation rates.

Fig. 14.6 Ratios of Anthracene/ (Anthracene + Phenanthrene) [AN/(AN+P)], Benz[*a*] anthracene/(Benz[*a*]anthracene + Chrysene) [BA/(BA+C)], Indeno(1,2,3-*cd*)pyrene/(Indeno [1,2,3-*cd*]pyrene + Benzo[*g,h,i*] perylene) [IN/(IN+BPE)] each plotted against Fluoranthene/ (Fluoranthene + Pyrene) [FL/(FL +PY)] showing main PAH source types in the Bodo area sediments (after Yunker et al. 2002); for sample identities see Tables 14.2 and 14.3; data points in line are at limit of detection; all data are colour-coded: blue = petroleum from oil spills including those resulting from the 2008 pipeline failures and illegal refinery sites; black = petroleum combustion from regional oil industry flaring, vehicular and industrial emissions and local illegal refinery sites; and red = biomass combustion (wood, grass)
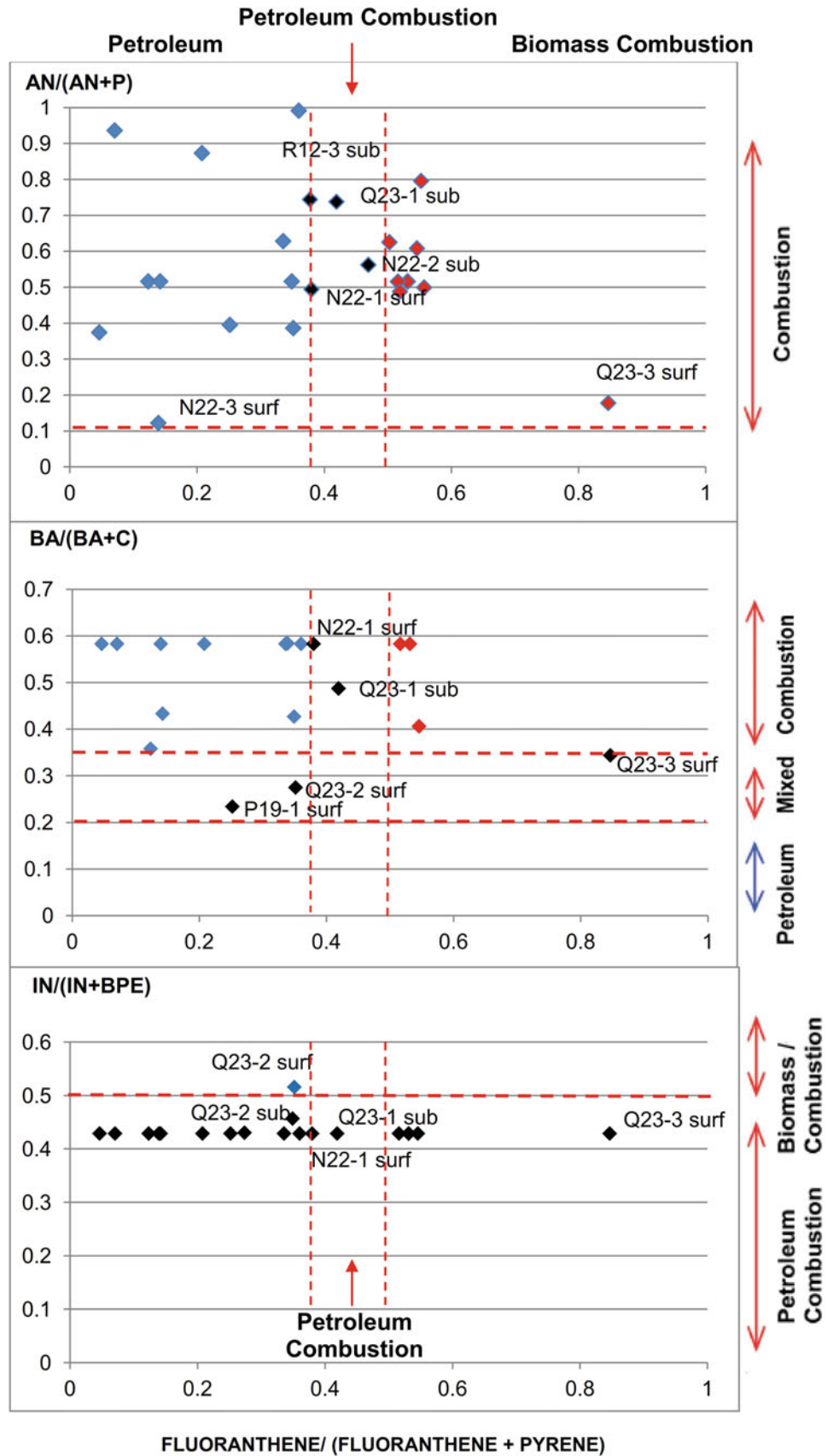
Fig. 14.7 Aerial view of Kpador Channel near Bodo showing continuously-oiled mangroves in the intertidal zone, with mobile free-phase oil in the creeks; also showing impacts from pipeline RoWs and failed road-building projects before the 2008 spills, and from illegal refineries since those spills (smoke and blackened trees left of center), 17 April 2010 (Credit: J. Pålsson)

14.4   Discussion

The surveyed area near Bodo which includes the typical substrates of the mangroves is extremely contaminated by residues of crude oil, either released into the environment after accidental oil spills and leaks, or due to illegal activities such as oil theft from pipelines and the artisanal refining of the stolen oil. In 2015 oil was observed across the intertidal mangrove habitat surface, and also draining into creeks, although not generally as seriously as was seen on 17 April 2010 (Fig. 14.7, showing the area of sampling stations N21 - N24 inclusive, see Fig. 14.1). However, it has not always been like this, and the contamination is patchy. This patchiness is important to understand if the future cleanup is to avoid adding to the impact of the original oil by physically removing too much of the relatively clean subsurface layers during cleanup, as found in other oil spill cleanups (Little et al. 2003). A range of cleanup methods will be required, often in combination, rather than total sediment removal (Gundlach 2017).

The mean TPH concentration appears to have increased by almost three times from 2690 mg/kg (1983) to 7500 mg/kg (2010), and another three-fold increase in mean TPH concentration to 28,904 mg/kg took place by 2015. To establish whether these apparent changes were due to the incomparability of the methods, the minimum TPH concentrations in Bodo sediments were compared between 1983, 2010 and 2015. The GC-FID traces give an indication of the background TPH status in the area, with a relatively low Unresolved Complex Mixture (UCM) of weathered petroleum and some biogenic resolved peaks. The background concentrations ranged from 110 mg/kg (1983), to 279 mg/kg (2010), and 163 mg/kg (2015). This background stability through time suggests reasonable comparability between the methods.

Whereas the sampling and analytical methods used were broadly comparable between all three of these surveys, the intertidal field site locations within Bodo were different, and thus not directly comparable, as follows:

- 1983: northern Bodo south to Kpador channel/Bonny River confluence (Baker 1983);
- 2010: across tidal regions of southern Gokana LGA (Lindén and Pålsson 2013); and

– 2015: the present survey of the Bodo TNP pipeline spills area targeted for cleanup (Fig. 14.1).

It was found in the analysis of over 660 samples from UNEP surveys across Ogoniland in 2010 that frequency distributions of contaminant concentrations were strongly left-skewed with 91% of all samples being less contaminated than the TPH limit value of 5000 mg/kg. This large number of samples included inland soils and deeper layers sampled using hand augers (Thiergärtner and Holtzmann 2014).

However, of those surface 0–10 cm depth samples taken in 2010 in the intertidal zone closest to Bodo, the equivalent percentage of left-skewness for TPH was 33% <5000 mg/kg (Lindén and Pålsson 2013). This was similar to the 44% <5000 mg/kg in the 15–20 cm samples in 2015. The left-skewed frequency distributions in 2015 show that the 15–20 cm layers included several samples tending to background TPH levels. In contrast, the surface 0–5 cm samples in 2015 were more generally contaminated, and the left-skewness was therefore almost absent (only 3.6% <5000 mg/kg). The skewness indicates a degree of comparability between the 2010 and 2015 frequency distributions of TPH in the subsurface layer, but not in the surface layer, and this shows the success of the SCAT surveys in visually targeting the most polluted areas for cleanup.

The chemical analyses in 2015 generally confirmed the visual results from the SCAT field surveys in 2015. The visual description of the contaminated sediment ranged from 'rainbow sheen only', through 'moderate sheen', 'substantial oiling', 'black oil present' and 'oil soaked mud 10–25 cm deep' to 'surface tar' mainly on illegal refinery sites (Gundlach 2015a, b). The advantage conferred by embedding the 2015 chemistry sampling within the SCAT framework is that the analytical chemistry data from selected sampling sites are better understood in their field context. Equally, the chemistry is necessary to confirm the degree and nature of the contamination, which is above regulatory intervention values in either surface and/or subsurface layers at every site sampled, even if not visible on the surface until the sediment is agitated or algal mats are removed.

Furthermore, from this dual approach and understanding, the 'hot-spots' may be more clearly demarcated for cleanup without recourse to taking many thousands of samples. In future, the selection of field locations to monitor will be partly determined by the progress and effectiveness of the cleanup, and as prioritised by the SCAT surveys. The monitoring will compare changes in oiling conditions due to cleanup (before-after); any incremental impacts arising from cleanup (control-impact) will also require selected oiled sites to be 'set-aside' from cleanup (i.e., controlled) for scientific study using a BACI design.

The high statistical significance of the differences in contaminant concentrations between 0–5 and 15–20 cm layers suggests in this case that cleanup should selectively remove the 0–5 cm layer of highly contaminated sediments. However, there are important caveats on the use of the preliminary chemistry data in calibration of SCAT when considering decisions on cleanup, such as: (a) if the most highly contaminated layer is between 5 and 15 cm; (b) if the most highly contaminated layer is deeper than 20 cm; and (c) if the contaminated site is in close proximity to a sensitive receptor (e.g., Bodo waterfront).

The above cleanup recommendation from the preliminary samples is not a prescriptive protocol and it should not be extrapolated to other areas. This is a key point because the cleanup planning effort was initially designed for free-phase oil removal; then, due to ongoing weathering processes, 'free-phase' oil cleanup was extended from flushing and skimming to include the removal of accessible surface tar. It is emphasised that in the full cleanup phase the purpose of the SCAT approach is to facilitate more precise cleanup recommendations tailored to the 'hot-spots' of each new cell in the grid (Gundlach 2017).

In the surface sediments the mean concentrations of 25,045 mg/kg (C_{12}–C_{44} aliphatics) and of 17,015 mg/kg (EC_{12}–EC_{44} aromatics) are generally extremely high. A very similar concentration (24,664 mg/kg) of aliphatics (C_{14}–C_{29}) was detected in Owaza by Faboya et al. (2016). In contrast, the light aromatic EC_5–EC_{12} fractions have been measured in Bodo at relatively low levels, with the only exceptions of both samples at N21 and the subsurface at M26. The light end aromatics were reduced relative to the total aromatics EC_5–EC_{44}. This is also seen in many of the gas chromatograms and appears to indicate weathering and therefore a lower acute eco-toxicity of the pollution.

However, the abundance of dead mangroves clearly shows the negative impact of the crude oil residues at least on the flora and associated fauna (e.g., bivalves on mangrove prop roots) under the daily tidal influence (Gundlach 2017; Gundlach this volume). This chronic toxicity is likely to be partly attributable to the persistence of high molecular weight hydrocarbons and in particular the PAHs. Although PAHs are low in concentration in fresh Bonny Light crude oil, they increase in relative concentration during weathering processes, and are highly enriched in those areas with illegal refineries, even in the subsurface sediments. In Bodo, between the years 2010 and 2015 the mean PAH_{16} concentration increased by more than three times from 1.3 to 5.65 mg/kg, similar to the increased TPH concentrations. It is probable that the PAHs inputs from petroleum combustion are mainly from the illegal refineries that proliferated after 2009. This may be stated because the oil industry production and any well-testing and flaring activities near Bodo have been shut down throughout this period.

Pyrogenic emissions from towns, industry and traffic in the wider Ogoniland area are also likely sources. The multiple

sources of contaminants demonstrate the need for forensics quality hydrocarbon analyses in a subset of the sites sampled, not least because of the need to understand pathways and then prevent adverse impacts on human health. In the mangrove sediments of the Calabar River a similar mix of PAH sources was found using isomer ratios, but apparently without additional input from illegal refineries (Oyo-Ita et al. 2013).

In 1983, Bodo West was the most exploited of the five SPDC areas observed in terms of wood cutting (45% of sites), oyster gathering and fishing (50% of sites), activities that depend on sustainable reources. Apart from the physical presence of the oil production facilities and one spill site in Bodo West, no general biological impacts were attributed in 1983 to the oil industry (Dixon 1983). With evidence of oil industry presence at 32% of sites, Bodo West was less affected by oil industry disturbance than Forcados (37% of sites) and by urbanization and industry at Warri (27% of sites). The Bodo pipeline spills in 2008 and a subsequent increase in oil theft, transport and illegal refining have in combination caused catastrophic, habitat-scale and ongoing mangrove ecosystem impacts (Gundlach this volume).

The environmental situation in the Bodo area is clearly not beneficial for local people as well as the ecosystem supporting them. To put this subjective assessment in a comprehensive context, an environmental quality standard (EQS) could be derived scientifically and used for comparison with analytical results. There are intervention values used internationally for certain (parent) PAHs, and for single light aromatic compounds, such as benzene (EC_6). In The Netherlands an intervention value of 1 mg/kg benzene in soil is used (Into Dutch Soil 2014). However, there are no EQS for low molecular weight aromatics (EC_5–EC_{12}) fractions. The derivation of an EQS for chemical substances is a sophisticated process, influenced by chemistry, toxicology, epidemiology, phenomena such as metabolism, interaction of chemical compounds, and other factors that in combination affect the probability of adverse effects.

Official evaluation criteria for sediment contamination in Nigeria are set by DPR (1991): "Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN)". Because of the relevance of the oil industry to environmental impacts and the dominance of the Dutch company Shell in the oil-producing areas, EQSs from The Netherlands have been generally adopted by EGASPIN (Ministerie van VROM 2000). EGASPIN defines intervention values as those that indicate "the quality for which the functionality of the sediment for human, animal and plant life is, or is threatened with being, seriously impaired. Concentrations in excess of the intervention values correspond to serious contamination". However, compared to the control of oil and chemical pollution, the conservation of biodiversity and management of adverse ecological impacts are not the focus of EGASPIN (IUCN 2013).

This was recognized by the BMI when they agreed that the aim was to reduce oiling levels to those that would support the establishment or transplantation and growth of mangrove seedlings. Ecological restoration will also depend on correct definition of the ecological goals, and this will require detailed understanding of the inter-dependent mangrove species assemblages, communities and habitats. A cause for optimism is that a group of whimbrel *Numenius phaeopus* was observed by the authors at Bodo on 1 May 2015, indicating the functional importance of the ecosystem as a stopover for long-distance migrant birds. Conversely, the increased role of alien invasive species such as Nipa palm in the ecosystem is a major concern. It is fortunate that much of the essential knowledge is to be found in Bodo (Zabbey et al. 2010, 2014, 2017, in press; Zabbey 2012; Zabbey and Malaquias 2013; Pegg and Zabbey 2013; Zabbey and Uyi 2014; Zabbey and Tanee 2016).

Further constraints on applying the above-mentioned intervention value include the fact that it was established for unweathered hydrocarbons. Additionally, it is based on the 'Dutch list' (underlying EGASPIN) and is defined for a standard terrestrial soil type with 10% organic matter and 25% clay. This is different from the deltaic sediments in the mangroves, which consist of marine and coastal fine-grained sediments. Although not so much the case in Bodo as in other areas of the delta (e.g., Warri), the sediments are often affected by dredge spoils or composed of made ground of widely differing organic content and granulometry (Fig. 14.7).

UNEP (2011) pointed out that not having separate values defined in EGASPIN for triggering and closing out remedial interventions was a loophole that allowed negligible cleanup to be accepted. Criticism of EGASPIN has also focused on the high TPH intervention value of 5000 mg/kg, and on the lack of limits on individual PAHs especially Benzo(*a*)pyrene (IUCN 2013). A valid starting point to protecting the local population is to focus on those areas, transfer pathways and activities presenting the highest potential human exposure to toxic and persistent hydrocarbons. The elevated hydrocarbon concentrations in sites R12 and N09 are within a few hundred meters of human receptors in Bodo.

The intervention value for TPH of 5000 mg/kg in sediment adopted by DPR for comparison with the measured concentrations gives a good sense of the magnitude of the pollution in the intertidal sediment. In contrast, the intervention value for PAH_{16} of 40 mg/kg is too high by international standards (Tables 14.2 and 14.3). By considering the environmental regulatory standards of Nigeria and in conjunction with SCAT, the analytical results will need to be interpreted ecologically to derive recommendations regarding the net environmental benefit of remediation of the oil-contaminated sediment. This focus will help to minimize any extra impacts from cleanup in soft sediments, and to

avoid further unnecessary delays in the restoration of mangroves and livelihoods in the Bodo area.

14.5 Conclusions

Intertidal surface sediments near Bodo are widely and severely oiled since the 2008 pipeline spills, and in areas known to be subject to increases since 2009 in oil theft and illegal refinery activities. Of the total of sixty-four (64) samples taken at two depths (0–5 cm and 15–20 cm), in the surface sediment all but one sample had a TPH concentration well above 5000 mg/kg, the EGASPIN regulatory limit. In contrast, thirteen (13) samples in the deeper layer had TPH concentrations below the 5000 mg/kg limit. Although contamination by TPH, aliphatic and aromatic hydrocarbons was moderate to high in the deeper layer, it was shown statistically to be significantly lower than in the extremely contaminated surface layer.

Whereas TPH, aliphatic and aromatic hydrocarbon fractions decrease in concentrations from the surface towards deeper sediment as expected, the trends for the lower molecular weight aromatics differ. The latter are detected in much lower concentrations, with only twenty (20) out of 55 samples found at >1 mg/kg. In most samples, the concentrations of lighter aromatics increase with greater depth in contrast to the case of heavier hydrocarbons. This was as would be expected from surface evaporation and also due to chromatographic separation during oil infiltration, washing and draining through intertidal sediments.

Polycyclic aromatic hydrocarbons (PAH_{16}) concentrations range widely, with the higher values of PAH_{16} raising the possibility of potential health risk for any people exposed to the pollution. It should be recalled that seven (7) of the individual PAHs are classified by USEPA as probable human carcinogens, but this risk and the pathways of human exposure at Bodo are still not adequately quantified. Ecological risk is better understood in that the sediment PAH_{16} concentrations in 55 samples show that international sediment quality guidelines are exceeded in fifteen (15) samples, of which seven (7) are in the subsurface. This explains ongoing adverse ecological impacts.

A preliminary forensics evaluation of the available PAH data suggests the following likely sources of PAHs in the area: petroleum, combustion of petroleum, and combustion products from biomass (wood, grass). Such sources typify inputs from oil industry spills and illegal refinery activities, overprinted on a baseline of traditional biomass fuel usage. The petroleum and petroleum combustion inputs are consistent with the lingering effects of the 2008 SPDC spills and the increase in oil theft and illegal refining since then.

14.6 Recommendations

Using public health and demographic data (NPC 2004), recent work has compared siblings conceived before and after onshore Nigerian oil spills; the study showed that neonatal mortality rates doubled after spills nearby (Bruederle and Hodler 2017). Therefore, an answer is needed to this legitimate question: "Is the existing contamination of the Bodo area lethal only for mangroves and the associated fauna, or does it also endanger the health of the local people?" Independent health officials should evaluate the chemistry data as soon as possible to determine the best course of action to protect the local people from any ongoing exposure to toxins of unknown but potentially significant magnitude. This recommendation is made because of the very high sediment concentrations of aromatics (EC_5–EC_{44}) and other hydrocarbons, especially PAHs. The factors determining the hazard posed by toxic substances are a function not only of their concentrations and distribution, but also of pathways and duration of exposure. The pathways are demonstrable for mangroves, their epifauna, and sedentary infauna in contaminated sediments all under tidal submersion twice daily, but remain unclear for the Bodo human population (e.g., via skin contact, inhalation and ingestion). When the sediments begin to respond to remediation and the restored mangrove system undergoes recolonization by edible fauna, the present avoidance of contaminated areas by fishermen may cease, and exposure to food-borne contaminants could then resume. To the extent that anyone still relies on potentially-contaminated water for drinking and household use, they should be provided with clean water until remediation is complete, as recommended by UNEP (2011).

The first appropriate and apparently obvious response is to remediate the Bodo intertidal and shoreline sediments in accordance with applicable Nigerian laws and guidance (i.e. EGASPIN). From the work of the BMI, this chapter is a contribution to such a response. A properly designed confidential medical screening programme and epidemiological investigation might also be among the appropriate responses to contamination in Bodo, and similar recommendations were made for Ogoniland by UNEP (2011). The UNEP studies were not able to consider fully the exposure scenarios typical for the Bodo area such as the consumption of contaminated water and seafood, children fishing and bathing in the creeks, and local people working there now or in the past. The latter exposure scenarios should include those whose work on-site has been legal or illegal, with or without appropriate Personal Protective Equipment.

The PPE provided for the work force should be protective against a release of volatile hydrocarbons from subsurface layers once the surface layer (0–5 cm) has been removed during cleanup. The provision of hand-held gas detectors

and face masks should follow international best practice and SPDC safety standards. This is needed because evaluation of the analytical data shows that volatile fractions penetrated further than the bulk of the oil, and are currently sequestered in the subsurface layer. Removal of the upper layer of contaminated sediment could lead to the renewed evaporation of volatiles into the breathable air.

The visual and photographic data from the SCAT surveys should continue to be calibrated by chemical analyses at selected sites. This is important because better risk assessment is both necessary and possible using high quality analytical methods in situations where remediation of the environment or the protection of people is required. The SCAT approach should continue to characterize the oiling conditions in the field, to develop cleanup strategy, and to design and monitor segment-by-segment tactical plans. Laboratory and field approaches should continue to be linked in the various stages of operations (planning, gridding, sampling, analytical, data processing, interpretation, public communications, and scientific publications).

In addition to SCAT activities, chemistry monitoring will require selected oiled sites to be set-aside as controls for scientific study of cleanup effectiveness and impact, to distinguish them from the impacts of the original oiling(s). Preparing for the mangrove restoration will require the establishment of reliable lines of supply of propagules from mangrove nurseries. Restoration can begin when sediment hydrocarbons and ground conditions are suitable, but crucially only when security is such that vandalism and pipeline tapping have ceased, and proper inspections can take place. Necessary actions also include improving youth employment and training opportunities to help alleviate poverty (e.g., Rivers State Sustainable Development Agency). If supported by better law enforcement, these actions would also directly reduce oil theft and illegal refining activities that otherwise might recur and continue to damage mangrove habitats and human health.

The forensic evaluation of the chemical 'fingerprints' of Bodo sediments should be enhanced by a fuller PAHs profile including the alkyl homologues of parent PAHs. Additionally, the hopane and sterane biomarkers characteristic of crude oil and weathered refined products should be analysed by GC-MS. The PAH forensics results from the present study indicate oil industry and illegal refinery sources consistent with the 2008 spills and the subsequent increase in oil theft and illegal refining. However, the methods used so far are not adequately discriminatory for fine-grained sediments with multiple chronic inputs, and should be refined to ensure understanding of human and biota exposure to individual hydrocarbons.

On the basis of the present data, only the more highly-contaminated surface sediment layer (0–5 cm) should be physically removed. It is emphasised that in the full cleanup phase the SCAT approach will facilitate more precise cleanup recommendations tailored to each cell in the grid. The preliminary data show that intrusive remediation measures should concentrate on the more heavily oiled surface 5 cm of sediment because limiting the physical removal to 5 cm would reduce oil content without undue risk of mudflat erosion. This is needed because oily waste volumes would be minimised and environmental outcomes would be improved by avoiding accidental inclusion of relatively uncontaminated subsurface material among the wastes. Considering the resulting lower costs/hectare, a larger area could be remediated within a given budget. Such a sustainable approach would reduce pollution in Bodo without increasing: (a) direct trampling and compaction of the sediments; (b) multiple handling of larger volumes of oiled wastes; and (c) carbon footprint impact of traffic emissions.

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