SV-223

Mineral oil in a tropical forest

What are the impacts?
When is intervention with remedial measures required?

Final Report

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November 2003

Gouda, SKB

Stichting Kennisontwikkeling Kennisoverdracht Bodem

Titel rapport
Minerale olie in een tropisch regenwoud.
Wat zijn de negatieve effecten?
Wanneer is interventie met herstelmaatregelen vereist?
Definitief rapport

SKB rapportnummer
SV-223

Project rapportnummer
SV-223

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Aantal bladzijden
Rapport: 27
Bijlagen: 6

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Samenvatting
Het project heeft de overeenkomsten en verschillen bestudeerd tussen verschillende onderzoekstechnieken om te komen tot een evaluatie van de toepassing bij ruwe olieverontreinigingen in een tropisch regenwoud. Het onderzoek betrof vegetatiestudies, grond en grondwateranalyses op diverse fysisch/chemische parameters en nutriënten, bacterie- en nematoden-bepalingen en oliekarakterisaties. Het onderzoek omvatte diverse bemonsteringsrondes in Gabon en Nigeria.
De resultaten laten zien dat de vegetatiestudie waarbij de PQ-methode is toegepast en het bepalen van diverse fysisch/chemische parameters, waaronder oliekarakterisaties, een goed beeld geven omtrent het gedrag van ruwe olie in het ecosysteem van het tropisch regenwoud. Het nematoden-onderzoek is in dit project niet succesvol en de bacterie-bepalingen (-tellingen) niet zinvol gebleken.
Vanaf het begin was het doel van het project een onderzoeksstrategie te ontwikkelen gebaseerd op een conceptueel model waarbij hypotheses zijn opgesteld en geverifieerd. Dit vereist een basisbegrip over de processen die spelen in het ecosysteem van een tropisch regenwoud en die direct verband houden met de te volgen (directe) saneringsaanpak.
De hoofdconclusie van het project is dat olie snel kan afbreken in het tropisch regenwoud. Indien dit niet gebeurt is daar een duidelijke reden voor. Het vinden van deze reden is essentieel om te komen tot een efficiënte en economisch voordelige saneringsactie. Deze bestaat meestal uit simpele interventies, waardoor het ecosysteem van het tropisch regenwoud de biodegradatie van olie weer kan oppakken. Het ontrafelen van de processen die het gedrag van olie in de bodem van een tropisch regenwoud bepalen, vereist een meer dan standaard, multidisciplinaire onderzoeksaanpak.

Trefwoorden
Gecontroleerde termen
aardolie-industrie, afbreekbaarheid, afdekken, alifatische koolwaterstoffen, analysemethoden, anorganische verbindingen, aromatische koolwaterstoffen, bacteriën, biomonitoring, bodemverontreiniging, doorlatendheid, ecosystemen, effecten, humus, immobiliseren, inventarisatie, kennissystemen, kosten-baten, land-farming, lange termijn, mangrovebossen, meetgegevens, modellen, moerasbossen, monitoring, monstername, nematoden, normen, nutriënten, olie, onderzoek, ontbossen, ontwikkelingsgebieden, procedures, regenwouden, sanering, stofgedrag, toxiciteit, tropen, vegetatie, veldonderzoek, verspreiding, verstoring, wortelzone, zware metalen

Vrije trefwoorden
MINERALE olie, tropisch regenwoud, vegetatie studies, PQ-methode, fysisch/chemische parameters, oliekarakterisatie, natuurlijke afbraak, bioremediatie, ecologisch herstel

Titel project
Minerale olie in een tropisch regenwoud

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Dit rapport is verkrijgbaar bij: SKB, Postbus 420, 2800 AK Gouda

Report title	**SKB report number**
Mineral oil in a tropical forest What are the impacts? When is intervention with remedial measures required? Final report	SV-223 **Project report number** SV-223

Author(s)	**Number of pages**
Drs. Philip van Diest Drs. Flip van Keulen	**Report:** 27 **Appendices:** 6

Executive organisation(s) (Consortium)
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Publisher
SKB, Gouda

Abstract
The project investigates the parallels and differences between investigative techniques to evaluate an implement remedial action in cases of soil contamination by crude oil in tropical forest. An investigative programme was set up and executed including vegetation studies, sampling for physicochemical parameters, nutrients, bacteria and nematodes and oil characterisation. Several sampling campaigns were carried out in Gabon and Nigeria.
The evaluation learns that, the vegatation survey using the PQ-method, the physico-chemical parameters including oil characterisation provide a good insight in crude oil behaviour in tropical forest. The investigation ofnematodes has not been susessful in this research. The enumeration of bacteria is considered useless in this type of investigations.
From the start, the project was directed towards the development of an investigative strategy, which was based on the use of a conceptual model where hypotheses were postulated and tested. This provides a basic understanding of the processes involved in the tropical forest that has a direct implication for plan for emergency response and remedial action.
The major conclusion of this project is that oil degrades fast in tropical forest and if not, there is a reason. Finding this reason is the key to efficient and low cost soil remediation, often based on simple interventions that help the tropical forest ecosystem to cope with oil. Finding this reason requires a more than standard, multidisciplinary approach to the investigative strategy in tropical forests.

KeywordsControlledTerms
See datasheet in Dutch

Uncontrolled terms
bacteria, bioremediation, ecological recovery, mineral oil, monitoring, natural attenuation, nutrients, nematodes, oil characterisation, physico-chemical parameters, pq-method, tropical forest, vegetation studies

Project title	**Projectmanagement**
Mineral oil in a tropical forest	Fugro Ingenieursbureau B.V. (Drs. Flip van Keulen+31-703111222)

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Netherlands Centre for Soil Quality Management and Knowledge Transfer (SKB)

INHOUD

SAMENVATTING

Minerale olie in een tropisch regenwoud

Twee jaar lang hebben Fugro Milieu Consult B.V. en IWACO (Royal Haskoning), Shell Global Solutions Int., Shell Gabon, SPDC (Shell Petroleum Development Company of Nigeria), het project "Minerale olie in een tropisch regenwoud" uitgevoerd, dat financieel werd ondersteund door de Stichting Kennisontwikkeling en Kennisoverdracht Bodem.
Middels dit project worden de overeenkomsten en verschillen tussen onderzoekstechnieken onderzocht om saneringsmaatregelen te evalueren en uitvoeren in gevallen van olievervuiling met ruwe olie in tropische regenwouden. Er is een onderzoeksprogramma opgezet en uitgevoerd. Dit programma omvatte onder meer vegetatieonderzoek, proefnemingen voor fysisch-chemische parameters, voedingsstoffen, bacteriën en rondwormen en oliekarakterisering. Er zijn verschillende steekproefonderzoeken gehouden in Gabon, en in Nigeria.
Na evaluatie van toepassing van deze technieken in tropische regenwouden is gebleken dat als we de informatie gebruiken die is verzameld bij veldonderzoeken, veldwerk en literatuuronderzoek, het vegetatieonderzoek volgens de PQ-methode, de fysisch-chemische parameters een goed inzicht bieden in het gedrag van ruwe olie in tropische regenwouden.
De telling van rondwormen en de interpretatie van de rondwormenpopulatie is bij dit onderzoek niet succesvol geweest. Er is maar weinig bekend over de rondwormen in de bodem van tropische regenwouden. Daarom is het niet duidelijk of de kennis van rondwormen in de betreffende temperatuurszones ook van toepassing is op het tropische ecosysteem. De telling van bacteriën wordt bij dit soort onderzoek als nutteloos beschouwd.
Vanaf het begin werd het project in de richting van de ontwikkeling van een onderzoeksstrategie gestuurd, een strategie die gebaseerd was op het gebruik van een conceptmodel waarin aannames werden gedaan en onderzocht. Dit leverde een fundamenteel begrip op van de processen die plaatsvinden in het tropische regenwoud, dat een directe uitwerking heeft op een plan voor noodsituaties en te nemen saneringsmaatregelen.

De belangrijkste conclusie van dit project is dat olie in een tropisch regenwoud snel wordt afgebroken en dat, indien dit niet gebeurt, hier een redden voor is. Het vinden van deze reden is de sleutel tot een efficiënte bodemsanering tegen lage kosten, vaak gebaseerd op eenvoudige ingrepen waarmee het tropische regenwoud geholpen wordt bij de verwerking van de olie. Voor het vinden van deze reden is een meer dan standaard, multidisciplinaire benadering nodig van de onderzoeksstrategie in tropische regenwouden.

In Gabon is de sleutel bij saneringsmaatregelen het mengen en stabiliseren van de olie, waarbij stabilisatie op locatie met behulp van bedekking met vegetatie (milieubeheer met behulp van planten) een belangrijk aspect is. Op basis van de bevindingen van dit project is er een voorstel voor een onopvallende, langetermijnbenadering, waarbij selectief en bewust gebruik wordt gemaakt van natuurlijke middelen, met maximale inzet van plaatselijke arbeidskrachten. Deze benadering kan worden ondersteund door een saneringsplan dat internationaal acceptabel en verdedigbaar is.
In Nigeria is de sleutel tot effectieve sanering het mengen van de olie en biologische afbraak, waarmee verdere verspreiding naar gebieden met een lage bacteriologische activiteit voorkomen wordt.

SUMMARY

Mineral Oil in a Tropical Forest

For two years Fugro Milieu Consult B.V. and IWACO (Royal Haskoning), Shell Global Solutions Int., Shell Gabon, SPDC (Shell Petroleum Development Company of Nigeria), have executed the project "Mineral Oil in a Tropical Forest", funded by the Centre for Soil Quality Management and Knowledge Transfer.
The project investigates the parallels and differences between investigative techniques to evaluate and implement remedial action in cases of soil contamination by crude oil in tropical forest. An investigative programme was set up and executed including vegetation studies, sampling for physico-chemical parameters, nutrients, bacteria and nematodes and oil characterisation. Several sampling campaigns were carried out in Gabon, and Nigeria.
The evaluation of these techniques applied in tropical forest learns that when using the information collected during field visits, fieldwork and literature survey, the vegetation survey using the PQ-method, the physico-chemical parameters provide a good insight in crude oil behaviour in tropical forest.
The enumeration of nematodes and the interpretation of the nematode population have not been successful in this research. Little is known about the nematodes in tropical forest soils. Therefore it is not clear if the knowledge of nematodes in the temperate zones is applicable to the tropical ecosystem. The enumeration of bacteria is considered useless in this type of investigations.
From the start, the project was directed towards the development of an investigative strategy, which was based on the use of a conceptual model where hypotheses were postulated and tested. This provides a basic understanding of the processes involved in the tropical forest that has a direct implication for plan for emergency response and remedial action.

The major conclusion of this project is that oil degrades fast in tropical forest, and if not, there is a reason. Finding this reason is the key to efficient and low cost soil remediation, often based on simple interventions that help the tropical forest ecosystem to cope with the oil. Finding this reason requires a more than standard, multidisciplinary approach to the investigative strategy in tropical forests.

In Gabon, the key to the remedial action will be mixing and stabilisation of the oil, where on-site stabilisation using vegetative covers (phytoremediation) will be an important aspect. Based on the findings of this project there is a proposal for a low profile, long-term approach, making selective and deliberate use of natural resources, with a maximum input of local labour. This approach can be backed up by a remedial plan that is internationally acceptable and defendable.
In Nigeria, the key to efficient remediation is mixing and biological breakdown, which prevents further spreading to area's of low biological activity.

CHAPTER 1

INTRODUCTION

The 29th of May 2000, The SKB (Centre for Soil Quality Management and Knowledge Transfer), Shell Gabon, SPDC (Shell Petroleum Development Company of Nigeria), Shell Global Solutions, Fugro Milieu Consult B.V. and IWACO (Royal Haskoning) finalised the contract for the execution of the project "Mineral Oil in a Tropical Forest".

1.1 Background

The exploration and production of crude oil has had an impact on tropical rainforests around the world. As a result of activities related to the construction of roads and production facilities, the attraction of manpower and a limited understanding of the ecological implications, which vary from area to area, there is concern about the effects that this impact has had and in future may have on tropical ecosystems.
In addition, the significant reduction of the tropical rain forest area is also seen as an ecological implication that clearly deserves international attention because of its essential role in the production of oxygen and the capture of carbon dioxide.

1.2 Tropical Rainforest

Although the tropical rainforest ecosystems in America, Africa and Asia are quite different, there are a number of specific conditions, which are common to most tropical regions. In general these conditions are significantly different from those in more moderate climatic areas, as northern Europe.

Oil exploration in tropical rainforests occurs in the Niger delta, along the African coast between Angola and Cameroon, in Ecuador, Peru, Venezuela, Borneo, Brunei and Indonesia. The chemical and biological processes in tropical soil are quite different from those found in temperate climates. Destruction of the rainforest itself or the topsoil layer can result in irreversible damage.
The tropical rainforest comprises a great diversity of species and many of which require very specific conditions for survival. The relationship between flora and fauna is not comparable to that found in temperate forests. Localised ecological changes may therefore have a profound impact on a species' population or even lead to the extinction of certain species. The density of plants (i.e. biomass) in a tropical rainforest is 5 to 15 times higher then the biomass of forests in more moderate climatic areas. This volume of plants is directly dependent on the uppermost soil layer. In the lowlands, peat is formed on a large scale. Organic material does not degrade readily, despite the ideal moisture and temperature for micro-organisms.

To describe the behaviour of crude oil at least two types of forest were observed for the dominantly sandy soils of the project pilot sites. They form the end members of a gradual change from topographically high to low, dry to wet. This photo shows the contaminated forest in Gabon, looking for a high position to the wet areas below. Most contaminated sites include some high soils and some low soils forming one ecosystem. This photograph is taken at pilot site Z52, in Gabon. The ribbon on the tree was used to mark the extension of the pilot site. Photo: ©FMC

Photo 1. Tropical Forest in Gabon.

1.3 **Oil contamination**

During the production and transportation of crude oil, spills have occurred both at the production sites as well as along the transport lines. In recent years many of these contaminated areas have been remedied. The cleanup approach was usually practical and dependent on the available resources. Remedial activities included burning, burying and covering with sand and to a lesser extend excavation.

Burned oil spill in Nigeria.
Burning an oil spill achieves a reduction of the quantity of oil and stabilises the leftover, but the result is wasteland, covered with asphalt like topsoil. This photo is taken upstream of the project pilot site in Ogoniland, Nigeria.
Photo:© FMC

Photo 2. Burned oil spill.

Cleanup operation in Gabon.
Excavation of the oil spill is not feasible without destroying the forest. The result is infertile sand, where major efforts are required for re- vegetation.
Photo:© DEC environmental contractors

Photo 3. Remedial works in Gabon.

Increasing knowledge of the fate of hydrocarbons in soil (e.g. transport processes, degradation, etc.) and the development of the risk-based approach has led to a more balanced approach to soil remediation both in the US and Europe. The transfer of this approach to tropical regions depends on the validity of the assumptions underlying the risk assessments. One of the assump-

tions is based on the occurrence of natural attenuation, which may not be valid in the tropical rainforest because of the differences in microbiological and physical/chemical processes in the soil, referring to the concept of natural attenuation. Other assumptions are based on the availability of technology, the economics of the remediation processes and the cultural attitudes in the US and Europe.

It is therefore crucial to understand the ecological and biological processes in tropical soils and to adjust models and decision support systems to local conditions.

1.4 **Clean up Experiences in Gabon**

The remediation of oil contamination in the Gamba/Ivinga oil field has been based on a Risk-Environment-Costs (REC) approach similar to the decision support system RMK, which was developed within NOBIS, and other international procedures such as Risk Based Corrective Action (RBCA), and Shell's RB-ESA. Shell Gabon, with the support of FUGRO and IWACO, had to take a large number of REC based decisions during the execution of this large remediation project (encompassing more then 70 sites and more then 300.000 m^3 of contamination soil). Questions like, 'how many trees should be removed for the clean up of 1 m^3 of mineral oil?' or 'how much clean sand should be brought in for the construction of an access road for the removal of contaminated soil?' had to be answered. The decisions were based on assumptions which differ from the approach developed in the US and Europe, but appear to be reasonable.

Choosing remedial approaches had to be done pragmatically and could not always be based on long term experience or monitoring results and in many cases lacked the support of scientific evidence. Decisions were made by a panel of experts to overcome the obstacle of limited (scientific) knowledge.

The objective of the remediation project which has been carried out was to reduce the risks to acceptable levels comparable with the approaches adopted in the US and Europe. The assessments were based on the source/pathway/receptor concepts:

- essentially all sources of contamination were identified during the historical investigations, field inspections and soil investigations;
- a good understanding of the pathways along which the contaminants migrate could be determined from the first part of the soil remediation operation completed the previous year;
- the identification of receptors and the impact of exposure leading to an actual risk, however, were a more difficult process.

There is very little experience and limited scientific data available to predict the effects of crude oil contamination on the ecosystem (especially on the soil) of a tropical rainforest.

1.5 **Problem Definition**

At the start of the project the impacts of (crude) mineral oil contamination on tropical soils and ecosystems was unclear or undocumented. There was limited (scientific) justification for the selection and execution of remedial action and for the determination of clean-up targets in tropical regions.

Internationally operating oil companies are faced with the fact that in most cases only a limited regulatory framework exists. However, remediation that satisfies local requirements may not safeguard these companies from future claims or liabilities due to changes in government or legislation to comply with internationally accepted legal requirements (e.g. World Bank).

Biodiversity is short for "biological diversity" – the extraordinary variety of life of Earth.
The impact of exploration and production activities by energy companies on biodiversity is an international concern. This issue is being explored in Gamba (Gabon) through a project by the Smithsonian Institution's Monitoring and Assessment of Biodiversity Program (MAB) through a $2.8 million 5 year grant from the Shell Foundation.
Understanding the impact of crude oil contamination on biodiversity is an essential aspect in the discussion of remedial approach.
Photo: ©Gabon Vert

Photo 4. Biodiversity.

Numerical standards have been developed for temperate climatic conditions that take local conditions and risk approaches into account. However, these values cannot be used in a tropical forest without a scientific adaptation that could be effectively applied under distinctly tropical conditions. Therefore it is important to gather more knowledge for tropical conditions to allow the application of a more appropriate REC (Risk-Environment-Costs) approach, as developed in NOBIS. This project focussed primarily on the assessment of impacts of mineral oil on tropical rain forest.

1.6 **Objectives**

The objectives of this project are:
- determination of the key processes in tropical forest soils in relation to crude oil contamination;
- a scientific assessment of the effects of oil contamination on tropical rain forest/vegetation and ways of measuring those effects;
- To determine the ecological recovery potential of a tropical ecosystem in comparison to ecosystems in the Netherlands, both when no action is taken and after remedial action.

The final output of the activities outlined in this project are an investigative strategy and infrastructure, which has been tested at pilot sites in Gabon.

The long term objective of this project in the following 3 to 5 years, is to contribute to the development of a decision support system (beyond the scope of this project) similar to and based on the REC-approach. In principle this should facilitate assessing the need for remediation and make the development of cleanup targets possible. The principles are generally applicable in other tropical regions, allowing national governments, international and national companies and other stakeholders like NGO's and local communities to evaluate remedial plans and the result of cleanup actions.

The infrastructure required for oil exploration and production allows access to formerly undisturbed forest. This has lead to the development of ecotourism in or near the oil fields. The interest of ecotourism through NGO's is becoming an important aspect in oil spill prevention and remediation. The photo shows the marsh forest vegetation, with a very specific fauna of apes, monkeys, antelopes, birds, reptiles and fish, all feeding on fruits, nuts and each other. Elephants do cross but prefer feeding on the transition of forest and savannah.
Photo:© FMC/Shell Gabon

Photo 5 and 6. Ecotourism.

CHAPTER 2

APPROACH

The approach to the project has been a practical one.

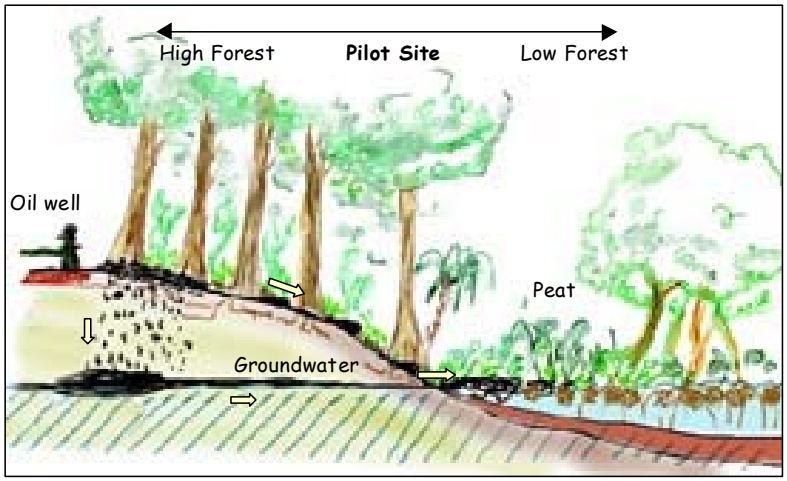
In conjunction with the standard environmental survey a number of additional investigative techniques were applied on a number of selected pilot sites. While working towards solution of the problems of the oil companies involved in this project, a general strategy for application of these techniques was extracted and discussed with the experts within and outside this project.

Starting point of the approach is the standard environmental survey: Identification of the spatial distribution of contaminants, particularly their relative fractionation in subsurface solids and water and the potential exposure pathways. There are many comparable standard procedures, guidelines and standards available for soil investigations, published by countries, and companies, all with their specific application, indicating required number of samples, boreholes, depth of penetration, parameters, etc.

The additional techniques were screened in the proposal phase of the project. The selection criteria required that the technique should have been applied in the Netherlands and has lead to generally acceptable results. Within the Nobis/SKB-framework, much work has been carried out on this subject, so the selection was straightforward and well motivated. The techniques are discussed in the basic project plan; the application is discussed in the protocol, developed during the project. (Report I7v3)

Also for the selection of pilot sites, during the proposal phase, criteria were developed. These criteria were applied in Gabon and Nigeria, leading to 5 pilot sites and two control sites in Gabon, and three pilot sites and two control sites in Nigeria. The process of site selection, and a comprehensive description of the selected sites is provided in the projects reports on site selection: I1v2.pdf, Site description (Gabon) and I3v2.pdf: Site selection Nigeria.

The Basic Project Plan describes a preliminary conceptual model based on a basic understanding of behaviour of crude oil in the forest for Gabon and Nigeria. The model was refined and verified using the available information in literature or documents and the interpretation of field results. The conceptual models for Gabon and Nigeria were described in the reports I2v2.pdf, Conceptual Model Gamba-Ivinga (Gabon) and I4v2.pdf, Conceptual Model East Nigeria.



A *conceptual model describes the way the oil is spreading or accumulating in the ecosystem of the contaminated forest. It combines the classic mapping of oil contamination, the environmental aspects and available information from literature to a comprehensive description of the source, the pathways and objects. In its first concept, the model includes a number of hypotheses on behaviour of crude oil in the environment that will be verified later. The model should be clear on facts and hypotheses.*

Fig. 1. Conceptual Model.

Before each major step in the project, workshops were held with a panel of experts to discuss the planned activities: Before the first sampling campaign the approach and technical details of the sampling approach were discussed and adjusted according the recommendations. The second discussion took place when the results of the first sample campaign were made available. The discussion focussed on the protocols for sampling and the implications of the results for the conceptual model. Based on the first results, a scientific workshop was organised including scientists of the universities. The last expert meeting was organised when all results were available after the last sampling campaign. Major subject of the discussions were the conception of the investigative strategy for crude oil in tropical forest, and the results in view of resolution the problem owners problems.
Of all meetings, minutes were made and reported (M1v1.Pdf, M2v1.Pdf, M3v1.pdf, M4v1.pdf, M5v2.pdf, M6v1.pdf)

Fieldwork was carried out in Gabon and Nigeria. In Gabon, four sample campaigns were organised: June 2000, October 2000, March 2001 and October 2001. In addition, during regular groundwater quality monitoring activities by Fugro further sampling was carried out. In Nigeria three sample campaigns were organised: January, June and December 2001. Sample campaigns are reported in the factual reports (F1v1.PDF, F2v1.PDF, I3v2.pdf, F4v1.PDF, and F5v2.pdf)
Before fieldwork, the sampling approach and protocols were described and discussed. During fieldwork these protocols were tested and adjusted, based on the preliminary results, where required.

Because oil contamination is an important political issue in Nigeria and because of the general security problem in this part of Africa, the selection of sample sites and the execution of fieldwork required a high level of planning and preparation. Photo:©FMC

Photo 7. Fieldwork in Nigeria.

Laboratory tests for the physico-chemical parameters have been performed by the former Iwaco laboratory and incidentally by Alcontrol, for quality control. Bioclear determined the microbiological parameters. TTE has carried out the oil characterisation. For the nematodes enumeration, in first instance, the Faculty Nematology of the Agricultural University of Wageningen was used, later the laboratory of Blgg in Oosterbeek.

Throughout the entire project, knowledge was exchanged between Gabon/Nigeria and the Netherlands. In Gabon, the project subcontractor is Gabon Vert, a local environmental company, with close relation to the University of Libreville. In Nigeria, the contacts with the scientific world was through the temporary staff of SPDC, who are affiliated to the University of Port Harcourt and Prodec Fugro, a company that found its origin and is still closely related to the university of Port Harcourt (Nigeria).

An essential contribution to the knowledge exchange and development came from consulting, participation, and interaction with several ecotoxicological projects within SKB (e.g. Triade), ecotoxicological discussion fora (e.g. within NARIP) and research and consultancy institutes in the Netherlands (e.g. Bioclear, Alterra). Members of these projects, fora or institutions participated in the workshops, and were member of the expert panel that discussed the project progress.

Further knowledge transfer will be accommodated at the workshops to be organised in Gabon and Nigeria to present and discuss the project results with the problem owners, their consultants and other interested parties.

In figure 2 the project activities and their relation are described.

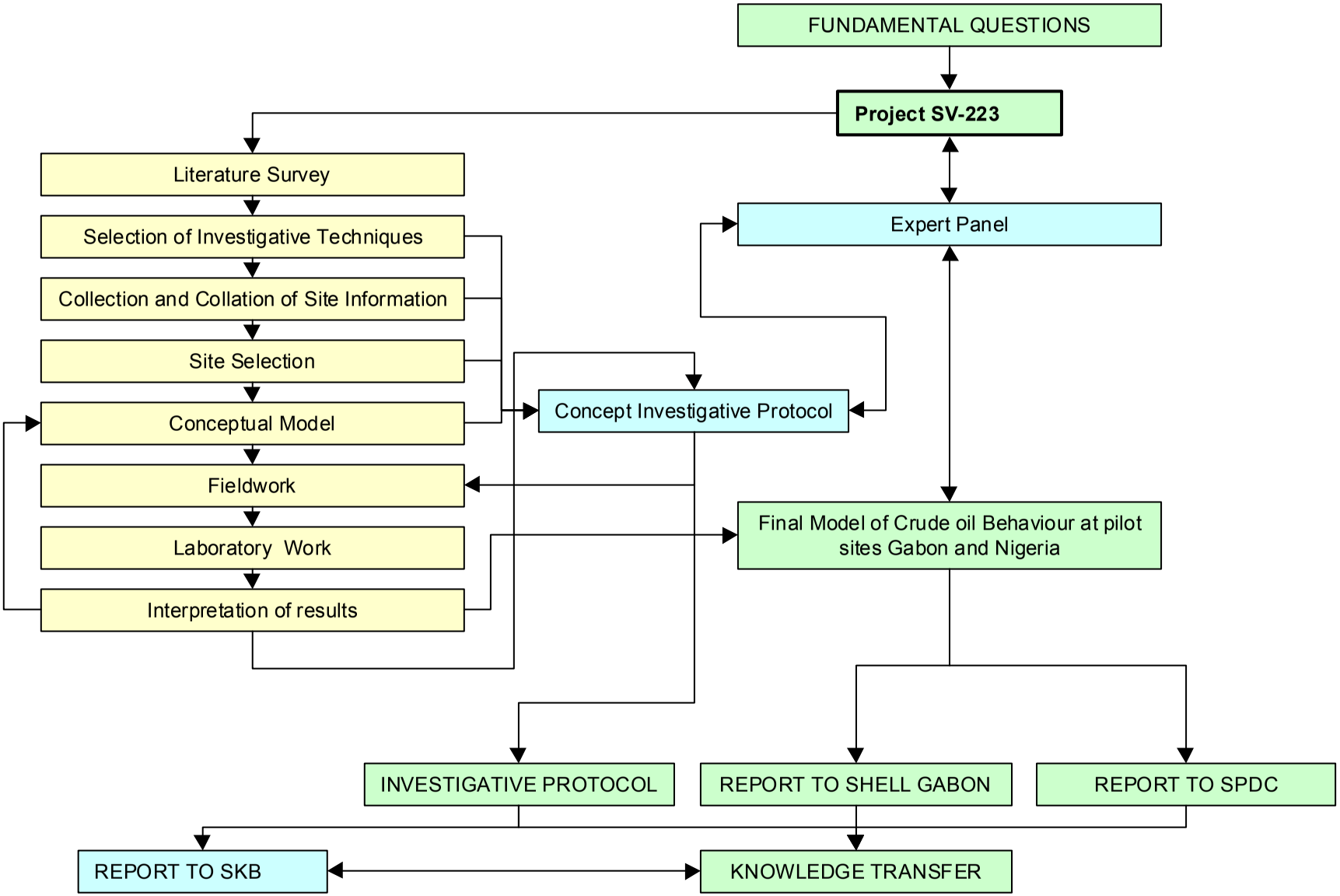


Fig. 2. Flow Chart of Project Activities.

CHAPTER 3

RESULTS

3.1 Introduction

The multidisciplinary approach of the project, where consultants, that formerly contributed to resolve different parts of the puzzle co-operated to build a conceptual model for the key processes has resulted in a comprehensive synopsis of the key processes in tropical forest in relation to crude oil contamination.

Research into process parameters of oil degradation indicate that the conditions in a tropical forest can be evaluated as being good to very good for natural breakdown; high temperature throughout the year, good moist conditions and sufficient bacteria that can digest oil. The nutrient situation is less favourable; there is much competition from the tropical flora and micro fauna.

The field information and results of investigations collected in this project confirm this general statement and give good insight in the processes and conditions that are the driving force for natural breakdown. Report l6v2.pdf summarises the results of the parameters of the monitoring programme (Vegetation, Physico-Chemical, Oil Characterisation, Microbiology and Nematodes) and discusses the relations between these results.

The moderately or good conditions are limited to the biologically active zone in the forest. Oil accumulations that are outside this zone may show little or no natural attenuation. Starting from the "ideal" situation, the key aspects that slowed down, or halted the process of natural attenuation in these "traps" are unravelled, using the results of the "classical" environmental survey, the additional techniques that were subject of this research project, field observations and last but not least the discussion between the various disciplines involved in this project.

This has lead to the development of an investigative protocol that can be used in any oilfield or oil contamination in tropical forest.
The application of this protocol, during its development in the oilfields, subject of this study, has provided answers to a number of basic questions formulated during the conception of this project and has provided scientific background to a more balanced approach for the remedial works in Gabon and Nigeria.

3.2 Processes and Conditions

3.2.1 *Determination of the key processes*

The processes and conditions that decide on the rate, speed and final result of oil degradation are described using a descriptive model, in the first stage indicated as a conceptual model.
A conceptual model describes the way the oil is spreading or accumulating in the ecosystem of the contaminated forest. It combines the classic mapping of oil contamination, the environmental aspects and available information from literature to a comprehensive description of the source, the pathways and objects.
The development of the model starts with the source of crude oil contamination, it describes the pathways and objects with special attention to biological active zones and zones (potential traps) where oil may accumulate. Each "type" of oil is described in its environmental setting: Physical description, Vegetation, Micro fauna, Composition and Processes (Formation, degradation, spreading).

In general the following types of oil can be expected:

- he original crude oil before the spill occurred plus associated production water;
- oil on or near the surface including vegetation, wet or dry, exposed to the atmosphere;
- oil that has penetrated the soil but has not yet reached the groundwater;
- oil floating on groundwater;
- oil that has accumulated in peat bogs/swamps/ etc.;
- oil components in groundwater.

The models for Gabon and Nigeria are reported in the project documents I2v2.PDF, Conceptual Model Gamba-Ivinga (Gabon) and I4v2.pdf, Conceptual Model East Nigeria.

3.2.2 *Scientific assessment*

Discussion of the models developed for the test sites during its concept and more final phases by the multidisciplinary project team indicated that certain "types" of oil that logically should be found using the source-pathway-target approach were missing, or poorly presented. In Gabon there was no oil on the soil of dry (not inundated) forest and very low and only incidental cases of groundwater contamination. Verification in the field of forest soils indicated that in many cases oil has been present, but was degraded to minor remnants. Consequent monitoring of wells placed in the middle of contamination showed rapid decrease of oil concentrations in the groundwater. In Nigeria at locations of severe oil spills, the topsoil was remarkably clean; finding good spots for sampling of the topsoil was more difficult than anticipated.

The multidisciplinary project team included the disciplines of biology (vegetation, wildlife), microbiology, toxicology, soil science, (hydro)geology and chemistry.
The photo is taken during a field visit in Gabon. Not visible on this photograph is the fact that below the surface litter layer the first 50 cm of soil consists of pure crude or peat soaked with crude oil, continuing below the trees.

Photo 8 and 9. Site Visit.

It was concluded that these "types" of oil were missing because of rapid natural breakdown.
The evidence for rapid breakdown in the topsoil is obvious through many field observations and the subsurface investigations in Gabon and the success of the remedial approach by SPDC's Past Impacted Area (PIA) Remediation Department who, with simple means, achieve a remarkable recovery of the grade of contamination in the topsoil.
The pilot site Z71 is located about 100 meter from the source of the oil spill. At the source some hard oil is found on the savannah. Between the source and the spill, only the eye of an expert, who knows that a large amount of oil has passed, will find some evidence of former oil contamination; some unnaturally hard peat, grains of black material that floats like wood etc. At pilot site Z7, where several spills have occurred from a weak point of the pipeline, the forest, between the pipeline at some altitude and the contaminated swamp, has conserved some evidence. Some trees and roots above the topsoil level are covered with dry hard black remains of crude oil, and

the topsoil contains the black material considered the ultimate result of microbiological breakdown (see photo 10).

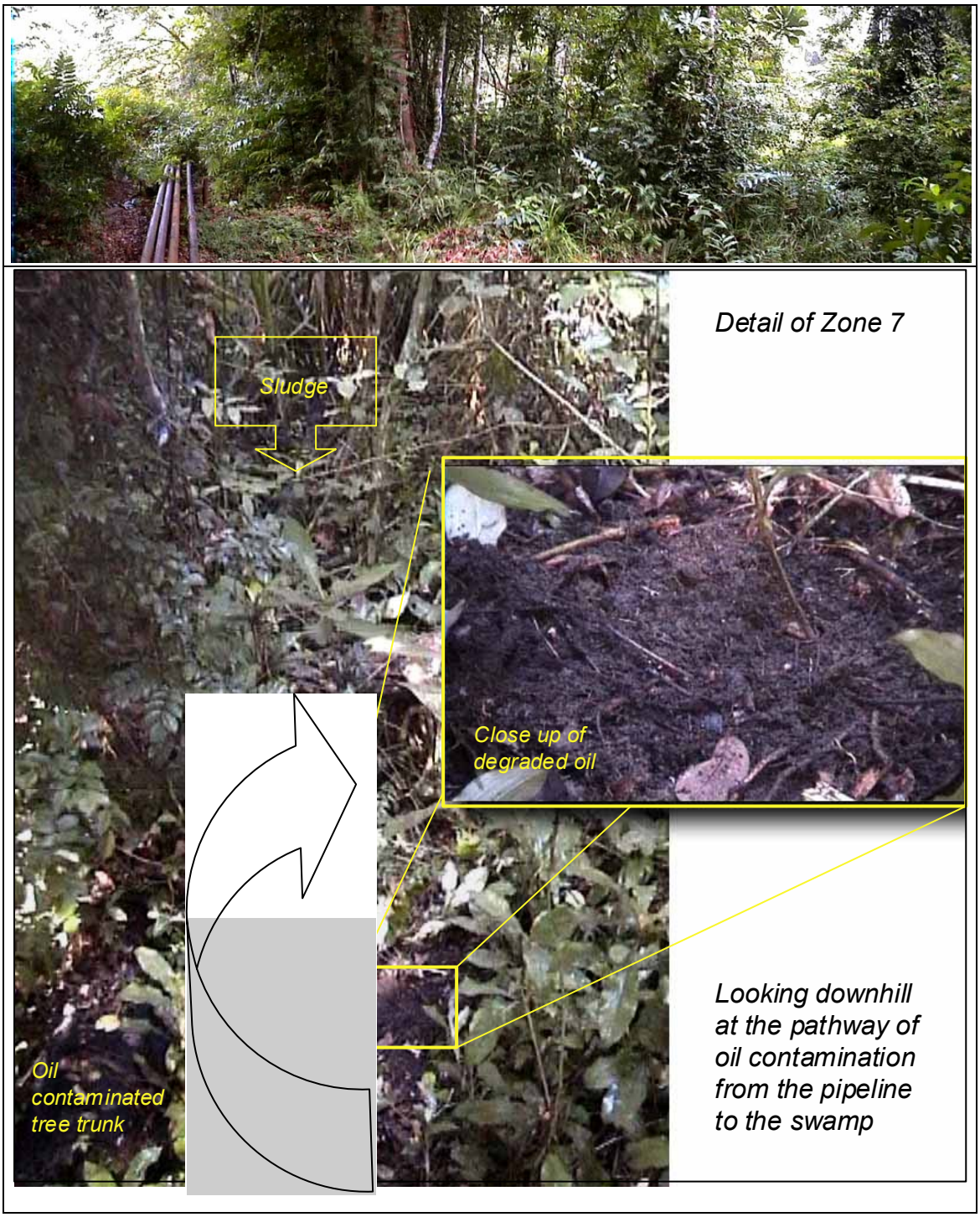


Photo 10. Z7 from pipeline (left) to polluted area (right) and detail of the forest (*Photo © FMC).*

The evidence for rapid breakdown in groundwater of Gabon could be attributed to limited solubility. However, the oil characterisation and the composition of the original crude indicate a considerable amount of soluble oil components. Disturbance of the equilibrium by installing a well in contaminated areas leads to high starting values, slowly decreasing to concentrations near or below the limit of detection. This effect is caused by biodegradation of TPH in solution.

In the next section, this observation is placed in the context of "transport": disturbance mixes the oil water, microorganisms and nutrients, leading to fast breakdown, until the "separation between oil in the soil, and clean groundwater is re-established.

In Nigeria, the project did not sample for groundwater. However, a number of projects were studied and discussed, all with, in the objective of the experience in moderate climates, an amazingly low level of groundwater contamination. This includes the SKB-project site in Ogoni land. Many of these cases were attributed to poor standards of sampling and sample preservation, and poor performance of Nigerian Laboratories. We conclude however that not understanding the system by the experts may be an important aspect. The oxygenated groundwater, rich in organic matter of the tropical forest appears to be much more efficient in natural attenuation than the generally anaerobic groundwater in temperate climates. (See also report I6v2.pdf)

3.2.3 *Understanding the system*

The zones of rapid natural attenuation are indicated as biological active zones, the zone where the conditions allow the process of microbiological and chemical breakdown and transport of components to achieve a considerable reduction of the oil concentration.

The other "types" of oil, in particular where huge quantities of oil have accumulated, can be situated in a zone where the conditions for natural attenuation are less favourable.
Comprehension of the conditions or factors that have prevented degradation of the oil is the key to predict the behaviour of oil contamination in the future and the associated risk.

In this study, four aspects are considered as being rather independent but important factors when describing the process of degradation of oil. Of coarse, these factors are interrelated, and of coarse there are other, but these four are sufficient to direct the investigative process.

(Bio)degradability: The degree and rates of hydrocarbon biodegradation depends first of all, upon the structure of the oil components. The paraffin compounds biodegrade faster than aromatic and naphthenic substances. With increasing complexity of molecular structure as well as with increasing molecular weight, the rate of microbial decomposition usually decreases. It is the simple question can the microorganism attack the chemical structure, and how much energy does it gain from this at the end. Chemical transformations of oil mainly have an oxidative nature and often involve photochemical reactions under the influence of ultraviolet waves of sunlight.

Conditions: Temperature and moisture conditions can accelerate or stop microbiological or chemical (weathering) reactions. Extreme temperatures and changing moisture conditions may enhance chemical degradation/weathering while at the same time may prevent biodegradation.

Nutrients/oxygen: The availability of nutrients and oxygen, or oxygen donators. Important nutrients are Potassium; Nitrate and Phosphate but the role of a number of trace elements should not be neglected. Oxygen donors include atmospheric oxygen, ironhydroxides, nitrates, and sulphates, going from aerobic to anaerobic conditions.

Transport: All chemical and biological equilibrium reactions stop, if there is not a mechanism that provides the components that are consumed, and removes the reaction product.

In Gabon the "type" called Hard Oil, oil accumulated on or mixed with the topsoil above water level, on the Savannah, with an asphalt, tar or rock like appearance was in the first approach classified as not biodegradable, because it was out there for so long. The oil characterisation however indicated this material as more biodegradable as the original crude, with a significant

change in chemical composition because of exposure to extreme temperatures, sunshine and intense rain. The fact that it was not biodegraded is caused by the very unfavourable soil conditions for microorganisms, not only because of poor nutrient status, but also because of extreme temperatures in the dry season and very poor moisture condition. While this material in former remedial works was transported to a depot in Gabon, pilot tests have started for bioremediation under improved conditions (mixed with straw, fertiliser and sprinkled).

For the type of oil contamination, indicated as "sludge" or contaminated peat, found in Gabon as well as in Nigeria, it became apparent that the factor transport is important to explain the persistence of this type of oil contamination.
Sludge is found in the low-lying areas, inundated in the wet season, normally inside the forest or at the forest rim. This type of material is also found in pits. Sludge is the general term describing free product, or free product mixed with peat or sand to a plastic, more or less coherent paste. Contaminated peat is oil soaked peat. The thickness generally is between 20 cm and 60 cm, but may be more than 1 m.

In the nursery, a leftover of a large revegetation project, required to fill the sandy scars that resulted from remediation by excavation, soil washing and transport to depots, Gabon Vert, as consultant for Shell Gabon, has started a large experiment to evaluate potential plants and trees that can root into contaminated soil. For this purpose, root trainers are used with contaminated soil in the bottom, exposed to a hydrologic regime comparable to the contaminated sites. The first results have shown a number of promising candidates for Phyto remediation in the tropics. Photo © FMC

Photo 11. Shell Gabon Plant Nursery.

Although seasonally inundated, there appears to be only groundwater movement through cracks and larger canals. Biologic activity is limited to the surface layer of litter, as the nematodes, biological enumeration and vegetation study indicates.

In groundwater a slow but consequent decrease of the oil concentration is observed in those monitoring wells that have been installed in severely contaminated soil (concentrations of TPH in soil above 30.000 mg/kg, Ref. GABGIS). In the soil, where oil is trapped, there is little or no contact between the soluble components of oil and and water, leading to low or zero oil concentration in groundwater. The disturbance of introducing a well changes this situation, and a certain amount of oil is available in solution for the micro organisms. After about one year, the equilibrium is re-established, and the oil in solution is either degraded or absorbed. The oxygen content slowly increases to its original value (that we were not able to measure as our first sampling was 2 weeks after installation of the well) indicating the slow down of microbiologic activity.
Disturbance of the soil is considered improvement of transport.

Improvement of transport and at the same time the physical stability of this material is considered to be achievable using plants or trees with roots that penetrate the oily layer. Inspired by the first results of the SKB-project SV-233, Shell Gabon has started nursery experiments parallel to this project, to investigate potential plants and trees that root into sludge. Interventions to improve drainage are evaluated, but are site dependent.

At the same time, one of the pilot sites, used by this project, fertiliser was applied superficially (not ploughed in). The monitoring period for this experiment (application October 2001) is too short to present reliable results, but the impression exists that the fertiliser has not reached the oily layer below the superficial layer of litter (see photo 12).

At zone 71, below the superficial layer of litter, a large amount of sludge and contaminated peat is present. At this spot, fertiliser was added in October 2001. In June 2002, a remarkable green band of fresh plants stretched from the site to the nearby stream, indicating superficial spreading of the fertiliser.
Photo ©FMC

Photo 12. Sampling at Zone 71.

3.3 **Measuring the Effects of Oil Contamination**

The scientific assessment of the impact of crude oil spills in a tropical forest requires a broad and multidisciplinary approach. In the western world the desired result of emergency response and cleanup operations is well defined, the guidelines and standards refer however to industrialised estates and "secondary" nature reserves. The impacts of oil exploration and production in arctic nature reserves are intensively studied. The vulnerable ecosystem in the arctic does not compare to the system in tropical forest.
Assuming that the future land use of oil contaminated land will be nature reserve, or production forest, the investigations shall be directed to appraise the recovery potential of the contaminated forest.
The recovery potential of the forest is huge as long as the biological active zone is preserved. Destruction of the active zone, either by the impact of the oil spills, or the impact of interventions

is disastrous. Not only will it take much effort and a long time to grow a secondary forest; also the driving force for natural attenuation is killed.

In this project investigative techniques were tested, which are in a phase of development that acceptable and reproducible results can be expected and at the same time provide valuable information that contributes to understanding the system. The interpretation requires a multidisciplinary approach, more comparable to the approach for impact assessments, than the approach of standard environmental surveys. The techniques were applied additional to standard environmental surveys, carried out in by the oil companies, or their consultants.

The systematic description of the vegetation, following the PQ-method, is very useful to provide insight into the impact of oil contamination in the ecosystem of the forest. Additionally it shows the different impacts of remedial actions on the forest. The method is reproducible and perfect for long time monitoring. The reports can be interpreted, or can support biologists that have not visited the site to evaluate environmental impact and risk.

The first classification of the oil contamination at Z71, Gabon, one of the pilot sites of this project, was "nice forest", with oil in patches between the trees. The vegetation survey indicated the forest to be secondary, growing on a large oil contamination, that killed most of the trees (probably due to the associated salt water) but not the biological activity, leading to rapid re-growth of the forest. Excavation of the supposed patches of oil would have revealed a much larger contamination, and finally have destroyed the forest.
Photo © FMC

Photo 13. Zone 71.

Soil description and classification following one of the international soil taxonomies allows the interpretation of soil processes, its potential and behaviour. In combination with the examination of standard soil physico-chemical parameters (nutrients, grain size, pH, etc), soil scientist can give far-reaching recommendations on the recovery potential of a forest. Nutrients in relation to soil contamination include Potassium, Nitrate, Phosphate and Sulphate.

The mangrove peaty clay, or "chikoko" is found in large areas of the lower Niger Delta. It is the dominant soil type of the lower areas. In the reduced environment where mangrove trees form their intensive root system, the rate of breakdown of organic material is slow. The material consist of vascular fibres and bark from the roots of Rhizophora (mangrove). The mangrove roots are fibrous organic materials that forms quite firm peat that can adsorb large quantities of water. In case of crude oil spills the peat has almost irreversibly adsorbed large quantities of crude oil. This oil is outside the active zone, but small quantities of oil are permanently leaking out, spoiling surface water and smearing vegetation. The photo shows a settlement in the Niger Delta, with mangrove peaty clay soil in the lower areas. Photo ©TotalFina Elf Nigeria.

Photo 14. The Niger Delta.

Bacterial enumeration indicates the potential number of oil degrading bacteria. Oil eating bacteria appears to be present throughout tropical forest, where waxy leaves and oily nuts are common. Although this test is almost one of the standard parameters in environmental investigations in Nigeria, the use of this parameter is considered to be useless. Batch incubation tests can determine the biological removal of oil under optimised condition (Slurry batch incubations) and under simulated landfarm conditions (Field capacity tests) for a "type" of oil.

The oil-contamination can be divided in one part that is dissolved in the soil water, while the other part is bound to the soil matrix. Since nematodes live in the soil pore water, they are in direct contact with the dissolved oil-contamination. From chemical analyses of the total oil concentration it is not clear how much of that oil is dissolved and how much is bound. It is even harder to determine the effect of the oil contamination on the soil microfauna. But the enumeration of nematodes and the construction of the nematode population provide information about the biological activity and the ecological damage and recovery of the superficial soil horizon.

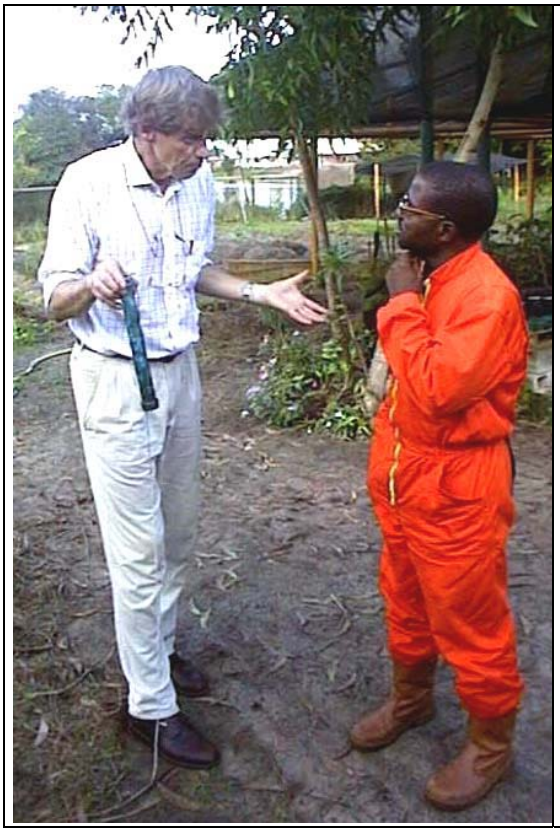
The enumeration of nematodes and the interpretation of the nematode population have not been successful in this research, because the method for sampling, sample preservation and the determination for nematodes in tropical forest are still under development. In this research, the methods, developed and used in temperate zones, are applied to the tropical forests. Little is known about the nematodes in tropical forest soils. Therefore it is not clear if the knowledge of nematodes in the temperate zones is applicable to the tropical ecosystem.

From the intensive nematology research in temperate zones, it is clear that enumeration of nematodes combined with the interpretation of the nematode population is a very useful tool in monitoring ecological recovery. For both the short term and the long term, several recommendations can be made to make nematodes a useful tool in tropical ecosystems.

For the short term, it is recommended to extract the nematodes in Gabon or Nigeria instead of in the Netherlands. It appears that the nematodes died in the time between sampling and extraction in the Netherlands. Normally in the Netherlands, the nematodes are extracted several days after sampling, while it took 14 days with the Gabon and Nigeria samples. The extraction process is not difficult and after extraction the nematodes can be preserved for determination in the Netherlands. Furthermore, it is recommended to count nematodes in ten undisturbed soil samples from near the oil-contaminated samples. In this way a broad scope of the nematode population in undisturbed tropical soils is obtained, which can be used as a local reference.

For the long term, it is recommended to put effort in scientific nematode research of tropical soils. This means analysing nematodes in a wide variety of tropical soils and determining their life- and feeding strategy. With these determined life- and feeding strategies it is possible to define a CP-classification for tropical soils.

The oil characterisation will give information on the general characteristics of a "type" of oil contamination in relation to its composition, biodegradability, solubility and the risk. It provides information on the chemical and physical behaviour of the type of oil. The results of oil characterisation are presented in a form that people, not trained in this field, can apply the results, but the participation of expertise on this field in the discussion on the ecological recovery potential, parameters and processes is very useful. The oil characterisation itself has limited use for regular monitoring: derived variables should be extracted.



A mesocosm is a specific amount of soil, which contains a known pollution content. That soil is put in a porous container, which is installed in the biologically active zone of soil and adopts the condition of its environment. After some time the mesocosm is extracted and the content analysed. The changes reflect changes, as they would occur in the soil. In this project the mesocosms were introduced in a later stage. One year after placement, the first mesocosm were analysed. The results show a decrease of about 10-15 % in oil content. It is concluded that microbiological breakdown took place in the mesocosms. This result is attributed to intensive mixing (improving transport). It proves the potential breakdown after intervention, but is not a measure for actual degradation for this type of material. It is concluded that mesocosms may be a help in understanding the system of degradation in the tropical forest, but that this type of experiments need better preparation:

- *Describe the object of investigation;*
- *Select testable hypotheses;*
- *Design and implement according to the object and hypotheses;*
- *Select Analytical methods and sample programme;*

The photo shows one of the mesocosms before burial and the on-site discussion on application.

Photo ©Shell Gabon

Photo 15. Mesocosms.

Groundwater quality and the spreading of contaminants in groundwater appear to be of lesser importance in tropical forest.
Tropical trees and plants root very superficially and are focussed on recycling the nutrients liberated in the topsoil. In Gabon and Nigeria several cases of severely contaminated groundwater are described, with no influence on the vegetative cover on top. The composition of groundwater in tropical forest is distinctly different from the temperate zones, with high TOC, low pH and the water is generally not or only weakly anaerobic. The scientific proof that natural breakdown in groundwater of tropical forest is much faster and efficient than anticipated from experiences and models based on the temperate zones are scarce, but provide strong indications. Standard groundwater investigations shall be part of the environmental survey to establish moisture regime, groundwater table, and basic groundwater quality in relation to toxic components and nutrients.

3.4 The Ecological Recovery Potential

Understanding of the (eco)system of the tropical forest, in combination with the impacts of crude oil contamination, as discussed in this section allows for a good and defendable estimation of the ecological recovery potential of a certain contaminate site, or "type" of oil contamination, defined in the conceptual model.

To estimate the recovery potential, it is desirable to sample in the past, present and future.
Most oil fields have a record of oil contamination that start at the development of the field, and continue until present. Inclusion of older spills, when investigating a fresh spill, or inclusion of a fresh spill, when investigating an older one, and using the same investigative techniques provides valuable information on the development of contamination in time.
The investigative protocol, presented in this project, gives through the conceptual model, the definition of active zones and traps, the description potential (bio)degradation from the oil characterisation a firm background for estimation of ecological recovery.
The future can be investigated by the design and implementation of a monitoring programme, the execution of pilot tests, the installation of mesocosms, or incubation tests in the laboratory.

If not destructed by the salty production water associated with the crude oil spill at the time of occurrence, the recovery of the ecosystem of a tropical forest is fast and efficient. (Most oil in the active zone is degraded within a certain time span: Light Nigerian crude may take less than 2 years, the waxy Gamba crude several years more), depending on the type of crude and spilled quantity. Trapped oil may for prolonged periods (more than 50 to 100 years) have a negative effect on the health of the ecosystem, but slowly, as long as the forest survives, it will be overgrown, covered with peat or dispersed.

3.5 Project Output

3.5.1 *Project Output to Shell Gabon*

Synchronous with the publication of the final report the project team will present the project results to Shell Gabon Management.
Apart form nice scientific results we will propose a shift in the basic approach of remedial work in Gabon. The former approach to remediation was based on the risk for humans, calculated from concentrations of toxic components (primarily Benzene) leading to cleanup values. The driving force of the corrective action in 1998 was removal of concentrations and quantities that surpass the (risk-based) guidelines.

Political and Social context
Remedial actions cannot be judged without their political context. In Gabon, the government involvement in the development of the Ga-Iv field has considerably increased the last five years. The government's interest, apart from the production of oil revenues, is creating employment for local staff and stabilising the economic development of the region.
Shell Gabon is very determined to resolve its inheritance of 40 years of oil production and has invested in several studies, projects and pilot trials in preparation of a second phase of soil remediation, while at the same time investments were made to prevent further contamination of the environment. The latter has resulted in a major improvement of the discharge facility of waste production water; finding solutions for treatment of sludge from the storage tanks and minimisation of flaring to decrease the CO_2 output below international and company requirements. At the same time, the development of eco-tourism and the bio-diversity project by the Smithonian Institute has changed the attitude of government and oil companies towards the tropical forest.

In this political context, there is no place for a major soil cleanup project, that would destruct the forest, disrupt the local community and would provide mainly revenues to international contractors and foreign workers.

The SKB-project has shown that a low profile approach is technical feasible, helping nature to finish the job it started 40 years ago.

Risk Assessment
The risk assessment, which was based on the HESP-model, has not changed much in view of risk to human health. The insight in risk for the environment has increased significantly; The SKB-project shows by using the monitoring parameters Vegetation, Bacteria and Nematodes that the risk of oil contamination for the ecosystem is limited, while of coarse for individual species no conclusions can be drawn.

Impact
The evaluation of the impact of remedial action has significantly changed. The SKB-project shows clearly two levels of intervention:
- the first with preservation of the biological active zone, leading to a certain but acceptable impact on the forest, and long term recovery;
- and the second, which leads to destruction of the local ecosystem, resulting in a lake or almost barren sandy wasteland.

Remedial approach
For the remedial approach, the SKB project has collected, evaluated and discussed all the aspects of remedial action in a tropical forest using a team of experts from different disciplines. This has lead to a basic understanding of the processes of crude oil degradation in the forest, which allowed for recommendations for remedial action that support the political and social requirements of the Gabonese Government and Shell Gabon.
Four major problems were defined in relation to the Ga-Iv remediation:
- large quantities of sludge in the forest;
- large surfaces of hard oil;
- major free product layers;
- no treatment facilities for excavated material.

For the sludge in the forest, the SKB-project has contributed to the understanding that the only risk of this material is direct contact, as spreading has reached its maximum, and the toxicity is low, after decades in the forest. The key to risk reduction is stabilisation of the sludge. The key to remediation is improving the transport by mixing, either mechanical or biological. Improving or constructing a vegetative cover achieves biological mixing. In the biologic active zone, by bioturbation the process of breakdown is activated or improved. Apart from the remedial experience in Nigeria, the SKB-project has documented in Gabon the strong positive effects of mixing and vegetation on natural attenuation in our field observations, the positive effects of disturbance caused by installation of wells and the positive effect of mixing in the mesocosms. Certain undesirable concentrations of crude oil shall be accepted to remain because we can predict that within a certain time span it will have lost its toxic components, while if excavated and stored in a depot, upon failure of the depot in 50 or 100 years, it will have conserved its toxic components. Small interventions to move trapped oil into the biological active zone, by improving drainage, phytoremediation and on site landfarming will be, in view of total environmental gain and costs much more effective. The SKB-project recommends a low profile, long-term approach, making selective and deliberate use of natural resources, with a maximum input of local labour.
For the Hardoil problem, the findings of this project indicate clearly indicate that improving the temperature and moist conditions, combined with mixing will activate the biological breakdown of

this type of oil; it is recommended to bring the hard oil, or contaminated soil in the biological active zone.

At Z4, Shell Gabon has applicated the findings of the SKB research in a pilot test, executed by Gabon Vert. The temperature and moisture condition is regulated by the application of a layer of straw (photo left); the hard oil is intensely mixed with fertiliser and seeds, leading to an overwhelming green oasis on the barren hard oil surface (photo right). (Photo ©Gabon Vert).

Photo 16 and 17. Revegetation.

The SKB-project has contributed in the understanding that spreading of oil components in solution from the free product layers is an overestimated risk, however the free product layers still need to be removed, using classical techniques.
Treatment of contaminated soil was not subject of this study. However, the good understanding of biological breakdown of oil components in Gabon soil has indicated the way to explore more sustainable solutions for treatment of contaminated material by Shell Gabon. This includes the design of holding basins covered with a vegetative cover, a long-term self-sustainable solution composed of soil and plants growing in and/or over waste in a landfill. Plants control erosion and minimise seepage of water that could otherwise percolate through the landfill and form contaminated leachate. In addition, vegetative caps can be designed not only to control erosion and seepage of water, but also to enhance the degradation of underlying materials in the landfill.

Monitoring
The proposed investigative strategy recommends including the PQ-method and regular nematode surveys on yearly basis to the monitoring activities of Shell Gabon to evaluate and validate the remedial results of their corrective actions. It is recommended to use the oil characterisation as addition to regular soil sampling and analyses to monitor potential and actual degradation.

General
The systematic and multidisciplinary study to unravel the behaviour of crude oil in the forest of Gabon by the SKB project and its promoters within Shell Gabon and SKB has resulted in a fundamental shift in approach of soil remediation by Shell Gabon.

3.5.2 *Project Output to SPDC*
The results of the site investigations and interpretation have provided a scientific support for the straightforward approach of remedial action, developed and executed by the SPDC Value Creation Remediation Program. SPDC's Remediation team has developed a Risk Based approach for remediation of all impacted sites in Nigeria. A Generic Conceptual Site Model for the Delta Region of Nigeria was the first step to guide the investigations and initial remedial actions.
The risk based management (RBM) approach is based around identifying and reducing risks associated with contamination to a level protective to human health and the environment.

The team has recognized that the methodology for ecological risk assessment is as yet not as well developed as for the human health risk assessment.
The results of the site investigations and interpretation in this project have provided a scientific support for the straightforward approach of remedial action, developed and executed by SPDC's program on Remediation of Past Impacted Sites. Further implementation of the remediation program needs additional data collection and interpretation to support the overall approach.
Special attention is needed in the sensitive mangrove swamp areas where remedial actions potentially can have more negative effects on the environment then the natural attenuation approach. For these sensitive areas a specific Conceptual Site Model will be generated. Here the results of this project can support SPDC in executing effective and efficient remedial actions.

The political and socio-economic situation in which the Oil Industry in Nigeria has to operate is very complicated. The major cause, number and extend of the countries Oil Spill sites is related to vandalism and acts of sabotage. Special the spills in the Pipeline Right of Ways do have the most significant impact on the environment due to superficial spreading of oil over large areas because of the heave rainfall and the delayed access to do repair, recovery and clean-up work. Assessments have shown that most of the impact is superficial and that most of the problems can be handled through landfarming of the contaminated top layer of the soil. This method proved to be environmentally effective leaving the least environmental impact of remedial actions in the environment.
The SKB-project has further showed that natural attenuation of contamination, caused by Nigerian crude, through evaporation and dissolution in addition to landfarming, is an important contribution.
The presented protocol for the investigative strategy will be a useful tool, if properly introduced and applied.
In this project data was insufficient to develop the monitoring proposal for SPDC (Nigeria). SPDC has planned further data collection in 2003 and based on this information, combined with monitoring experiences in Gabon, a monitoring proposal for SPDC will be developed.

3.5.3 *Project Output to the Oil Industry*

Oil companies that explore and produce in tropical forest operate often under difficult conditions, a harsh environment but a sensitive ecosystem, a local population that does not benefit directly from the revenues, difficult political regimes and criticism from NGO's.

During this project, many cases of "standard solutions" to spills and cases of soil contamination have been studied and results of these approaches evaluated. In most cases solutions, that did not take into account the basic understanding of the ecological system of the tropical forest, did have a disastrous effect on the environment. Seeking a cheap solution has not been the driving force, as sometime major investments were required where probably a much less costly solution would have been much more effective.

It starts with a good understanding of the tropical ecosystem one is producing and transporting oil in. Secondly, having an emergency response that takes into account the strong and weak points of this ecosystem.

If contamination occurs and appears to be resistant or to accumulate, it is essential to invest in an investigative strategy, as described in this project, to unravel the true cause. Based on good understanding, sometimes amazingly simple corrective action can be proposed and implemented, that will lead to very acceptable results.
There is a tendency in the oil industry, to seek for solutions when facing a problem. This project shows that oil in the forest is not the problem, so there is no immediate need for a contractor to solve this problem. This project shows that disturbance of the ecosystem is the problem, and recommendations are required to restore the ecosystem.

The Dutch approach of soil remediation, based on good insight of the problems, determination of vital parameters and independent consultancy is a much more efficient way to deal with oil contamination compared to the “out-contracting” of the problem to contractors with standard solutions, secret formula’s or "innovative" technical solutions.

The proposed investigative strategy is a great help in understanding the problems of the ecosystem, if an oil spill occurs or needs to be remedied in a tropical forest.

3.5.4 *Project Output to the SKB*

The project has proven that the development of oil characterisation as supported by SKB is a very useful tool, and can be used throughout the world to evaluate oil contamination. At the same time, the project indicates that the development of other monitoring techniques, heavily funded by Dutch government, still will require much additional work and funds before reproducible results outside the narrow border of one well-defined ecosystem will be achieved.

CHAPTER 4

CONCLUSIONS

4.1 Answering Fundamental Questions

In the project plan, the focus was on a number of fundamental questions relating to the clean up of mineral oil contamination in tropical regions. These fundamental questions were the translation of the problems to be solved by this project (see table 1). Most questions were not yet or only partially answered.

Table 1. Answering Fundamental Questions.

What happens to mineral oil (biological, chemical and mechanical decay) in a tropical soil and in tropical swamps?	Depending on the type of crude, fairly rapid to fast breakdown occurs, except where oil gets trapped on the surface of savannah, in free product layers, or in a swamp where peat accumulates. Setting up a good conceptual model will indicate these traps.
What are the effects of the contamination on the nutrient balance in the subsoil?	The chemical results indicate that there is little or no influence on the already poor nutrient situation in the subsoil of tropical forest. All nutrients are stored in living material. The vegetation study indicates differences in vegetation type on contaminated sites that may be an indication of improved nutrient availability.
How can we measure the ecological effects and impacts?	By measuring the vegetation using the PQ or comparable method and by enumeration of the nematodes. In addition local “hobbies” including, snails, worms, fungi, plant diseases etc may contribute to better insight in the ecosystem.
How much time does an oil-contaminated ecosystem need without intervention for recovery to an acceptable level?	Depending on the type and amount of crude a few years to several decades. Oil in traps may take ages to degrade, but does not necessarily have a negative effect on recovery of the ecosystem.
At which concentration level can the ecosystem recover without intervention?	A forest recovers from almost any concentration, as long as the biological active zone, or topsoil is not destructed over a surface that is large enough to be permanently exposed to the sun. Mangrove seems to be more vulnerable, but is not investigated.
How much time does an ecosystem need for recovery after the execution of remedial measures?	Natural re-growth of larger surfaces of tropical forest may take ages. Re-growth where the active zone, or topsoil is not destructed may be achieved within a few years, showing a nice forest after less than 20 years
What key components of the ecosystem are mainly exposed to risks, and what are the impacts of that exposure?	In Gabon, all but the very small animals are exposed to smearing with oil. The effect of skin contact may vary from death (mosquito larvae) through long term effects, to beneficial. In Nigeria the main focus is on human health risk.
What are the economical advantages and disadvantages, increase/decrease in the value of a region, implications of a reduction in remedial efforts, effects on public opinion with respect to mitigative measures by a multinational company?	A good impact assessment, following the world bank guidelines, can evaluate these aspects. The proposed investigative approach can help to unravel the environmental and ecological aspects, which are the basis of an impact assessment.

4.2 Conclusions on the Investigative Techniques

The development of an investigative protocol was based on the conclusions of the application of investigative techniques on the pilot sites:

- The systematic description of the vegetation, following the PQ-method, is very useful to provide insight into the impact of oil contamination in the ecosystem of the forest.
- The waxy leaves and oily nuts in the tropical forest cause oil-eating bacteria to be present throughout tropical forest, and can lead to erroneous TPH-concentrations in surface soil samples.
- If an approach for nematodes is developed comparable to the approach for vegetation the measurement of nematodes can give a comparable valuable contribution as the vegetation survey, and should be a very useful tool in monitoring ecological recovery.
- The investigation of older and fresh spills, combined with laboratory bacterial incubation test provides vital information to enable predictions on the recovery potential of a forest.
- Oil characterisation provides direct and essential information on the fate of oil in the forest.

4.3 Oil in Tropical Forest

On the fate of crude oil spills in tropical forest, it is concluded:

The key process in tropical forest in relation to crude oil contamination is the very fast and efficient breakdown of crude oil in the biological active zone, and the slow or virtually non-existent breakdown of oil outside the biological active zone.

The ecological recovery potential of a forest impacted by crude oil is determined by the impact on the biological active zone by the oil or by the corrective action to remove this oil.

The investigative strategy shall be based on consequently understanding the system, the classification the types of oil occurrence in the system and the election and determination of the key parameters to monitor the system.

The impact of groundwater contamination on the ecosystem seems to be limited, not only because tropical vegetation does not use groundwater, but also because different chemistry leads to faster attenuation of oil related components, compared to the experience and predictions in more temperate zones.

CHAPTER 5

RECOMMENDATIONS

It is recommended to use the developed investigative strategy for the evaluation of crude oil in tropical forest.

It is recommended to fine tune emergency procedures and remedial strategies in such a way that interventions do not cause more damage to the environment than the zero option. Interventions should be planned from a basic understanding of the eco-system of tropical forest.

Many aspects of crude oil behaviour and the response of nature are considerably different than experiences in the moderate climate zones. To present remedial plans for tropical forest, it is recommended to provide a basic understanding of the system where the interventions take place; the presented investigative approach provides a number of tools to achieve this goal.

It is recommended in the evaluation of interventions to be very careful with the active zone: the live supporting topsoil and vegetative cover. Not only is it a valuable asset, it is also the only place where rapid and efficient natural breakdown will take place.

If oil accumulates, or persists in a tropical region, there is a reason. Finding the reason is the key to simple on site remedial techniques. Often, the reason is lack of transport (the mechanism that provides the components that are consumed, and removes the reaction product). Mixing, or creating a biological active zone can improve this.

The pilot site at Rukpokwu, a fresh spill in Nigeria, has burned completely after our last field visit. The motivation for burning oil spills is as complicated as the motivation for the bush fires in the south of France, and varies from arsonist for fun to local political or economical reasons. The impact of fire on the contamination is disastrous. Although a part of the oil is burned and evaporated, another part of the very liquid hot oil penetrates deeper in the soil, and attaches firmly to the soil texture, creating an asphalt like, infertile topsoil. At the same time the soil structure is destroyed and all seeds are burned.

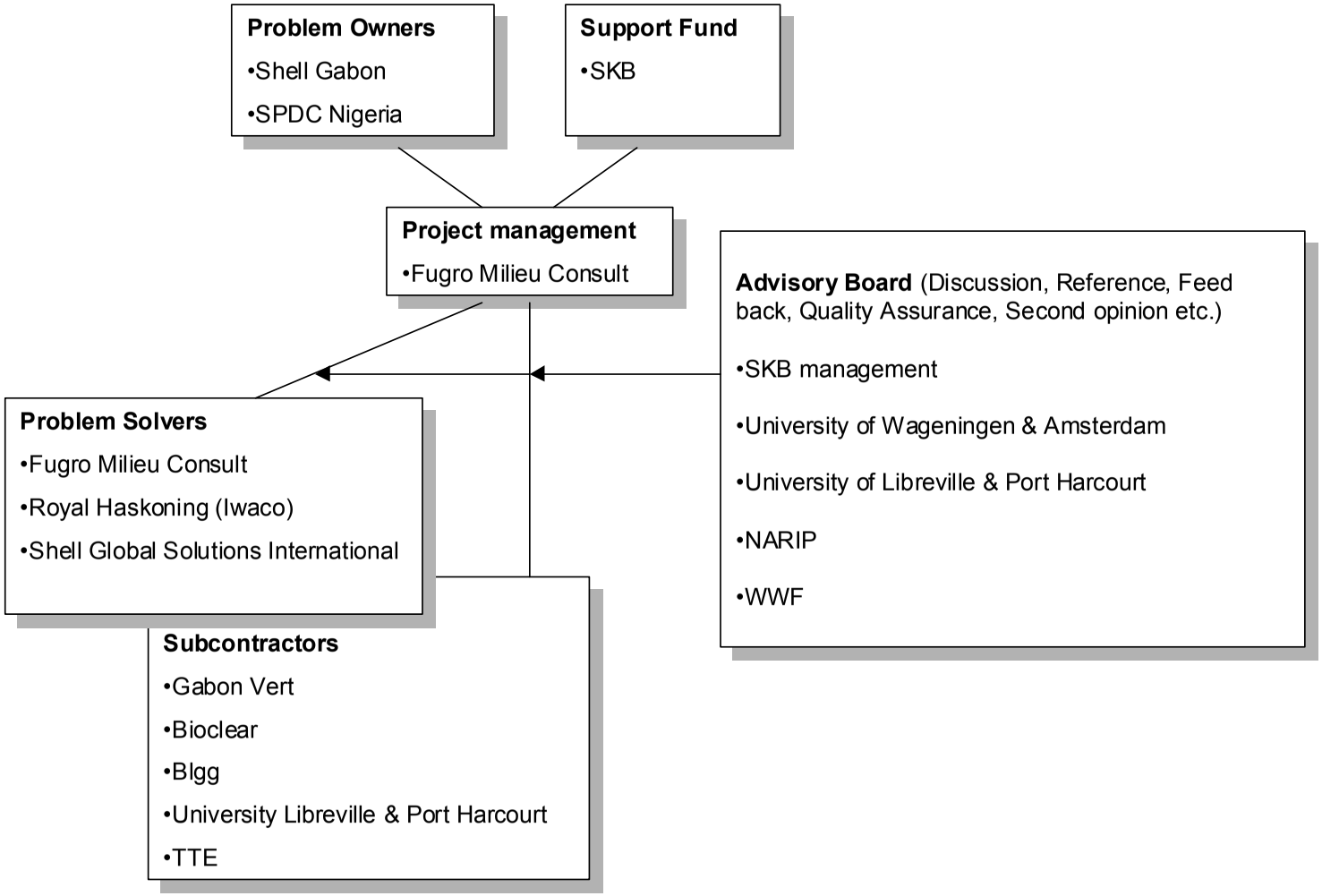
The impact is far worse than normal bush fires that only under extreme conditions destroy the topsoil; the oil provides the extra fuel for complete destruction.

Photo 18. Rukpokwo.

APPENDIX A

PROJECT ORGANISATION

Project Organisation



APPENDIX B

LIST OF REPORTS

MINERAL OIL IN A TROPICAL FOREST (PROJECT SKB: SV-223)

List of Basic Reports

Activity	Subject	Title	Author	Code	Date
FIELDWORK					
GABON	PILOT SITES SELECTION	SITE SELECTION GABON (GAMBA/IVINGA FIELD)	FUGRO/ GABON VERT	I1v2.PDF	09 04 01
	TEST SAMPLING	TEST SAMPLING 06/2000 GABON	FUGRO	F1v1.PDF	05 04 01
	SAMPLING ROUND 1	SAMPLING 10/2000 GABON	FUGRO	F2v1.PDF	09 05 01
	ADD. SAMPLING ROUND1	ADDITIONAL SAMPLING 03/2001GABON	FUGRO	F4v1.PDF	15 06 01
	ADD. SAMPLING2 ROUND1	ADDITIONAL SAMPLING 2, 10/2001, GABON	FUGRO	F5v2.pdf	29 03 02
NIGERIA	PILOT SITES SELECTION	SITE SELECTION NIGERIA (IMO RIVER F./ OGONI LAND/RUKPOKWU/ALETO RIV.)	FUGRO/ SPDC N.	I3v2.pdf	29 03 02
	TEST & ADD. SAMPLING ROUND 1	TEST & ADDITIONAL SAMPLING, 01/2001 & 12/2001, NIGERIA	FUGRO	F3v2.pdf	29 03 02

RESULTS DETERMINATIONS/ANALYSES					
GABON	VEGETATION	VEGETATION PILOT SITES GABON (PQ-METHOD) RESULTS	FUGRO/ GABON VERT	E7v1.pdf	04 10 02
	PHYSICAL/ CHEMICAL/MO/ NUTRIENTS	LABORATORY TEST RESULTS GABON	IWACO	E3v1.pdf	08 06 01
	GROUNDWATER	GROUNDWATER ANALYSES GABON	FUGRO	I5v3.pdf	15 09 02
	OIL-CHARACTERIZATION	OIL CHARACTERIZATION GABON	TTE	E2v3.pdf	18 02 02
	BACTERIA	OIL DECAY BY BACTERIA, GABON	BIOCLEAR	E5v1.pdf	08 06 01
	BACTERIA	OIL DECAY BY BACTERIA, GABON	BIOCL./ Royal Haskoning	E5v2.pdf	12 04 02
	NEMATODES	SPECIES OF NEMATODES GABON	IWACO	E6v1.PDF	04 09 01
NIGERIA	PHYSICAL/ CHEMICAL/MO/ NUTRIENTS	LABORATORY TEST RESULTS NIGERIA	Royal Haskoning	E9v1.pdf	18 02 02
	OIL-CHARACTARIZATION	OIL CHARACTERIZATION NIGERIA	TTE	E10v2.pdf	18 02 02
	BACTERIA	OIL DECAY BY BACTERIA NIGERIA	BIOCLEAR	E11v1.pdf	18 02 02
	NEMATODES	SPECIES OF NEMATODES NIGERIA	Royal Haskoning/ UNIV. PH	E12v1.pdf	18 02 02

LITERATURE RESEARCH					
GABON/ NIGERIA	SOILFAUNA	SOILFAUNA OF GABON AND RELIABLE BIOMONITORING	IWACO	E1v1.pdf	05 04 01
	VEGETATION/ PQ-METHOD	VEGETATION MONITORING TROPICAL FOREST OF GABON & NIGERIA, BY THE PQ-METHOD (DUTCH)	FUGRO	E4v1.pdf	08 08 01

WORKSHOPS/MEETINGS					
NEDERLAND	SKB PROJECT SV-223	WORKSHOP NETHERLANDS OCT, 6, 00	FUGRO	M1v1.PDF	22 02 01
GABON/ NIGERIA	SKB PROJECT SV-223	WORKSHOP GABON OCT, 18, 00	FUGRO	M2v1.PDF	22 02 01
NEDERLAND	SKB PROJECT SV-223	R. GABON, SAMPL. 06/00, 10/00 & 03/01	FUGRO	M3v1.pdf	06 09 01
	SKB PROJECT SV-223	MEETING WAG.SEP, 12, 01	FUGRO	M4v1.pdf	29 03 02
	SKB PROJECT SV-223	R. GABON&NIGERIA, SAMPL2000&2001	FUGRO	M5v2.pdf	17 04 02
	SKB PROJECT SV-223	WORKSHOP (NETHERLANDS, GOUDA)	FUGRO	M6v1.pdf	03 07 02

CONCEPTUAL MODELS					
GABON	CONCEPTUAL MODEL SKB PROJECT	CONCEPTUAL MODEL OF GABON SHELL GABON	FUGRO	I2v2.PDF	12 04 02
NIGERIA	CONCEPTUAL MODEL SKB PROJECT	CONCEPTUAL MODEL OF NIGERIA SPDC NIGERIA	FUGRO	I4v2.pdf	29 03 02

FINAL REPORTS					
SKB REPORT 0		BASIC PROJECT PLAN	CONSORTIUM	Basic Project Plan.pdf	22 08 00
SKB REPORT I	RELATIONS BETWEEN PARAMETERS RESULTS	DATA INTERPRETATION (MONITORING2000-2001, GABON & NIGERIA)	CONSORTIUM	I6v2.pdf	22 12 02
SKB REPORT II	PROTOCOL INVESTIGATIVE STRATEGY OIL POLLUTION	INVESTIGATIVE PROTOCOL(OIL POLLUTION TROPICAL SWAMP FOREST)	CONSORTIUM	I7V3.pdf	15 04 03
SKB REPORT III	SKB PROJECT SV-223 (GABON & NIGERIA)	FINAL SKB REPORT	CONSORTIUM	I8v4.pdf	15 04 03

PRODUCT SHEETS					
	PRODUCT SHEET	Investigative Protocol Crude Oil Contamination in a Tropical Forest	FUGRO	PS1v1.pdf	11-07-03
	PRODUCT SHEET	Crude Oil Remediation by Ecological Attenuation	FUGRO	PS2v1.pdf	11-07-03

List of MPEG Movies.

File	Subject	Description
GABON	PILOT SITES	
MPEG\Control1.mpg	Control 1	Transition of forest to swamp, peat on sand soils, far from long time ago closed production well.
MPEG\Control2.mpg	Control 2	Transition of forest to swamp, peat on sand soil.
MPEG\Z7.mpg	Z7	Sand fill with rim of freshly emerging crude, covered by vegetation.
MPEG\z52.mpg	Z52	Experimental excavation between trees, and partly untouched contaminated forest.
MPEG\Z71.mpg	Z71	Contaminated swamp forest. Large surface of fresh peat on major layer of contamination.
NIGERIA	PILOT SITES	
MPEG\Ogoni.mpg	Ogoniland	The first part shows the contaminated swamp forest, the second part the results of burning of oil.
MPEG\IMO+control.mpg	Imo 2 & Ogoniland control	Large land-farmed area near a IMO2 flow station. Sampling in clean forest near Ogoniland site. (peat on sand soil)
MPEG\rukpokwu.mpg	Rukpokwu	A large spill on savannah, that has widely spread in the forest.