Management of contaminated sites of the petrochemical industry

Manual

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Manual

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List of abbreviations

BATNEEC	Best available techniques not entailing excessive costs
BTEX	Benzene, toluene, ethylbenzene, xylene
CAPEX	Capital expenditure
CAS	Chemical abstracts service
CPT	Cone pressure test
CVOC	Chlorinated volatile organic compounds
DNAPL	Dense non-aqueous phase liquid
DPE	Dual-phase extraction
EOD	Explosive ordnance disposal
ERH	Electrical resistance heating
ETBE	Ethyl tert-butyl ether
GAC	Granular activated carbon
GOSP	Gas-oil separation plant
HASP	Health & safety plan
HSSE	Health, safety, security & environment
ISCO	In-situ chemical oxidation
ISTR	In-situ thermal remediation
LIF	Laser induced fluorescence
LNAPL	Light non-aqueous phase liquid
MIP	Membrane interface probe
MNA	Monitored natural attenuation
MPE	Multi-phase extraction
MTBE	Methyl tert-butyl ether
NAPL	Non-aqueous phase liquid
NORM	Naturally occurring radioactive material
NPV	Net present value
NSZD	Natural source zone depletion
OPEX	Operating expenditure
P&ID	Piping and instrumentation diagram
PAH	Polycyclic aromatic hydrocarbons
PDB	Passive diffusion bag

(P)EC	(Predicted) environmental concentrations
PID	Photo ionization detector
PNEC	Predicted no effect concentrations
RBTL	Risk-based targets level
RfP	Request for proposal
ROI	Radius of influence
SEE	Steam enhanced extraction
SOD	Soil oxidant demand
STAR	Self-sustaining treatment for active remediation
SVE	Soil vapor extraction
TBA	Tert-butyl alcohol
TCH	Thermal conduction heating
TDI	Tolerable daily intake
TPH	Total petroleum hydrocarbons
UBA	Umweltbundesamt (German Environment Agency)
UXO	Unexploded ordnance
VOC	Volatile organic compounds

Preface

The complexity of problems associated with contaminated sites has become a matter of serious concern for environmental authorities in Europe and also globally during the last decades. It has become evident that the elimination, or at least mitigation, of pollution-related hazards is urgently required for protecting or restoring the quality of the environmental media air, water and soil. For achieving this goal, considerable financial efforts are required.

In Europe, EU directives stipulate requirements for the protection of the environmental media. EU member states have transposed them into national law, accession countries are in a process of doing so. Nevertheless, there are still significant differences in national legislation, inter alia, related to soil and groundwater protection and their practical implementation – also regarding the management of contaminated sites. Particularly in many Eastern European countries, progress is necessary to make the inventory, assessment and restoration of contaminated sites adhere to the requirements of respective EU legislation.

In many countries, methodical and technical guidelines and related tools for contaminated site and brownfield management, which pursue a systemic and holistic approach and which address subjects of strategic relevance for authorities as well as for various industrial branches, are missing.

The competent authorities in the countries face the challenge to obtain timely and reliable information as well as conclusions on potential risks that may be associated with contaminated sites in order to start, to accompany and to successfully complete processes of contaminated site management. Guidance is necessary to clarify the state of a site suspected to be contaminated, to derive realistic remediation targets and to design effective and efficient remediation measures – on the side of all actors involved in the process of contaminated site management and its different phases, e.g. site owners, site users, engaged consultants and competent authorities. Such guidance has to be based on up-to-date scientific information as well as on profound practical expert knowledge.

This manual shall contribute to improve technical and administrative workflows of contaminated site management with a focus on the petrochemical industry, in particular (but not exclusively) on the oil & gas industry, and its three specific types of (onshore) sites:

- Exploration and production sites comprising drilling rigs with drilling mud pits and oil sludge pits,
- Tank farms and
- Refinery sites including acid tar lagoons.

Most of the regulatory, technical and administrative information of this manual is also applicable to pipelines and related facilities, although these are not addressed in detail.

The manual can be used like an educational book which introduces to regulatory, technical and administrative state-of-the-art knowledge with a structure that first presents general information, then follows the different phases of contaminated site management and towards the end addresses some strategic aspects. The manual's regulatory information refers to national and international provisions, inter alia of EU legislation as well as of Germany's environmental legislation and associated principles which are relevant for managing contaminated sites of the oil & gas industry. Regarding technical approaches, conventional as well as innovative investigation and remediation technologies are presented for the three sector-specific types of sites. Because of their relevance, the subjects of naturally occurring radioactive material (NORM) and unexploded ordnance (UXO) from acts of war on oil & gas sites are addressed in this manual, too. Furthermore, information on decision-making support tools and on the tendering of services is given. An overview of site development strategies and future site use scenarios for former industrial sites addresses strategic questions of contaminated site management and possible financial implications. A chapter on health & safety requirements highlights the importance of respective provisions in the management of contaminated sites of the oil & gas industry.

This manual was developed in a project with Romania which was initiated by the German Environment Agency (UBA) in response to a series of consultations on the subject in order to provide orientation and guidance. The project led to a Romania-specific manual as well as to this more general manual. It was financed by the Advisory Assistance Programme (AAP) of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

Because the information about the management of contaminated sites of the petrochemical industry presented in this manual is mostly not country-specific, we would like to share this information with interested parties. Feel invited to use this manual in its entirety or as a selection of specific chapters.

In case of further interest, feel free to contact the German Environment Agency (UBA).

Dr. Lilian Busse

How to use the manual

This manual is intended to be used as a guiding document for people who work on the subject of potentially contaminated and contaminated site management of the oil & gas industry and of other industries of the petrochemical sector. It provides advice on how to manage potentially contaminated and contaminated site in accordance with internationally accepted standards and procedures and on how to put the requirements of relevant environmental legislation and regulation into practice.

The information of this manual is in compliance with environmental legislation of the EU and therefore of relevance for EU member states and for EU accession countries – and it is also in compliance with international standards and therefore of relevance also for countries beyond the EU. Because of their relevance, the manual addresses environmental, health- & safety-related and strategic economic aspects of contaminated site management. It focusses on known and proven national and international approaches and practices, inter alia, from Germany's soil and groundwater legislation.

The technical and administrative approaches that are described in this manual should not be implemented dogmatically but instead site-specifically because each potentially contaminated or contaminated site exhibits specific framework conditions and therefore requires a site-specific strategy. Furthermore, each decision of competent authorities should follow the guiding principle of proportionality.

Legal framework conditions as well as technologies and procedures develop over time. Therefore, it is imperative for all involved stakeholders to ensure that each activity in the course of contaminated site management takes into account the current applicable legislation as well as state-of-the-art and site-specific criteria.

1 Regulatory and administrative background for managing contaminated sites

1.1 Explanatory note

Member states of the European Union (EU) basically comply with the environmental acquis communautaire in force as well as with international conventions and treaties signed by the EU.

In this chapter, some principles of relevant environmental legislation of the EU, particularly with respect to soil and groundwater protection and their implications for the management of contaminated sites, are summarized.

The legal framework regarding operational permitting and licensing for facilities of the oil & gas industry ("license to operate") is basically not subject of this manual, although there might be aspects that may have to be considered in the context of contaminated site management.

1.2 Legal background

A basic element in environmental legislation on a global scale is the **polluter pays principle**. This principle has been enacted in most countries of the OECD and the EU. It is also a fundamental principle in environmental law of the United States of America (USA).

In the EU, the polluter pays principle is a core element of the "Directive 2004/35/EC on environmental liability with regard to the prevention and remediation of environmental damage" (Environmental Liability Directive) of 2004 and subsequent amendments in 2006, 2009, 2013 and 2019. This directive establishes a comprehensive liability regime for damage to the environment and defines "environmental damage" as damage to protected species and natural habitats, to water and to soil. According to the Environmental Liability Directive, numerous activities of the oil & gas industry (but also of other industrial sectors) fall under strict liability.

Other relevant EU directives which aim at the prevention and clean-up of soil contamination are:

- EU Waste Framework Directive (2006/12/EC): It addresses the prevention of pollution from waste and defines any contaminated materials, substances or products resulting from remediation with respect to land as waste;
- EU Water Framework Directive (2000/60/EC): It requires a program of measures including measures to address land contamination that causes water pollution;
- EU Groundwater Directive (2002/118/EC): It aims to prevent or to limit pollutants, including pollutants from historical contamination of land, in groundwater;
- Industrial Emissions Directive (2010/75/EC): It aims to control and to reduce the impact of industrial emissions on the environment.

These EU directives have basically been transposed into national law by the individual EU member states. However, not all EU member states have a specific legislation on soil protection at national level, (e.g. as Germany has with its Federal Soil Protection Act). Thus, some elements of Germany's environmental legislation and associated principles which are relevant for managing contaminated sites of the oil & gas industry will be considered in this manual, too.

1.3 Liability for subsoil contaminations

As described in the previous chapter, the polluter pays principle is fully applicable in the EU and beyond. However, in some cases the responsibility (and liability) to perform site investigations (the historical Phase I environmental site investigation and, if the case may be, the technical Phase II environmental site investigation) and risk assessment relies with the economic operator or site owner even if they are not the polluter, e.g. if the polluter cannot be identified or if the economic operator or site owner cannot provide evidence that the contamination has been caused by a third party. The same liability applies to remediation works.

Complications regarding the clarification of liability may arise in the following cases:

- If multiple subsequent operators may have been responsible for soil and/or groundwater pollutions at a site: An allocation of environmental damages could be achieved by appropriate and sophisticated investigation technologies and analytical methods (e.g. age dating and isotope analyses of specific contaminants), but this is not always possible and has an element of uncertainty;
- If a new or current owner of a site goes bankrupt: In that case, the remediation liability may go back to the previous site owner;
- If the party that is obliged to remediate (in the following referred to as the “liable party”, e.g. the economic operator) refuses to carry out (or initiate) remediation for any reason: In that case, the regulator, e.g. the competent authority, may commission remediation measures directly or in a preventive context and recovers costs from the liable party (“substitute performance”) through judicial decision;
- If the site has been sold, the previous site owner usually remains liable if the site owner was aware of the contamination before selling the site (“fraudulent misrepresentation”).

Contractual agreements on the liability for soil, subsoil and groundwater contaminations between site owners, economic operators and other involved parties play a very important role and should be addressed in a diligent manner.

1.4 General approach for managing contaminated sites

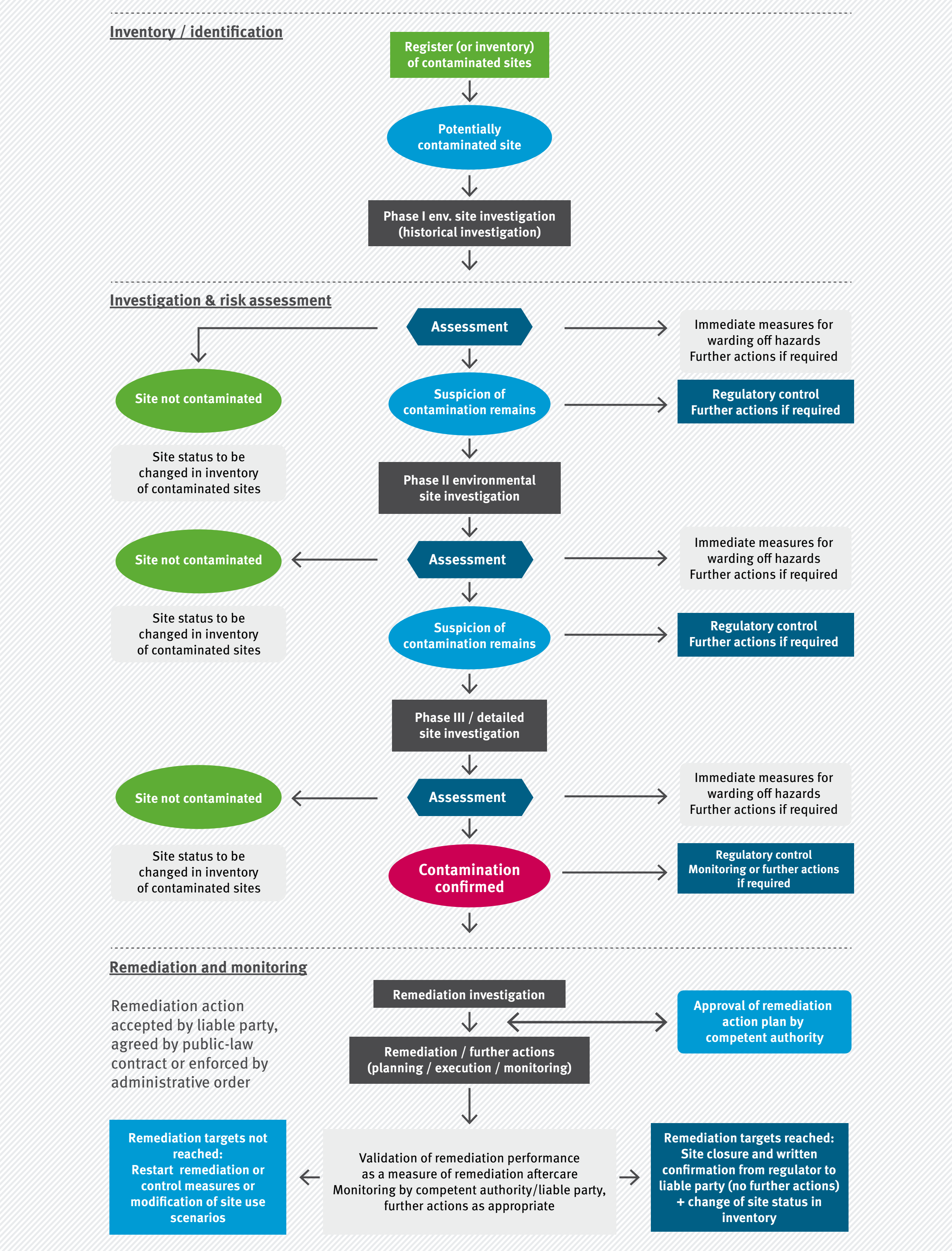
According to the publication “Progress in management of contaminated sites” (European Environment Agency, 2019), four management steps are defined for the management and control of local soil contamination, namely site identification (or preliminary studies), preliminary investigations (in this manual referred to as Phase I environmental site investigation), main site investigations (in this manual referred to as Phase II environmental site investigation) and implementation of risk reduction measures. Progress with each of these steps provides evidence that countries are identifying potentially contaminated sites, verifying if these sites are actually contaminated and implementing remediation measures where these are required. Some countries have defined targets for the different steps.

In Germany, the management of contaminated land and water is determined in the Federal Soil Protection Act and associated ordinances. The steps from identification over risk assessment up to remediation and monitoring that have been established as common practice in numerous countries are outlined in Figure 1 and may be used as an example of a systematic approach addressing potentially contaminated land as well as sites where contamination has already been proved. The following information has been taken from the Manual for Management and Handling of Contaminated Sites (ICSS - International Centre for Soil and Contaminated Sites, 2007) and from the EUGRIS-Portal for soil and groundwater management in Europe – Germany overview (EUGRIS, 2007).

According to the European Environment Agency, the majority of the EU member states maintain comprehensive inventories of contaminated sites at national or local level. Almost all of these inventories include information on polluting activities, potentially contaminated sites and contaminated sites.

Figure 1:

Flow diagram for managing contaminated sites



Source: After "Manual for Management and Handling of Contaminated Sites", ICSS, 2007.

After the identification of potentially contaminated sites, a **Phase I environmental site investigation** (historical investigation, sometimes also referred to as preliminary investigation) of a suspected contaminated site is carried out where all available data about the former industrial sector, the technologies implemented or the waste released through the manufacturing processes are compiled (Chapter 4).

A Phase I environmental site investigation aims for the best possible understanding of a site with respect to site and underground conditions, past and current site use, activities and events, which may have caused the uncontrolled release of hazardous substances into the subsoil, and information regarding existing and potential contaminations, including unexploded ordnance (UXO), based upon already existing and available data and information. This information shall provide the basis for a preliminary risk assessment, a site prioritization, the identification of data gaps and for the planning of a Phase II environmental site investigation, if required.

If the Phase I environmental site investigation has provided evidence for potential contamination, a **Phase II environmental site investigation** (technical investigation) that comprises intrusive investigation works, soil sampling and chemical analyses is performed (Chapter 5).

A Phase II environmental site investigation shall provide data and information regarding the geological underground structure, hydrogeology, spatial delineation and mass of contaminants (also in the aquifer), mobile or mobilizable parts of the contamination, natural biodegradation potential, hydrogeochemistry, transport possibilities, possible receptors and pathways. If the data that is obtained during the Phase II environmental site investigation turns out to be insufficient, an additional, more detailed site investigation (in Figure 1 referred to as Phase III) might be required.

A site-specific **environmental risk assessment** (Chapter 7) and a solid **conceptual site model** (Chapter 6) allow to decide whether further measures such as monitoring or remediation are required. In case that remediation is required, subsequent steps comprise the preparation of a **remediation feasibility study** (Chapter 8), the preparation of a **remediation plan** including tendering of the required technical services and equipment (Chapter 9), and – after approval of the plan by the competent authority – **remediation performance** including implementation and operation of the agreed remediation measures (Chapter 10).

After termination of a remediation project, further measures including a validation of the remediation success and **remediation aftercare** (e.g. monitoring) might be required, depending on the outcome and success of the remediation project (Chapter 11).

An important aspect of managing contaminated sites, and particularly of the definition of remediation goals and remediation targets, is the **principle of proportionality**.

The following definitions for remediation goals and remediation targets are applied in this document:

- **Remediation goals** (also referred to as remediation objectives): formally defined and desired outcome of a remediation project;
- **Remediation targets**: numeric remediation parameter (e.g. concentrations of specific contaminants, mass flux values).

The principle of proportionality implies that the remediation goals and related target values for clean-up activities should aim for the remediation of contaminated sites to a functionality level suitable for **current and future site use** (Chapter 12) – in relation to the costs of remediation. The definition of remediation goals and targets by the competent authorities should be based upon a proper environmental risk assessment for each individual site and should be technically feasible and economically appropriate.

1.5 Significance of public law contracts and private law for managing contaminated sites

Commonly, the main driver for conducting investigation and remediation activities on potentially contaminated and/or contaminated sites are regulatory requirements subject to public law. Public law requirements are targeted to avert any harm or damage to sensitive receptors and the public in general. In some countries, it has become common practice to address the obligation to remediate and to define the terms and conditions and the remediation targets in a public law contract between the liable party and a legal entity under public law, such as a municipality or city.

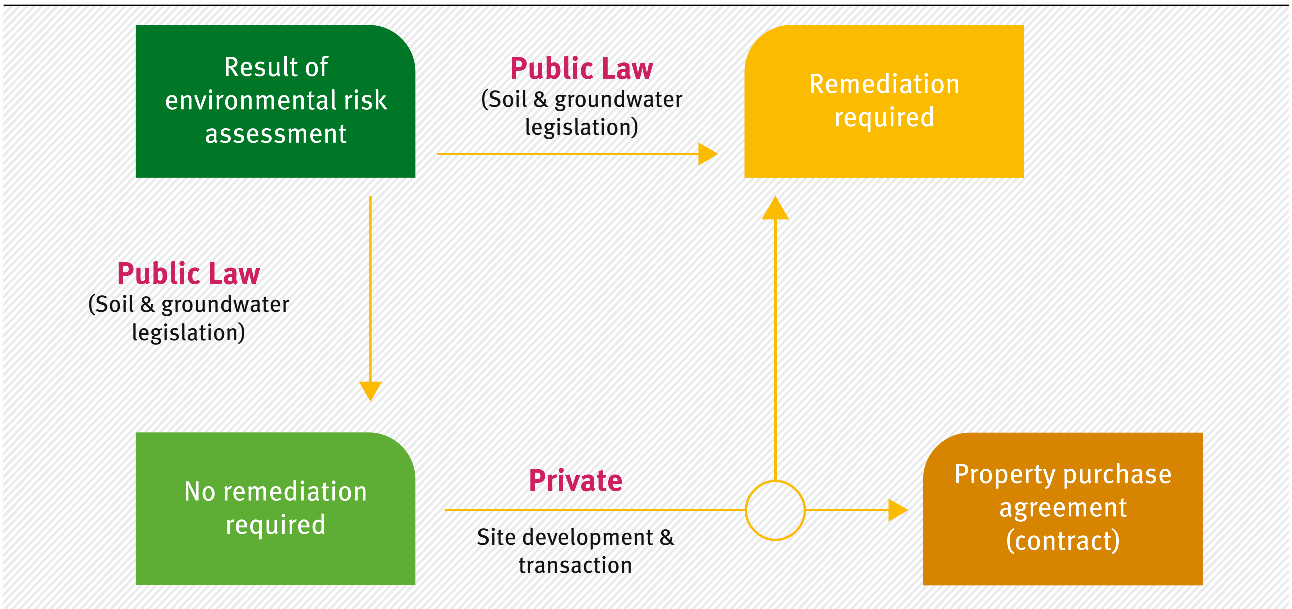
A public law contract can provide a reasonable compromise between the interests of the regulator (and, potentially, also of the site owner or economic operator if these are not the polluter) in view of a comprehensive and in the long-term effective remediation of a contaminated site on one hand and the interests of the liable party in a time- and cost-efficient manner on the other hand.

A contract under public law can provide a high level of legal certainty for all involved parties and for the liable party, in particular, as the framework conditions and obligations (e.g. remediation targets, limitations, possible future site use scenarios, financial framework conditions, etc.) are clearly defined and are also binding for the regulator. Remediation targets are derived from existing legal and regulatory requirements (e.g. soil and groundwater legislation) and must be technically and economically realistic and achievable within a defined time frame. A public law contract replaces official administrative orders (administrative decisions) for remediation by the regulator towards the liable party as well as legal claims by the liable party against the regulator.

Challenges of public law contracts could be the need for realistic and reliable cost estimates for

Figure 2

General contractual scenarios of public and private law for managing contaminated sites



Source: (Arcadis Germany GmbH, 2014)

remediation measures (which could be solved by a financial "cap" in the contract), subsequent claims by third parties or if remediation targets cannot be achieved in a time- and cost-efficient manner. In that case, remediation targets may be defined as "preliminary" if the remediation process has a high level of uncertainties and/or if site conditions are very complex ("element of flexibility"). Also, actions in case of technical infeasibility to achieve the remediation targets can be agreed upon in the contract ("fallback scenarios").

It would exceed the scope of this manual to go into further details of public law contracts, but it is highly recommended to evaluate the applicability of this approach, particularly for large-scale remediation projects of the oil & gas industry, on a case-by-case basis.

In some cases, strategic thoughts or other considerations beyond the framework of public law requirements and provisions may trigger proactive investigation and/or remediation activities which may be subject to obligations related to private law such as:

- Gaining certainty on the status of a site in terms of potential contaminations (e.g. with respect to company-internal risk management standards or for building-up required financial reserves),
- Fulfilling contractual obligations between site owners and site users, e.g. economic operators,
- Increase of the value of a site or plot in the context of a purchase or sale of a property,
- Increase ("upgrade") the quality of a site for a more sensitive future site use.

Both areas of law have basically to be considered separately. However, under certain circumstances public law requirements may influence processes or obligations under private law as well, e.g. if an environmental site investigation that has been required by the regulator reveals significant soil contaminations which would impact the value of the site. At any rate, remediation activities have always to be agreed with the responsible competent authority and must comply with the respective environmental regulations as described in the previous chapters.

Regulatory and administrative background for managing contaminated sites

EU as well as international environmental regulations imply the full application of the "polluter pays principle". A number of EU directives referring to (ground)water and aspects of soil protection does exist and has been transposed into national law. However, not all EU member states have specific legislation on soil protection at national level (e.g. as Germany has with its Federal Soil Protection Act).

An important aspect of managing contaminated sites, and particularly of the definition of remediation goals and (numeric) remediation targets, is the "principle of proportionality" which implies the application of technically feasible and economically appropriate remediation measures based upon a site-specific risk assessment and which considers future site use scenarios.

The common driver for the remediation of soil and/or groundwater contaminations under public law provisions are the competent authorities. In some cases, investigation or remediation activities might be triggered by factors related to private law or by strategic considerations. In any case, remediation activities must comply with the respective environmental regulations.

The competent authorities take a key position in the procedures which are applicable for the management of contaminated sites such as investigation, risk assessment and remediation. This includes also the preparation of a register (or inventory) of contaminated sites with the support (data input), e.g. by site owners or economic operators. The competent authorities will be responsible for the approval of remediation plans to be prepared by the liable party (or an appointed consultant) and for the monitoring of the remediation works during execution.

Once a remediation project has been completed in accordance with the agreed remediation targets, the competent authority should send written approval to the liable party and confirm that the obligations have been fulfilled. Also, the status of the respective site in the register of contaminated sites shall be adjusted accordingly.

Particularly for large-scale remediation projects, the applicability of public law contracts between the liable party and a legal entity under public law, such as a municipality or city, should be evaluated. Such contracts provide legal certainty, e.g. regarding remediation goals and targets and the associated costs.

2 General site characteristics and environmental impact

2.1 The oil & gas value chain

The value chain of the oil & gas industry is basically divided into three major sectors: the upstream, midstream and downstream sector (Figure 3).

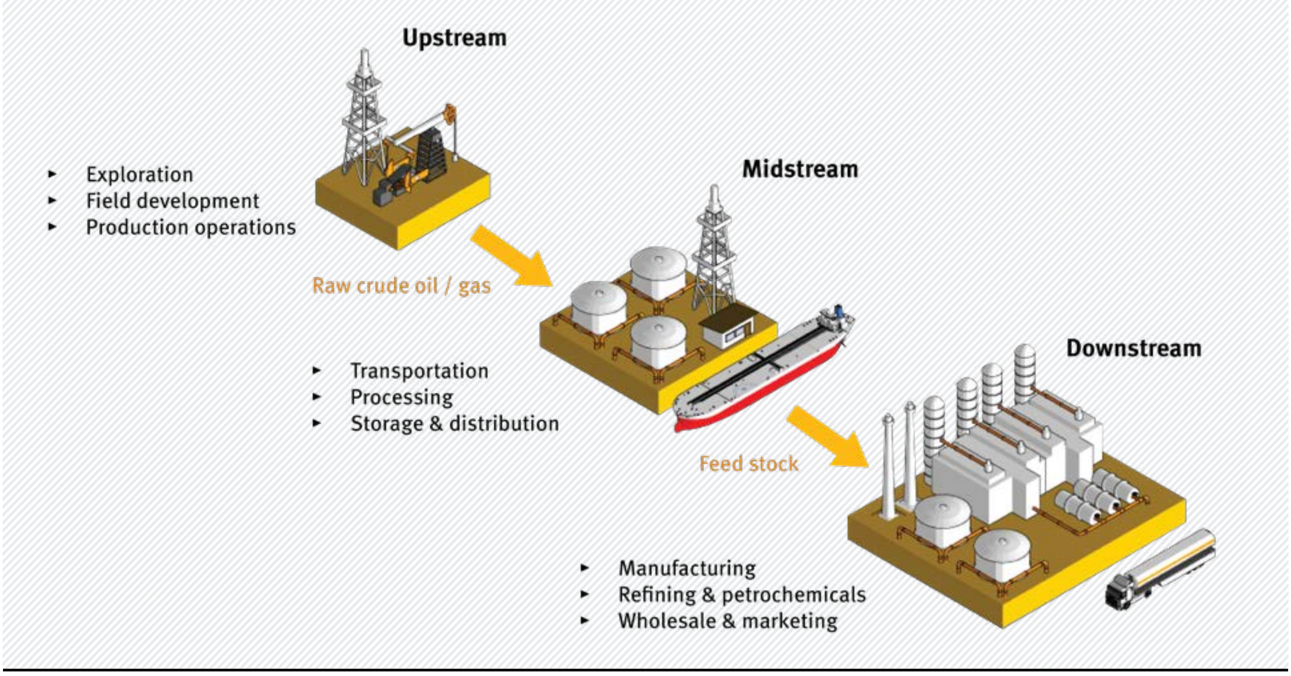
The **upstream sector**, also known as the exploration and production sector, includes the exploration (search and detection) for crude oil and natural gas fields in on- and offshore environments, the drilling of exploratory wells and subsequently drilling and operating of production wells for the recovery of crude oil or natural gas.

The **midstream sector** comprises the transportation of crude oil or refined petroleum products by pipeline, tank railcars (tank wagons), tank ships[1] (barges[2] and oil tankers[3]) or tank trucks from production sites to refineries and petrochemical plants or between these processing facilities to downstream distributors. Furthermore, the midstream sector includes the storage of petroleum products in tank farms. In the case of natural gas, pipeline network systems move gas from processing and/or purification plants to downstream customers, such as local utility operators.

The **downstream sector** includes the refining of crude oil and the processing and purifying of raw natural gas as well as the marketing and distribution of the end products, such as gasoline and diesel fuel, marine and aviation fuel, lubricants, bitumen products, such as asphalt, natural gas and liquefied petroleum gas (LPG) as well as a large diversity of petrochemical products.

Figure 3:

The oil & gas value chain: upstream, midstream and downstream sector



Source: Arcadis, own figure

1 Tank ships: general term for barges and oil tankers
2 Barges: tank ships usually used on rivers and lakes
3 Oil tanker: tank ships on oceans

2.2 Types of sites and contaminations considered in this manual

2.2.1 Overview

In the following, the site-specific characteristics of the three basic types of sites that are typical for the oil & gas industry and, therefore, will be covered by this manual (exploration and production sites, tank farms as well as refineries, see Figure 3) including the resulting, partly different requirements for the management of these types of contaminated sites are described and discussed. In order to understand where and how a release of contaminants into the environment could potentially occur, the way of the product from the input to the output needs to be examined since these ways are potential sources of contamination.

In addition, the site-specific characteristics of the investigation and remediation of these sites are to be considered. This includes, but is not limited to, the following aspects:

- Typical location,
- Products and waste materials,
- Potential contaminant inventory (the entirety or total mass of contaminants present at a site),
- Characteristic pollutant sources and entry points,
- Relevant receptors (groundwater, water, arable land, residential areas, etc.),
- Suitable investigation methods (intrusive, non-destructive, etc.),
- Suitable remediation approach (source and/ or plume restoration, in situ, ex situ, active and passive measures, etc.).

Since oil & gas facilities were strategic goals during World War II in numerous countries, many of these facilities have been damaged or destroyed to a high extent during that period. Reconstruction of the facilities usually did not rebuild exactly the previously existing structures. Moreover, it must be assumed that the reconstruction was done in a substantial different way. This results in the fact that for example on former industrial areas that are today derelict land plots, tank farms or oil processing units may have existed before World War II.

Another potential source for vast damages on industrial facilities, including facilities of the oil & gas industry, are natural catastrophes, such as earthquakes or floods, in regions where such catastrophes have occurred in the past and are likely to occur in the future.

Investigation programs need to be based on meticulous historical investigations (see Chapter 4 on Phase I environmental site investigation). Typical contaminations are described in Chapter 2.3.

2.2.2 Considerations regarding active and derelict sites

In general, a distinction is made between active and derelict (abandoned) locations for all three site types, and differences in the legal status of active and derelict sites are presented. This is, for instance, relevant with respect to currently existing operating licenses requiring not to exceed specific contaminants emission limits into soil, water and air. It might be also relevant with respect to a planned re-use of a site (e.g. compliance with remediation target values for more sensitive after-use). For this purpose, this manual elaborates on which requirements are derived from national legislation and on the extent to which these have to be taken into account when designing restoration and remediation measures depending on the site status (active or derelict).

The advantage of working on derelict sites with respect to the performance of investigation and/or remediation activities is that little or no care needs to be taken with respect to operational processes including infrastructure. Still, there might be decommissioned technical installations on site which could carry a potential risk for investigation or remediation activities, such as old underground tanks or pipelines that contain residual petroleum products.

Additional differences between active and derelict sites must also be considered. These include:

Active sites or sites that are only temporarily inactive:

- Limited or no access to critical investigation spots and locations (points of contaminant entry) at technical facilities (tanks, process facilities, wells, pumping stations, etc.) and infrastructure facilities (e.g. roads, railways, buildings);
- This results in limitations with respect to applicable investigation and remediation methods (frequently only patch investigation possible);
- Limitations, e.g. for the placement of monitoring wells;
- Consideration of legal aspects (e.g. implications of mining law and of the soil and groundwater legislation for exploration and production sites);
- Usually very stringent health, safety, security & environment (HSSE) requirements, higher risk potential (e.g. presence of hazardous substances, fire and explosion risk, road and railway traffic on site, etc.).

Derelict sites without any current site use:

- Facilities demolished or still existent;
- No implications because of no existing license to operate;
- Generally better access to critical investigation spots and locations (points of contaminant entry);
- Usually lower risk potential, HSSE requirements might be not that stringent;
- Fewer limitations regarding investigation and remediation methods in view of accessibility (e.g. intrusive investigation in a narrow grid is possible);
- Higher number of applicable remediation technologies (including complete decommission, source removal by soil exchange or a narrow network of injection wells for in-situ remediation);
- Consideration of future site use, e.g. when defining remediation targets.

2.2.3 Exploration and production sites

Exploration and production activities are the first phases of the oil & gas value chain (Devold, 2013):

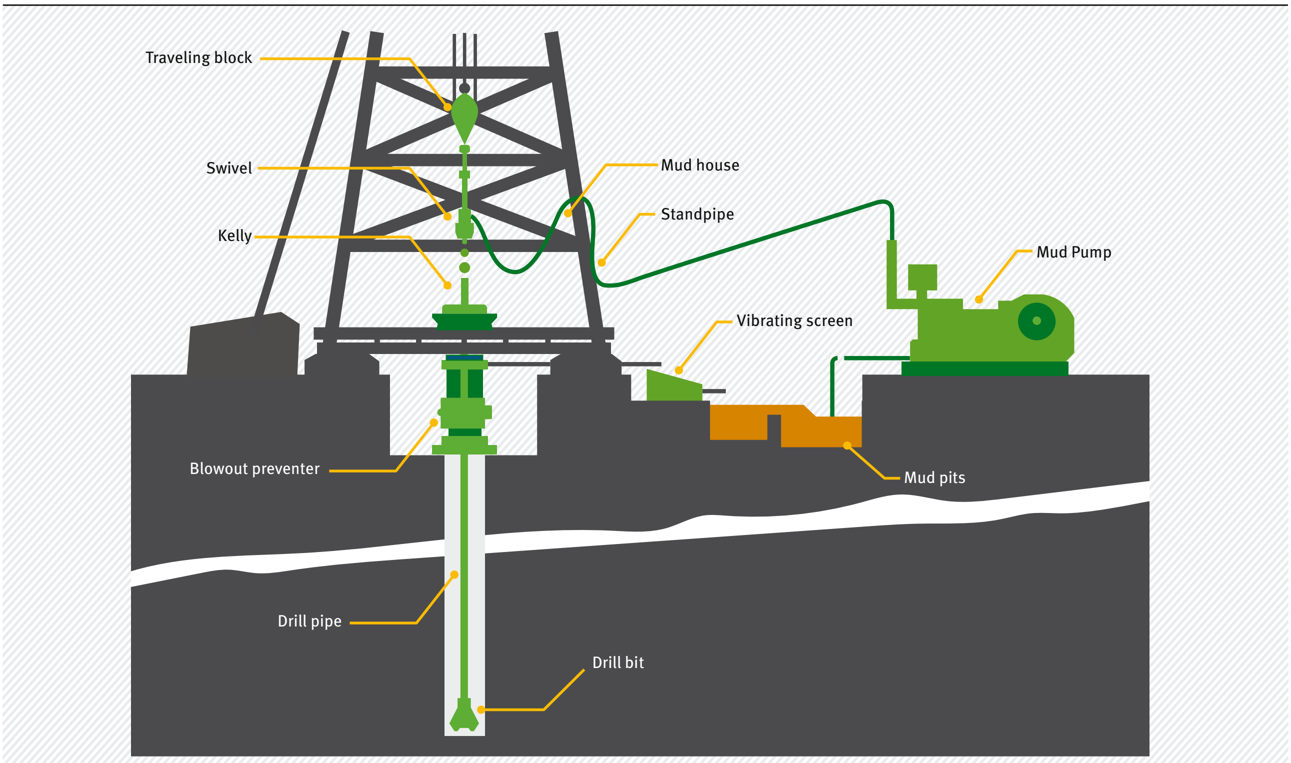
- **Exploration**[4] includes prospecting, seismic and drilling activities which take place before the development of an oil or gas field is finally decided. The process usually starts with broad geological mapping through increasingly advanced methods, such as passive seismic, reflective seismic, magnetic and gravity surveys, which are interpreted via sophisticated analysis tools to identify potential hydrocarbon bearing rock as "prospects". Drilling will only be done when models give a good indication of source rock and probability of finding oil or gas. During the first well drilling in a region, nothing is known about potential risks, such as the downhole pressures that will be encountered, and therefore require particular care and attention to safety equipment. If a find is made, additional reservoir characterization, such as production testing, appraisal wells, etc., are needed to determine the size and production capacity of the reservoir to justify a development decision.

- **Production** typically refers to all facilities for production (recovery) and stabilization of oil & gas from a completed production well.

A simplified schematic layout of an oil drilling rig is shown in Figure 4 and oil rigs in an oil field are shown in Figure 5.

Figure 4:

Simplified schematic layout of an oil drilling rig



Source: Arcadis, own figure

4 Offshore production facilities are not considered in this manual.

Figure 5:

Oil rigs near Bucharest (Romania)

Source: Shutterstock

Although there is a wide range of sizes and layouts, most production facilities have almost the same processing systems and general configuration as shown in a simplified overview in Figure 6.

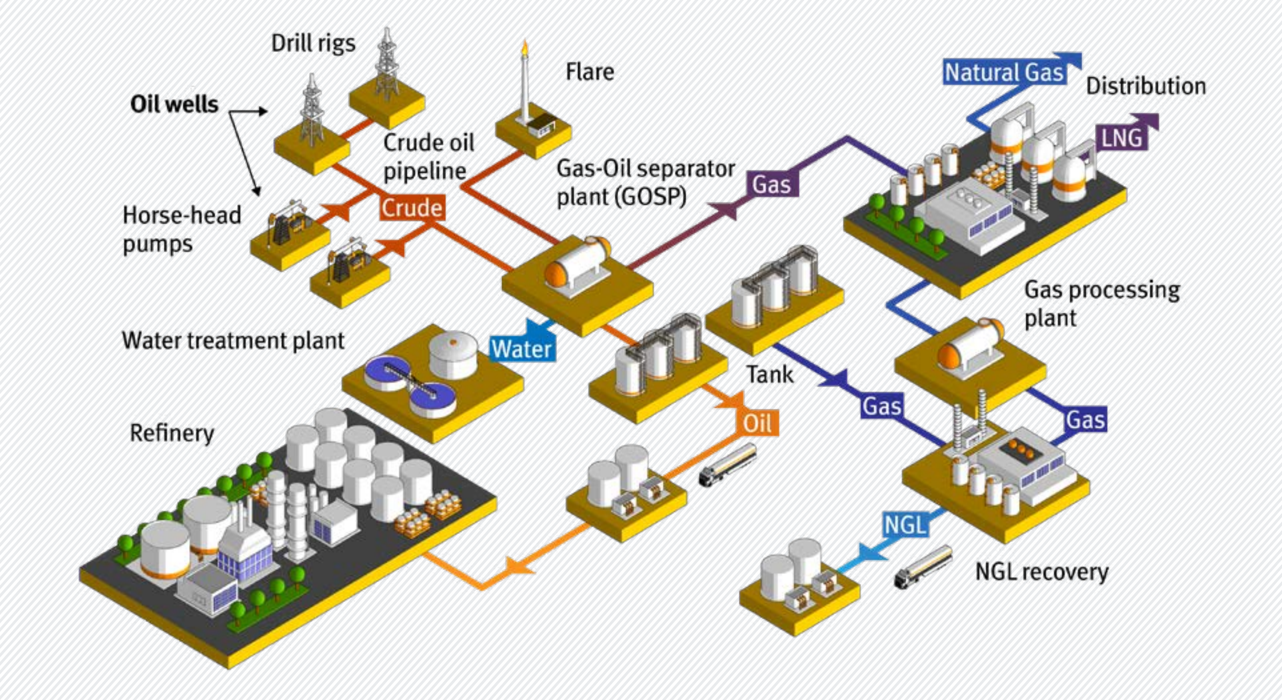
After the successful installation of an oil or gas production well, the production stage starts. The drilling rig and all related technical installations that have been used for well drilling and development are removed, and the top of the well is equipped with an assembly of vales and connections that is referred to as a “Christmas tree” (Figure 7). The vales are used for the regulation and control of the flow rates and the pressure, and therefore, the Christmas tree is also one of the most important safety devices of a production well. In addition, it is important for accessing the borehole if technical modifications of maintenance works are required.

Through the outlet valves and fittings, oil & gas is fed in a controlled manner into a connected pipeline system. Crude oil is usually transported to tank farms or refineries for processing, and natural gas is transported to compressor stations.

As long as the pressure in the reservoir remains high enough, the production tree is all that is required for the extraction of oil or gas. If the pressure depletes and if it is considered economically viable, an artificial lift method such as the commonly used “horse-head pumps” (see Figure 8) can be employed. Mature, already depleted oil or gas sources are “stimulated”, e.g. by explosive fracturing, acid injection or hydraulic fracturing (“fracking”).

Figure 6:

Oil & gas production process overview



Source: Arcadis, own figure

Figure 7:

“Christmas trees” of oil production wells at onshore field (Thailand)

Source: Getty Images

Figure 8:

Horse-head pump in an oil field (Romania)

Source: Getty Images

The liquids extracted from the production wells are fed from the wellheads into production and test manifolds (gathering system)[5]. While there are only oil or gas installations, more often the well flow will consist of a full range of hydrocarbons, ranging from gas (methane, butane, propane, etc.), condensates (medium density hydrocarbons) to crude oil. With this well flow, also a variety of unwanted components, such as water, carbon dioxide, salts, sulfur and sand, are extracted. The separation of these unwanted components from the produced gas and oil takes place in a gas-oil separation plant (GOSP). The purpose of the GOSP is to process the well flow into clean, marketable products: oil, condensates or natural gas. Also included are several utility systems which are not part of the actual process but provide, for instance energy, water and air to the plant.

In the case of onshore production, a gas gathering network can become very large, with production from thousands of wells, several hundred kilometers apart, feeding into a processing plant. For the smallest reservoirs, oil is simply collected in a holding tank and picked up at regular intervals by tank trucks to be processed at a refinery.

Usually, the products are sent from the plant by pipelines or tank ships. The production may come from many different license owners, so the metering of individual well flows into the gathering network is an important task. The aspect of diverse license owners and economic operators is also relevant in view of liability considerations with respect to soil and groundwater contaminations as a result of the production activities.

Some oil extraction companies target very heavy crude and tar sands that became economically extractable with higher prices and new technology (unconventional extraction by stimulating the geological deposits through fracking or acid injection, etc.). Heavy crude oil may need heating and diluents to be extracted. Tar sands have lost their volatile compounds and are strip-mined or can be extracted with steam.

Since about 2007, drilling technology and fracturing of the reservoir have allowed shale gas and liquids to be produced in increasing volumes.

The wellhead structure must allow for a number of operations relating to production and well workover. Well workover refers to various technologies for maintaining the well and improving its production capacity.

5 The contents of this and the following paragraphs has mainly been taken from the oil and gas production handbook (Devold, 2013).

Some wells have pure gas production which can be taken directly for gas treatment and/or compression. More often, the well produces a combination of gas, oil and water with various contaminants that must be separated and processed.

The production separators may have many different forms. The classic option comprises gravity separation. The well flow is fed into a horizontal vessel, the retention time is typically five minutes, allowing gas to bubble out, water to settle at the bottom and oil to be taken out in the middle. The pressure is often reduced in several stages (high pressure separator, low pressure separator, etc.) to allow controlled separation of volatile components. A sudden pressure reduction might allow flash vaporization leading to instability and safety hazards.

From the environmental point of view, there are a variety of hazardous substances, raw and waste materials and potential sources for soil and/or groundwater contaminations on oil & gas production sites. The typical characteristics of these sites are listed in Table 1.

Table 1:

General characteristics of onshore oil & gas drilling and production sites

Parameter	Description
Size	0.8 – 1.5 ha
Typical products, raw and waste materials	Crude oil, gas, condensate, reservoir water, back flow, drilling additive, fracking fluids, drilling fluids, drilling mud, oil sludge; contaminated scales (incrustations, e.g. of sulfates), e.g. in tubes and pumps, etc.
Potential contaminants	TPH, light volatile hydrocarbons, heavy metals (e.g. arsenic, mercury), chemicals from additives in the drilling fluids, naturally occurring radioactive material (NORM), partly technically enhanced (TENORM), e.g. radium, radon, thorium
Main contaminant sources and areas	Mainly spot-like, e.g. drilling points, tanks for additives, fuel tanks; Partly spatial, e.g. drilling mud and oil sludge pits
Mechanism of contaminant release	Leaks at pipes, pumps, fittings and connections, defective equipment (wellheads, valves, “Christmas trees”), uncontrolled release of back flow at the surface or in the borehole, spills of drilling fluids, deposition of drilling mud and oil sludges in pits or basins with insufficient or without bottom sealing

The historical evolution of the production sites is also essential for understanding where and which contaminations may have occurred. In some areas, the production activities might have been ongoing for decades or even have stopped a long time ago (“historical contaminations” that have been caused before activities were stopped). The age of sites, local conditions, previous or existing safeguard measures (e.g. liquid-tight sealing of oil sludge pits) and known environmental impacts must be considered in these cases to correctly plan investigation and remediation measures.

Furthermore, the contaminants of concern and areas of potential contamination vary depending on the type of site (oil or gas, conventional or unconventional drilling, application of fracking technology, etc.). Therefore, it is important to know and identify all byproducts and waste products in the production process and their production, transport pipeline and storage locations. This should be considered in the Phase I environmental site investigation and also in subsequent investigation measures.

In terms of the common presence of drilling mud and oil sludge pits on exploration and production sites, these are characterized as follows (Engeser et al., 2015):

- **Drilling mud pits.** Deposits of drilling mud that contain little or no mineral oil (< 5 %), instead drilling fluids including chemicals, cuttings, sediments, which are mostly located close to the drilling rig. They usually show only limited environmental risk potential. However, hydrocarbon-containing drilling mud may also occur in some cases, e.g. where hydrocarbons have been added to the drilling fluid.

- **Oil sludge pits.** Deposits of waste oil and oil-containing residues from the oil & gas exploration, production and/or separation of liquid and solid components. These materials are usually disposed into pits at or near the production sites. In principle, they show a higher environmental risk potential.

In some cases, drilling mud and oil sludge were mixed, which is why the environmental risk potential depends on the storage quantities and methods, the overall total petroleum hydrocarbons' (TPH) content and composed material.

Some other critical aspects to be considered when dealing with potential environmental impacts on exploration and production sites are the public perception and sensitivity as well as the site ownership and contractual situation for the site itself and its potentially impacted neighborhood.

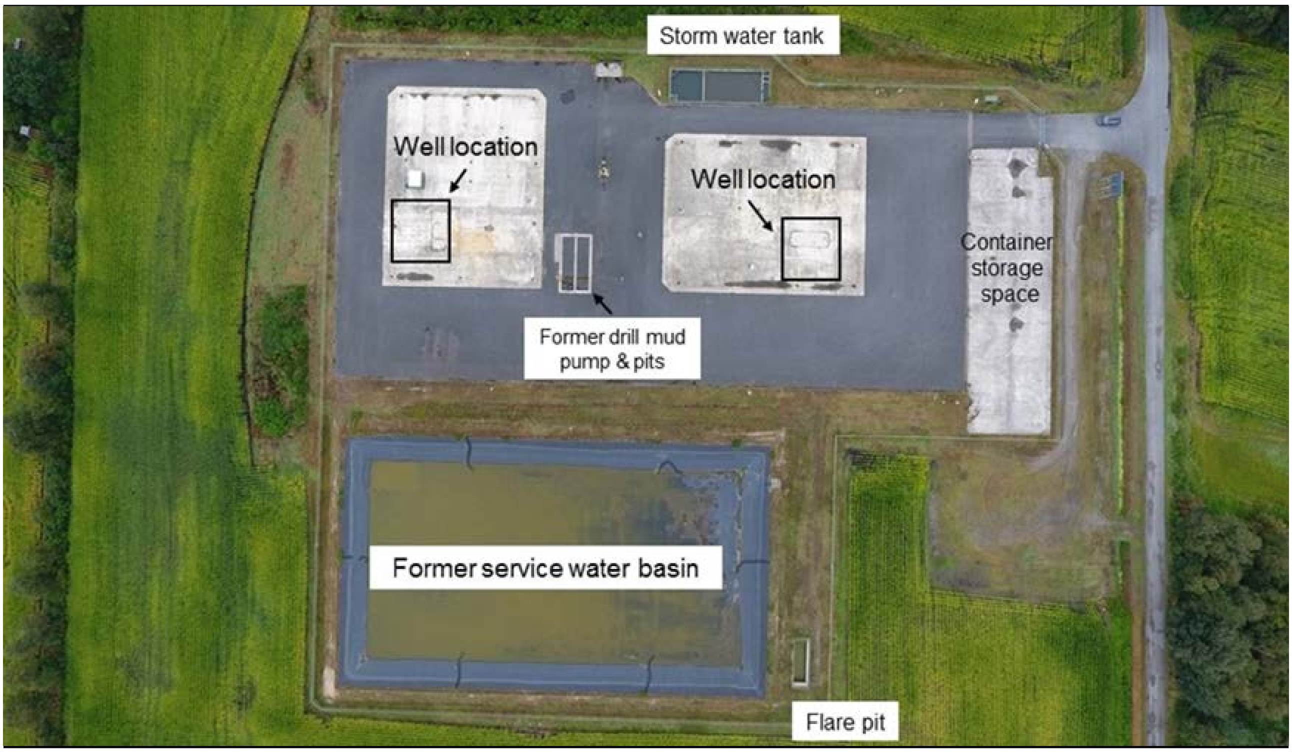
After completion of operational activities on a drilling or production site, technical installations, such as drilling rigs, pumps, auxiliary equipment, etc., are usually removed, and the site becomes generally accessible for conducting investigation and remediation works (Chapters 6 – 11) if there are indications for soil and subsoil contaminations, which is usually the case on such sites.

The investigation program shall consider the relevant areas of concern, which are usually the former locations of wells, pumps, storage spaces for hazardous substances, ponds for drilling fluids and drilling mud, etc. Figure 9 shows a typical gas production site after deactivation and removal of technical installations and buildings.

Potential source areas for subsoil contaminations are the former well locations (drilling rigs, wellheads, horse-head pumps, pipelines from the production wells to the GOSP), drilling mud and pump pits, process and/or service water basins and flare pits. In addition, areas for the storage and handling of hazardous substances (drums, containers) and oil sludge pits on oil production sites need to be considered for the investigation and the risk assessment process.

Figure 9:

Aerial view of an abandoned gas drilling site (Germany)



Source: Arcadis, own figure

2.2.4 Tank farms

Tank farms (also referred to as tank terminals, oil terminals, tank depots or oil depots) are industrial facilities for the storage of oil and/or petrochemical products. As such, they are logistic facilities receiving a high volume of product and usually distributing it in lower volumes to end-users or to further storage facilities. A tank farm consists of assemblies of storage tanks (mainly aboveground, sometimes also underground or a combination of both) of different sizes where crude oil and/or refined products are stored. Aboveground tank fields are surrounded by bund walls, which act as spill containments in case of uncontrolled products' releases or spills.

Furthermore, supporting infrastructure and technical installations are integral elements of tank farms. These include connecting pipelines, pumping stations, fittings and measuring devices, on- and offloading facilities such as road and railway loading bridges, jetties (structures for on- and offloading tank ships at sea harbors and at rivers) and a variety of safety installations.

While crude oil is delivered to storage tanks on refineries and is subsequently processed e.g. to fuels and petrochemical products, refined products are delivered to tank farms and then further distributed to the consumers mainly by train, truck and pipelines.

In the production sector, tank farms are used for the temporary storage of crude oil from production wells. Such tank farms may also be equipped with gas-oil separation plants. In addition, some facilities use tanks to store brine that is used to displace product in the operation of underground storage (salt) caverns. Some tanks may also be used for the temporary storage of residual process fluids ("flowback") and wastewater from the oil & gas production process. Consequently, a tank farm may contain large quantities of diverse products which are hazardous to the environment if uncontrolled releases occur.

Tank farms are frequently situated close to an oil refinery or in locations where tank ships containing products can discharge their cargo (usually at sea or river harbors). Some tank farms are attached to pipelines from which they receive their products or can also be fed by rail, by ship and by tank trucks. Most tank farms have tank trucks operating from their grounds and these vehicles transport products to petrol stations or other users. A picture of a modern tank farm is shown in Figure 10.

Figure 10:

Aerial view of the Eurotank Terminal, Amsterdam (the Netherlands)

Source: Shutterstock

A tank farm is a facility of comparatively low technical complexity. In most cases, there is no processing or other transformation of the products on-site. The products which reach the tank farm from a refinery are in their final form suitable for delivery to customers. In some cases, specific additives may be added to the products in tanks. Modern tank farms comprise the same types of tankage, pipelines and gantries as those in the past, and although there is more automation on-site, there have been few significant changes in operational activities over time.

For a safe and efficient operation, tank farms dispose of a variety of safety systems for the prevention of incidents and spills, such as devices for real-time process monitoring and control, tank-level monitoring, leak detection and overpressure detection. Emissions are continuously monitored by gas analyzers.

Modern tanks are based in a concrete tank pit (including tank basement) or bund walls sealed with a solvent-impermeable layer. In former times, sealings often were lacking. Underground pipelines are in general in a depth of 60 – 80 cm below ground unless they are covered with additional backfill material during site reconstruction activities. In many cases, it is unclear for abandoned underground pipelines whether they have been emptied completely or not. Hence, it must be avoided to damage these pipelines during investigation or remediation. Today, aboveground pipelines are used almost exclusively.

Since spills cannot be avoided in any case, surface water is collected and cleaned by oil-water separators with subsequent biological degradation of dissolved compounds.

Some tank farms have been refineries in the past and thus may have a more complex contamination pattern or unexpected contaminants on the site. From time to time also other raw materials for the chemical industry are stored (referred to as diverse chemicals). Analytically they might be detected as TPH. Therefore, a rather wide range of (petro)chemical substances have to be considered as potential contaminants on tank farms. Typical characteristics of tank farms are summarized in Table 2.

Table 2:

General characteristics of tank farms

Parameter	Description
Size	50 – 500 ha
Typical products, raw and waste materials	Crude oil, petrol and diesel fuel, heating oil, heavy fuel, naphtha, liquid gas, alcohols, diverse chemicals
Potential contaminants	TPH, BTEX, oxygenates (MTBE, ETBE, TBA) PAH, arsenic, lead, diverse chemicals
Main contaminant sources and areas	Spot-like, linear or spatial, e.g. tanks, tank fields inside bund walls, pipelines, on-/offloading facilities (truck, ship and railway), pump stations, sewer systems
Mechanism of contaminant release	Similar to refineries (see Chapter 2.2.5), but there are usually fewer and less complex technical systems and facilities on tank farms. Also, no high-temperature processes and associated hazards (e.g. releases of gas, dust, etc.)

2.2.5 Refineries

Most parts of the following definitions and descriptions of the processes on refineries as well as the environmental implications that could result from refinery sites have been extracted from: Environmental Impact of the Petroleum Industry, Environmental Update #12 (Hazardous Substance Research Centers/South & Southwest Outreach Program, 2003).

Definition of a petroleum refinery. Petroleum refineries separate crude oil into a wide array of petroleum products through a series of physical and chemical separation techniques. These techniques include fractionation, cracking, hydrotreating, blending or combination processes as well as manufacturing and transport. The refining industry supplies several widely used everyday products including petroleum gas, kerosene, diesel fuel, motor oil, asphalt and waxes.

Processes involved in refining crude oil. The process of oil refining involves a series of steps that includes separation and blending of petroleum products. The five major processes are briefly described below:

- **Separation processes.** These processes involve separating the different fractions of hydrocarbon compounds that make up crude oil based on their boiling point differences. Crude oil generally is composed of the entire range of components that make up gasoline, diesel, oils and waxes. Separation is commonly achieved by using atmospheric and vacuum distillation. Additional processing of these fractions is usually needed to produce final products to be sold on the market.
- **Conversion processes.** Cracking, reforming, coking and visbreaking are conversion processes used to break down large longer-chain molecules into smaller ones by heating or using catalysts. These processes allow refineries to break down the heavier oil fractions into other light fractions to increase the fraction of higher-demand components such as gasoline, diesel fuels or whatever may be more useful at the time.
- **Treating.** Petroleum-treating processes are used to separate the undesirable components and impurities such as sulfur, nitrogen and heavy metals from the products. This involves processes such as hydrotreating, deasphalting, acid gas removal, desalting, hydrodesulfurization and sweetening.
- **Blending or combination processes.** Refineries use blending or combination processes to create mixtures with the various petroleum fractions to produce a desired final product. An example of this step would be to combine different mixtures of hydrocarbon chains to produce lubricating oils, asphalt or gasoline with different octane ratings.
- **Auxiliary processes.** Refineries also have other processes and units that are vital to operations, e.g. power generation, waste treatment and other utility services. Products from these facilities are usually recycled and used in other processes within the refinery and are also important with respect to minimizing water and air pollution. A few of these units are boilers, wastewater treatment plants and cooling towers.

Environmental hazards of petroleum refineries. Refineries are generally considered as sources of pollutants in areas, where they are located, and are regulated by a number of environmental laws related to air, water and soil.

- **Air pollution hazards.** Petroleum refineries are potential sources of hazardous air pollutants such as BTEX compounds (benzene, toluene, ethylbenzene, xylene). They are also a source of critical air pollutants, e.g. particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), hydrogen sulfide (H_2S) and sulfur dioxide (SO_2). Furthermore, refineries release some hazardous hydrocarbons, such as natural gas (methane) and other light volatile fuels and oils. Air emissions can come from several sources within a refinery, including equipment leaks from valves or other devices, high-temperature combustion processes in the actual burning of fuels for power generation, heating of steam, and process fluids and from the transfer of products.
- **Water pollution hazards.** Operational activities on refineries may lead to groundwater and surface water contaminations. Some refineries used (or still use) deep-injection wells to dispose of wastewater generated in the plants which may cause hazards to the groundwater. Wastewater in refineries may be highly contaminated given the number of sources it can come into contact with during the refinery process, such as equipment leaks and spills and the desalting of crude oil.

This contaminated water may be process wastewaters from desalting, water from cooling towers, storm water, distillation or cracking. It may contain oil residuals and other hazardous wastes. This water is recycled through many stages during the refining process and goes through several treatment processes, including a wastewater treatment plant, before being released into surface waters. Groundwater contaminations may also be caused by direct releases of petroleum products into the subsoil as a result of spills and technical defects.

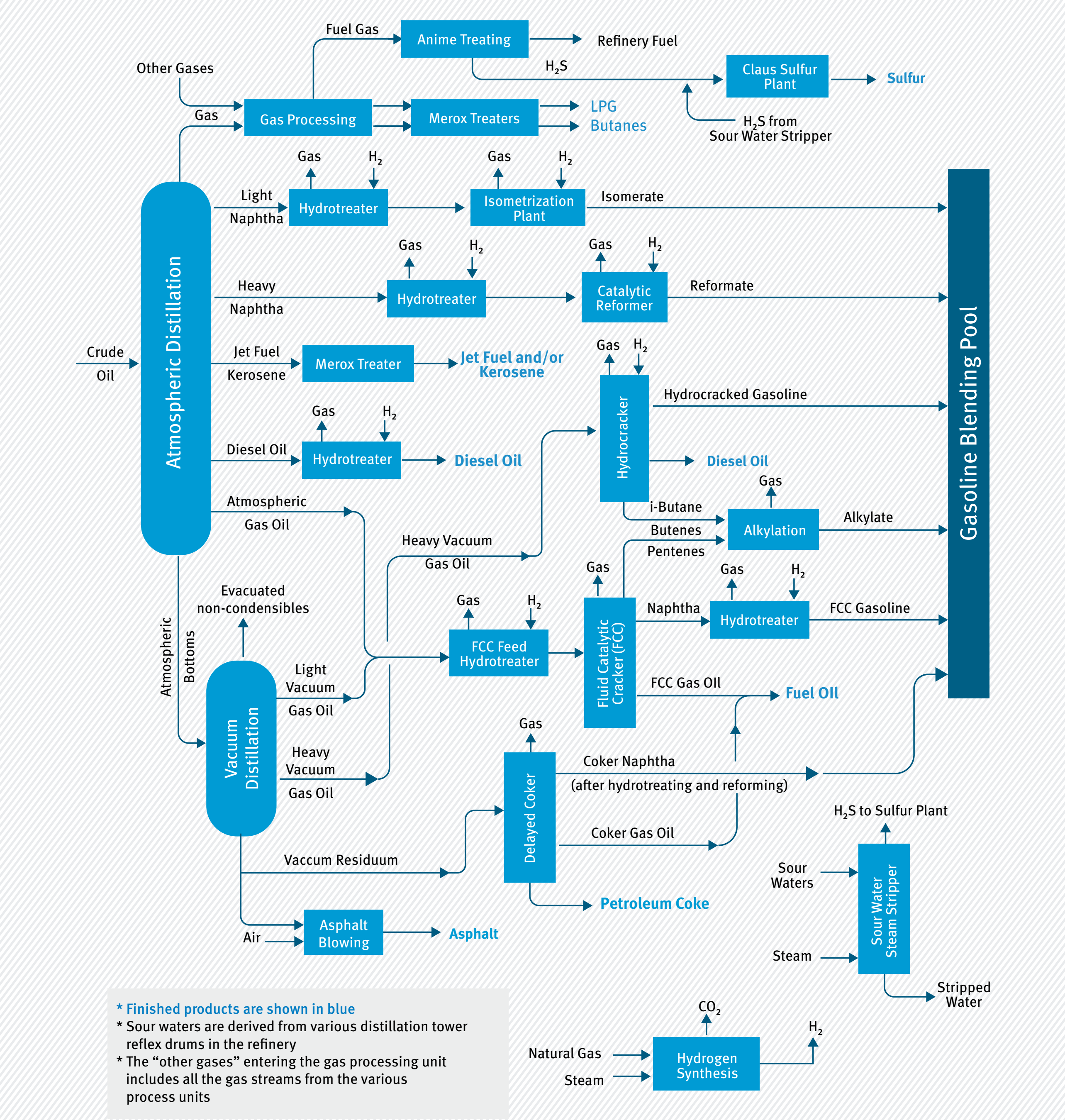
- **Soil pollution hazards.** Contamination of soils from the refining processes is generally a less significant problem compared to the contamination of air and water. Past production practices may have led to spills on the refinery property that now need to be cleaned up. Natural attenuation processes are often effective in cleaning up petroleum spills and leaks compared to many other pollutants.

Many residuals are produced during the refining processes, and some of them are recycled through other stages in the process. Other residuals are collected and disposed of in landfills (e.g. former acid tar lagoons), or they may be recovered by other facilities.

Figure 11 shows a simplified flow diagram of the refining process and the most important refining products. Subsequent blending processes are indicated but not further displayed in the flow diagram.

Figure 11:

Schematic process flow diagram of the processes used in a typical oil refinery

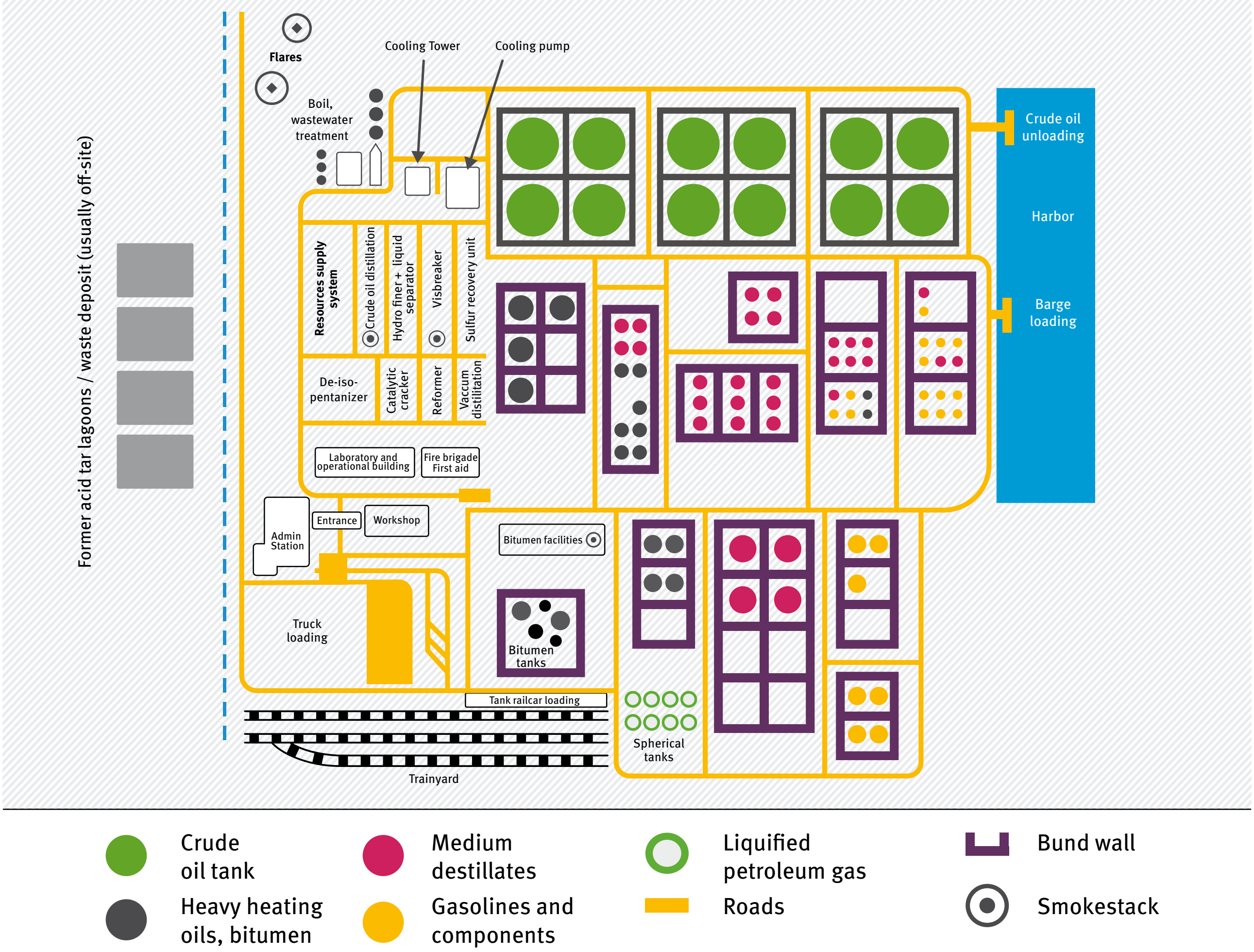


Source: Flow diagram by Mbeychok, licensed under CC BY-SA 3.0 (https://commons.wikimedia.org/w/index.php?curid=67297997)

For the identification of the potential sources and pathways for soil, groundwater and air contaminations on a refinery, it is important to understand the technical configuration and the locations of the diverse technical components, e.g. tank fields and stored products, processing and refining facilities, logistical facilities, etc. A simplified general layout of an oil refinery is shown in Figure 12, an aerial view of the process fields of an oil refinery is displayed in Figure 13.

Figure 12:

Schematic layout of a refinery site



Source: Arcadis, own figure

Besides the prominent features such as tanks, columns and flares, a refinery usually has an extensive infrastructure consisting of roads and railway tracks, including on- and offloading facilities for tank trucks, tank railcars, tank ships such as loading bridges, docks and jetties. Furthermore, a network of pipelines and conduits connect tanks and process facilities. On most refineries, crude oil is also delivered through pipelines.

The collection and purification of contaminated storm and process water and the subsequent discharge into a river or the sea takes place via a sewer system, oil and light substance separators and a wastewater treatment plant.

Technical safety devices, such as redundant automatic overfill protection, gas monitoring, gas detection and gas pressure release systems, safety valves and computerized plant control systems, shall prevent incidents, such as fire, explosion or uncontrolled releases of hydrocarbons and other petrochemical substances into the environment. A comprehensive health & safety management system shall ensure that no incidents, injuries or any other risks to employees on site and in the surrounding areas occur.

Figure 13:

Aerial view of the process fields of an oil refinery

Source: Shutterstock

There are several aspects regarding the management of environmental liabilities on refineries that have to be taken into account:

- **Changes in site use and technical configuration over time**. Most refineries have been operational for decades, and technical installations and configurations may have been modified repeatedly. Also, soil and groundwater contaminations have occurred over the entire life cycle of almost all refineries. Thus, overlapping of contaminations and especially plumes in the groundwater from multiple sources over time and by different contaminants makes it difficult or even impossible to delimit individual events of contaminant releases.
- **Date of construction, impact of war**. The impact of war is addressed in the Chapters 2.2.1, 2.4, 4 and 13. It can be assumed that extensive releases of petroleum products at all stages in the refining process (reaching from crude oil to high-quality fuels) have occurred on all refineries that have been hit by air strikes or any other kind of war effects. Besides combat-related damages as a result of bombing and shooting, it was common practice to intentionally discharge petroleum products from tank railcars to the ground during air-raid alarms in order to prevent strong explosions and fire in case that the tank trains would be hit.
- **Existing data on on-site contaminations and off-site plumes**. Most refineries (as well as tank farms) have more or less structured, partly already digitized files and data records on current and previous soil and groundwater contaminations. These are usually evaluated during the Phase I environmental site investigation and provide the data basis for all subsequent investigation and remediation activities.
- **Incidents (e.g. fire, explosion) and spills**. All information and data regarding incidents, such as fire and explosion as well as spills due to technical or human failure on site, provide important hints on the extent and potential contaminants of recent soil and groundwater contaminations and support efficient and targeted investigation planning and execution. Information on such events should be recorded and stored on the respective site. Reporting obligations to the local authorities have to be followed.
- **Site location in view of receptors**. This subject is of high relevance for the selection of appropriate action items. The location of the site with respect to sensitive receptors such as lakes,

rivers, drinking water protection areas but also agricultural or urban areas has a strong influence on the decision on and selection of necessary investigation and remediation activities in order to exclude or at least minimize negative impacts on those receptors.

- **Future site use – relevance regarding remediation goals and targets**. The current use of a site and the future site use scenario are important parameters for an environmental risk assessment. Furthermore, the future use of a site (no change, more or less sensitive) has a strong influence on the definition of realistic and achievable remediation targets.

Significant risks and consequently restrictions have to be considered when planning investigation or remediation measures on active refinery sites. For example, intrusive subsoil investigations cannot be carried out in areas where an increased risk of explosion does exist or where access is limited because of existing facilities and ongoing operations. Consequently, the range of suitable investigation techniques and remediation methods might be rather limited.

On abandoned refineries, much more options for investigation and remediation activities do basically exist (see Chapter 2.2.2).

Acid tar lagoons. A specific aspect of environmental concern at refinery sites are acid tar lagoons which exist in many countries globally. Acid tar is a sulfuric acid-containing waste product from former processing conducted by the petroleum industry with concentrated sulfuric acids, primarily when refining waste oil. It is an acrid, corrosive substance with persistent hazardous properties. Since technologies for avoidance or recycling of acid tar have not been available in the past, acid tars were dumped into open depressions or ponds (acid tar lagoons). This practice was applied until the late 1990s.

Acid tar lagoons are very frequently located at or near refineries but also in close proximity to urban areas or other locations of sensitive use. They pose a potentially significant risk to humans and the environment. In many cases, acid tar lagoons do also contain a variety of other wastes such as drums filled with waste oil or other petroleum hydrocarbons, industrial or domestic waste. Acid tars are technically difficult to handle because of their physical properties (viscosity), the extreme acidity and the SO_2 odor and dust emissions when moved or excavated. Thus, odor control and further health & safety concerns are important for the investigation and, particularly, for the remediation of acid tar lagoons. Consequently, they cause a very high sensibility of the public, particularly when remediation works are carried out.

Remediation approaches comprise basically four options and a pilot test for the identification of the most suitable approach is usually performed upfront.

- **On-site in-situ treatment**: stabilization (immobilization) through mixing of the acid tar with stabilizers such as lime, Portland cement or specially developed substances – without removal from the lagoon by using, e.g. a mixing device;
- **On-site ex-situ treatment**: stabilization (immobilization) through mixing of the acid tar with stabilizers such as lime, Portland cement or specially developed substances – after removal from the lagoon, on-site treatment and subsequent backfill into the lagoon;
- **Off-site treatment and backfill** into the lagoon;
- **Excavation and "thermal recycling"** (incineration), e.g. in cement cairns.

At any rate, the presence of unexploded ordnance (UXO) in all acid tar lagoons that have existed by the end of World War II has to be considered and appropriately addressed, see Chapter 2.4, 4 and 13.

Figure 14:

Acid tar lagoon before remediation (excavation) in 1999 (Germany)

Source: Arcadis photo archive

Figure 15:

Acid tar lagoon after remediation (excavation) in 2002 (Germany)

Source: Arcadis photo archive

Table 3:

General characteristics of refineries

Parameter	Description
Size	300 – 600 ha
Typical products, raw and waste materials	Crude oil, petrol and diesel fuel, heating oil, additives (MTBE, etc.), liquified gas, aviation fuel, special fuels, bitumen, acid tar, process water and wastewater, etc.
Potential contaminants	TPH, BTEX, oxygenates (MTBE, ETBE, TBA), PAH, arsenic, lead, diverse chemicals
Main contaminant sources and areas	Spot-like, linear or spatial, e.g. tanks, pipelines, process facilities (cracker, blending, etc.), on-/offloading facilities (truck, ship and railway), sewer systems
Mechanism of contaminant release	Corrosion and other damages at aboveground and underground storage tanks, pipelines and technical equipment (e.g. pumps), spills, incidents (fire, explosion)

Mercaptans, ammonium compounds, naphthenic acids and thiosulphates are usually summarized under different contaminant classes and are not considered separately.

Types of sites and contaminations considered in this manual

Exploration and production sites (including drilling mud and oil sludge pits), tank farms and refineries (including acid tar lagoons) are the three types of sites and facilities of the oil & gas industry that are considered in this manual. Most of the technical, regulatory and administrative information of this manual is also applicable to pipelines and related facilities, although these are not addressed in detail.

The three types of sites differ to some extent regarding size, typical products, raw and waste materials, potential contaminants, main contaminant sources and locations as well as mechanism of contaminant release. The mechanisms of contaminant releases into the environment is mainly related to the individual characteristics of each type of sites with respect to material and product flow, handling, storage, processing and transport mainly of hydrocarbon products and chemical substances such as additives but also regarding the disposal of waste products during the operational processes. The site-specific potential sources of contamination and types of contaminants need to be addressed during site investigation and remediation.

Because oil & gas facilities and, particularly, refineries have basically been strategic goals during World War II, some of these facilities have been damaged or destroyed to various extents. This may have caused a wider spreading of contaminants. Since post-war reconstruction of the facilities usually did not rebuild exactly the previously existing infrastructure, possible contaminant releases before World War II may have occurred at different locations. These facts need to be considered during investigation and remediation planning.

Finally, the current status of sites (still active or derelict) has a considerable influence on the planning and execution of site investigation and remediation measures. At active sites the access to sampling points may be restricted and additional requirements in terms of health & safety requirements, particularly for staff working on site, must be considered.

2.3 Most common contaminants and their characteristics

The products of crude oil processing by distillation are defined as mineral oil. Through distillation of the crude oil, products with different boiling ranges are obtained (see Table 4).

Additives are added to some mineral oil products, especially fuels, to enhance some of their properties or inhibit others. Common additives are antiknock agents, including the so-called oxygenates like MTBE (Methyl tert-butyl ether) and ETBE (Ethyl tert-butyl ether). Currently, these ethers are the mostly used antiknock agents.

At oil & gas sites, contaminants like TPH, BTEX, oxygenates (MTBE, ETBE, TBA), PAH, phenols, heavy metals and naturally occurring radioactive material (NORM) may occur. The characteristics of these compounds are described below. Other contaminants like chlorinated volatile organic compounds (CVOC) are due to secondary activities like cleaning or degreasing of metals during construction activities and are not considered in the manual.

Table 4:

Product groups of crude oil distillation[6]

Mineral oil product	Solubility in water [mg/l]	Boiling range [°C]	C-atoms	Density at 20 °C [g/cm³]
Gasoline	Approx. 100	36 – 175	Approx. 5 – 10	Approx. 0.7
Kerosene	Approx. 10 – 100	150 – 280	Approx. 8 – 17	Approx. 0.8
Diesel, heating oil	Approx. 5 – 20	160 – 390	Approx. 9 – 24	Approx. 0.8
Lube oil	Very low	300 –525	› 17	Approx. 0.9
Heavy heating oil, bitumen	Not soluble		› 40	

TPH. Total petroleum hydrocarbons (TPH) is a term used to describe mixtures of hydrocarbons that originate from crude oil. Since there are several hundred different chemicals in crude oil and in other petroleum products (linear, branched, circular, saturated and unsaturated hydrocarbons), it is not practical to analyze each compound individually. Instead, it is useful to analyze the total amount of TPH (as TPH-Index, EN ISO 9377-2:2000) at a site.

TPH can be classified in sub-groups, showing similar characteristics and behavior in the environment. These groups are called petroleum hydrocarbon fractions[7] , each containing many individual chemicals. Some chemicals that may be found in TPH are hexane, aviation fuels such as kerosene, mineral oils, benzene, toluene, xylene, naphthalene and fluorene as well as other petroleum products and gasoline components.

TPH are biodegradable under aerobic and anaerobic conditions. In general, the biodegradability of TPH depends on their composition. Aliphatic compounds with 10 to 16 carbon atoms are the fastest biodegradable petroleum hydrocarbons, whereas the short-chain hydrocarbons are toxic in higher concentrations and therefore inhibiting biodegradation. At the same time, the bioavailability decreases with increasing number of carbon atoms, mainly due to the also decreasing solubility of these compounds.

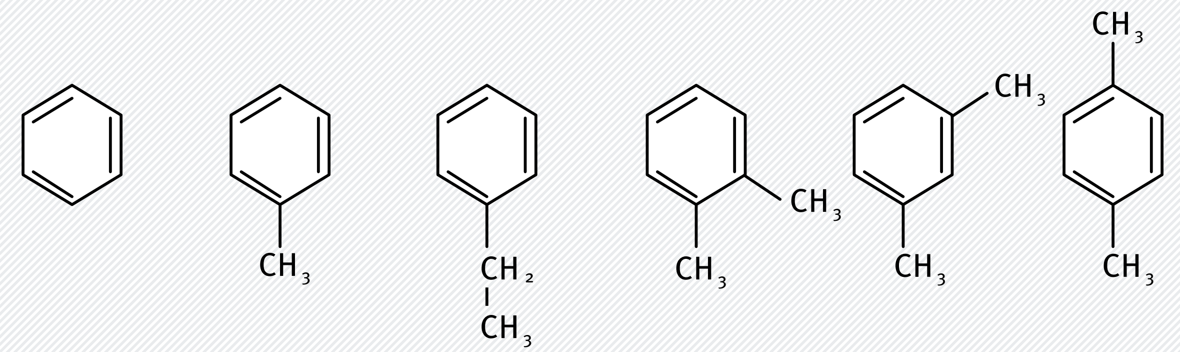
6 (KORA - Themenverbund 1, 2008)
7 Common hydrocarbon fractions used for risk assessment purposes are the ATSDR TPH fractions (ATSDR - Agency for Toxic Substances and Disease Registry, 1999): Aliphatics: C5 - C8 (e.g. n- Hexane), C9 - C16 (e.g. JP-5, JP-7, JP-8, kerosene, dearomatized petroleum stream) and C17 - C35 (e.g. mineral oils) Aromatics: C6 - C9 (e.g. benzene, toluene, ethylbenzene, xylene), C10 - C16 (e.g. isopropyl benzene, naphthalene) and C17 - C35 (e.g. fluorene, fluoranthene, benzo(a) pyrene)

Saturated aliphatic and non-branched compounds are better biodegradable than unsaturated and branched molecules. The anaerobic degradation is substantially slower (KORA - Themenverbund 1, 2008, S. 20-25).

BTEX. The BTEX group consisting of the (mono-) aromatic hydrocarbons benzene, toluene, ethylbenzene and the xylene isomers (o-, m-, p-xylene) are also components of mineral oil products.

Figure 16:

Structural formulas of BTEX[8]



Left to right: benzene, toluene, ethylbenzene, o-, m-, p-xylene

The BTEX are composed of an aromatic ring with substitution(s) with alkyl group(s) (except for benzene). The group of alkylated benzenes includes also further compounds like styrene (vinylbenzene), cumene (isopropyl benzene) and the trimethylbenzene isomers (hemellitol, pseudocumene, mesitylene) forming the so-called aromatic hydrocarbons (AHC). In Table 5, the most relevant physicochemical characteristics of the BTEX compounds and styrene are indicated.

Table 5:

Physicochemical characteristics of BTEX[9]

Compound	Solubility in water at 20 °C [mg/l]	Boiling range [°C]	Log Kow at 20 °C	Density at 20 °C [g/cm³]
Benzene	1780	80	2.13	0.88
Toluene	515	111	2.90	0.7
Ethylbenzene	152	136	3.15	0.87
Xylene	162 – 185	138 – 144	3.06 – 3.18	0.86 – 0.88
Styrene	280	145	2.99	0.91

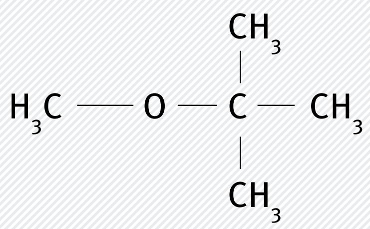
8 (KORA - Themenverbund 1, 2008, S. 20-25)
9 (KORA - Themenverbund 1, 2008)

The solubility decreases from benzene to ethylbenzene, whereas the affinity to the soil (sorption), e.g. of toluene is approx. 1.5 times and of xylene 2.8 times higher than benzene. BTEX are biodegradable under aerobic and, at lower rates, anaerobic conditions (KORA - Themenverbund 1, 2008, S. 20-25). Contamination by BTEX is usually caused by inappropriate handling of fuels (e.g. at petrol stations, tank farms, underground storage tanks).

Oxygenates (MTBE, ETBE, TBA). MTBE and ETBE have been used since the 1970s as antiknock agents in fuels. The MTBE quantity in fuels differs depending on the fuel quality (e.g. 0.3 Vol.-% in normal gasoline and 6-12 Vol.-% in the gasoline product "Super-Plus"). The MTBE-concentration differs in various countries. In the USA, for instance, some products are containing > 11 Vol.-% oxygenates. TBA (tert-butyl alcohol) is the main metabolite produced from MTBE and ETBE by natural biodegradation. However, it can also be present naturally in the fuel in low concentrations (currently approx. 0.2 Vol.-%) (KORA - Themenverbund 1, 2008, S. 10-11). The structural formula of MTBE is shown in Figure 17 and the physicochemical characteristics of the oxygenates are shown in Table 6.

Figure 17:

Structural formulas of MTBE[10]



The very low odor and flavor detection threshold of MTBE (20-40 µg/l) causes concerns if drinking water sources are contaminated. TBA is fully miscible with water. Correspondingly, TBA has a low vapor pressure and a much lower Henry's law constant[11], a term which expresses the tendency to evaporate, i.e. the tendency of contaminants to volatize from the aqueous phase into the soil vapor[12]. Hence, TBA does not strip and remains in solution, whereas MTBE can be volatilized from contaminated groundwater using air stripping. Neither MTBE nor TBA sorb strongly to organic matter including activated carbon. Therefore, both compounds migrate early with the velocity of the groundwater flow (API - American Petroleum Institute, 2012).

MTBE and ETBE are biodegradable under aerobic and, at lower rates, anaerobic conditions. Although the biodegradability was confirmed in several laboratory studies, the degradation rate in the field is low (KORA - Themenverbund 1, 2008, S. 26-29). When MTBE and ETBE are biodegraded, TBA accumulates in between but can undergo further biodegradation or mineralization (API - American Petroleum Institute, 2012).

The main potential sources of MTBE, ETBE and TBA are tank farms (KORA - Themenverbund 1, 2008, S. 10-11).

10 (KORA - Themenverbund 1, 2008)
11 The larger this value, the more likely the contaminants are to move from the water phase to the gas phase.
12 Also sometimes referred to as soil air or soil gas.)

Table 6:

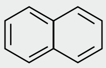
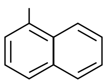
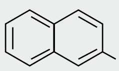
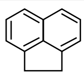
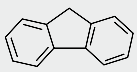
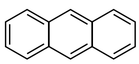
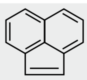
Physicochemical characteristics of MTBE[13]

Compound	Solubility in water at 20 °C [mg/l]	Boiling point [°C]	Vapor pressure [mm Hg]*	Hc [dimensionless]*	Log Kow at 20 °C	Density at 20 °C [g/cm³]
MTBE	42.000	55	251	0.055	1.06	0.74
ETBE	12.000	73	152	0.11	1.74	0.74
TBA	soluble	83	41	0.00049	0.35	0.79

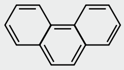
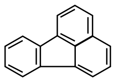
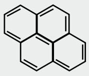
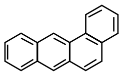
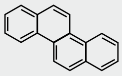
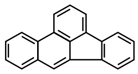
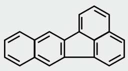
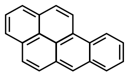
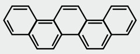
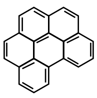
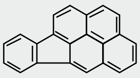
PAH. Polycyclic aromatic hydrocarbons (PAH) are hydrocarbons that are composed of multiple aromatic rings and originate mainly from creosote. Creosotes are a category of carbonaceous chemicals formed by the distillation of various tars and by pyrolysis of fossil fuel. PAH are all persistent and some are carcinogenic. The volatility, solubility, mobility in soil and groundwater are decreasing in tendency with increasing molecular weight. Also, the toxicity is different for each PAH compound. In laboratory analyses (ISO 18287:2006), usually 16 selected PAH (according to the U.S. Environmental Protection Agency) and in addition 1-methylnaphthalene and 2-methylnaphthalene are analyzed. The main characteristics of these compounds are listed in Table 7 (KORA - Themenverbund 2, 2008, S. 11-12).

Table 7:

Characteristics of PAH[14]

Compound [CAS-No.]	Structural formula	Solubility in water at 20°C [mg/l]	Log Kow at 20 °C	Molecular mass [g/mol]	Toxicity[1]
Naphthalene [91-20-3]		31	3.36	128.17	C, (M), (G)
1-Methylnaphthalene [90-12-0]		25.8	3.38	142.20	(C)
2-Methylnaphthalene [91-57-6]		24.6	3.86	142.20	n. a.
Acenaphthene [83-32-9]		3.57	3.92	152.20	H
Fluorene [86-73-7]		16.1	4.07	166.22	M, G
Anthracene [120-12-7]		0.043	4.45	178.23	(M), (G)
Acenaphthylene [208-96-8]		1.98	4.18	152.20	M, G

13 (KORA - Themenverbund 1, 2008), (Moyer & Kostecki, 2003)
14 (KORA - Themenverbund 2, 2008, S. 13-14)

Compound [CAS-No.]	Structural formula	Solubility in water at 20°C [mg/l]	Log Kow at 20 °C	Molecular mass [g/mol]	Toxicity[1]
Phenanthrene [85-01-8]		1.15	4.5	178.23	M, G
Fluoranthene [206-44-0]		0.26	4.95	202.26	C, M, G, H
Pyrene [129-00-0]		0.135	4.88	202.26	(M), (G), H
Benz[a]anthracene [56-55-3]		0.014	5.61	228.29	n. a.
Chrysene [218-01-9]		0.0063	5.66	228.29	C, M, G, H
Benzo[b]fluoranthene [205-99-2]		0.001	6.57	252.32	n. a.
Benzo[k]fluoranthene [207-08-9]		0.001	6.84	252.32	n. a.
Benzo[a]pyrene [50-32-8]		0.000003	5.97	252.32	C, M, G, H
Dibenz[a,h]anthra-cene		0.001	6.84	278.35	n. a.
Benzo[g,h,i]perylene [191-24-2]		0.002	7.23	276.34	n. a.
Indeno[1,2,3-cd] pyrene [193-39-5]		‹ 0.000062	7.7	276.34	n. a.

1) C = carcinogenic, G = genotoxic, M = mutagenic, H = high ecotoxicity (data in brackets show potential but not certainly demonstrated toxicity), n. a. = data not available

PAH with few aromatic rings, like naphthalene and phenanthrene, are completely biodegradable. The more aromatic rings exist (i.e. the higher the molecular weight), the lower the solubility and consequently bioavailability of the PAH, which leads to lower degradation rates. PAH with four or more aromatic rings are therefore degraded predominantly during so-called cometabolic processes. Cometabolic degradation means in this case that PAH with few aromatic rings (primary substrates) are degraded, allowing the microorganisms to grow and to gain energy. The low specificity of the biodegradation process allows the degradation of the PAH of a higher molecular weight as a side effect. In general, the cometabolic biodegradation does not allow the growth of the microorganisms nor the gain of energy.

The main removal process for PAH with a high molecular weight is humification, i.e. bonding of the partially oxidized degradation products to the humid matrix of the soil (KORA - Themenverbund 2, 2008, S. 25).

Phenols. Phenols (sometimes also called phenolics) are a class of chemical compounds consisting of a hydroxyl group (-OH) bonded directly to an aromatic hydrocarbon ring. The simplest of this compound class is phenol (C_6H_5OH), the more complex compounds are alkyl-substituted phenols. Furthermore, polyphenols, aggregates of several phenol units in the molecule, may occur. Most of these compounds are soluble. Molecules of lower molecular weight can be volatile (Wikipedia, 2020).

Phenols are found in nature but also in wastewater or in groundwater contaminated by petroleum products. In this case, they are a complex mixture of organic compounds, predominantly phenol, cresols, xylenols and other alkylated phenols obtained primarily from cracked naphtha or distillate streams by alkaline extraction (ECHA - European Chemical Agency, 2017).

The biodegradability and toxicity of phenols depend on the specific compound and are only well known for the simple phenol. Microorganisms capable of degrading phenol are common and include both aerobes and anaerobes. Many aerobic phenol-degrading microorganisms have been isolated and the pathways for the aerobic degradation of phenol are nowadays established (van Schie & Young, 2007, S. 1). Exposure to phenol by any route can produce systemic poisoning. Phenol has not been classified for carcinogenic effects, but it is a known promoter of tumors (ATSDR - Agency for Toxic Substances and Disease Registry, 2014).

Heavy metals. Lead is the most prevalent heavy metal contaminant and the only one directly associated to petroleum products. As a component of tetraethyl lead ($(CH_3CH_2)_4Pb$), it was used extensively in gasoline in the period 1930 – 1970. Although the use of leaded gasoline was largely phased out (e.g. in North America by 1996), soils next to roads built before this time retain high lead concentrations (Wikipedia, 2020).

Furthermore, the natural biodegradation of TPH can create reducing redox conditions in the aquifer, which reduces some soil metals (e.g. iron, manganese) or metalloids (e.g. arsenic) to their more soluble form. It should also be kept in mind that some remediation technologies (e.g. in-situ chemical oxidation, ISCO) alter the redox conditions and/or the pH may cause an increase of the heavy metals (mainly chromium, mercury) concentrations in groundwater.

Chromium, arsenic, cadmium, mercury and lead have the greatest potential to cause harm to the environment due to the toxicity of some of their redox status. In the human body, they can cause a deterioration of human health, sometimes fatal. Chromium (in its hexavalent form) and arsenic are carcinogens; cadmium causes a degenerative bone disease; and mercury and lead damage the central nervous system. Other heavy metals noted for their potentially hazardous nature include manganese which damages the central nervous system.

NORM. The production process of oil & gas mobilizes naturally occurring radionuclides from deep underground reservoir rock, which are either deposited as naturally occurring radioactive material (NORM) in production, treatment and transport facilities or appear in produced water. The radionuclides that are primarily mobilized and appear in sludges and scales[15] are ^{226}Ra, ^{228}Ra (radium) and ^{210}Pb (lead). Each of these radionuclides generate daughter radionuclides by radioactive decay, some of them (^{210}Pb from ^{226}Ra and ^{228}Th (thorium) from ^{228}Ra) are durable. Some radionuclides are very volatile (e.g. ^{222}Rn, radon) and may occur as gases.

When NORM-containing material is concentrated, e.g. in mineral scales inside pipes, contaminated equipment or components, produced waters or oil sludges and sediments, it is referred to as **TENORM** (technologically enhanced naturally occurring radioactive material). Through the concentration processes, radiation intensities of TENORM may reach significant higher levels than the original, NORM-bearing fluids.

Radiation protection strategies usually comprise measures to reduce exposure to external radiation and to prevent internal contamination by ingestion, inhalation and absorption of radioactive particles during production work as well as investigation and remediation. Laws and rules governing the fate of waste materials differ widely between countries (European Commission - Nuclear science and technology, 1997, S. 7).

However, NORM and TENORM have basically to be considered in the planning process and subsequent execution of investigation activities, particularly on active or abandoned oil & gas production sites.

Most common contaminants and their characteristics considered in this manual

Conventional contaminants at oil & gas sites are TPH (total petroleum hydrocarbons), BTEX (benzene, toluene, ethylbenzene, xylene), oxygenates (MTBE, ETBE, TBA; with MTBE and ETBE being used since the 1970s as antiknock agents in fuels) and PAH (polycyclic aromatic hydrocarbons). Of heavy metals, lead is the only one directly associated with petroleum products. Tetraethyl lead was used extensively as a gasoline component in the period 1930 – 1970. Understanding the solubility in water, boiling range, density, vapor pressure, tendency to evaporate (expressed as Henry's law constant), lipophile strength (expressed as log Kow) and biodegradability helps in the evaluation of fate and transport of these contaminants. Furthermore, the physicochemical properties of the contaminants dictate the sampling and measurement procedure to be used. Finally, naturally occurring radioactive material (NORM) may be mobilized during the production of oil & gas. NORM-enrichments within the oil & gas processing infrastructure are referred to as TENORM (technologically enhanced NORM).

15 Scales are mineral precipitates caused by changes of pressure or temperature.

2.4 Unexploded ordnance

According to the Protocol on Explosive Remnants of War (Protocol V to the UN Convention on Certain Conventional Weapons) (United Nations, 2006), unexploded ordnance (UXO) is defined as "explosive ordnance that has been primed, fused, armed or otherwise prepared for use and used in an armed conflict. It may have been fired, dropped, launched or projected and should have exploded but failed to do so".

UXO, which may be found at sites, onshore as well as offshore, basically originates from four principal sources:

- War-related combat activities (particularly bombing) during World War I and World War II, long-range shelling, placement of mines and locations of other war activities (anti-aircraft batteries, artillery emplacements, etc.),
- Abandoned ammunition production facilities,
- Areas where UXO have been dumped or disposed of in an improper manner,
- Military training sites.

In countries where air strikes and other combat-related activities have occurred during World War II, many sites and facilities of the oil & gas industry are (often significantly) impacted by UXO that still pose a risk of explosion, even many decades after they were used or discarded. Particularly refineries (see Figure 18), tank farms and also oil production facilities have been targets of air strikes.

On refineries, acid tar lagoons are consequently impacted as well. UXO may be present in the acid tar layers, at the bottom (base) of the lagoons, directly below the base or in the top layer of the soil that frequently covers the lagoons, depending on the age (pre- or post-war) of a lagoon. Dumped ammunition are most likely located on the edges of the lagoons and possibly near former anti-aircraft locations, bunkers, trenches and foxholes[16].

The possibility of UXO being encountered at a site during intrusive investigation, excavation or construction works falls within the category of a potentially significant risk and is therefore a matter that should be addressed as early as possible in the life cycle of a remediation project.

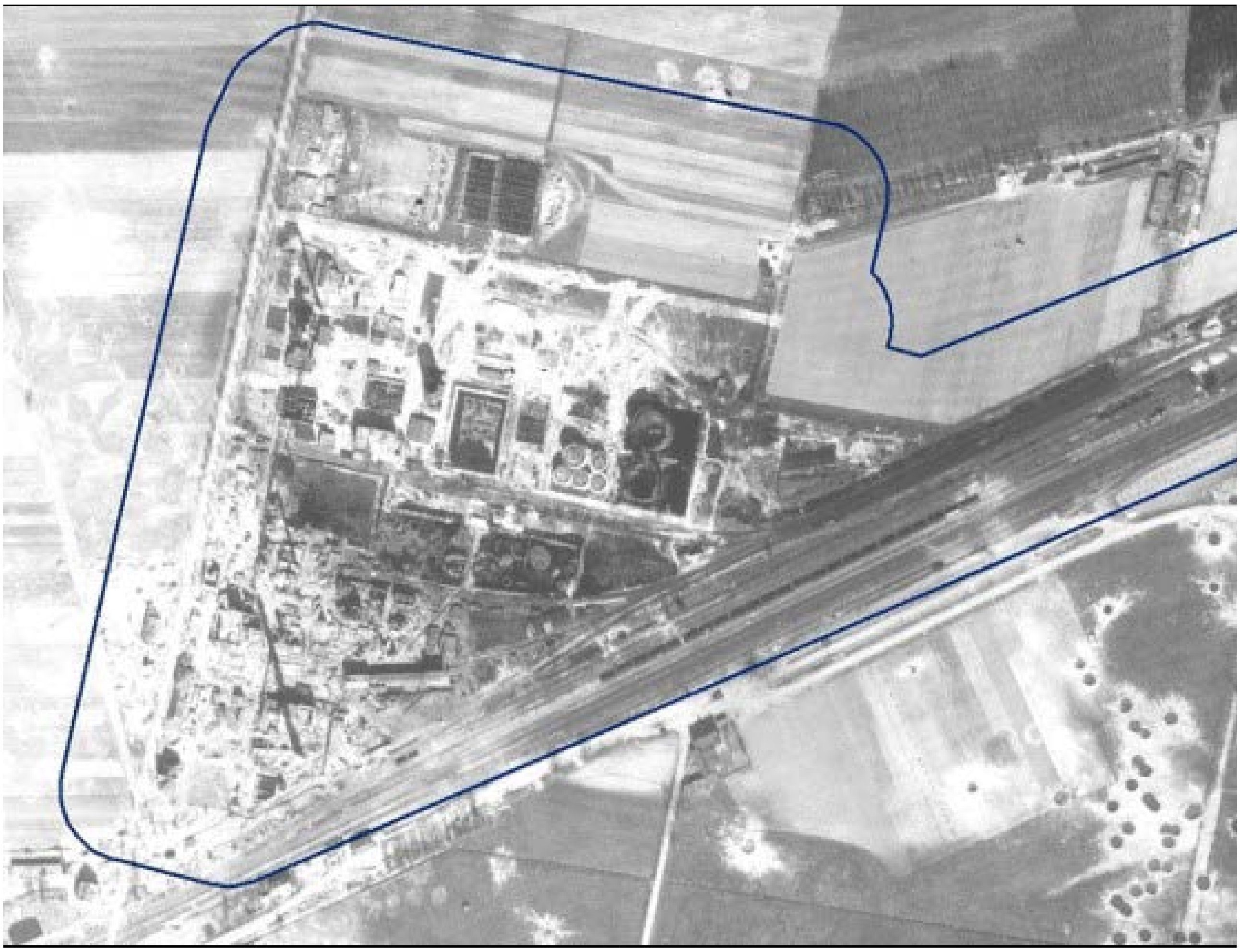
Various guidelines and recommendations for a systematic UXO risk management exist in many countries at national and regional (county) levels. There is a general consensus that a systematic, 3-step approach should be applied for addressing the UXO risk appropriately. A summary description of the approach is provided below and is also displayed in the flow diagram in Figure 19:

- Phase 1 (historical research and preliminary risk assessment): desktop study regarding a potential UXO impact and a preliminary risk assessment based on existing data;
- Phase 2 (investigation and detailed risk assessment): technical investigation by specialized companies and detailed risk assessment;
- Phase 3 (risk mitigation): concept for site clearance activities; tendering and contracting of UXO recovery and site clearance; execution of clearance measures; in case of detection of still armed UXO, defusing and disposal by an authorized explosive ordnance disposal (EOD) service.

16 A foxhole describes a pit where soldiers take cover during combat operations.

Figure 18:

Heavily destroyed refinery in Germany after air attack in 1945



The area southeast of the refinery site has been impacted probably due to aiming errors. This demonstrates that UXO must be expected also in the surrounding of respective sites

Source: Luftbilddatenbank Dr. Carls GmbH

Phase 1 (historical research and preliminary risk assessment). The first step of the UXO investigation process comprises an overview desktop study on the site history and indications of a potential UXO impact in the early planning stage of a project, based upon information that is basically available to consultants, planners and UXO specialists as free accessible information or on request. A preliminary risk assessment provided by specialized companies typically consults the following sources to obtain historical information regarding UXO contamination:

- Local and national archives such as the explosive ordnance disposal (EOD) archives,
- Aerial photographs from government archives and private companies,
- Governmental departments which deal with UXO and emergency planning such as Ministry of Defense establishments, e.g. official abandoned bomb registers.

Phase 2 (investigation and detailed risk assessment). The assessment enables an estimate to be made of the likelihood of creating an UXO hazard at a site, giving due consideration to the development and construction methods to be employed. The detailed risk assessment follows recommendations such as given by the Construction Industry Research and Information Association, CIRIA: Unexploded ordnance (UXO) risk management guide for land-based projects (C785) (K. Stone, A. Murray, S. Cooke, J. Foran, L. Gooderham, 2009) and involves the following information:

- Initial site screenings,
- Detailed risk assessments including a risk analysis and risk quantification,
- Major development of a detailed UXO risk zoning plan,
- Historical data collation and analysis based on geographical information system (GIS).

Phase 3 (risk mitigation). In case that a risk of encountering UXO during intrusive works has been identified during the previous phases, the following aspects, as a minimum, should be considered prior to field works, and assistance should be sought from expert contractors:

- Risk mitigation strategy design,
- Operating guidelines,
- Survey design,
- Equipment certification,
- Technical specification,
- Quality assurance and quality control (QA/QC) plan,
- Development of an emergency response plan as part of the site health & safety plan (HASP).

Risk mitigation strategies shall be developed and implemented on a site-by-site basis. UXO mitigation measures include geophysical detection methods and site personnel trained in UXO detection. Geophysical methods include, e.g. the use of magnetometers and ground penetrating radar.

Magnetometers may be used:

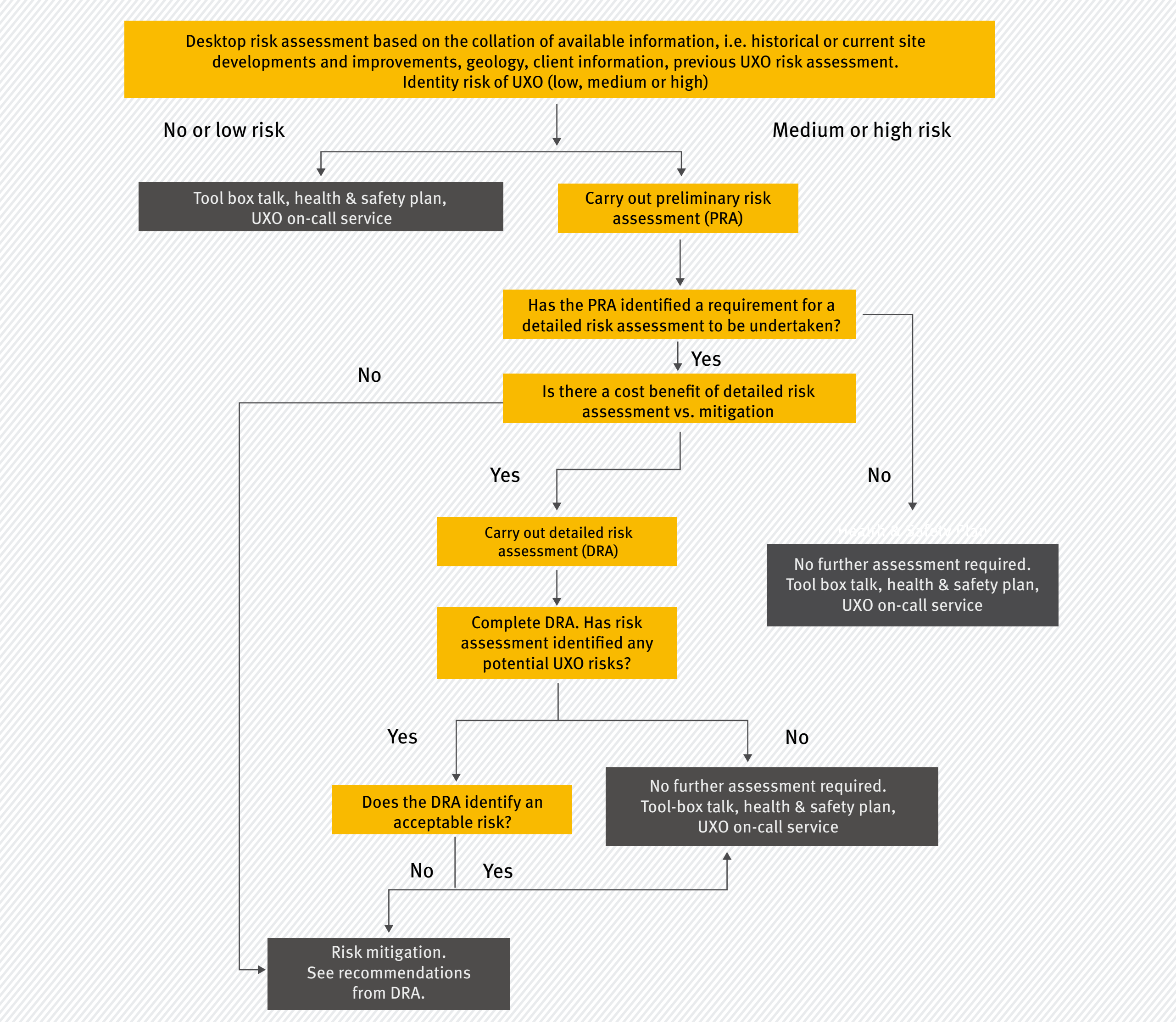
- Surface deployed,
- Downhole deployed ("Foerster-Probe"),
- In-situ deployed.

Also, the use of site personnel trained in UXO identification and detection to supervise excavation works may be applied on a case-by-case decision or, if required, by the responsible authority.

Finally, UXO recovery, defusing and subsequent disposal is mainly carried out by EOD experts of national or regional governmental institutions, the police or military forces. In some countries, certified private companies may also be authorized for UXO recovery and defusing.

Figure 19:

UXO risk assessment and clearance flow diagram



Source: (Arcadis Germany GmbH, 2010)

Unexploded ordnance

Particularly refineries, tank farms and also oil production facilities have been targets of air strikes during World War II. Hence, unexploded ordnance (UXO) that still pose a risk of explosion must be expected on these sites, even many decades after they were used or discarded. The UXO risk is usually addressed in a 3-phased approach. Phase 1 (historical research and preliminary risk assessment) is a desktop study, Phase 2 (investigation and detailed risk assessment) includes technical investigation, and Phase 3 comprises a concept for site clearance activities in case of detection of UXO. While the detection of UXO on site is usually performed by specialized private companies, the UXO recovery, defusing and subsequent disposal is mostly carried out by respective experts of the responsible authorities such as the police, the department of defense or an authorized explosive ordnance disposal (EOD) service.

3 Contaminant fate and transport

The basic processes, which are to be considered in the evaluation of the contaminant fate and transport as basis for investigation and remediation measures, are described in the following paragraphs. The four phases soil, water, soil vapor and non-aqueous phase liquids (NAPL) are closely interrelated in a very small space, and contaminant concentrations in each of them are, indeed, never in a static equilibrium in the contaminated area. Nevertheless, in many cases contaminant distributions are observed, which are perceived as constant depending on the investigation and monitoring accuracy.

Most of the contaminations at oil & gas sites occur as TPH spills in form of light non-aqueous phase liquids (LNAPL). The TPH seeping into the underground is impregnating the unsaturated soil (vadose zone) and reaches the groundwater level fluctuation zone (also called "smear zone", because fluctuating groundwater levels can cause the "smearing" of the contaminant, especially in the case of LNAPL, in the depth interval of the groundwater fluctuation). From the vadose zone, the volatile TPH faction may evaporate and cause a contamination of the soil vapor. In the smear zone, TPH are dissolved in groundwater and transported via natural groundwater flow. Only a few TPH are dense non-aqueous phase liquids (DNAPL) (e.g. creosote) and can therefore sink to the aquifer bottom where they accumulate. From these accumulation zones, the TPH dissolve into the groundwater.

Groundwater. If contaminants are released into the environment, they can penetrate though the vadose zone either dissolved in water or as NAPL. If the pollutants quantity is sufficiently high, they can reach the groundwater surface. Depending on the subsoil structure, product phase may enrich on top of low-permeable interbedded layers. NAPL in the aquifer are mobile as long as their concentration exceeds the residual saturation (maximum mass of product phase that can be immobilized in the soil matrix). The residual NAPL cannot be mobilized unless boundary conditions, in particular the water content, change. Since the maximum residual saturation of the saturated and the vadose zone is different, a drop in the groundwater level can lead to a new release of mobile phase in the smear zone. Reversely, a rising groundwater level can lead to the submersion of LNAPL, so that at points where an LNAPL layer floating on the groundwater was measurable at low groundwater level, no LNAPL are measurable anymore. The LNAPL are "trapped" in the saturated zone as residual, immobile NAPL. This shows that the hydrological and hydrogeological conditions and the assessment of the contaminant transport processes, in particular with regard to the variability or stagnation of the contaminant plume, are essential.

In groundwater, the contaminants are transported with the natural groundwater flow. Since they tend to adsorb onto the soil matrix (retardation) due to their substance-specific properties, they are transported slower than with the natural groundwater flow rate. The diffusion of the contaminants into hydraulically low-permeable areas also reduces the speed of the contaminant propagation along the groundwater flow direction. Parallel to the fluctuation of groundwater levels, a temporarily change of the groundwater flow direction has to be taken into account.

For a natural microbial biodegradation (mineralization, i.e. degradation to the final products CO_2, CH_4 and water), the microorganisms occurring in the aquifer require in addition to some nutrient salts, mainly electron acceptors. This can be oxygen in the simplest case. Nitrate, manganese (IV), iron (III), sulfate and CO_2 are also used as electron acceptors under oxygen deficiencies. If sufficient electron acceptors are available and at appropriate site conditions, a natural microbial degradation of the contaminants in the groundwater can take place. The microbial and the abiotic degradation can considerably reduce the contaminant mass transport in the groundwater flow direction.

If the biodegradation is occurring to a sufficient extent, the plume can reach a quasi-stationary state. This means that there is an equilibrium between the contaminant mass flux still released from the source and the rate of microbial degradation within the plume. Then the length of the contaminant plume does not change as a result, the net sorption is zero and the diffusion is virtually negligible. When observing a single sampling point, the concentration remains constant over time.

In general, the distribution of the contaminants within the source and the plume is inhomogeneous, especially when NAPL is present. The heterogeneity of the source (also referred to as the source architecture or internal structure) is reflected in the plume. This also means that there is a heterogeneous distribution within the plume with regard to the contaminant concentrations.

The plume development after a contaminant release (e.g. a spill) can be divided into three phases: expansion, stationary, shrinking. The duration of the expansion phase immediately after the spill as well as of the reversed phase of shrinking after a source removal is generally short compared to the duration of the stationary phase. Most of the lifetime of a contaminated site, the plume will therefore be in a nearly un-changing state. Natural fluctuations in the groundwater formation (mainly due to precipitation) may lead to measurable but usually only moderate temporary changes in the contamination extent, to the “smearing” of the contaminant (especially in the case of LNAPL) in the smear zone. The groundwater level fluctuations control the contaminant mobilization from this zone (solubilization). This can also lead to a change in the concentrations of the electron acceptors and thus the degradation processes. The same effect can be caused by changes in the groundwater flow direction. Over time, these effects mostly based on seasonal changes become less evident, opposite effects overlap and so compensate one another. The stationary state persists until the source has completely been removed or exhausted by dissolution of the contaminants in the groundwater or under given conditions also in the soil vapor. In case of contaminations with heavy metals or metalloids, the chemical reaction with the matrix of rocks that possibly results in the formation of new minerals also leads to an exhaustion of the source.

If there are no more contaminants discharged into the plume, the contaminant concentrations begin to drop within the plume, which results in a concentration gradient between the contaminants dissolved in the groundwater and the ones sorbed to the soil or present in the low-permeability zones. The subsequent desorption of the contaminants from the soil matrix as well as the back diffusion from low-permeability zones lead to the fact that also the fate of the plume is time-delayed. Even if the contaminant supply to the plume is completely eliminated, for example by containment of the source, the plume extent decreases relatively slowly compared to the natural groundwater flow.

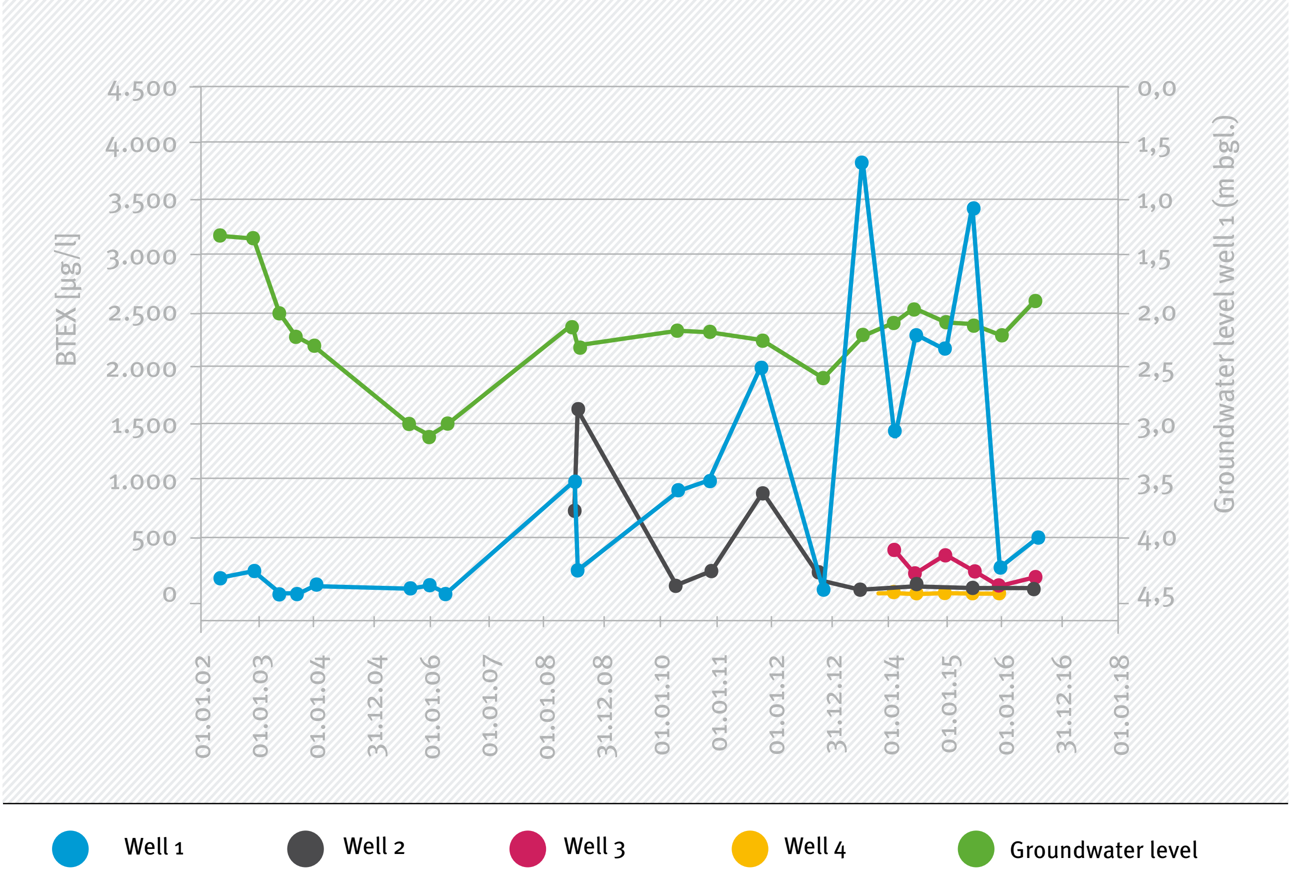
After the termination of many remediation projects, a rebound (re-increase of contaminant concentrations) occurs. This means that there is an adjustment of the concentration equilibrium between dissolved contaminants (in groundwater or soil vapor) and the contaminants sorbed on the soil matrix, occurring in residual phases or in low-permeable areas. Figure 20 shows an example of the rebound in “well 1” in a bioremediation case.

After the end of the active remediation, some effects (consumption of residual biodegradation-fostering reagents) are still recognizable. However, as soon as the substrates provided in the remediation phase have been completely depleted and the microbial degradation stops, the contaminants begin to accumulate in the groundwater. If the monitoring is sufficiently long, the rebound reaches a concentration plateau. At this point, the biogeochemical conditions in the aquifer, which have been altered by the remediation, have completely recovered. This effect should be demonstrated in the post-remediation monitoring.

Surface water. Surface waters are affected by an input from groundwater if both are in contact, from the vadose zone of the aquifer by lateral drainage, by erosion or by direct discharges. The contaminants are also mobile as NAPL as long as the residual saturation of the transport medium is exceeded. Dissolved contaminants and NAPL can accumulate in the sediment or the suspended particles. The distribution of the aqueous phase and the suspended matter are influenced by the waterbed structures and rarely mixes completely over the entire cross section. Sediments tend to accumulate temporarily or permanently where the flow velocity is reduced, e.g. before obstacles. There, back-dissolution of contaminants previously bound to the sediment into the water may occur. Due to fluctuations in the water level or mass flow due to meteorological conditions,

Figure 20:

Rebound after remediation finalization



Source: Arcadis, own figure

the main interaction between the groundwater and the surface water occurs in the shore zones. The contaminant mass discharge from the groundwater into the surface water can change significantly depending on the water level conditions (high and low water levels).

NAPL, soil, soil vapor and groundwater. The soil in the vadose zone is characterized by a contaminant concentration equilibrium between NAPL, soil, soil vapor and groundwater. The distribution of a contaminant between the three phases NAPL, solid and liquid depends essentially on the nature of the contaminant, the amount and type of organic soil content as well as on the porosity including petrographic aspects of rocks and the matrix, the water content and the temperature of the soil.

Whereas the Henry's law constant expresses the tendency of contaminants to volatize from the aqueous phase into the gas phase, for contaminants dissolved in groundwater, the situation is different for NAPL (also occurring as residual phase). For NAPL, the vapor pressure is the parameter that describes the tendency to volatilize into the gas phase. This process plays predominantly a role in the smear zone and in the vadose zone. The larger these values, the more likely the contaminants are to move from the liquid phase to the gas phase.

The contaminant transfer within the vadose zone is mainly caused by diffusion and convection. Diffusion processes are based on molecular motions due to differences in concentration of pollutants. Convection processes are based on mass transfer due to pressure differences or differences in density or temperature. The migration of the volatile gaseous contaminants takes place in the vadose zone essentially by diffusion along concentration gradients.

Significant convection processes take place in case of active gas formation, such as BTEX or benzene gases. In addition, changes in atmospheric pressure play an important role. An atmospheric pressure decrease intensifies the transfer of contaminants into the atmosphere or into indoor spaces, as long as a migration pathway is present (e.g. gas permeable building floor). Conversely, a rising atmospheric pressure leads to the vertical penetration of atmospheric air into the vadose zone, which can also cause horizontal air flow if the soil surface is sealed in some areas. This transport, referred to as a barometric pump, is, in addition to diffusion, essential for penetration into indoor spaces. Overall, this convective contaminant distribution only occurs to a small extent, so that the contaminants in the soil vapor are essentially restricted to the entry area.

It cannot be excluded, however, that contaminants volatilize also from the plume. Because of the lower concentrations in the plume, the impact on the soil vapor is correspondingly lower.

If volatile contaminants from contaminated sites are emitted into the atmosphere, they spread out quickly and widely. A very rapid and extensive dilution of the volatile contaminants takes place in the atmosphere.

Contaminant fate and transport

In most cases, contaminants enter the subsurface as free product phase (non-aqueous phase liquid, NAPL). NAPL are subject to complex dissolution, transport, retardation and biodegradation processes varying in the different media like groundwater, surface water, soil and soil vapor. In general, the contaminants as well as their fate and transport processes are distributed heterogeneously. The knowledge and understanding of these processes is a prerequisite for an adequate site investigation and remediation.

4 Phase I environmental site investigation (historical investigation)

4.1 Objective of the Phase I environmental site investigation

A Phase I environmental site investigation (also referred to as historical or preliminary investigation) is a desktop study that comprises a review of already available data and information of the site.

The Phase I environmental site investigation is usually the first step of a site investigation process. In addition to the evaluation and assessment of available data, an inspection of the site (site visit) is undertaken, including a photographic documentation.

The advantages of carrying out a Phase I environmental site investigation before performing physical investigations, such as sampling and intrusive works, comprise:

- Efficient targeting of project resources,
- Preparation of the preliminary geological model,
- Budget savings by avoidance of inappropriate intrusive ground investigations,
- Early warning regarding delays or budget implications through previously unknown site characteristics,
- Information on possible contaminants and anticipated areas of contamination.

The investigation of the history of a contaminated site serves for the identification of places where hazardous substances are handled or had been handled in the past. Especially with the background that installations of the oil & gas industry had been severely destroyed during World War II and that the reconstruction had been done in a different way makes it necessary to investigate also historical site maps. Moreover, these kinds of reconstructions may have taken place during the entire lifetime of the site. In many cases incidental spills are documented when they have occurred. Hence, the task of the Phase I environmental site investigation is to identify potential areas of spills and the potential spreading thereof. To achieve this goal, all available information is used as a data basis. The purpose of the systematic evaluation of documents and archives in the context of a Phase I environmental site investigation is to collect all available information relating to the suspected contamination case. The data collected should have a quality sufficient to provide the basis for the more technical Phase II environmental site investigation (see Chapter 5), if necessary. The scope and expenses of such an evaluation of documents and archives should be appropriate to the dimensions and significance of the suspected contaminated site (principle of proportionality).

All data that are collected during a Phase I environmental site investigation are usually compiled and displayed in a so-called conceptual site model (see Chapter 6). The conceptual site model is continuously updated and adjusted during the course of the subsequent project steps.

4.2 Sources of information

Information of the site operation (including lists of used chemicals) may be derived from a variety of sources. The most important ones are described by the International Centre for Soil and Contaminated Sites ICSS (ICSS - International Centre for Soil and Contaminated Sites, 2007, pp. 10-17). Since the oil & gas industry is regarded as an industry with a high potential of environmental contaminations (expected high level of hazard potential of the substances and of the toxicity), the following list focusses on oil & gas site specifically.

Maps. Official topographic maps should be taken into consideration in the first place as they provide important information on the geographical site conditions and the surroundings of a site. City maps of different ages are useful for the investigation of the building stock during different periods of time. These maps also display aspects of present and former site use such as industrial and urban areas as well as infrastructure facilities, and they provide various further information such as names of companies and the types of industrial facilities. Indications regarding potentially contaminated sites, such as dump sites, former gravel pits (which may have been used for the disposal of industrial waste) as well as oil sludge pits, could be identified as well. City maps are updated on a regular basis, almost continuously since the beginning of industrialization, which makes them a valuable source of information. Online maps, such as Google Maps and Google Earth, have become increasingly important sources of information during the last two decades.

Other important thematic maps for investigation are:

- Maps of protected areas (e.g. water protection areas, nature protection areas),
- Maps showing already know contaminations (environmental maps),
- Geological maps,
- Hydrographical maps,
- Maps of detailed scales showing oil & gas fields as well as mining activities,
- Thematic maps or plans containing industrial information.

Maps, however, do not always offer exhaustive information. In general, smaller objects are not included and enterprises are often indicated only with their names and outer boundaries of their sites.

More detailed information may be obtained from company and site-specific documents and archives. The following important documents and archives could serve as sources of information:

Manufacturing files. Such documents and files are to be found in enterprises, municipal offices, etc. They contain the names of the company, the name of the industrial branch, the location of the site, the period of operation as well as permits, description of technologies and equipment (handling of substances and many other data).

Construction files. The files of the construction authorities contain information relating to obligatory building permit activities (applications, permits). Construction files are usually sorted by address or plot. They contain plans of building sites, descriptions of the production line and the equipment from which conclusions could be drawn as to the industrial processes, the production methods and disposal practices. Construction changes in parts of buildings and changes in their use often give indications about suspected contaminated areas (for example transfer stations). However, it should be considered that the construction documentation contains also plans which have not been implemented.

Company files. These files usually provide useful information but are mostly difficult to access due to confidentiality aspects and legal implications unless the respective companies have granted permission to examine the files.

Documents of environmental authorities. The environmental authorities keep files, e.g. regarding landfills, areas where soil has been backfilled into pits, etc. They also keep files on accidents involving substances that are hazardous to water (type of substances, volumes, extent of impacted area, etc.). Information on relevant receptors (water protection areas, drinking water wells, etc.) can, in general, be obtained from the competent authorities (i.e. Ministry of Environment, Environmental Protection Agency).

Aerial photographs. The examination of aerial photographs, if available, is compulsory. Through the evaluation of a timely series of photographs, it is possible to collect information about:

- Extent of the suspected contaminated sites,
- Duration of the period of operation or disposal,
- Gaps in the history of operation,
- Inaccessible areas,
- Damages caused by earthquakes,
- Impact of war (e.g. destructions caused by air strikes).

In general, these photos do not provide precise location data. The use of aerial photographs focuses on two aspects: the historical investigation (Phase I environmental site investigation) and the determination of the present situation. It can help to fill temporal information gaps (destroyed or confidential documents) for the period during and shortly after World War II but also for later periods. Thereby, the following data can be obtained:

- Information about the morphology at a certain point in time (important to locate backfills),
- Effects of war and/or earthquakes (buildings damaged or destroyed),
- Accidents,
- Reconstruction activities.

Although the use of aerial photographs can provide important information on a site, it should be considered that the purchase and particularly the evaluation of aerial photographs implies considerable efforts. Also, they may display potentially sensible information of a site and adjacent areas. Therefore, the site owner (if this is not the liable party) should be asked for approval before aerial photographs are used within the course of a historical research, for avoiding unnecessary costs and potential legal implications.

Telephone, address and branch directories. Using telephone and address books as well as branch directories (recent and historical ones) as an information source in the Phase I environmental site investigation is expensive and should be made only if the manufacturing and construction files lack information relating to the addresses and periods of operation. As with the manufacturing files, however, the main source of error is that the owner's place of residence is indicated and not the company headquarters. In addition, addresses are often not given in full, which makes the localization of the site difficult.

Local chronicles. Local chronicles are a reliable background information on the industrial and infrastructural development of a region. In addition, they describe the old-established enterprises of importance to the region.

Municipal and local archives. After a certain period of time, the files of the municipal or community administrations are stored in the archives of the respective cities or communities. Whenever data are collected, it should first be verified whether files have already been moved to archives.

The state land register. The state land register contains information about the former and present owners. It is the binding source from which the owner of a potentially contaminated site can be identified.

Energy supply. The energy suppliers have valuable information relating to renaming of streets, changing of house numbers and addresses, etc.

Personal interviews. Direct witnesses are often a valuable source of information about the former function of existing buildings or the material disposed in abandoned landfills. In the cases of abandoned landfills for which economic operator files do not exist, detailed information can be obtained from neighbors or from former employees of municipal offices (local speakers, mayors). As far as former industrial sites are concerned, former workers of the enterprise could be found. Very often they live in the same place, even in the close vicinity of the company. In most cases of enterprises which are still active, the former workers are known by name and address. Tracking of former owners of properties with a frequent change of ownership is more difficult. This can considerably hinder the interviewing of witnesses.

In addition to knowing the location, witnesses have comprehensive knowledge of the regular running of the production process, handling of materials, location of spills, accidents at the site, etc. This knowledge should be inquired through interviews and site inspections. The interviewer should have good knowledge of the production process and potential contamination to be able to raise questions purposefully. It is reasonable to look for appropriate people to conduct an interview also at municipal offices. Before conducting time-consuming interviews of contemporaries, a general concept should be drafted including:

- Listing of the information required,
- Defining of the group of people to be interviewed according to data gaps and availability,
- Defining of the interview technique,
- Preparation of questionnaires,
- Documentation of all information obtained (minutes of the interview including additional information collected and not included in the questionnaire; possibly tape recording).

Register of contaminated sites. In case such registers are available at local or national level, they may provide valuable information on the site, the used production processes and the contamination potentially arising thereof.

Site inspections. Site inspections are a compulsory part of the Phase I environmental site investigation. In general, they take place together with people who are familiar with the site such as managers, owners, etc. For that reason, they are closely connected with witnesses. The main elements of a site inspection are:

- Overall assessment of the state of the area,
- Investigation of the possibilities for sampling (e.g. wells, presence of buildings' foundations or underground floors),
- Photo documentation, which should document the present situation at the suspected site in addition to the notes and sketches of the interviewers. The places from which the photographs were taken should be indicated on a location sketch.

The following checklist gives an overview of the data that could possibly be obtained during a site inspection:

- Size and boundaries of a site,
- Correspondence with available plans (comparison of the present site conditions such as locations of buildings in comparison to already existing plans),
- External areas, internal premises (condition, odor, visible waste or harmful substances, etc.),
- Special features of construction, discoloration of buildings,
- Anomalies of the territory, unusual topography,
- Local geology,
- Leakage of seepage water and landfill gas (gas emissions are possible also in the further surroundings),
- Drainage conditions (erosion pathways, discharge into water bodies, etc.),
- Vegetation, damage of vegetation,
- Characteristics of the soil (morphology, odor, consistence, type of soil organic content, etc.),
- Condition of water bodies,
- Use of the site and the surrounding area,
- Protection against unauthorized access,
- Location and condition of damaged building structures or installations.

4.3 Data interpretation and documentation: Report

The aim of a Phase I environmental site investigation is to make an initial assessment of potential hazards originating from a site. A report documents the assessment which is carried out with respect to contaminants in soil and the relevant pathways to groundwater, surface water and atmospheric air. The documented information should set a reliable basis for decision-making for the subsequent Phase II environmental site investigation (see Chapter 5). Illustrative material like tables, graphics, diagrams, photographs and maps contribute to make the document leaner and easier to use as a reference. An exemplary content breakdown for a Phase I environmental site investigation report is shown in Annex 1.

Phase I environmental site investigation (historical investigation)

The investigation of the history of a potentially contaminated or contaminated site aims for the identification of locations where hazardous substances are handled or have been handled in the past before frequently occurring site reconstructions (also after possible destruction during World War II). Thus, the Phase I environmental site investigation will identify potential areas of spills and the potential spreading thereof. To achieve this goal, all available information shall be used as a data basis. Documents and archives will be evaluated to collect all available information related to a suspected contamination. In addition, in many cases historical incidental spills are documented.

All data that are collected during a Phase I environmental site investigation are usually compiled and displayed in a so-called conceptual site model (see Chapter 6). The conceptual site model is continuously updated and adjusted during the course of the subsequent project steps.

5 Phase II environmental site investigation (technical investigation)

5.1 Objective and work scope

At oil & gas sites, environmental contamination can originate from incidents or spills during transport, transfer, storage, processing and use of mineral oil. The mineral oil products can reach the groundwater, for instance, if piping or tanks are not tight (corrosion, material degradation, wrong installation, incidents, etc.), if a tank overflows or if some product drops on the ground surface during the handling of petroleum products (KORA - Themenverbund 1, 2008, S. 8). Typical source areas for each of the three types of sites that are considered in this manual are described in Chapter 2.2.

If the Phase I environmental site investigation (see Chapter 4) came to a reasoned suspicion that the site of concern is contaminated, an intrusive investigation is needed, which includes obtaining samples for chemical analyses and carrying out investigations of the subsurface (hydro-)geology and (hydro-) geochemistry. In general, a phased (step-by-step) approach is selected to minimize the expenditure for the investigation:

- Limited soil and groundwater investigation,
- Detailed soil and groundwater investigation,
- Environmental risk assessment.

The objective of the investigation is to collect the information necessary to assess the risk for the relevant migration pathways and receptors identified through the Phase I environmental site investigation. The key questions to be clarified through the investigation are:

- What are the quantities of contamination?
- Have harmful substances already spread in the direction of the receptors – and if yes, how far?
- Have the harmful substances already reached or damaged the receptors?

The result of the investigation must be documented in a report (see Chapter 5.5).

During the **limited soil and groundwater investigation** from the presumably most contaminated locations identified during the Phase I environmental site investigation, a limited number of subsurface soil samples will be taken and analyzed for the contaminants used or potentially spilled at that location. During the limited site investigation, it is not sufficient to investigate only the soil. Moreover, it must be checked which other source-pathway-receptor aspects are relevant. For each of them investigations need to be performed to determine the relevant pathways and resources to be protected as well as to exclude irrelevant pathways and targets. If indications for potential groundwater contamination are identified or if an impact on the groundwater cannot be excluded, groundwater samples shall be taken and analyzed for the relevant parameters.

Potential contamination sources for which no proof of hazard has been found should be excluded from further consideration.

If the limited soil and groundwater investigation has come to an indication that the contaminant concentrations are so high that the site is to be regarded as potentially contaminated, a **detailed soil and groundwater investigation** is necessary. During this investigation, a variety of parameters needs to be determined:

- Entire extension of the contamination in the vadose and saturated zone, distribution of contaminant concentrations and contaminant inventory,
- Contaminant transport, including fate (e.g. biodegradation) and mass flux,
- All relevant source-receptor pathways,
- Geology and hydrogeology including water level, groundwater flow direction and velocity and seasonal fluctuations,
- (Hydro-)geochemical conditions.

In summary, the objective of the Phase II environmental site investigation is to characterize the ground conditions sufficiently to allow the development of safe and economic remediation methods and to reduce, as far as possible, the impact of unforeseen conditions and the occurrence of unforeseen events. All investigation steps as described above are referred to as Phase II environmental site investigation.

Furthermore, the risk associated to the relevant pathways and resources to be protected is preliminarily assessed in this phase according to the procedure described in Chapter 7. In the end, based on the results of the detailed site investigation and the environmental risk assessment it can be derived whether corrective actions are needed.

One decisive criterion is the question whether the extension of the contamination is stationary or not. In the first case, the contaminant release from the source is compensated by the natural biodegradation forming a so-called quasi-stable contaminant extension. The results of the environmental risk assessment can be used directly for the decision, whether a remediation is needed.

In case the contaminant extension is unstable or seems to be unstable, a forecast should be used for the final assessment of the contamination. The prognosis may be done applying a reactive fate and transport model. Since this is labor-intensive, in many cases the modelling is replaced by a monitoring over a specific period of time to check if the contaminant concentrations change at specific points. Depending on the mobility of the contaminants, this monitoring period may take years.

A conceptual site model (see Chapter 6) shall be developed by the end of a Phase II environmental site investigation at latest. If a conceptual site model has already been prepared after the Phase I environmental site investigation (see Chapter 4), it is necessary to update the existing model and to incorporate all new data and information.

5.2 Investigation plan

A Phase II environmental site investigation is a core element of a structured investigation process for contaminated and potentially contaminated sites. It aims at the detailed technical investigation of the soil, soil vapor, groundwater and surface water conditions based upon the results of the Phase I environmental site investigation and at localizing and characterizing sources of contamination. Appropriate investigation methods of a Phase II environmental site investigation are selected depending on site-specific conditions, such as access to the site, logistical aspects, current site use and ongoing operations on site, geological and hydrological conditions, location of potential contaminant sources and the relevant receptors such as human health, (ground)water and nature protection areas, etc.

Hence, prior to the start of the investigation an investigation plan is prepared in which the details of the planned investigation are fixed. An investigation plan contains at least the following aspects:

- Goal of the investigation including relevant source-receptor pathways,
- Drilling locations including site map, drilling technology, diameter, depth, sampling intervals for soil vapor and soil, etc.,
- Necessity for installation of groundwater monitoring wells including construction details (depth, diameter, location of the filter screen, etc.),
- Sampling of groundwater,
- Pretreatment of soil and groundwater samples, analyses to be performed,
- Discharge of contaminated groundwater or soil derived from the investigation,
- Health & safety regulations (see Chapter 13) required for active and inactive sites.

In general, the investigation plan is submitted to and approved by the competent authorities prior to the commencement of the investigation. The investigation plan may also be used for the preparation of tender documents and for the request for proposal (RfP), see Chapter 9.5.

Phase II environmental site investigation (technical investigation)

The aim of the Phase II environmental site investigation is the identification of all contaminants and their locations on site. The entire extension of the contamination in the vadose and saturated zone, distribution of contaminant concentrations and contaminant inventory need to be determined in high resolution. Furthermore, all contaminant migration pathways, including fate (e.g. biodegradation) and mass flux, as well as all relevant source-receptor pathways need to be identified. This includes detailed investigation of the (hydro-)geology and (hydro-)geochemistry. The data derived should be sufficient to perform an environmental risk assessment. The planned investigations are described in a detailed investigation plan.

A conceptual site model shall be developed by the end of a Phase II environmental site investigation at latest. In case of an existing conceptual site model from the Phase I environmental site investigation, it must be updated with all new data and information.

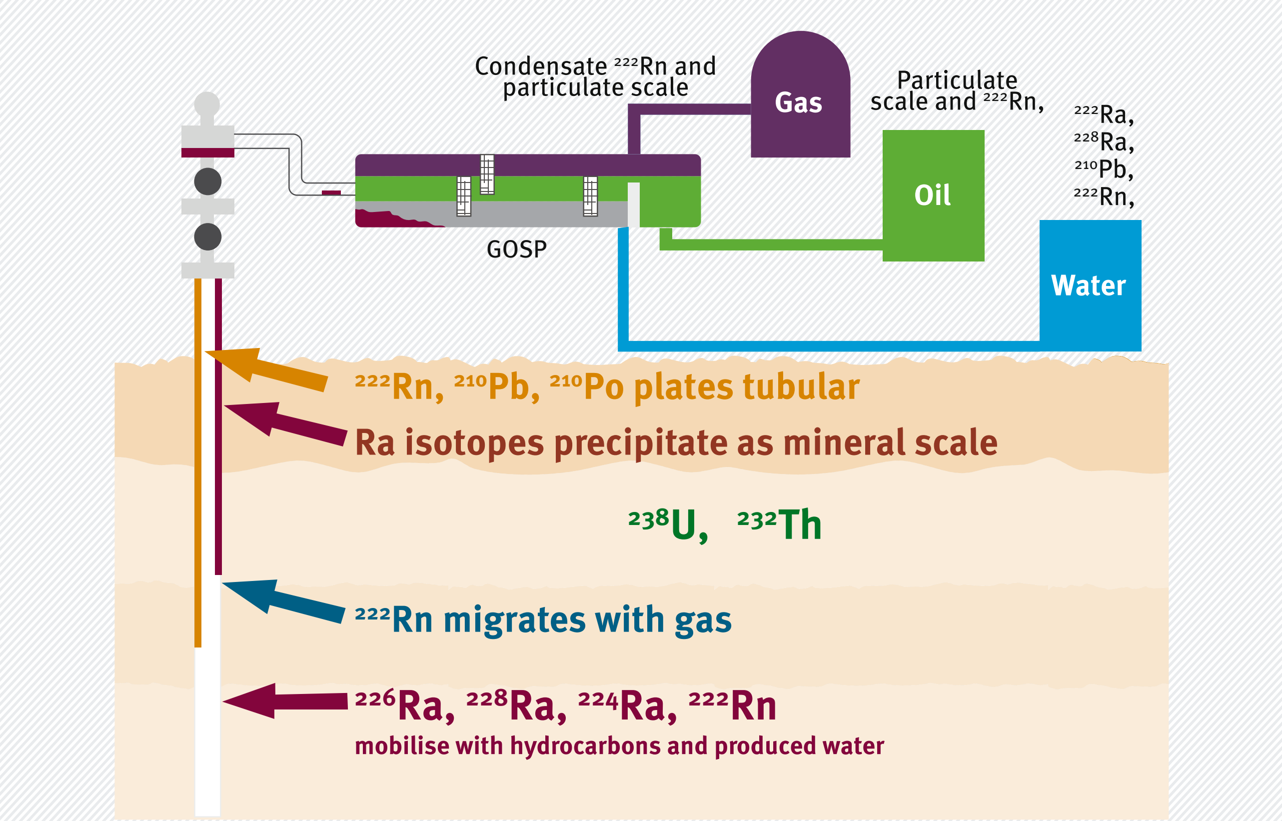
5.3 Investigation of sites contaminated with naturally occurring radioactive material (NORM)

Most information in this chapter has been taken from "Guidelines for the management of Naturally Occuring Radioactive Material (NORM) in the oil & gas industry (Report 412)” (OGP - International Association of Oil and Gas Producers, September 2008) and its revised edition "Managing Naturally Occurring Radioactive Material (NORM) in the oil and gas industry" (IOGP - International Association of Oil & Gas Producers, 2016).

The origins of naturally occurring radioactive material (NORM). Radioactive material such as uranium and thorium were incorporated in the Earth’s crust when it was formed. They normally exist at trace (parts per million, ppm) concentrations in rock formations. Decay of these unstable radioactive elements produces other radionuclides that, under certain conditions depending on pressure, temperature, acidity, etc., in the subsurface environment are mobile and can be transported from the reservoir to the surface with the oil & gas products being recovered (Figure 21).

Figure 21:

Origins of NORM and NORM accumulation during the recovery process



Source: (OGP - International Association of Oil and Gas Producers, September 2008)

During the production process, NORM flows with the oil, gas and water mixture and accumulates in scale, sludge and scrapings. It can also form a thin film on the interior surfaces of gas processing equipment and vessels. The level of NORM accumulation can vary substantially from one facility to another depending on geological formation, operational and other factors. To determine whether or not a facility has NORM contamination, NORM survey, sampling and analysis need to be conducted. Figure 21 indicates where NORM may accumulate, e.g. at wellheads in the form of scale, at gas-oil separation plants (GOSP) in the form of sludge and at gas plants in the form of thin films as the result of radon gas decay.

The NORM nuclides of primary concern in oil production are ^{226}Ra and ^{228}Ra. These decay into various radioactive progeny before becoming stable lead. ^{226}Ra belongs to the ^{238}U decay series and ^{228}Ra to the ^{232}Th decay series.

Further details regarding the radionuclides of concern, their radioactive half-lives, decay mechanism, which are the source e.g. of health-effecting gamma radiation, and the way they are mobilized are described in detail in the OGP report as mentioned above.

NORM may occur at facilities of the oil & gas industry as follows:

- As sulfate, carbonate or sometimes silicate scales in pipes, valves, fittings and other technical installations,
- In sludges and scrapings, produced sands and produced waters,
- In gas-processing facilities,
- In seawater injection systems.

Health hazards of NORM. There are two ways in which personnel can be exposed to NORM, namely:

- Irradiation – external exposure where the source remains outside the body, and
- Contamination – internal exposure when radioactive material is taken into the body via inhalation, ingestion or absorption via dermal contact.

The health effects associated with exposure to ionizing radiation vary depending on the total amount of energy absorbed, the time period, the dose rate and the particular organ exposed. A key consideration related to NORM is that exposures are generally quite low and below regulatory radiation dose limits. In some situations, exposure to low-level ionizing radiation may not result in any adverse health effects.

Exposure to NORM will not result in acute and severe effects in contrast to those effects associated with exposure to high radiation levels from man-made sources. Chronic exposure of the general public to NORM above dose limits, caused e.g. by inadequate safety precaution measures, may lead to typically delayed effects such as the development of certain forms of cancer. A variety of cancers has been associated with exposure to ionizing radiation. It is important to understand that the potential health effects are strongly dose-related. In addition, based on extensive scientific studies over many decades, radiation exposure is not associated with all forms of cancer.

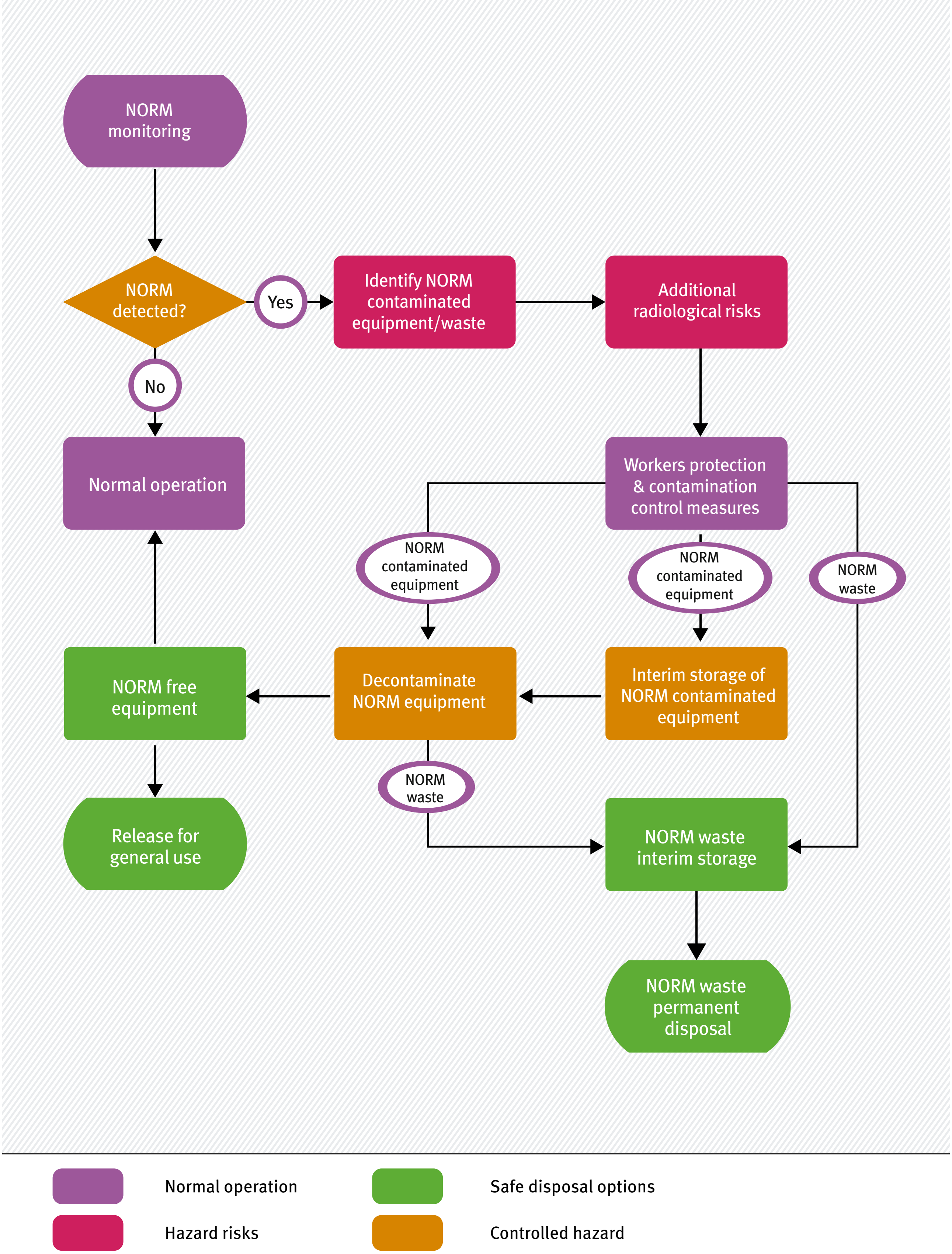
Environmental problems associated with NORM. Handling, storage, transportation and the use of NORM contaminated equipment or waste-media without controls can lead to the spread of NORM contamination and result in contamination of areas of land, resulting in potential exposure of the public.

NORM management process cycle. To ensure that all aspects of NORM management are highlighted, structured and managed, the following process cycle has been developed. The process cycle indicates where action and controls may be required to ensure adequate protection of workers, public and the environment in a practical and efficient manner. The process cycle is detailed in Figure 22.

It is important that NORM management is planned and carried out following consultation and engagement of stakeholders. Specifically, the approval of the competent authorities will be required. NORM management is not an activity that companies can undertake independently, given the contentious nature of radioactivity and radioactive material.

Figure 22:

NORM management process cycle



Source: (OGP - International Association of Oil and Gas Producers, September 2008)

If NORM is identified at a site, monitoring, survey measures and operational assessments may be required in order to guarantee safe operations and to exclude negative health effects to site personnel. Important threshold values regarding exposure to NORM-related radiation are NORM action limits, i.e. radiation doses that, if exceeded, require hazard prevention and control measures. Action limits for the disposal or control of NORM waste material may be stipulated in national regulations. In the absence of national regulations, recommended general action limits or exemption values in compliance with current international practices can be obtained from the sources mentioned hereinafter.

Particularly on sites with 'legacy contamination', it is important to evaluate and address the topic of NORM appropriately. Legacy contamination is contamination which results from operations before the implementation of a NORM management strategy. Areas with potential legacy NORM contamination include, but are not limited to, land disposal sites, evaporation ponds, disposal pits and areas used for equipment storage, cleaning and maintenance where NORM contamination was potentially accumulated over time.

More detailed information about NORM can be obtained from the OGP/IOGP Report No. 412 of 2008 and 2016 and from the IAEA Safety Reports Series No. 34: Radiation protection and the management of radioactive waste in the oil and gas industry (International Atomic Energy Agency (IAEA), 2003).

Investigation of sites contaminated with NORM

Decay of unstable natural radioactive elements produces other radionuclides (primarily ^{226}Ra and ^{228}Ra (radium)) that, under certain conditions depending on pressure, temperature, acidity, etc., in the subsurface environment are mobile and can be transported from the reservoir to the surface with the oil & gas products being recovered. During the production process, naturally occurring radioactive material (NORM) flows with the oil, gas and water mixture and accumulates in scale, sludge and scrapings.
The site personnel can be exposed to NORM via irradiation or inhalation, ingestion and absorption via dermal contact. It is necessary to evaluate the risk associated with NORM and to identify measures for worker protection.

5.4 Investigation matrices and methods

5.4.1 Soil

The collection of soil samples is usually performed by borings (e.g. percussion drilling, rotary drilling or auger drilling) and in some cases (for sampling of shallow soil layers down to approx. 30 cm) by extraction of soil using a spade or sampling cylinder. Essential to the sampling strategy for soil investigation are the definition of the area to be investigated and the geometrical sampling scheme in horizontal and vertical direction. The objective of the sampling strategy is to achieve a vertical and horizontal delineation and characterization of the contaminated volume. The Phase I environmental site investigation constitutes the basis for the sampling strategy as it contains information about the former use of the territory and the contaminants to be expected in every potentially contaminated area.

A thorough site inspection is usually very useful to integrate the information from the Phase I environmental site investigation and to complete the sampling strategy.

On former or active sites of the oil & gas industry, samples should preferably be taken in known or suspected areas where contaminations can be assumed due to the past or present site use ("targeted sampling"), e.g. at or underneath the locations of former or existing installations such as tanks, pumps, pipelines, process units, production wells, waste deposits, buildings, etc. (see Chapters 2 and 5) or where a Phase I environmental site investigation has provided evidence that pollutants could have been released to the soil and groundwater (see Chapter 6). However, on active sites particular attention has to be paid to health & safety concerns if sampling activities are planned. Also, it needs to be ensured that no interference with or disruption of ongoing operations and processes may be caused by intrusive investigation measures.

If no reliable information regarding potential sources of contamination is available, it might be necessary to take samples in a rather systematic approach by application of grid sampling over the entire area. The sample grid as well as the sampling interval and depth are depending on a variety of factors, for instance the size of the site (topography, geological features like monoclines, etc.), the investigated source-receptor pathway and planned site use after remediation.

Following procedures and best practices that are published, for instance, in Germany's Federal Soil Protection Act, it is recommended that the sampling depth for planned residential areas should be defined as the usual depth at which playing children would dig, i.e. max. 35 cm (spade depth) with horizon-specific sampling. With respect to an oral soil intake and/or dust inhalation, samples should be taken at the following depths depending on the existence of vegetation:

- Without vegetation: 0 – 2 cm, 2 – 10 cm and 10 – 35 cm;
- With vegetation: 0 – 5 cm, 5 – 10 cm and 10 – 35 cm.

If the soil is going to be used to grow edible plants, the relevant sampling depth for the collection of data for risk assessment is the digging depth of a spade (35 cm). Only in specific cases, sampling up to the depth of root penetration of about 1 m might be necessary.

When a contamination is assessed on sites which are anticipated to be used for agriculture in the future, the main migration pathway to human and the presumable contaminant concentrations in the food products are the most relevant parameters. Hence, mass transfer factors (soil → agricultural plant) must be considered during an environmental risk assessment (see Chapter 7).

Regarding the investigation of the pathway soil → agricultural plants, numerous international publications exist which refer to the number of shallow samples to be taken. Table 8 lists the minimum number of shallow samples according to Germany's Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV) of July 12, 1999.

A composed sample has a weight of about 1,000 g and comprises 15 – 25 single boreholes randomly distributed over the investigation area.

Table 8:

Recommended numbers of samples for contaminations at shallow depth and of homogenous distribution

Size of site	No. of samples
< 5 ha	3 composed samples
10 ha	Split of sampling area into 3 – 10 subareas, 1 composed sample per subarea
> 10 ha	Split of sampling area into 10 subareas, 1 composed sample per subarea

If potential sources of contamination are not known, the sampling points should be arranged, if possible, in a regular grid covering at least the entire impacted areas. A typical investigation grid to investigate the deeper soil ranges from 20 m to 50 m (distance between investigation points), depending on the size and the condition of the area. For areas bigger than 100 ha it is possible to increase the grid up to 100 m x 100 m. For very small areas (< 1 ha) at least 4 sampling points are necessary.

In case of a strong heterogeneity, it should be evaluated if the contamination is more likely to be concentrated in certain areas to which the investigation efforts should focus. It is recommended to choose a radial arrangement of the sampling points in various directions from the (supposed) contamination centers. In this way, the distribution and limits of contamination can be determined effectively.

Samples are taken from the entire vertical soil profile down to the water-impermeable horizontal layer (aquiclude) or at least to a depth of 1 m below the deepest sample showing evidence of contamination (organoleptic assessment or field measurement). Drilling through water-impermeable horizontal layers should be avoided because it could cause cross-contamination of the groundwater underneath the interbedded aquiclude. However, if the deeper aquifer is already known to be contaminated and therefore needs to be investigated, it is possible to avoid such a cross-contamination. This is done by installing a casing down to the depth of the aquiclude. The drilling is then performed within the casing through the low-permeability layer. The aquiclude is restored either by filling the borehole with low-permeability material (usually a cement-bentonite mixture) or by building a sealing layer with the same material as if a well is installed in the borehole.

Composite soil samples are taken each meter of the soil core or, if the geological formation changes (change in composition, condition or color), even at smaller distances. In some cases, it is necessary to perform a high-resolution sampling (e.g. every 20 cm). Cores should be sampled as densely as possible because the additional sampling costs are insignificant compared to the drilling costs if drilling had to be repeated. Separate samples should be always taken when:

- The overall number of samples is small,
- Different geologic layers can be distinguished,
- A certain depth range shows evidence of contamination,
- Objects are encountered such as tanks or piping with unclear content,
- Contamination by highly volatile contaminants is expected,
- Samples are taken from layers directly above compacted soil layers, and
- Samples are taken from the groundwater fluctuation zone (so-called smear zone, see Chapter 3).

In the handling of samples (sampling material, storage spaces, etc.), the relevant quality and safety requirements should be observed. In general, samples containing presumably volatile contaminants are overlain with methanol. All samples are stored dry, in the dark and at 4 °C. Not all the samples taken have to be analyzed in the first campaign, some samples may be stored as backup samples and only analyzed if needed.

The most common methods to gain soil samples include:

- Hand or machine excavated trial pits,
- Hand augering,
- Windowless sample boreholes,
- Cable percussive boreholes,
- Hollow stem and solid stem rotary boreholes.

For taking soil samples within the saturated zone, inliner (PVC-casings that protect the integrity of the soil core) are needed. Attention should also be paid to appropriate sample storage and transportation to avoid e.g. the loss of volatile compounds.

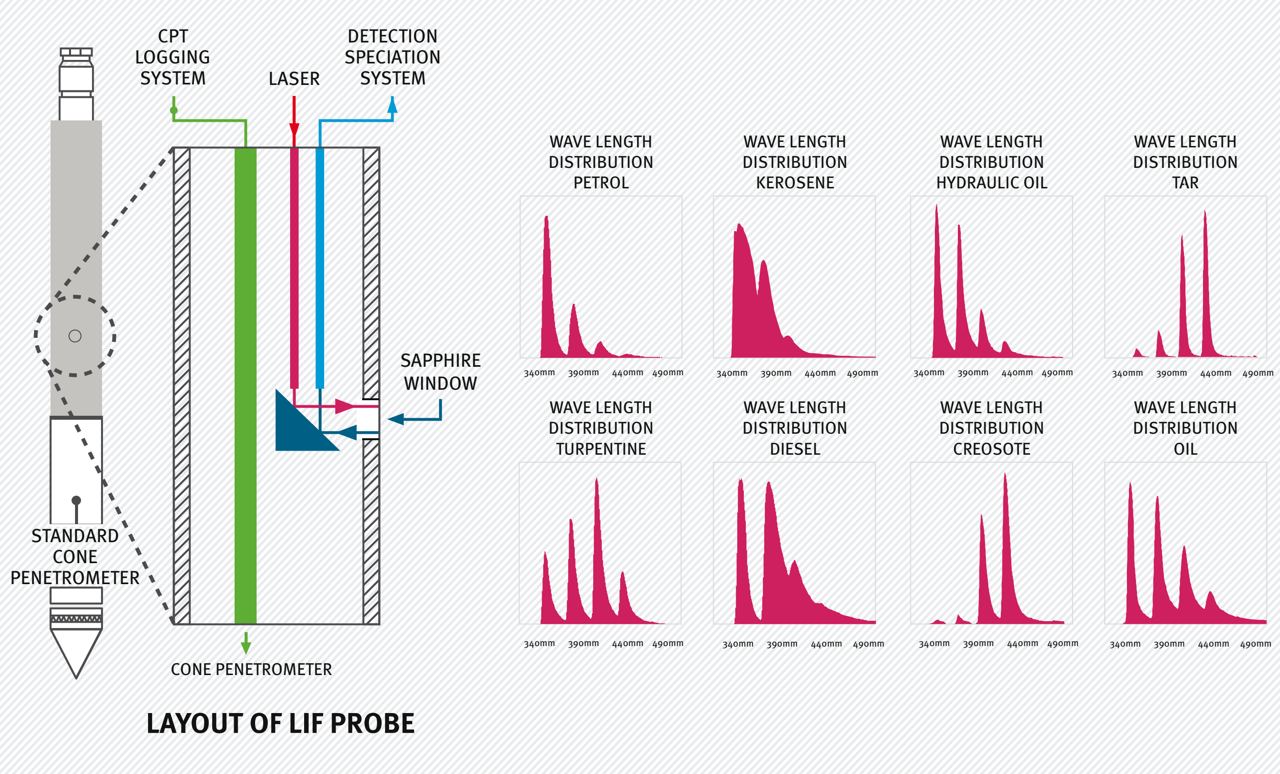
Another frequently used technology is Direct Push. With this method, probes are inserted into the subsurface – either continuously pushed via oil-pressure hydraulics or discontinuously by hammering. At the tip of the probe a variety of instruments may be installed. In the simplest way it is just a probe measuring the electrical conductivity (hammering system). The continuously pushed system may have a cone pressure test (CPT) probe, measuring the tip back-pressure and the sheath friction. All these data can be used to determine which kind of soil is currently penetrated (based upon norms and standards for the geotechnical works). The detection of contaminants is performed by additional probes, e.g. by membrane interface probes (MIP). A MIP contains a heating block for heating up the penetrated soil to temperatures in the range of 110 – 120 °C. This increases the volatilization of volatile organic compounds (VOC), which are substances showing a low solubility in water and a boiling point of ≤ 180 °C. These contaminants are passing a semi-permeable membrane and are transported via a nitrogen-gas carrier-stream to the surface where the gas mixture is analyzed by detectors like flame ionization detectors (FID), photo ionization detectors (PID) or others. The result, a signal in mV corresponding to the concentration of the VOC must be calibrated. This requires that soil samples of a defined depth are taken, analyzed in the laboratory and the values are correlated with the MIP-signal in mV.

Another innovative investigation method is the laser induced fluorescence (LIF) probe, see Figure 23. This method uses laser light that is emitted into the soil. PAH and mineral oil hydrocarbons which occur as residual products are excited by the light and are emitting a fluorescence signal which is recorded at four different wave lengths. The height of the signal is proportional to the contaminant concentration and the fluorescence pattern shown in Figure 23 is indicative for the type of contamination.

The Direct Push-LIF and Direct Push-MIP investigations are very valuable tools helping to delineate the contamination in the subsurface in three dimensions and to estimate the inventory of contaminants and of residual product phase.

Figure 23:

General procedure of the LIF investigation method



Source: (OGP - International Association of Oil and Gas Producers, September 2008)

5.4.2 Groundwater

The purpose of groundwater investigation is to delineate the contaminated groundwater volume vertically as well as horizontally and collect data about the distribution and mobility of the contaminants in groundwater. In no case it replaces the compulsory investigation of soil-associated contaminants in the saturated zone.

To gain information from groundwater, groundwater monitoring wells distributed in a monitoring network are required.

Groundwater should be sampled in the potentially contaminated area as well as upstream and downstream from the suspected sources of contamination. The number of necessary downgradient groundwater sampling points depends on lateral plume extension and the size of the plume. In general, groundwater wells with a short filter screen (≤ 3 m) are used. The screen location in the vertical extension and the number of monitoring wells (optionally with filter screens in varying depths) is chosen to obtain representative data from all contaminated aquifer layers. If the contamination shows a large vertical extension in the aquifer, a number of groundwater well bundles (each showing a filter screen in a different depth) are usually needed. In case that the contaminants occur as NAPL (LNAPL or DNAPL, see Chapter 3), the filter screens must cover the smear zone (relevant for LNAPL) to allow the measurement of the NAPL thickness. In case of DNAPL, the groundwater well should contain a so-called “pump sump”, i.e. an unscreened tube at the bottom of the well which serves as DNAPL trap. Wells that are used for trapping NAPL are generally not suitable for sampling groundwater. Extended heterogeneous conditions (e.g. complex stratigraphic conditions, fractured bedrock aquifers) usually require more groundwater sampling points to collect enough information for the conceptual site model (see Chapter 6).

Groundwater sampling methods should utilize low-flow procedures, consistent with published protocols or in accordance with existing regulations or standards (e.g. EN or ISO standards). The basic tenet of the low-flow technique is to collect groundwater from a discrete portion of the well screen at a rate that most closely replicates the natural recharge of groundwater from the formation into the well screen.

This is accomplished by removing groundwater at low flow rates (typically between 100 and 500 ml/min) while monitoring the water level within the well to ensure minimal drawdown.

While the well is being purged, field parameters are monitored at the wellhead using a flow-through cell. Dissolved oxygen, oxidation-reduction potential, temperature, pH and electrical conductivity are monitored and recorded at (typically) 10 min intervals while the well is purged. When these readings stabilize within ± 5 %, the groundwater is considered to be representative of the aquifer, and groundwater samples for laboratory analysis are collected directly from the pump discharge at the surface.

Depending on the depth to water and diameter of the existing wells at the site, different pumps should be used. Submersible pumps with frequency-controlled flow rates can be used in most conditions. At extreme depths, the pumps tend to get hot, which could volatilize constituents in the sample. Thus, for deeper depths, bladder pumps should be preferred. Sites that have very small diameter wells and shallow depths to water may require the use of peristaltic pumps. At any site (or well), efforts should be made to use the same pump and purging method, so that any variability associated with the purging method can be minimized in the generated data set. Although reliable, the sampling techniques described require a significant amount of equipment, supplies and labor.

Efforts to simplify and optionally reduce the cost of groundwater sampling have resulted in the development of passive diffusion bags (PDB) sampling devices. The underlying principle behind PDB sampling devices is that contaminants in the dissolved phase (here: groundwater) are naturally driven from the areas of high concentration to areas of low concentration. Polyethylene bags are utilized as semi-permeable diffusion membranes and filled with deionized water. These bags are installed in the screened interval of monitoring wells and left in contact with the groundwater for varying periods of time (usually 4 weeks). Because of the concentration gradient, the contaminant molecules diffuse through the membrane until the concentrations in the bag are equilibrated with the surrounding groundwater. The PDB are only applicable for contaminations with (mono)aromatic hydrocarbons (Suthersan, 2005).

The organoleptic parameters such as coloring, turbidity, odor and sedimentation are also determined qualitatively on site. Pumping and sampling parameters have to be documented in a protocol.

Most groundwater or surface water samples need to be stabilized (e.g. pH adjustment or chemical conservation) to avoid precipitation or biodegradation of the analytical targets and shall be stored in cooling cells at 4 °C.

In addition to sampling, wells can also be used to run tests to collect information about the hydrogeological properties of the aquifer. Pumping tests are usually preferred to other hydraulic tests because they provide reliable data about large portions of the aquifer, whereas faster tests[17] are usually representative only for the immediate proximity of the well.

17 Fast tests for hydrogeological properties are, for instance, the so-called slug and bail tests. In these tests, a solid body is injected into or removed very fast from the groundwater well. This causes an oscillation of the groundwater level which can be used to calculate the hydraulic permeability.

5.4.3 Soil vapor

Soil vapor sampling is carried out to investigate the concentration of volatile organic compounds (VOC) in the gas phase of the unsaturated zone (vadose zone) of contaminated sites. VOCs are predominantly substances showing a low solubility in water and a boiling point of ≤ 180 °C.

The distribution of the gaseous contaminants may be influenced by the location of the contaminant sources (determined from the history and evolution of the contaminated site), supply and sewer systems (which may serve as a preferential flow path), depth to the groundwater table and the hydrogeological situation (heterogeneity of the gas permeability of the subsurface). The sampling plan must address all these aspects and, in addition, possible contaminant migration pathways to sensitive receptors (especially residential buildings).

The sampling depth is determined by the vertical geological structure and the depth of the groundwater table (as displayed in drilling profiles and/or geological cross sections) and is typically in the range of 1,5 – 4 m under the surface. If the geologic structure is homogeneous, the samples are taken always from the same depth.

In case of extended vadose zones (> 8 m thickness), it can be reasonable to take samples from different depth levels (e.g. 2 and 7 m below ground). If low-permeable interbedded layers (e.g. clay, silt, loam, marl or lutit) dissect the vadose zone in various sublayers, samples should be taken from each layer showing higher permeability.

Only in case it can be assured that the lower permeable layer has been protected by the low-permeable interlayer, additional samples can be omitted. The horizontal distance between the sampling points depends on the size of the source zone. In case of grid sampling, the distance between the sampling points is typically in the range of 10 – 50 m. Along the migration pathway from the source to the sensitive receptors also sampling points are needed.

The sampling points for soil vapor can be boreholes, Direct Push probes and stationary soil vapor wells. The most frequently used investigation is done via boreholes. In the borehole (usually 1.5 – 2 m deep), a vapor probe is inserted, and the borehole is sealed with bentonite against the atmosphere. From the probe, the soil vapor is extracted. In the case of Direct Push, a sampling probe is pushed down directly into the soil without drilling. The Direct Push probe directly allows the sampling of the soil vapor. Boreholes and Direct Push probes are usually applied for a single sampling, whereas stationary soil vapor sampling wells are installed for repeated sampling at various times. The drilling or installation of soil vapor sampling points is always performed by dry drilling, avoiding any drilling fluids. Sampling can be done in two different ways:

- Without contaminant enrichment (direct method): The sample is collected in an inert container (e.g. Tedlar bag or headspace vial);
- Including enrichment: A defined volume of contaminated soil vapor is pumped through an adsorbing material (in most cases activated carbon). This method is recommended in case the contaminant concentrations are low (< 0,1 mg/m³).

For the sampling process itself, a variety of aspects must be considered:

- The sampling point must be tight to avoid a shortcut with atmospheric air. This can be checked with smoke.
- The sampling point is purged until the field parameters (O_2, CO_2, CH_4, optionally H_2S) show stable values. In case the methane concentration is in the range of 4.4 – 16.5 % and oxygen is present, the gas mixture is explosive. The sampling must then be interrupted immediately.
- During sampling, the applied vacuum is recorded as well as the vapor temperature and relative moisture. The sample is taken before the gas reaches the pump to avoid any cross-contamination. All parts of the sampling system which have been in contact with the soil vapor during sampling should be used only once or cleaned before being re-used.
- If the sampling campaign takes more than one day, at least two of the measurements of the previous day should be repeated to check possible changes caused by varying atmospheric conditions.

- The presence of condensed water can bias the analytical results. Therefore, condensate has to be removed from the gas flow via a gas-liquid separator before sampling. To avoid condensation on the sorption material, soil vapor sampling should be avoided at temperatures < 10 °C.

5.4.4 Landfill gas

The occurrence of landfill gases on contaminated sites of the oil & gas industry is basically known for the following types of sites:

- **Acid tar lagoons**: very common occurrence of sulfur dioxide (SO_2); other gas emissions may occur if the lagoon has been used for dumping any other kind of waste in the past;
- **Oil sludge pits**: BTEX vapors may occur in oil sludge pits if BTEX concentrations are high and/or if the vapors cannot escape from the deposit, e.g. because of a liquid- or gas-tight cover;
- **Drilling mud pits**: similar to oil sludge pits but lower risk of BTEX vapor occurrence;
- **Sites with ongoing natural attenuation processes**: in case of strong reductive biodegradation, elevated methane (CH_4) concentrations may accumulate on top of the groundwater layer; however, it is rather seldom that significant methane volumes accumulate above ground level and impose a risk to human health or, e.g. the risk of explosion.

Most relevant hazards related to the occurrence of landfill gases are health & safety concerns (e.g. impact on human health caused by inhalation or risk of explosion). Particularly the remediation of acid tar lagoons in the vicinity of urban areas require comprehensive precaution measures such as careful planning, a suitable remediation method and/or precaution measures for controlling SO_2 emissions and gas monitoring.

Landfill gases are commonly detected and measured by gas detectors such as multi-gas detection devices, which allow the simultaneous and continuous measurement of several gases. Such devices, however, indicate the presence and the concentrations of gases that commonly occur on landfills but do not allow the extraction of samples.

Investigation matrices and methods

The collection of soil samples is usually performed by borings and spades or sampling cylinders for samples from shallow soil layers. The collection of samples from deeper subsoil strata or solid rock layers usually require technically more complex approaches. An essential aspect is the sampling strategy, which is defined, inter alia, by the site conditions and the known (based on existing data) or suspected vertical and horizontal contamination patterns. While targeted sampling should preferably be applied in areas where information on actual or possible contaminations is available, the application of grid sampling over the entire suspected area might be required where such information is missing.

Sampling grids as well as sampling intervals and depths depend on a variety of factors. Recommendations for systematic sampling are described in this chapter. Attention should also be paid to appropriate sample storage and transportation to avoid, e.g. the loss of volatile compounds.

Sampling methods for soil and subsoil include manual techniques such as hand augering as well as machine-driven methods such as hollow stem auger or rotary drilling systems. Special soil investigation and sampling techniques are, e.g. Direct Push systems in combination with cone pressure test (CPT) devices, the membrane interface probe (MIP) and the laser induced fluorescence (LIF) probe, both for downhole detection of volatile organic compounds (VOC).

Groundwater investigations commonly aim for the delineation of contaminated groundwater volumes and the collection of data about the distribution and mobility of the contaminants in groundwater. The most common method of groundwater sampling is by low flow pumping of groundwater wells using submersible pumps. Another efficient sampling method uses passive diffusion bags (PDB) sampling devices, which allow passive sampling of groundwater over a certain period of time.

Moreover, groundwater wells may also be used for pumping tests to collect information about the hydrogeological properties of the aquifer.

Soil vapor sampling is usually carried out for the investigation of VOC in the gas phase of the vadose zone of contaminated sites. Sampling points for soil vapor can be boreholes, Direct Push probes and stationary soil vapor wells. Samples may be extracted with or without enrichment of contaminants, depending on concentrations. Soil vapor sampling has to be carried out in a very careful and diligent way for ensuring usable results.

Landfill gases on sites of the oil & gas industry may occur at acid tar lagoons, oil sludge and drilling mud pits or as methane emissions caused by reductive biodegradation. Gas detection devices allow the identification of landfill gases.

5.5 Data interpretation and documentation: Report

Data interpretation and documentation is usually performed by consultants commissioned by the liable party (economic operator or site owner). An exemplary content breakdown for a Phase II environmental site investigation report is given in Annex 2. It is the task of the competent authorities to check the supplied documentation for plausibility. Some points that may be checked are:

- Completeness of documentation:
  - Are all sampling protocols and analytical data attached?
  - Are site maps, cross sections and plans (e.g. groundwater contour maps) correct and the related data accurate?
- Plausibility of data:
  - Are the values of the field parameters (temperature, pH, electrical conductivity, dissolved oxygen, oxidation-reduction potential, groundwater level) comparable to previous sampling campaigns? If not, are the deviations explained comprehensibly?
  - Are all data in the text referenced to space and time?
  - Do the contaminant concentration data fit to previous investigations?
  - Are there any data outliers? Is there an explanation for the outliers?
- Process understanding:
  - Does the data fit to the conceptual site model (see Chapter 6)?
  - Is the understanding of the contaminant distribution correct?
  - Can the contaminant distribution be explained by previous fate and transport processes?
- Legal requirements:
  - Are all legislative references used still in force?
  - Is the environmental risk assessment done in a correct way?

The text of the Phase II environmental site investigation report must be written in an understandable and comprehensible manner. It must be avoided to explain a mass of data in words. If ever possible, graphs need to be used to visualize the processes. Graphs are preferred over tables. Tables may be used to explain simple relationships.

6 Conceptual site model

After completion of the site investigation steps that have been described in the previous chapters, numerous data are available about a site. These include not only information about the contaminant transport along the source-receptor pathways but also extensive data on the description of the contaminant source. Further site-specific data will be generated during the remediation planning and subsequent remediation execution. Thus, a large amount of various data are collected in the course of the entire investigation and remediation project. It is therefore necessary to present the data that is relevant to the site in a clear and transparent structure. This is achieved with a format that is easy to process, to understand and to apply – the conceptual site model. The conceptual site model can include a textual description of the location and/or a graphical representation of all relevant physical site parameters and/or a clustered presentation of possible exposure pathways[18] across the various environmental media. It is also helpful to record all data about the site in tabular form.

The conceptual site model combines all the data (contaminant entry characteristics, geology, hydrogeology, contaminant distribution, geochemical anomaly maps, migration pathways and processes as well as degradation processes) of a site into a comprehensive picture and thus allows a detailed understanding of the site. For areas in which there is no technical evidence for any processes, interdisciplinary expert knowledge (hypotheses) is used. The hypotheses are, if necessary, verifiable by collecting additional site data. Under no circumstances should the conceptual site model be used to filter out data that do not appear to fit into it. Reversely, it must be checked self-critically whether the apparent outliers are actually errors or whether site-specific processes have been overlooked.

Considering the events that caused the contamination, the contaminant distribution determined today must be fully explained. If this is the case, all processes relevant to the contamination development must have been assessed and considered. If this is not the case – and the conceptual site model makes it easier to identify data and information gaps – an additional investigation is necessary to describe the processes that have not yet been assessed. Thus, the conceptual site model also helps to prioritize open questions to be clarified.

The core elements of a conceptual site model comprise:

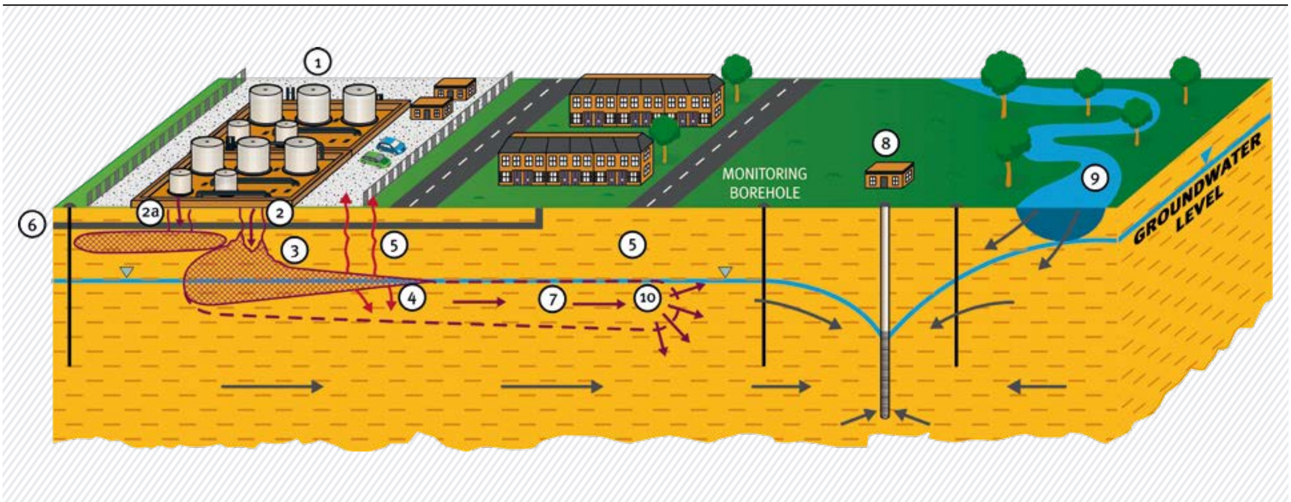
- Contamination generation scenario (sources, relevant contaminants),
- Spatial and temporal distribution of the relevant contaminants considering the physical state of the contaminants in the various environmental media concerned,
- Current and future use of the site and the groundwater,
- Description of soil stratigraphy, hydrogeology, meteorological influence and, if present, surface waters,
- Description of natural retardation and degradation,
- Historical redevelopment activities and their influence on the distribution of contaminants,
- Exposure model that identifies relevant receptors under current and future site use conditions.

18 The difference between migration pathway and exposure pathway results from the contaminant concentrations along the pathway. Contaminants must be present for causing an exposure. Attenuation processes like sorption, dilution or biodegradation may cause a complete elimination of the contaminants along the migration pathway.

The area under consideration must be at least so large that all the contaminant migration pathways are depicted. If, for example, a transport of a contaminant with the natural groundwater flow into a surface water body is of relevance at the site, this must be illustrated in the conceptual site model. The development of a conceptual site model already starts with the Phase I environmental site investigation or, at latest, with the Phase II environmental site investigation and is continued with every further step of the remediation until the completion of the remediation. The conceptual site model is thus the standard process for integrating site data. Based on the conceptual site model, additional investigation programs can be developed to close data gaps and to complete the understanding of the site. As a result, an increasingly better understanding of the site features is achieved. A complete and detailed conceptual site model is thus also a valuable tool which facilitates a well-founded decision-making during the remediation procedure.

Figure 24:

Example of graphic representation of a conceptual site model



1. Source: loss of contaminant from facility
2. Pathway: migration through unsaturated zone - will be dependent on permeability

2a. Migration retarded by less permeable clay layer

3. Floating product (non-aqueous clay layer)
4. Pathway: dissolved into groundwater
5. Pathway: volatilisation
6. Pathway: preferential flow in backfill of man-made constuct e.g. sewers
7. Pathway/receptor: transport of dissolved phase impacts in groundwater/impacts to groundwater aquifer
8. Receptor: e.g. public water supply borehole

9 Receptor: stormwater feature at risk if borehole pumping (8) were to stop

10. Dispersion and dilution of groundwater aquifer

Source: (Energy Institute, 2015)

The importance of the conceptual site model can be explained best through an example. In Figure 24, DNAPL (e.g. tar oil) and BTEX have spilled in the underground from a maintenance pit and an underground storage tank. While the DNAPL are transported within the aquifer as expected, the BTEX accumulated as residual LNAPL in the lower area of the sand pack around the tank and in the lower sand layer interbedded in the aquifer. This becomes clear when the groundwater level is observed over the years. The deepest water level occurred at the lower edge of the sand layer and allowed LNAPL to sink down to this layer. At a first glance, it is not possible to explain the transport of dissolved BTEX to very great depths. This effect is only understandable after measurements have shown a significant downwards-directed, vertical groundwater flow.

It is intuitive that the complete understanding of the contaminant distribution and transport is the basic prerequisite for a reliable remediation planning.

The experience of the last few years has shown that insufficient understanding of contaminated sites frequently led to failures of remediation efforts which could have been avoided with a comprehensive conceptual site model.

Conceptual site model

The conceptual site model combines all the data (contaminant entry characteristics, geology, hydrogeology, contaminant distribution, migration pathways and processes, receptors as well as harmful degradation processes) of a site into a comprehensive picture and thus allows a detailed understanding of the site. The boundaries of the conceptual site model should be selected in a way that all relevant source-receptor pathways are contained in the conceptual site model.

For areas in which there is no technical evidence for any processes, interdisciplinary expert knowledge (hypotheses) is used. The hypotheses are, if necessary, verifiable by collecting further site data.

A solid conceptual site model is basis for the development and performance of reliable remediation scenarios.

7 Environmental risk assessment

7.1 Exposure pathways

The data collected during the Phase I and Phase II environmental site investigations together with an assessment of all relevant potential receptors constitute the basis for the environmental risk assessment.

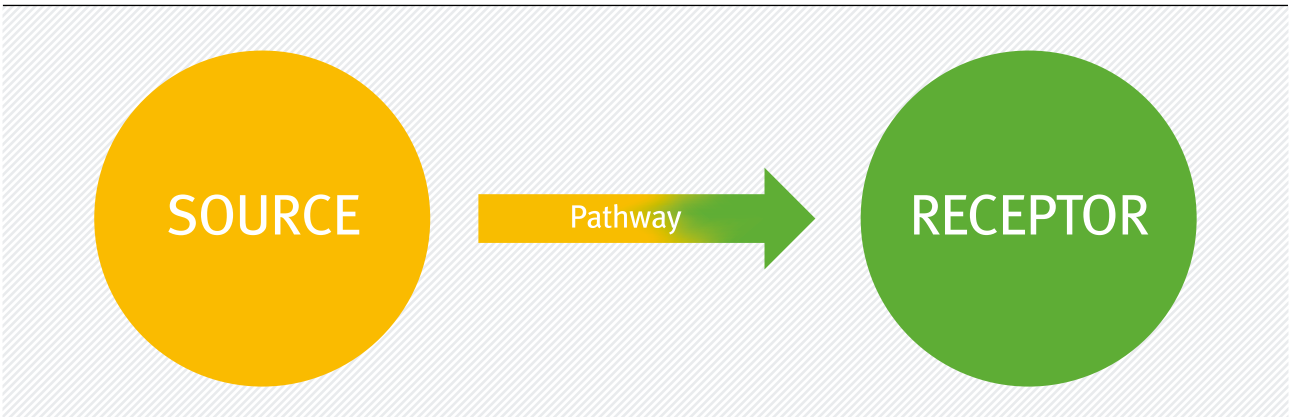
The environmental risk assessment is a systematic process of evaluating the potential risks related to soil, groundwater or soil vapor contamination. Environmental risk assessments can be used for varying purposes, e.g. as a tool...

- to evaluate the necessity of remediation,
- to evaluate the urgency of remediation,
- to evaluate whether precaution measurements are required or not,
- to set risk-based remediation targets.

The risk itself is a combination of a hazard and an exposure towards a receptor. If one of these three components (source, pathway, receptor) is missing, there is no risk (Figure 25).

Figure 25:

Source-pathway-receptor model



Source: Arcadis, own figure

A **source** is a substance or an area that has the potential to cause harm or adversely affect human health or ecological integrity. A source of hazard at an industrial site could be, inter alia, leakage from storage tanks and pipelines, vapor releases, spillages from poor housekeeping, permitted discharge. These sources may lead to contamination in soil, groundwater and soil vapor. To this end the definition of the source is here slightly different from the one of typical brownfield management where the "source" signifies the area where contamination entry has taken place and which is showing high soil-associated contaminant concentrations.

The **receptors** can be differentiated into the following types:

- Human health (e.g. construction workers, site residents, children at home or at school),
- Ecological system/environment (e.g. water quality, sensitive species, habitat).

National regulators define what kind of receptors shall be considered (e.g. human health, ecological systems, water protection areas, etc.).

The **pathway** is the route that links the “source” with the “receptor”. There are three main categories of exposure pathways:

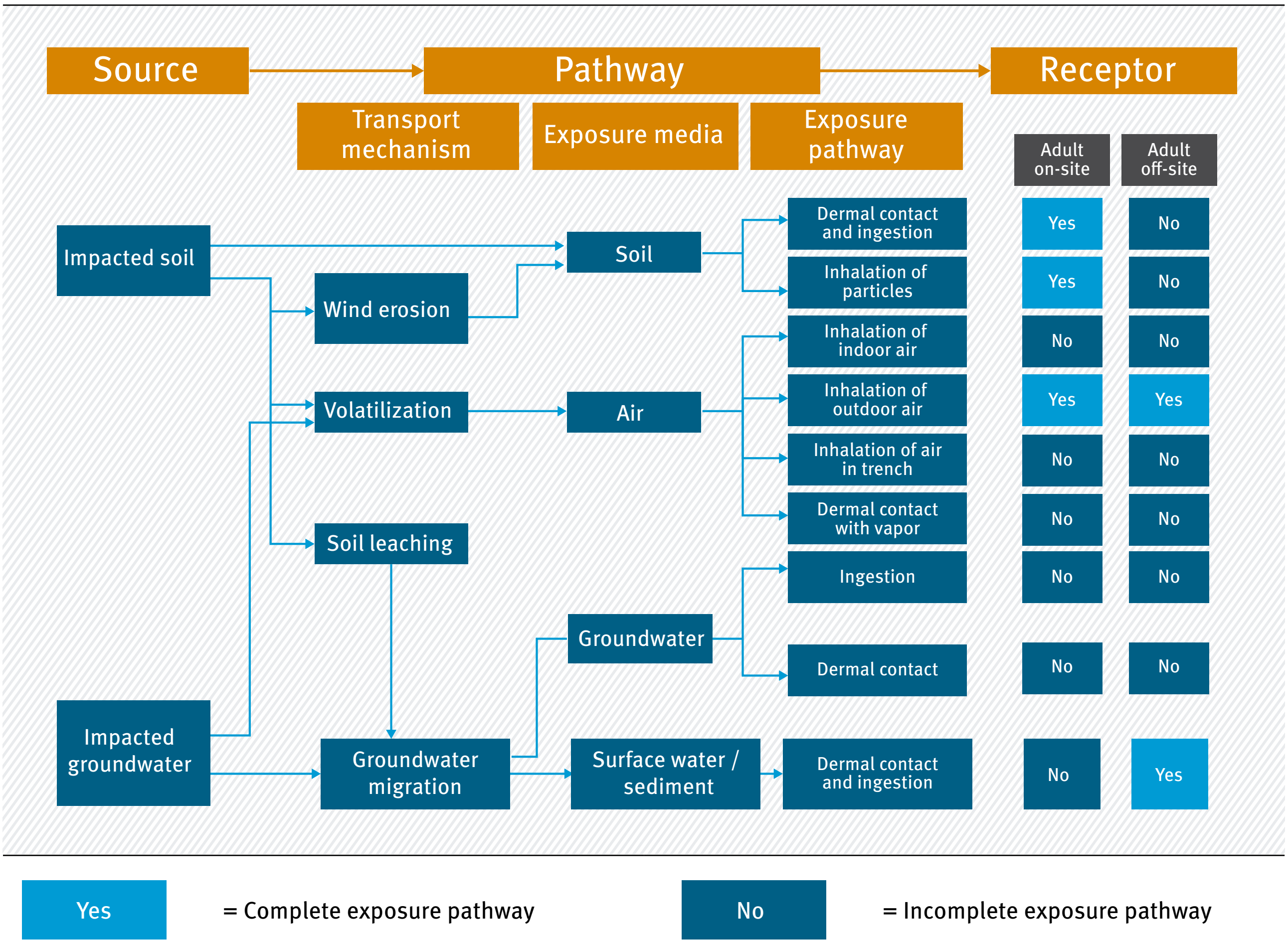
- Adsorption via dermal contact, e.g. touching contaminated soil or washing in contaminated water sourced from a contaminated aquifer or river;
- Inhalation exposure, e.g. inhalation of contaminated dust, usually caused by wind erosion on the surface of contaminated soil, or inhalation of vapor (the contaminants within the soil vapor might evaporate and accumulate indoor where they can be inhaled. Evaporation to the atmosphere will generally not lead to critical concentrations in atmospheric air due to the immediate dilution);
- Ingestion, e.g. oral intake of contaminated soil, eating food grown in contaminated soil.

Also, migration of contaminants dissolved in groundwater may represent an exposure pathway to off-site receptors. In this case, an environmental risk assessment shall consider retardation, dilution and degradation factors.

In general, the exposure pathway is a combination of fate and transport and exposure. Fate and transport describe how a contaminant migrates and attenuates in the environment (see chapter 3). Considering all relevant attenuation processes, the assessment of fate and transport helps to predict the concentration of a contaminant at a point of exposure distant from the source. The exposure describes how a person or other organism interacts with the contaminant at the point of exposure. Both mechanisms (fate and transport in combination with exposure) are visualized in Figure 26.

Figure 26:

Example of a conceptual site model with respect to the human health (showing site-specific relevant pathways)

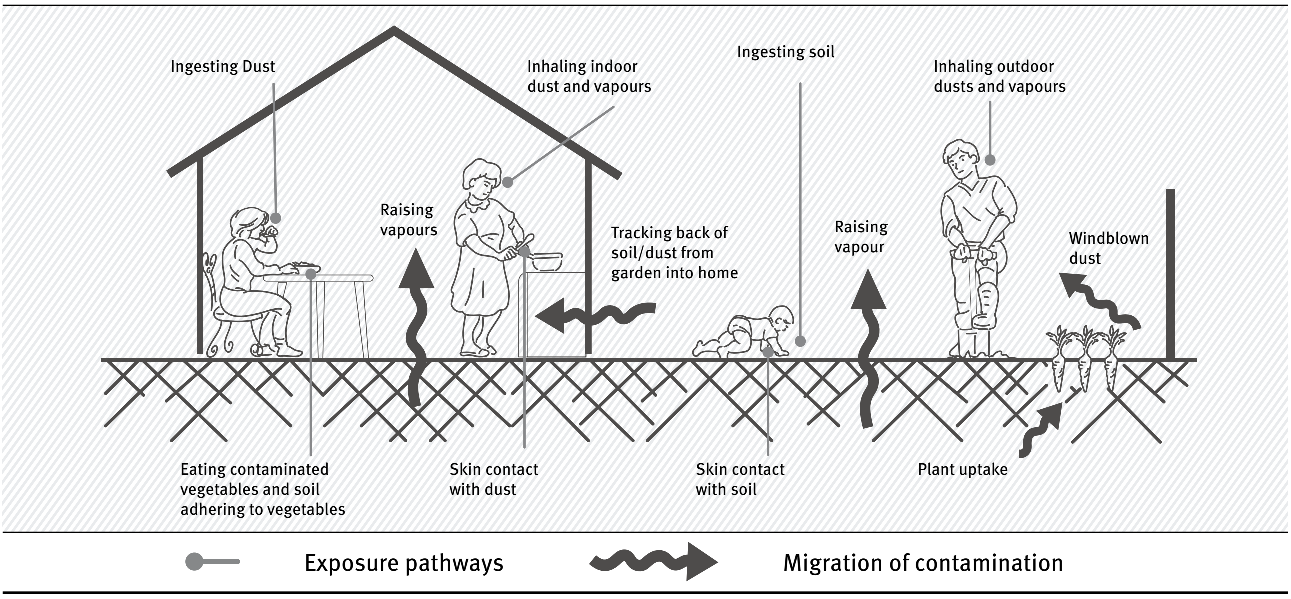


Source: Arcadis, internal database

As shown in Figure 27 and in Figure 28, there is a wide range of possible exposure pathways. The exposure pathways that shall be considered at a specific site are depending on the conceptual site model (see Chapter 6). The conceptual site model and the understanding of the link between source, pathway and receptor is the basis for an environmental risk assessment.

Figure 27:

Potential exposure pathways in a residential environment



Source: (Jeffries, J. & Martin, I., 2009)

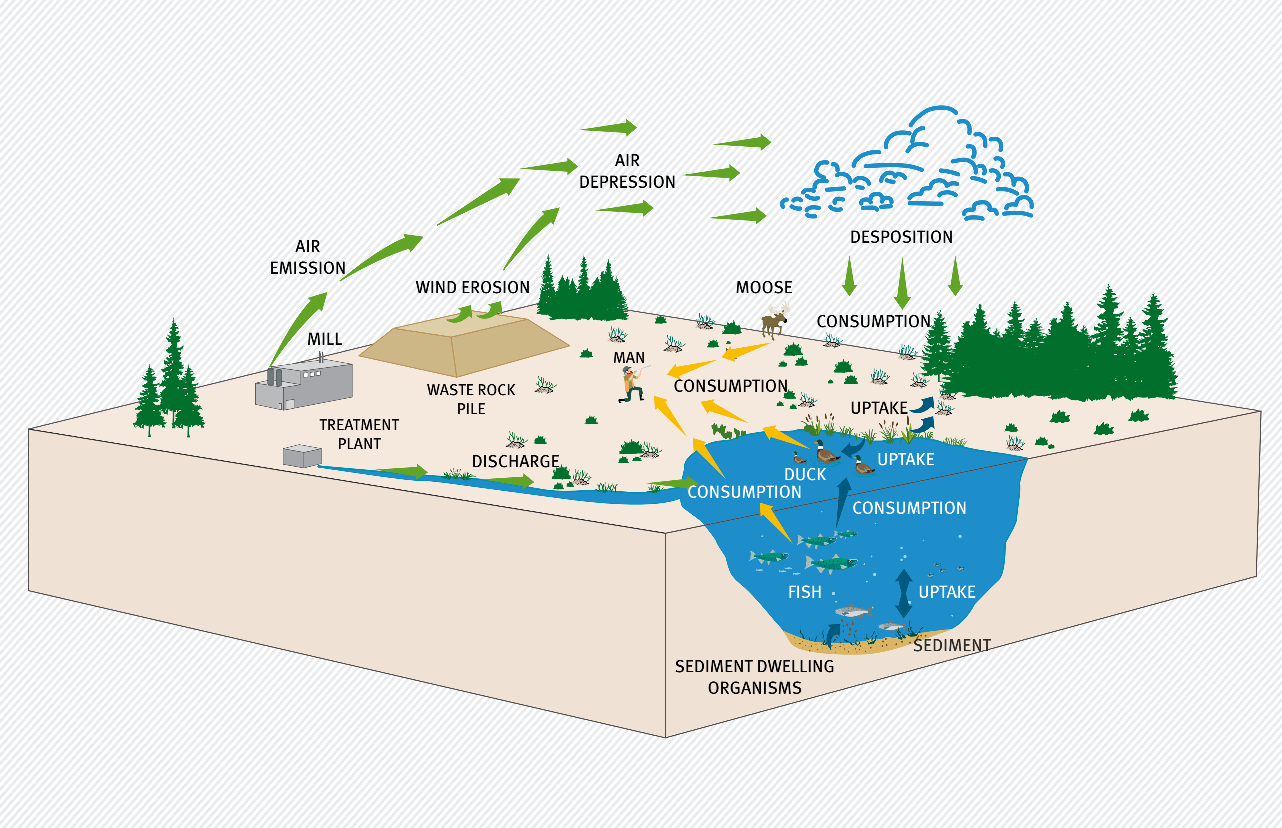
In some countries, the source-receptor pathways to be considered are regulated in local or national guidance documents. Apart from the typical pathways considering dermal contact, inhalation and ingestion of soils, also following critical pathways may be considered:

- Groundwater → surface water → aquatic species (environmental risk assessment),
- Soil → plant roots → vegetables, crop plants → humans, animals.

Among others, both pathways are visualized in Figure 28.

Figure 28:

Example of a conceptual site model including bioaccumulation and consumption of crop plants



Source: (Arcadis Germany GmbH, SENES Consultants, 2015)

In case of the pathway groundwater → surface water → aquatic species, concentrations of contaminants in surface water may be estimated or measured and are described as the **(predicted) environmental concentrations (P)EC**. These concentrations will be compared with **predicted no effect concentrations (PNEC)**. PNEC are concentrations below which exposure is not expected to cause adverse effects. PNEC concentrations are generally based on generic ecotoxicological data. In case of toxic, bioaccumulative substances, the (P)EC in the food of a predator (e.g. a fish) will be compared with the PNEC of the predator (e.g. a fish-eating bird). In case of $(P)EC_{food\ predator} > PNEC_{predator}$, there is potential for bioaccumulation and secondary poisoning.

When considering environmental risk assessments at oil & gas sites, especially in case of exploration and production, also a radiological risk assessment shall be considered (see Chapter 5.3). Exposure pathways towards radioactive material could be the inhalation of airborne radioactive material, the ingestion of food, soil or drinking water and external exposure (e.g. gamma radiation). Dermal exposure is only considered for tritium. In a radiological risk assessment, the amount of radiation energy that might be absorbed by an exposed individual will be calculated and compared to radiological dose limits provided by regulators.

7.2 Risk calculation or estimation

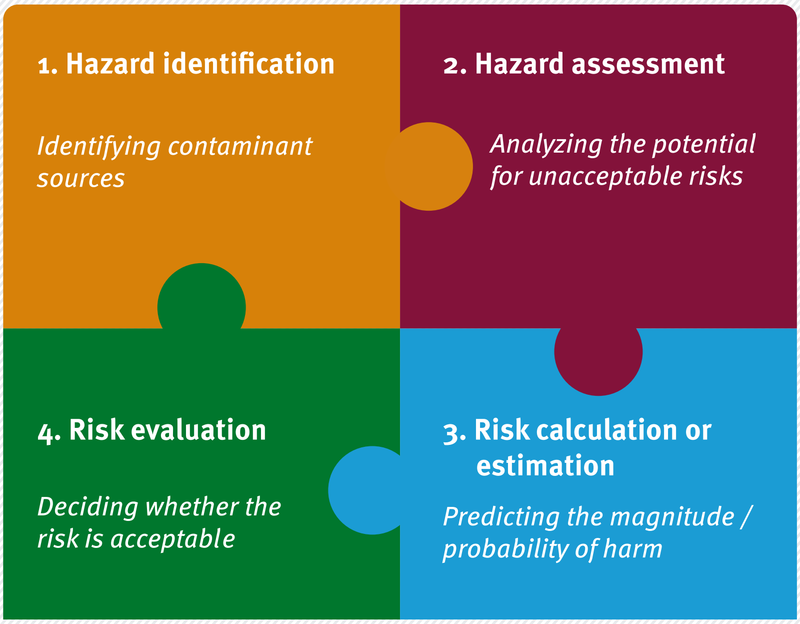
A typical environmental risk assessment comprises four stages as shown in Figure 29. During the **Hazard identification** phase (Step 1), the following questions need to be answered:

- What are the potential primary sources?
- Which environmental media could be affected?
- Which contaminant types could be present?

The **Hazard assessment** (Step 2) is the evaluation of the effects that the hazards could have, e.g. on humans and on environment, depending on the current and future site use.

Figure 29:

Four stages of environmental risk assessment (as an iterative process)



Source: Arcadis, own figure

The **Risk calculation** (or estimation, if a proper calculation is not possible) (Step 3) itself can be qualitative, screening or site-specific. The goal of numeric risk calculations is to predict the effect of a source on one receptor or on multiple receptors and, if applicable, to derive the remediation targets. This is called a "forward" risk assessment and uses measured concentrations of contaminants at the source to predict a concentration at a sensitive receptor (e.g. water quality within a river) or a concentration at the point of exposure by a human or ecological receptor.

Exposure calculations are then used to calculate the dose for each human or ecological receptor. The methodology how to perform the risk calculation is often depending on local regulations and may require the use of modelling software. Two modelling approaches from the 1990s are used globally:

- Risk-Based Corrective Action (RBCA, known as "Rebecca") developed in the USA and
- CSOIL developed in the Netherlands.

Both models use equations for modelling different exposure routes. Although they have many similarities, there are also some differences. Each model contains a set of model parameters with default values such as breath volume of an adult, diffusion coefficients in soil, etc. The most important variable parameters in the exposure to contaminants in the different site use scenarios are:

- Time spent on the site. For instance, in industrial areas the employees will stay only for approximately 8 h (working time) on the site;
- Amount of ingestion of soil and dust. For adults, the uptake of soil and dust by ingestion in industrial areas is higher compared to the soil uptake in living areas;
- Demographic group. In general, a separate calculation is made for children and adults depending on the site use scenario; in industrial areas, the exposure is calculated only for adults;
- In some models, also information about the organic material and clay content as well as the depth of the contamination is included as input parameter, others are working with default values.

The relevant exposure pathways will be quantified to obtain the total daily exposure (i.e. contaminant uptake). Other exposure pathways that are not applicable at a specific site (e.g. crop consumption, drinking water consumption) shall not be considered in the calculation. Depending on the case, exposure will be calculated from soil, groundwater or soil vapor concentrations. The highest measured concentrations at the source can be used for calculations as a worst-case scenario. The exposure due to all pathways is summed up and compared to the tolerable daily intake (TDI) or reference dose for oral exposure derived from toxicological data, e.g. no observed adverse effect level (NOAEL) and lowest observed adverse effect level (LOAEL) in combination with uncertainty factors to reflect the limitations of the data used, e.g. inter- and intraspecies variation.

This type of risk calculation is typically performed for non-carcinogenic compounds. For genotoxic carcinogenic compounds, the exposure during the entire lifetime (assumed to be 70 years) will be calculated. For industrial areas, the total exposure is calculated over the active work life period of (assumed) 45 years. The acceptable cancer-risk threshold is a threshold for one additional occurrence of cancer out of a given amount.

The **Risk evaluation** (Step 4) is the final interpretation of the findings referring to national regulations. The outcome of risk-modelling is the so-called risk index (RI) or the hazard quotient which can be defined as the relation between the calculated exposure (including background exposure) and the toxicologically derived TDI. In case that the RI is lower than 1 (calculated uptake < TDI), risks are not expected. In case that the RI exceeds 1, additional actions may be required, e.g.:

- Further field investigations to leverage the level of an accurate, site-specific environmental risk assessment as a RI exceeding 1 does not necessarily mean that adverse effects will occur,
- Emergency measures for risk mitigation,
- Long-term remediation measures,
- Site use restrictions.

The acceptable levels for a contaminant can vary significantly between countries, both in terms of how they are calculated (e.g. varying toxicological data sets, varying uncertainty factors), how a contaminant is considered (e.g. cancer effects) and which risk threshold is acceptable. For instance, in some countries, the threshold for an acceptable risk for cancer is $1:10^4$ (i.e. at maximum one individuum out of 10.000 will get cancer if exposed to the contaminant during the entire lifetime), in others the acceptable risk is $1:10^5$).

Re-assessment of risks is required if site conditions, legislation and guidance change. Therefore, the four steps of an environmental risk assessment are to be understood as an iterative process.

7.3 Derivation of risk-based remediation targets

The aim of remediation targets in the context of contaminated site management is to define minimum criteria for the elimination or at least mitigation of current or future hazards to relevant receptors caused by contamination along the migration pathway, e.g. via topsoil, subsoil, groundwater and surface water bodies.

Remediation targets are commonly defined as numeric values, but also non-numeric criteria can be defined as a target for the desired outcome of a remediation measure.

Accordingly, remediation targets…

- may be defined as textually described measures (e.g. “an off-site-migration of contaminants shall be prevented”) or as numeric values (e.g. 500 mg/kg for TPH in soil),
- shall be defined site-specific and in relation to current and future site use, taking into account the costs for remediation,
- shall be achievable by application of available technology and under the given site conditions,
- shall be justified, plausible and proportional,
- may be defined and adjusted stepwise throughout the course of an investigation and remediation project (preliminary → adjusted → final) depending on remediation progress and success,
- have a most significant impact on method, process, extent, costs, time and effectiveness of remediation measures.

In general, the derivation of numeric risk-based target levels (RBTLs) for a remediation is a “backward” risk assessment. The acceptable dose which a human or ecological receptor can be exposed to or of an acceptable water quality standard is used to back-calculate what concentration of a contaminant at the source is acceptable in maximum, using the same form of fate and transport and exposure models so that the RI at the receptors falls below 1. If concentrations of a contaminant are higher than the RBTLs, a remediation is required.

Even countries using screening levels instead of environmental risk assessments are using risk modelling tools to derive remediation target levels.

In general, it is recommended that not only technical and environmental factors such as the contaminant inventory and the concentrations, receptors and pathways are considered for site prioritization and classification but also criteria such as urban and spatial planning for the site and for the adjacent areas, possibilities for an economic development, interest of investors and other considerations in terms of the future development of the site.

Besides the remediation target values, remediation goals should also be defined as a result of the environmental risk assessment. According to (ICSS - International Centre for Soil and Contaminated Sites, 2007) these may be:

- A maximally admissible concentration of harmful substances,
- A maximally admissible mass flux of harmful substances (quantity) or
- A reduction of the contamination caused by harmful substances by a certain percentage, e.g. 90 %.

These values will be used as (preliminary) goals for the remediation feasibility study (see the following chapter).

Environmental risk assessment

The environmental risk assessment is a systematic process of evaluating the potential risks related to soil, groundwater or soil vapor contamination. It can be used as a tool (i) to evaluate the necessity of remediation, (ii) to evaluate the urgency of remediation, (iii) to evaluate whether precaution measures are required or not and (iv) to set risk-based remediation targets. The environmental risk assessment quantifies the contaminant migration along the source-receptor pathway taking concentration-reducing processes (retardation and degradation) into account. This requires a clear definition of the site-specific pathways and receptors as well as a quantification of the impact on the receptor. The derived data will be evaluated whether there is a real risk for the receptors.

8 Remediation feasibility study

8.1 Objective and process

The objective of the remediation feasibility study is to develop a remediation scenario which represents the best compromise in view of effectiveness and efficiency, based on the information derived from previous site investigations. A remediation scenario may be composed of various remediation methods that are applied at the same time in different areas or matrices or in a sequence (so-called "treatment train"). The (preliminary) remediation goals to be considered during the remediation feasibility study are already defined as a result of the environmental risk assessment (see Chapter 7).

In general, as a result of an ongoing communication with the liable party, the remediation feasibility study will be submitted to the authorities and, if appropriate, approved by them. In case that the environmental risk assessment revealed that the site poses a risk to human health and/or the environment and the problem owner does not fulfill the obligation in preparing a remediation feasibility study, the authorities may send an administrative (or official) order (enforceable order issued by a public authority, under the powers conferred to it by one or more statutes) to an individual or an organization to take certain corrective action or to refrain from an activity, forcing the problem owner to fulfill the obligation.

8.2 Summary of investigation results

As a basis for the remediation feasibility study, it is necessary to summarize the results of all investigations conducted at the site so far. First, the site location and site characteristics are described. Second, the geology and hydrogeology addressing any relevant seasonal (e.g. low or high groundwater level, tides) or historical (e.g. groundwater level increase over time due to reduced process water extraction) variations in the hydrogeological conditions are described. Then the data about contamination in each environmental matrix are presented: soil, groundwater, soil vapor as well as occurrence of NAPL. Usually concentration distribution maps, diagrams and graphics showing the concentration distribution (including concentration changes over time, if available) are very effective tools to present and analyze the data.

It should also be noted if a specific matrix (e.g. groundwater) has been proved to be uncontaminated.

Based on the source and plume geometry and contaminant concentrations, the total mass of contaminant present at a site, the contaminant inventory (see also Chapters 2.2 and 5), can be calculated. By combining hydrogeological data (hydraulic gradient, permeability, aquifer thickness, porosity) with plume geometry and contaminant concentrations, it is possible to determine the contaminant mass flux and mass discharge.

The site characterization also includes an overview of the natural biodegradation potential for the site-specific contaminants. This evaluation can be based on literature data and, if appropriate, on the interpretation of historical (already existing) data series at the site. If natural biological degradation seems to play a significant role in the contaminant removal and if the available data are not sufficient to quantify the actual contribution of this process to decontaminate the site, this aspect should be included in the data gaps list (see Chapter 8.11).

If remediation measures had been performed previously, these must be described as well as the success of these measures. All data should be summarized in the conceptual site model (see Chapter 6).

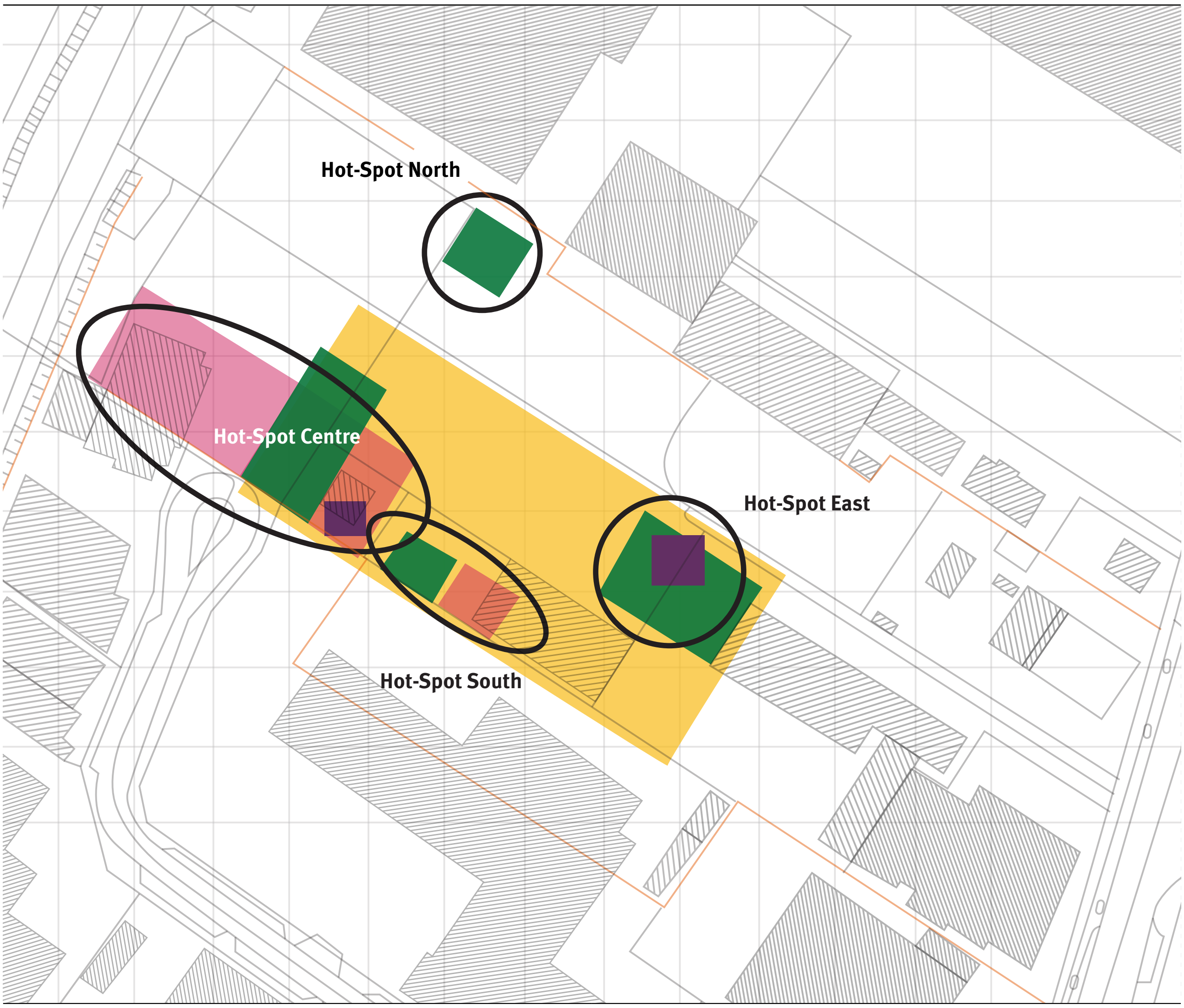
8.3 Definition of remediation zones

Not always can one single remediation technology be applied for a whole contaminated site. Often different remediation technologies must be selected for different zones. The most common criteria to differentiate the remediation zones are:

- Different media (e.g. vadose zone vs. aquifer, smear zone, mobile product phase, zones of different permeability or porosity),
- Spatially separated hot spots,
- Different contaminant treatability (physical, chemical, biological),
- Different underground permeability,
- Different site accessibility.

Figure 30:

Example of graphic representation of remediation zones



BTEX › 50 ug/L
CVOC › 20 ug/L
Volatile TPH › 1.000 ug/L
TPH › 0.5 ug/L

Source: Arcadis, own figure

An illustrative example of remediation zones definition based on the criteria separated hot-spots and different contaminant treatability is shown in Figure 30. Each of these remediation zones require a separate remediation feasibility study. The technology chosen may be different for each zone due to different contamination characteristics.

8.4 Specification of remediation goals

The basis for the specification of remediation goals is the data that has been collected during site investigations together with an assessment of all relevant potential receptors and the outcome of the environmental risk assessment (see Chapter 7).

The objective of a remediation is to reduce the risk deriving from a contamination to a tolerable (or acceptable) level. This level is calculated by the environmental risk assessment (see Chapter 7). Thus, the environmental risk assessment is an essential step in defining the remediation goals. Therefore, a summary and the results of the risk assessment are included in the remediation feasibility study including the description of the contamination migration pathways and risks for possible receptors. The (preliminary) fixed remediation goals must be listed.

However, other factors might influence the remediation goals. For example, the site owner might be interested in selling the property as soon as possible and aim for more stringent targets as the ones defined in the environmental risk assessment in order to avoid restrictions in the future site use. The intended sale of a site usually requires remediation technologies which are very fast. These are, in most cases, not the most efficient ones.

Reversely, if the environmental risk assessment results in remediation target values so low that they are technically impossible to be reached by remediation, other measures (e.g. containment, institutional control, see also Chapters 8.5 and 10.3.6) can optionally be considered. If, as a result of the cost-benefit analysis, it is determined that a proposed remediation is extremely expensive because of unproportionally strict targets, the remediation targets should be adapted.

8.5 Preliminary screening of possible remediation technologies

In general, remediation covers the two different approaches:

- Decontamination measures (contaminant removal) and
- Containment measures.

If the application of both is impossible or not achievable at reasonable costs or in case of a necessary short-term safety measure, institutional controls such as protection measures (e.g. construction of a fence, closing of a drinking water well) can be applied.

A comparison of the key features of decontamination and containment is shown in Table 9.

Table 9:

Key features of decontamination and containment

Decontamination	Containment
Reliable interruption of contaminant migration pathway (emission)	Reliable interruption of contaminant migration pathway (transport)
Contaminant removal	Contamination persists over very long times, high risk of failure of containment infrastructure over the time
Operation over a manageable time frame	Permanent operation and maintenance of the contained area including installations (> 50 years)
Moderate financial risks	High risks in calculation of operations' and maintenances times and costs
Risk mitigation possible in a manageable time frame	Permanent environmental liability of the site owner (risk of bankruptcy)
Moderate overall project risk	Incalculable overall project risk

In some countries, decontamination and containment are regarded as equivalent remediation options.

8.5.1 Decontamination

In the case of decontamination technologies, the contaminants are removed by biological, chemical or physical (e.g. thermal) methods. They provide the best possible and most durable results in remediation but are often expensive to implement. Decontamination can be further differentiated in in-situ technologies (treatment performed directly where the contamination is located) and ex-situ technologies (the media to be treated are extracted or excavated first, then treated). The most common decontamination technologies for the remediation of the saturated and vadose zone contaminated by petrochemical contaminants are listed and briefly explained below.

Biological

- **Aerobic**
  - **Oxygen supply (H_2O_2, O_2).** Microbial oxidation using oxygen is usually the fastest and most efficient biological degradation pathway for TPH, but the oxygen quantity in groundwater is limited and usually drops very fast in the presence of a contamination. Oxygen can be supplied to the groundwater as pure gas (injection) or hydrogen peroxide (infiltration diluted in water).
  - **Air-sparging or bio-sparging**. With this technology, oxygen is supplied to the aquifer in the form of atmospheric air (approx. 20 % oxygen) or pure technical oxygen, injected via special wells (small diameter, short filter screen) underneath the contaminated water. With air-sparging not only the aerobic biological activity is stimulated (oxygen dissolves in water) but also volatile compounds are stripped by the injected air. If VOC are present, air-sparging is usually combined with soil vapor extraction (SVE).
  - **Bio-oxidation wall**. The oxygen for the enhancement of aerobic biodegrading is delivered in a way that a reactive barrier perpendicular to the groundwater flow is generated in which oxygen is provided to the groundwater flow (e.g. high-pressure air-sparging).
- **Anaerobic**
  - **Injection of electron acceptors**. Other electron acceptors than oxygen (e.g. nitrate or sulfate) are injected as aqueous solutions in the aquifer to stimulate the biological degradation of contaminants, which are oxidized in the process. This technology is often suitable for TPH.
- **Monitored Natural Attenuation (MNA)** is rather a management approach than an active remediation technology. If it can be shown that no sensitive receptors are affected, that natural biodegradation is an essential process in contaminant fate and that the current spatial extension of the contamination is stable in space and time, MNA may be an acceptable approach. In a first step, the naturally occurring attenuation processes (biodegradation, volatilization, physicochemical immobilization or degradation, dilution) needs to be evaluated. Once the prerequisites are fulfilled, a long-term monitoring can be started. Over the time (usually very long periods), natural attenuation will lead to the decontamination of the site.
- **Natural Source Zone Depletion (NSZD)** is also rather a management approach than an active remediation technology. In contrast to MNA, NSZD refers to the natural elimination of NAPLs via vaporization, dissolution and biodegradation in the vadose zone or the aquifer.

Chemical

- **In-situ chemical oxidation (ISCO)**. Oxidizing agents (e.g. hydrogen peroxide, Fenton reagent, persulfate, permanganate) are injected in diluted aqueous solutions into the aquifer to allow completely spontaneous oxidization of the contaminants to harmless end products (CO_2, H_2O).

Physical

- **Dig-and-dump**. Excavation and usually disposal of the contaminated soil on landfills. It is also possible to decontaminate and to re-use the soil.
- **Pump-and-treat**. Contaminated groundwater is extracted via pumps and cleaned before discharging it to the sewer or re-infiltrating it. The groundwater extraction can be done via wells or drainages. For the treatment, there are several options depending mainly on the contaminant properties, the most common being sand filtration, stripping and sorption on granular activated carbon (GAC).
- **Soil vapor extraction (SVE)**. Contaminated soil vapor is extracted from the underground via wells screened in the vadose zone by applying a vacuum. Volatile compounds can be removed from the vadose zone with this technology and treated in a gas treatment plant. The most common treatment options are sorption on GAC and catalytic oxidation. For well combustible compounds at high concentrations, incineration can be an option.
- **Dual-phase extraction (DPE)** and **multi-phase extraction (MPE)**. These technologies comprise the extraction of two media (DPE: usually groundwater and soil vapor) or more media (MPE: groundwater, soil vapor and NAPL) at the same time. This can be done applying very high vacuum at a point in the subsurface just below the NAPL and separating the phases ex-situ or extracting each phase with a separate system (e.g. water pump, NAPL pump, compressor). Each contaminated media must then be treated prior to discharge.
- **In-situ thermal remediation (ISTR)**. This is the removal of contaminants (adsorbed, dissolved or as NAPL) by increasing the underground temperature. The mobilized (i.e. evaporated) contaminants are usually removed via SVE or MPE. There are different ISTR technologies using different principles of heat generation:
    - Thermal conduction heating (TCH),
    - Electrical resistance heating (ERH),
    - Steam enhanced extraction (SEE).
- **Smoldering** (in general referred to as self-sustaining treatment for active remediation, STAR) is also a thermal technology. Here, atmospheric air is injected into the saturated zone to allow – after ignition – the smoldering of residual product phase. Moderate increase in temperature can also be used to reduce the viscosity of NAPL and enhance their recovery rate or to promote biodegradation.
- **Soil flushing with alcohol or surfactants**. Alcohol- and/or surfactants-containing water is injected into the aquifer. The contaminants adsorbed to the soil surface or present as NAPL dissolve into the injected liquid because of the chemical properties of alcohol and surfactants. The injected fluids are usually recovered by pump extraction and treated.

8.5.2 Containment

Containment methods prevent the spreading (emission) of the contaminants. The selected containment measures are depending on the type of contaminant (i.e. gaseous, liquid or solid) and the migration pathways to the potential receptors (i.e. direct dermal contact) (ICSS - International Centre for Soil and Contaminated Sites, 2007, pp. 35-41).
They include:

- Surface lining or capping (to prevent gas release, direct dermal or inhalation contact or to avoid leaching by rainwater),
- Immobilization (addition of binding substances, such as cement, to immobilize harmful substances or addition of sorbing materials),
- Installation of extraction wells (hydraulic barrier),
- Construction of physical barriers (e.g. diaphragm, sheet pile walls, reactive barriers).

In the preliminary screening of possible remediation technologies, the complete set of applicable remediation methods is evaluated to select those appropriate for the site under consideration. Unsuitable methods are excluded from further consideration. The properties of the contaminants and soil properties have to be proved to be the main criteria for exclusion. However, other aspects play a role in the technology selection including:

- Age of contamination,
- Structure of the contaminated media,
- Matrix structure (materials and permeability),
- Plume thickness and 3D-distribution within aquifer and aquiclude,
- Biogeochemical environment,
- Contaminant distribution (mass storage zones vs. mass transport zones),

- Fluid transport characteristics (natural groundwater flow velocity, injectability of fluids),
- Mobility of product phase,
- Contaminant migration pathways and
- Site use.

It is not recommended to use published selection matrixes for technology screening. Many site-specific factors require expert judgment. In addition, a detailed knowledge of all available remediation technologies and their application limitations as well as of contaminant fate and transport processes is necessary to efficiently conduct this design step.

8.6 Development of remediation scenarios

For each preselected technology, the applicability at the site is described in detail in the remediation feasibility study (remediation pre-design, see Chapters 8.9 and 8.11). For the remediation of contaminated sites often complex measures are necessary. They could be composed of several methods applied in combination, in different zones or at various times. For example, the remediation of a landfill can include surface capping, gas extraction (and purification) as well as seepage water collection (and treatment). The remediation of a former industrial site can be implemented by excavating and treating or disposing of the soil from one zone and by covering the surface of another. That is why respective remediation scenarios referring to partial areas are to be developed to prepare the comparison of feasibility and costs.

8.7 Technical assessment of remediation scenarios

The assessment of the applicability of remediation scenarios shall be in first instance made according to the following criteria:

- Applicability of the technology with respect to contaminant-, soil-, materials- and site-specific constraints,
- Technical feasibility,
- Time required for remediation,
- Probability to achieve remediation targets,
- Relationship between costs and effectiveness,
- Impact on the neighboring persons or workers on the site,
- Impact on the environment (e.g. emissions and possibilities for emission reduction),
- Requirement of authorizations,
- Production, recovery and disposal of waste,
- Occupational health & safety measures,
- Monitoring possibilities,
- Possibilities for remediation optimization in case of suboptimal remediation outcome,
- Needs for aftercare.

The range of criteria and their importance for the specific project must be assessed in a discussion between the entity responsible for the remediation and its consultant. The result of the assessment is then presented and discussed with the regulator.

The assessment of these criteria can be done in textual form or in form of a matrix. For each criterion, including sub-criteria to be generated individually, points may be given. These may range from 1 (disadvantage) to 5 (well-suitable for the investigated scenario). Weighting is recommended. Multiplier can also range from 1 to 5. For example, if an early re-use of the remediated site is wanted, a fast remediation is much more advantageous than a slower one.

The final score for each scenario is the sum of products of the points assigned for each scenario and the respective weight. The scenario obtaining the highest final score represents the best option. An example of the application of such an approach is shown in Table 10 in which the option Scenario #4 was chosen as best option. The weight factor may vary and is chosen according to site-specific constraints.

The disadvantage of such an approach is that it is difficult to choose the right criteria and assign the correct weight to all scenarios. In any case, to avoid an overvaluation of less important parameters, multipliers are necessary.

Table 10:

Example of multi-parameter cost-benefit analysis

		Scenario (points = scoring x weight)					
Weight (1-5)	Parameter	#1	#2	#3	#4	#5	#6
5	Cost	2	4	4	3	3	0
5	Probability to achieve remediation targets	0	1	2	4	3	5
3	Time to completion	0	1	2	4	4	5
1	Maturity of the technology	5	5	3	2	3	4
1	Impact on neighboring persons	0	1	2	4	3	5
1	Health & safety at work	0	1	2	4	4	5
1	Impact on the environment	0	0	1	3	2	5
1	Production, recovery and disposal of waste	0	0	0	4	3	0
1	Uncertainties	0	1	1	3	2	4
Total		15	36	45	67	59	63

8.8 Assessment of long-term effectiveness

The long-term effectiveness of a remediation measure is a basic EU requirement. The consideration is based on three principles:

- **Suitability**. Achievability of the remediation goals,
- **Necessity**. Action is required if no other, equally effective, but for the stakeholder less demanding technology can be selected,
- **Appropriateness**. Balance between the extent and costs of the measure and its urgency and severity.

8.9 Cost estimate

The project-related costs for every remediation scenario must be estimated. This requires a **remediation pre-design** as a first step on which cost estimates are based. The considered remediation scenarios should be divided into individual measures so that a comparability is guaranteed.

The following subdivision is suitable for this purpose:

- Preliminary activities (planning, requests for proposal, invitation to tender and contracting),
- Constructing and other activities accompanying the technology (e.g. fences, intermediate storage, reconstruction of site facilities, site preparation),
- Core activities (remediation including supervision and reporting),
- Aftercare activities (e.g. monitoring, see Chapter 10.3.4. and Chapter 11).

The costs of all activities need to be calculated by combining the specific costs with the quantities required (e.g. number of wells, mass of soil to be remediated, duration of the remediation measure as well as staff and equipment costs).

Investment costs (CAPEX, capital expenditure) and operating costs (OPEX, operating expenditure) are to be differentiated. The budget needed at the beginning of a remediation project for the installation of the remediation system and the related infrastructure corresponds to the CAPEX, while generally lower expenditures for the ongoing operation and maintenance (OPEX) are required after the start of the remediation.

Hence, the overall costs can be calculated as follows:

$$\text{Costs} = \text{CAPEX} + \text{OPEX} \times \text{time}$$

The duration of the remediation can theoretically be determined as follows:

$$\text{Required remediaton time} = \frac{\text{Contaminant mass to be removed}}{\text{Removal or degradation rate}}$$

However, the removal or degradation rate usually changes over time. It also generally decreases as the contaminant concentrations become lower and is often difficult to determine. Therefore, this calculation may be very complex and very inaccurate. Currently, time estimates are based on experience. If the considered time frame is particularly long, it is possible that the remediation system must be completely replaced before the target value is reached. The life cycle of remediation installations (e.g. wastewater treatment plants) can be assumed to be approx. 20 – 25 years (individual components susceptible to wear such as pumps: 5 years), whereas containment installations may last longer (50 – 100 years, depending on the site conditions). The reinvestment related to the remediation system replacement is accounted for in the cost estimate. The costs may vary in a very broad range, usually mostly dependent on the remediation duration and the method used.

Remediation projects may take years or even decades to come to completion. In such long time frames, financial conditions like interest rates and inflation can change considerably. Therefore, these variations should be estimated and considered when estimating the total costs for a remediation. A common method is using the net present value (NPV) as a cost indicator.

$$\text{NPV} = C \times \frac{1}{(1 + z)^{T}}$$

With C = future payment (cost, individual event), T = time in the future; when payment is due compared to today: T = 0) and z = net interest rate (interest minus inflation). The interest and inflation rates can be derived from statistical databases. The sum of the NPV of all future expected expenses related to the remediation represents the total costs projected at the beginning of the project itself.

The cost estimate in the remediation feasibility study phase does not need to be overly accurate.

According to the *Cost Estimate Classification System* of the Association for the Advancement of Cost Engineering International (AACE International, 2016), the expected “*cost estimate accuracy range*” for a project depends on the level of project completion by the time when the cost estimate is performed and thus on the increasing availability of data and information during the course of a project.

For example, if the cost estimate is carried out at an early project stage (Estimate class 4: level of completion 1 % – 15 %), the expected accuracy range of the cost estimate is rather broad (low: -15 % – -30 %, high: +20 % – +50 %). In contrast, if the cost estimate is carried out at an advanced project stage (estimate class 2: level of completion 30 % – 75 %), the expected accuracy range of the cost estimate is significantly more precise (low: -5 % – -15 %, high: +5 % – +20 %).

As remediation feasibility studies are commonly performed at an early stage of the entire remediation project, the expected accuracy range of the cost estimate is rather broad.

As long as the data set on which the estimate is based presents uncertainties, the cost estimate cannot be a single defined amount but always has to be a range. Most typical low and high boundaries for this range are the best and worst case.

In the best case, the uncertainties are kept at the lowest plausible minimum and the minimum expected quantities are considered (e.g. minimum estimated source extension). The opposite is valid for the worst case. However, having a worst-case and best-case calculation is often not sufficient for the purposes of the liable party, who usually needs to provide reserves for the remediation activities. For this purpose and to provide a realistic amount to use for further evaluations, a third case – the so-called most reasonable case – can be calculated. This amount should not be arbitrarily set to the average of the worst and best case but rather be calculated based on assumptions dictated by extensive experience in the field of environmental remediation.

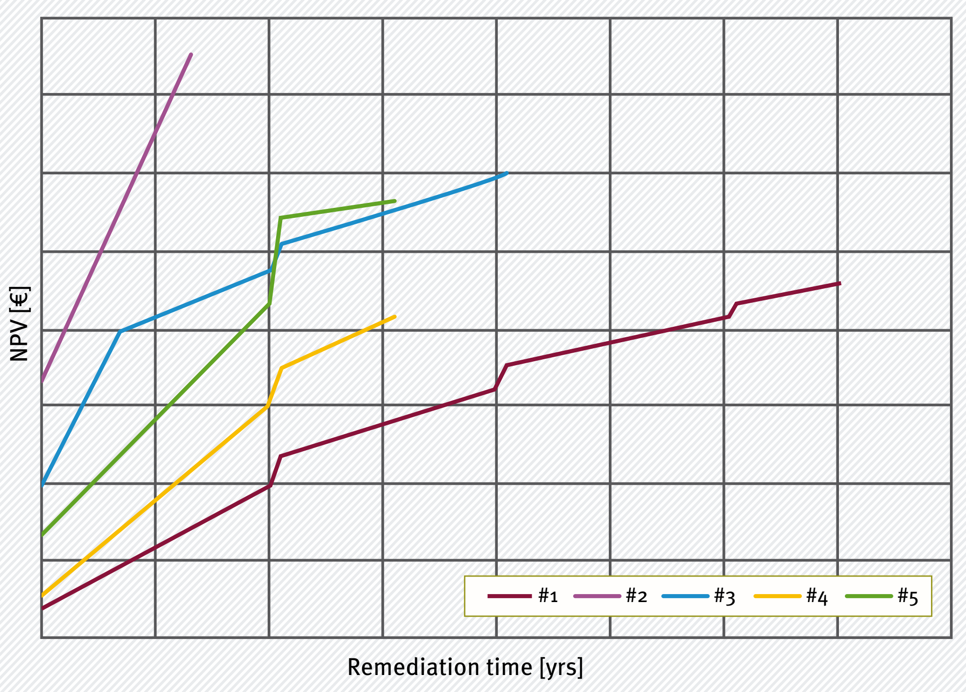
To check the plausibility of the cost estimate and to identify optimization options, a sensitivity analysis should be performed at the end of the cost estimate in order to verify which items will mostly influence the total costs. The information sources for the estimate of the most influencing costs must be as reliable as possible (e.g. concrete, multiple quotes from subcontractors, other projects with very similar conditions) to avoid biasing the overall cost estimate.

8.10 Cost-benefit analysis

As indicated, the scope of a remediation feasibility study is to find the best compromise of technical effectiveness and efficiency provided authorities approval is possible. Therefore, not only the costs but also other non-monetary parameters (see Chapter 8.7) are considered to make the final choice. To compare only the costs and have a good overview of the cash flow (when and how much is expected to be spent) graphs representing the cumulative costs of different options are often used. An example is shown in Figure 31.

Figure 31:

Examples of cumulative cost curves to determine the break-even point

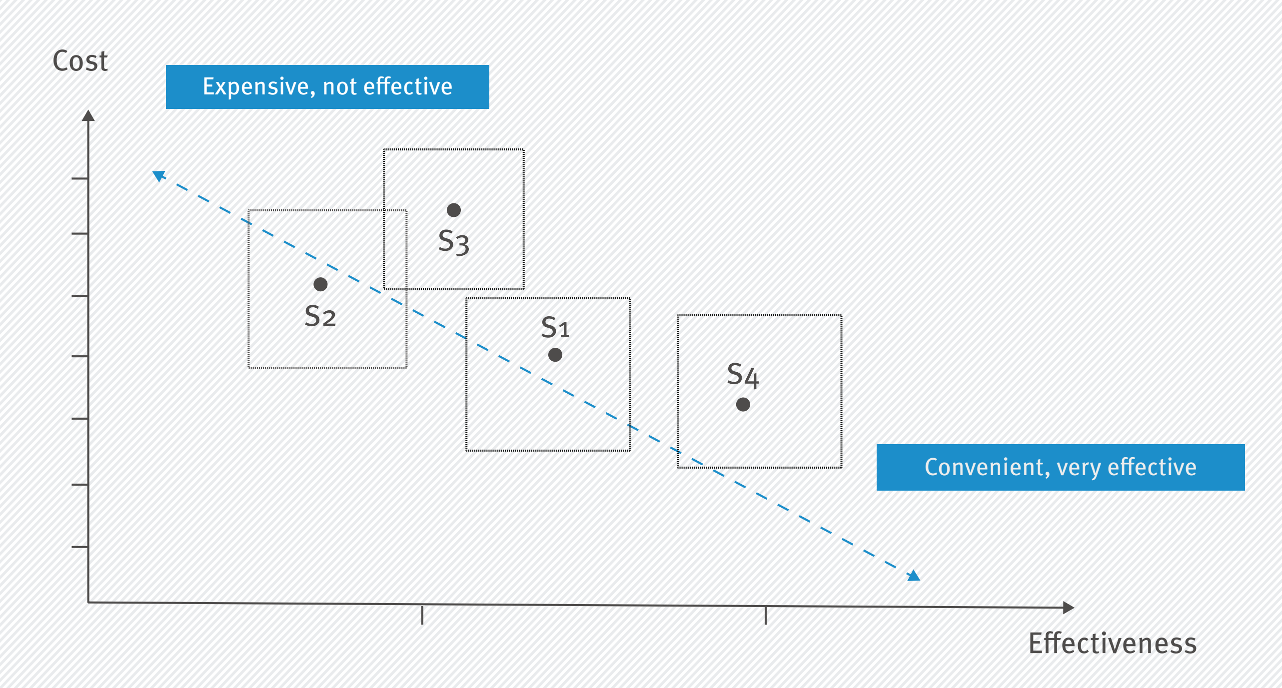


Source: Arcadis, own figure

These graphs also allow the identification of the so-called "break-even point", which is defined by the intersection of the cumulative cost curves for different scenarios. The time corresponding to the break-even point represents the time after which a certain scenario becomes more convenient than another. This can become essential in the scenario comparison if the operation of the system is limited to a certain number of years. Otherwise, the most important data that are easily readable and comparable from such a diagram are the overall duration and costs of each option as well as the cost distribution over time. In this example scenario #4 would be the best one because of the lowest costs and shortest time.

Figure 32:

Example of a cost-benefit analysis including minimum-maximum considerations



Source: Arcadis, own figure

A more obvious evaluation is shown in Figure 32. For each scenario, the benefit (sum of points of technical and non-monetary evaluation) is plotted against the costs (best, worst, most realistic case). On the left upper end appear the most extensive technologies with low benefit, on the right lower end appear those technologies showing high benefit and low costs. From the graph, the most appropriate technology becomes evident at one glance, in our case it is Scenario 4.

In general, the process for the selection of the most appropriate remediation technology follows the **best available techniques not entailing excessive costs (BATNEEC)** principle (see e.g. Sorrell, 2001). BATNEEC was first introduced in 1984 at EU level with the Directive 84/360/EEC (Industrial Plants Directive) and applied to air pollution emissions from industrial facilities. It is now a generally accepted principle for defining a suitable remediation approach while considering ecological and economic aspects based upon the principle of proportionality (see Chapter 1.4). This implies that there might still be residual contaminations after remediation has been completed, which may lead to restrictions regarding the future site use and/or appropriate aftercare measures.

8.11 Data gaps

At the end of the investigation phase, contaminant data are available that allow a detailed environmental risk assessment. In many cases the resolution of these data is not sufficient for an appropriate remediation planning. Furthermore, during the performance of the feasibility study, additional questions may arise which may be property- or technology-specific. Frequently, the following data are lacking:

Property-specific

- Detailed vertical delineation of the source and/or plume,
- Highly resolved data on contaminant distribution (especially in the saturated zone),
- Concentration of soil-associated contaminant concentrations in the saturated zone (concentrations of contaminants in groundwater are not sufficient),
- Hydrogeologic data, for instance soil permeability, porosity, aquifer thickness;

Technology-specific

- Radius of influence (ROI),
- (Bio)degradation potential and rate,
- Soil oxidant demand (SOD) if oxidation technologies are considered.

Filling these data gaps may be regarded as a part of the feasibility study. In reality, these studies (as well as potentially required pilot tests, see Chapter 8.12) are done in an additional step – the so-called “pre-design investigation”. The costs for the pre-design investigation are also estimated during the remediation feasibility study in order to quickly proceed to the implementation.

8.12 Pilot testing

A pilot test is a test of a technology on a smaller scale. The remediation technology selection as well as the cost estimate during the feasibility study are based on similar cases and literature data. However, for a more accurate cost estimate and for the preparation of the remediation plan, site-specific data are needed that depend on the selected technology. These data can be collected during additional investigations that are carried out as part of the feasibility study to fill the data gaps (see Chapter 8.11), in bench scale tests and/or in a pilot test. Whereas bench scale tests (small scale tests simulating the remediation being performed in the laboratory using soil and groundwater samples from the contaminated site) are not necessary in most cases, a pilot test is recommended for most remediation alternatives. A pilot test must be planned in detail. The following aspects are to be defined clearly before the test starts:

- What is the goal of the test?
- Which data can be collected?
- Which are the limitations of the test? Which information cannot be collected?
- Under which conditions must the test be considered as “failed” (which means that another technology needs to be chosen)?

The most important goal of a pilot test is to determine parameters needed for a full-scale planning (e.g. ROI during injection, injection pressure, optimal reagent concentration in injection fluid, NAPL recovery rates, etc.). In addition, the pilot test serves as a **proof of principle.** Only in very rare cases, the pilot tests are used to demonstrate that the remediation goals can be achieved since this would require a very long pilot test operation time.

The monitoring of a pilot is usually much more intensive than in the full-scale remediation in order to collect as much information as possible and to take some unforeseen test developments into account. For instance, if an injection technology is being tested for which the radius of influence is to be determined, it is recommended to set monitoring points in at least 3 directions (oriented at approx. 120° angular distance from one another) and to monitor the breakthrough of the injected media also at a shorter distance than the planned ROI, to avoid “missing” the breakthrough if it happens at a shorter distance than expected. Reversely, the monitoring frequency should be higher than what is reasonably required in order to be able to collect data even if the breakthrough happens faster than expected.

Because of the intensive planning and monitoring as well as a high probability of contingencies due to the nature of the test, the “specific cost” (cost per treated m^3 of soil or groundwater) can be relatively high for a pilot test. However, this is justified since it builds the basis for a solid full-scale planning. An exemplary content breakdown for a remediation feasibility study is shown in Annex 3.

Remediation feasibility study

The objective of the remediation feasibility study is to develop a remediation scenario which represents the best compromise in view of effectiveness and efficiency. Since this objective is based on information derived from previous site investigations, the relevant information should be summarized as first chapters of the feasibility study together with the results of the environmental risk assessment and the specification of remediation goals.

The feasibility study starts with the definition of remediation zones. Based on the contamination pattern, different zones may require different remediation technologies. The technologies which are feasible in principle are chosen from all available technologies in a preliminary screening. In a next step, the potentially feasible technologies are further assessed with respect to their applicability under the site-specific conditions.

Remediation technologies may include decontamination (biological, chemical or physical including thermal) or containment. Only in case that both are not feasible, institutional control (e.g. closing of a drinking water well or construction of a fence) may be selected.

Based on the derivation of the remediation zones and the detailed site-specific evaluation of suitable technologies, possible remediation scenarios are developed, technically assessed and non-monetarily evaluated. The estimation of costs of each scenario requires a remediation pre-design and an estimation of the time that is required for remediation. Usually the most efficient technology is chosen. In case the costs do not differ substantially, a multi-parameter cost-benefit analysis may help to find a decision.

Site-specific or technology-specific data gaps that are identified during the feasibility study are solved by additional site investigations. These may also comprise laboratory or pilot testing. During the pilot test, specific data are obtained that allow the full-scale planning of the remediation.

Finally, the remediation feasibility study will be submitted to the competent authorities, and after approval of the proposed preferred remediation method, the planning process can start.

9 Remediation planning and tendering

The selected remediation scenario is developed into a detailed remediation plan in which all elements of the planned remediation are described in detail. The remediation plan is submitted to the competent authority for approval. Once approved, the tendering process and thereafter the full-scale remediation can be started as planned.

9.1 Stakeholder involvement and management

Remediation projects comprise in general very complex measures affecting individual interests of several parties such as persons, companies and authorities (stakeholders). The following stakeholders should be involved:

- Liable party,
- Environmental regulator,
- Consultants for each party,
- Contractor performing the remediation.

In some cases, also the following stakeholders might be involved:

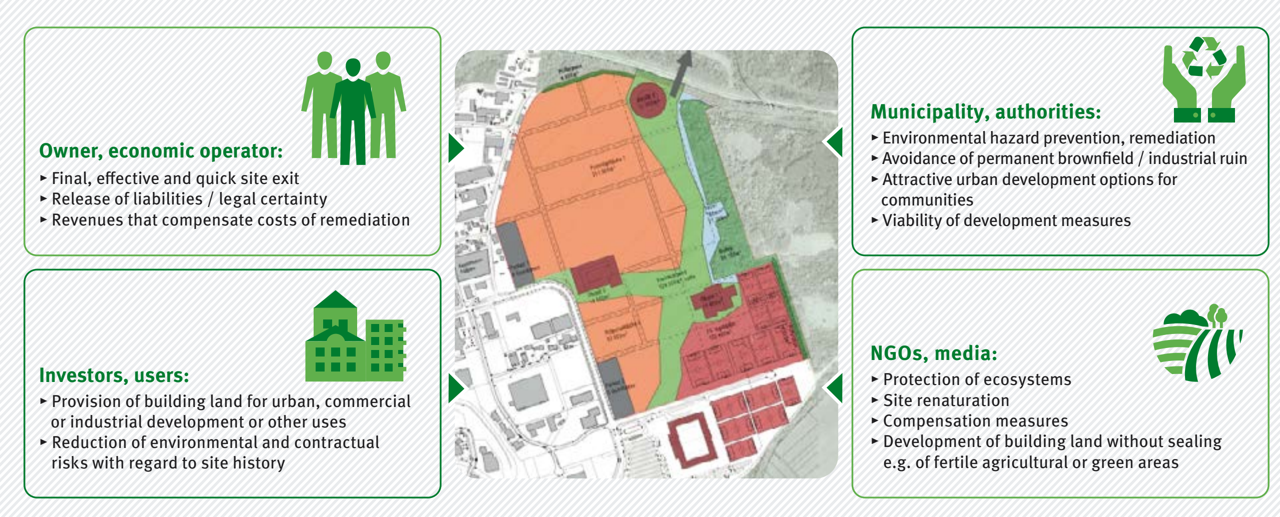
- Insurance of the liable party,
- Residents in the source or plume area,
- Press,
- Neighboring industrial sites or site owners,
- Local regulator,
- Civil society, e.g. environmental non-governmental organizations (NGOs).

It is important to identify all stakeholders in a project as soon as possible and to clarify for each of them clearly the role they play in the remediation procedure. Aspects to be considered are:

- Area of competence,
- Interest in the remediation (low/high, which aspects are a priority),
- Importance in decision-making,
- Liabilities involved,
- Phases in which stakeholders have to be informed and even involved.

Figure 33:

Stakeholder groups and their specific interests in a site development project



Source: (Arcadis Germany GmbH, 2018)

In projects with few stakeholders, their management can be simply integrated in the project management. In more complex cases (e.g. sites of national interest, risk for residents, etc.), it is recommended to engage a team with the task to manage the information exchange with all relevant stakeholders. It could be reasonable that this team meets on a regular basis to exchange information and to discuss required next steps, if appropriate. The team leader (usually a consultant or an external independent professional) may also set-up professional communication management methods like hotlines, question & answer databases, press releases and newsletters.

The stakeholder management and involvement shall be continued until the entire remediation project has successfully been completed.

9.2 Detailed planning of the remediation measures

The detailed planning of a remediation measures is a demanding task that requires in-depth understanding of the underground conditions and the applied remediation method and also a full understanding of the site-specific situation and possible restrictions. A major concern might be that many remediation technologies require full spatial access to the entire contaminated subsurface body, which could be explained by an example: If, for instance, in-situ chemical oxidation (ISCO) has been selected as the best suitable remediation technology, the oxidizing agent must be injected in form of an aqueous solution via various injection wells into the underground, and the volume of the injected aqueous solution has to be equivalent to the volume of contaminated groundwater within the treatment zone. For this example, full access to all injection locations which are required for ensuring the best possible efficiency of the remediation method might not be possible on some and particularly on active sites.

However, these aspects are usually considered already during the remediation feasibility study, and the general applicability of the selected method should have been verified and confirmed prior to the detailed planning of a remediation project and its measures.

9.3 Remediation plan

In the remediation plan, all aspects of the remediation project that are relevant for remediation execution are described in detail, including health & safety requirements, logistics, aspects of remediation supervision and subsequent measures such as monitoring activities during the remediation as well as post-remediation monitoring. A summarizing repetition of the specific situation at the site including lithological and hydrological properties and the type of contamination as well as a description of the chosen remediation technology is not necessary as these have been outlined in detail in the remediation feasibility study (see Chapter 8).

The remediation plan includes at least the following elements:

- **Project logistics**
  - Liable party,
  - Other involved stakeholders,
  - Competent authority;
- **Regulatory aspects**
  - Remediation targets,
  - Description of the required permits (see Chapter 9.4) and other general conditions;
- **Site logistics**
  - Set-up and organization of the working area,
  - Underground utilities in intervention area,
  - Aboveground infrastructure in intervention area,
  - Material handling (storage areas, transport routes, etc.),
  - Waste management (storage areas, transport routes, disposal methods, etc.);
- **Implementation criteria** (for each remediation zone)
  - Maps indicating the intervention points and/or areas (e.g. injection points, excavation areas, monitoring points),
  - Description of the remediation process and equipment used for the remediation, for instance the flow diagram and explanation of working principle of a treatment plant, the indication of the main characteristics of the equipment used (e.g. maximum pressure and flow rate to be performed by a pump),

  - Detailed description of the planned activities (work plan) including overall duration and deadlines for the completion of various elements of the remediation work,
  - Mass calculations (energy needed, injected reagents, extracted water, disposed soil, etc.);
- **Operation description**
  (for each remediation zone)
  - Operations' responsibilities,
  - Maintenance extent and frequency,
  - Monitoring activities including monitoring plans (see Chapters 10.3.4 and 11.2),
  - Criteria for performance assessment;
- **Remediation aftercare monitoring**
  (for each remediation zone) (see Chapter 11);
- **Health & safety aspects** (see Chapter 13)
  - A health & safety plan (HASP) in accordance with the occupational health & safety regulations of each respective country has to be developed, usually in cooperation with the technical contractors who deliver and install the remediation technology; thus, the HASP might be finalized only after contractor selection has been completed (see Chapter 9.5),
  - Safety-related aspects of technical installations for the remediation project ("Integrity Management", e.g. groundwater treatment systems) have to be considered as well,
  - Particularly on active sites, health & safety aspects which are related to the ongoing operations must be considered with respect to both task-related and technical processes;
- **Schedule**;
- **Cost estimate including annual cash flow.**

The remediation plan must be fully compliant with the existing (environmental) regulatory framework of the respective country. In addition, the plan has to be prepared and signed by a competent person who meets relevant formal and regulatory requirements.

9.4 Permitting process

In most countries, particularly of the EU, the liable party (site owner, polluter or other liable party) is responsible for submitting the completed remediation plan to the competent authority. The remediation plan must be approved by relevant authorities before the works are commenced. Optionally, the competent authority may require additional work on the remediation plan prior to the approval. The written approval may contain additional requirements, which must be considered or fulfilled during the remediation.

Once the remediation plan has been approved, the liable party may commence the remediation works. The competent authority should maintain a monitoring and inspection function throughout course of the remediation project.

Other aspects of the permitting process are potential additional permit requirements which comprise, but are not limited to, health- & safety-related permits in case that emissions could occur. These might be:

- Noise (e.g. during drilling works or the installation of steel sheet piles),
- Dust (e.g. during demolition and excavation works),
- Gases (e.g. during remediation of light-volatile compounds).

In addition, permits under water law might be relevant in case of groundwater remediation and particularly if substances with respect to the application of in-situ technologies (such as ISCO) have to be injected into the groundwater as part of remediation execution.

If investigation or remediation activities may interfere with public transport infrastructure (roads, railways), specific permits from the respective transport authorities, road or railway operator might be required as well.

It is strongly recommended that these aspects are considered in the project planning process as early as possible in order to avoid legal conflicts or delays in project execution.

9.5 Tendering process: Subcontractor selection and contracting

The remediation plan that describes in detail the needed equipment and activities and the approval by the authority constitute the basis for the request for proposal (RfP) of a remediation project. As a first step, the services that are required for the remediation are organized into packages which can be delivered by the same subcontractor. Common packages are:

- Drilling services,
- Construction of pipelines,
- Construction of remediation plants as well as subsequent operation and maintenance of the system,
- Analytical services,
- Consulting including engineering and supervision.

A RfP is prepared for each package.

There are different ways to find appropriate bidders. Often, it starts with a preselection of potential bidders. The most objective way of preselection is the publication of the RfP on internet portals with open access. In this case, the bidders have to provide together with the RfP additional documents which demonstrate their experience and quality and also proof that regulatory requirements (e. g. certifications according to regulatory requirements) are fulfilled. Usually, the RfP specifies which documents are needed for this purpose. If the RfP is not published on a public internet portal, at least five capable bidders should be asked for a proposal.

The level of detail of the services description in the RfP can vary depending on the kind of RfP:

- Usual RfP's are very detailed to avoid any ambiguity and misinterpretation. However, this requires a considerable effort and technical knowledge in preparing the RfP (on the side of the tendering entity) and sometimes also in preparing the proposal (on the side of the bidder). The additional costs for these increased efforts are usually compensated by a lower risk in the following project phases in comparison to the so-called "functional" RfP.
- The so-called "functional RfP" has a low level of detail in the services description. It is the tasks of the bidder to develop a detailed design of the requested activities during proposal preparation. Although this form of RfP saves engineering effort on the side of the tendering entity before the tendering process starts, it requires particular attention in the way the various items, for which calculations are requested, are defined. Too vague wording may lead to misinterpretations of the services requested and consequently to over- or underestimation of the costs.

A "functional" RfP can potentially lead to the assignment of the work to an inappropriate candidate, to inappropriate cost estimates and, in the worst case, to legal actions from contractors who feel disadvantaged in comparison to competitors because of an insufficient work scope description. For instance, if a contractor interprets the unclear wording to his/her advantage and calculates a lower price for a certain item, he/she may receive the contract; after the assignment, he/she could clarify his interpretation and request a change of contract to cover the additional expenses needed to provide the service that is actually needed. A competitor who interpreted the RfP correctly could have offered a higher price for the same item and would not have got the contract, although his/her total costs would be lower than the total costs of the bidder who received the contract with an inappropriate low price during the tendering process. The other competitor could sue the tendering entity. Hence, functional RfP's should be avoided as far as possible.

Independent of its form, a RfP shall include at least the following elements:

- Information about the **tendering process** and **involved parties** (site owner, liable party, authorities, deadlines, procedure, possibility to visit the site, contact data, criteria for contractor selection, etc.);
- General information about the **site**:
    - Location,
    - Accessibility,
    - Utility supply (energy, compressed air, gas, water, wastewater discharge possibilities, telephone and internet connection),
    - Availability of areas for storage of the remediation equipment and machines,
    - Relevant regulatory information (orders issued for the site, target values, emission limits, etc.),
    - Information about the media to be treated,
    - Other activities at the site at the time of the planned remediation;
- Detailed information about the **requested services** in the package, e.g. in the case of operation and management services for a groundwater treatment plant:
    - Description of the treatment process and equipment,
    - Operation and maintenance concept,
    - Management concept for consumables (e.g. activated carbon),
    - Disposal concept,
    - Analytical monitoring,
    - Quality assurance;
- **Legal aspects**:
    - Relevant general occupational health & safety regulations,
    - Project-specific health & safety regulations,
    - Required security services,
    - Operation instructions,
    - Compliance with all other relevant laws and technical regulations,
    - Staff training;
- **Requirements** and **compliance**:
    - Warranties,
    - Performance requirements;
- Annexes:
    - Site overview and detailed map,
    - Relevant documents (e.g. remediation order, discharge permit, etc.),
    - Package-specific documentation, e.g. for a groundwater treatment plant:
        - Piping and instrumentation diagram (P&ID),
        - Equipment list and characteristics,
        - List of and map indicating the sampling points,
        - Groundwater analyses,
    - Service specifications, i.e. a list of line items with a short description of the technical specifications, each with unit, quantity and space for inserting unit price and total price.

The proposals are evaluated with respect to the following aspects:

- **Content**. Have all requested information and documentation been delivered? Does the proposal comply with the RfP (complete, correct interpretation, etc.)?
- **Technical aspects**. Are the proposed services correct from the technical point of view? Can the proposed technical equipment comply with the requirements indicated in the RfP?
- **Calculation**. Are the indicated total prices correct? If not, it is assumed that the single prices are correct, and the total price is corrected by the consultant evaluating the proposal.
- **Additional proposals**. Has the bidder made additional proposals which may lead to a lower price or an improved remediation process? Are these technically sound, can they be accepted, and do they lead to cost savings?
- **Comparison**. Finally, the different proposals are compared to one another in terms of:
    - Price,
    - Proposed technical solutions if not specified in the RfP,
    - Other possible criteria, which are to be specified in the RfP (e.g. energy efficiency, experience and quality).

The price should not be the only criterion for the selection of the contractor. Very important is that the contractor has fully understood the scope of work, is reliable and has already shown good quality for an economic price in the past. Otherwise, many unexpected expenses may arise during remediation performance by mistakes or misunderstandings.

For the assurance of full comparability of the submitted proposals, the relevant proposal items (in general calculation and quality documentations) are transformed into a common format, and a scoring system is applied for the evaluation of the proposals.

For complex proposals and especially in the case of functional RfP's, it is recommended to conduct a clarification meeting with the bidders who are most likely to receive the contract. In the meeting, all technical details and uncertainties in the tendering process can be discussed and clarified. In general, the minutes of the meeting should be integrated into the contract. The finally selected contractor receives a purchase order (contract), either directly from the liable party or, if a general contractor is in charge of the project, from him.

After the contract has been signed, the project schedule prepared for the RfP is transformed to a cash-flow diagram. Both diagrams are the basis for the project management in the remediation phase.

Remediation planning and tendering

The implementation of the remediation project will be based on the approved remediation plan that has been developed based upon the outcome of the feasibility study. The process is a concerted effort of all involved stakeholder. First, the remediation project must be described in detail in the remediation plan (timing of the activities, necessary quantities of reagents, waste production and treatment or disposal, impacted areas, influences on neighbors, etc.). The remediation plan needs to be approved by the competent authority. The written approval may contain additional requirements, which must be considered or fulfilled during the course of the remediation project.

In general, all remediation activities are performed by (technical) contractors. The contractors are selected based on a formal tendering process. The request for proposal (RfP) should be very detailed to avoid any ambiguity and misinterpretation. During the evaluation of the proposals, the price should not be the only criterion for the selection of the contractor. At least as important is that the contractor has fully understood the scope of work, is reliable and has already shown good quality for an economic price in the past. For complex proposals, it is recommended to perform a meeting with the bidders in which all technical details and uncertainties can be clarified. The minutes of the meeting should be integrated into the contract.

10 Remediation

10.1 General goal

The general goal of remediation is to permanently eliminate the assessed environmental risk (i.e. to interrupt the source-receptor pathway reliably and permanently) by the performance of remediation measures. The remediation method is derived during the feasibility study and is further developed into an implementation planning within the so-called remediation plan. The subsequent remediation is carried out in three phases:

- Construction of the remediation infrastructure and test-phase (implementation),
- Regular operation and
- Termination of remediation.

10.2 Remediation implementation

The success of a remediation project depends always on the efficient cooperation between the liable party, the site owner, the contractor, the supervising consultant and the authorities. An implementation which satisfies the quality requirements depends considerably on:

- A comprehensive planning of the process,
- A competent and effective project management by all parties of the project,
- The qualification of the staff employed by the consultant and the contractor,
- An effective quality management.

The more complex a certain remediation measure is, the more comprehensive will be the requirements for operational planning. Each measure is subject to an individual planning with regard to schedule, placing of orders, execution and accounting, especially when executed by different contractors.

Before the beginning of the construction works, the tasks and responsibilities of all parties should be described clearly including delimitation of competences and responsibilities. It is recommended to present the organizational structure in the form of an organigram (ICSS - International Centre for Soil and Contaminated Sites, 2007, p. 45). In general, two approaches are conceivable:

- The commissioned contractor is responsible for the complete execution of the remediation and the task of the consultant is only to check the results presented; this is an option if the contractor guarantees the remediation result for a fixed price;
- The commissioned contractor is responsible for the execution of the remediation, whereas the consultant is steering the remediation within the boundaries fixed in the remediation plan.

In any case, the contractor carrying out the remediation is responsible for the management of the field activities as well as for the compliance with the applicable regulations including relevant legal and official provisions and requirements.

Compliance must be controlled by the liable party or, in substitution, by the consultant. The control by the authorities is, in general, carried out in the frame of a quality control. In this way, the competent authority also checks whether the remediation goals are achieved by the remediation measures. The official control can take the form of:

- Plausibility control of the reports presented by the liable party,
- Unannounced control visits to the remediation site,
- Participation in construction meetings and approval procedures.

To make all processes, results and decisions in the project implementation available for a future control and processing, the following documents need to be archived in written form:

- All contracts,
- Meeting minutes,
- Documentation of all planning steps,
- Issued permits including construction permits,
- Descriptions and documentation of the installed systems including operating manuals,
- Status and progress reports,
- Monitoring plan and results of internal and external monitoring,
- Quality control and assurance plan.

10.3 Remediation execution

10.3.1 Construction of the remediation infrastructure and test phase

As soon as the construction work has been completed, the remediation infrastructure is ready for use. In general, the company building the infrastructure also operates the remediation system. Nevertheless, after construction termination, at least the following activities are necessary:

- Contractor: delivery of the final plant documentation to the party who has commissioned the contractor, usually the liable party, including description of the equipment, list of machineries, data sheets, health & safety documents, operating manual, piping and instrumentation diagram (P&ID);
- Liable party (or their consultant): formal approval of the delivered equipment and confirmation that the installed equipment is conform with the requirements written in the contractor's proposal. In general prior to the approval, tests are run to check functionality of the infrastructure. The approval is documented in writing and signed by both parties.

After the approval, the remediation system can be taken into operation. Depending on the complexity of the installed infrastructure, the initial test phase can have different durations: For simple systems (e.g. only installation of GAC absorber to treat moderate contaminated groundwater), the test phase can be limited to a week, whereas for more complex systems (e.g. a system to inject substrate to enhance biodegradation), it can take weeks. The end of the test phase should also be documented. The routine operation starts from this date.

10.3.2 Regular operation

The activities to be performed by the contractor during the regular operation time are indicated in the remediation plan and include:

- **Operation**. It is the task of the contractor to operate the remediation infrastructure, either on his own discretion or based on the requirements of the consultant who has prepared the remediation concept. This also includes the control of the operation of the equipment.
- **Maintenance**. The extent and frequency of maintenance measures are defined in the remediation plan. The procedures are indicated in the operating manual. The purpose of proper maintenance is to minimize malfunctions of the equipment and to extend its operational life cycle in order to avoid replacement of equipment as far as possible.
- **Repair and substitution**. Repair and substitution are necessary in case of system malfunctions. The contract between the commissioning party and the contractor indicates clearly which party covers the costs for these activities. This may be done dependent on the height of costs, for instance by setting a deductible or requiring at least a certain number of quotes to approve expensive repair or substitution activities.
- **Adjustment**. Most remediation equipment needs periodical adjustment to ensure an optimized operation. Depending on the level of automation of the equipment, the adjustment of valves, inverters, pumps, blowers or other elements can either be conducted from remote or through a control panel or manually.
- **Consumables**. The exchange of consumables (e.g. activated carbon, ion exchange resins) is done when these are exhausted. Some consumables (e.g. propane to operate catalytic oxidation or an incinerator, water for liquid ring pumps, compressed air for automated regulation, reagents for the enhancement of chemical or biological remediation) must be refilled. This is done by the contractor after announcement and on basis of unit process costs provided with the initial remediation proposal.
- **Energy.** Supply of electricity for the remediation must also be considered. It is reasonable to agree on a fixed price during the tendering process.

10.3.3 Adaptive design

Fixed and unchanged operation conditions ensure an accurate cost estimate and control but, especially in the case of long-term remediation projects and/or fast-changing framework conditions, are not as efficient as flexible systems. Because the remediation is planned on the basis of selective information gained during the various investigation steps and because the full-scale remediation covers the entire contaminated subsurface body, it becomes clear that the necessity for adaptions is an intrinsic feature of remediation projects. For in-situ remediation, in particular, flexibility is essential for the remediation performance. Therefore, the so-called “adaptive design” concept was developed. Keys to this approach are a flexible infrastructure (e.g. the possibility to extract or inject in multiple wells) and an adaptable operation. This means that the infrastructure operation parameters must be alterable within a defined frame. The data from the monitoring and control activities must be immediately analyzed. This is essential in any case. The results of the analysis may lead to decisions on the next appropriate optimization actions. The remediation parameters are adapted accordingly during the whole remediation period.

10.3.4 Monitoring

The monitoring accompanies all remediation phases, from the start to the post-operation phases. The extent of the monitoring activities during remediation execution is set in the remediation plan. All media involved in the remediation (e.g. soil, groundwater, soil vapor), all contaminants of concern and all relevant source-receptor pathways are addressed in the monitoring. The number and location of the monitoring points (usually groundwater or soil vapor wells) involved in the monitoring as well as the monitoring frequency to achieve a representative understanding of the contaminant attenuation at the site are usually set in a monitoring plan, which is an integral part of the remediation plan (see Chapter 9.3). The specifications of the **monitoring plan**, especially the process monitoring (see below), is fine-tuned during the remediation in order to flexibly respond to unforeseen developments in the remediation process. Depending on their main scope, monitoring activities can be classified as follows (Suthersan, 2005, S. 342):

- **Process monitoring**. This covers sampling of the remediation wells (e.g. used for injection or extraction) and monitoring wells located in their immediate vicinity. Parameters are analyzed that allow the judgement of the functionality of the chosen remediation process. Hence, the intent of the process monitoring is to provide almost real-time feedback to control the remediation processes and to maintain these processes within the specified ranges to optimize the treatment efficiency. The process monitoring is particularly relevant in, but not limited to, in-situ remediation in which the biogeochemical parameters play an essential role. Therefore, process monitoring focuses on these parameters. The monitoring frequency is usually high (up to weekly) at the beginning of the remediation when the optimum operating conditions are established and gradually decreases as the processes stabilize.
- **Performance monitoring.** During the performance monitoring, the effectiveness of the treatment (i.e. the decrease of the contaminant concentrations) will be determined. Based on the results, it can be decided if an optimization of the remediation process will be needed. Hence, the performance monitoring starts when the process monitoring shows that the remediation process is working as expected. The performance monitoring is conducted not only in the source zone but also on wells in the plume area. The data collected in the performance monitoring can be analyzed to produce time-series curves of contaminant concentrations – a helpful tool to demonstrate the effectiveness of the remediation.
- **Compliance monitoring**. This kind of monitoring is performed to demonstrate that the requirements set for the site in the remediation contract or the applicable laws and guidelines are met. For example, if a point of compliance is set downstream of the source area where certain threshold concentrations shall not be exceeded, this monitoring points must be sampled to demonstrate compliance. The same applies for emission limits for gas and water after the treatment in remediation plants. The monitoring frequency and the sampling method are usually indicated in the respective regulatory framework or in international guidelines or is agreed with the competent authority.

All monitoring types include a so-called "**baseline monitoring**", which is performed to capture the site-specific conditions before the beginning of the remediation.

More in detail, the monitoring is quite different for both options: containment and decontamination. In case of containment, the contamination (i.e. the hazard potential) is not eliminated and remains for an undefined time at the site. Since the containment construction shows a limited lifetime, a long-term control of their effectiveness is required at regular intervals. The "control" is performed according to specific requirements by means of the following measures:

- Site visits for visual inspections, organoleptic observations or surface measurements (e.g. PID-measurements to check for evaporation of volatile contaminants),
- Control of the operation of the equipment (e.g. passive surface dewatering or soil vapor degassing),
- Long-term monitoring of the contaminant concentrations in groundwater, wastewater and soil vapor,
- Preparation of water balances and calculation of contaminant mass flux and discharge.

The monitoring activities should be focused on the impacted environmental media and, if possible, only on most important (mobile, toxic, persistent) contaminants.

Besides sampling of soil, groundwater and soil vapor, the monitoring of the decontamination processes may contain in addition:

- Calculation of mass balances (contaminants, reagents),
- Mass and volume balances (disposed soil, discharged groundwater).

After termination of active remediation measures, the remediation aftercare starts (see Chapter 11). The relevant monitoring measures are defined in the monitoring plan as integral component of the remediation plan (see Chapter 9.3). After the active remediation has been completed, the monitoring plan is confirmed or updated. In detail, it includes specifications for:

- Monitoring network (groundwater and/or soil vapor wells),
- Sampling frequency,
- Sampling parameters including parameters to be measured during sampling (e.g. water level, pH, electrical conductivity, oxidation-reduction potential, dissolved oxygen and temperature),
- Analytical parameters (contaminants, parameters indicating biogeochemical environment).

10.3.5 Reporting

The remediation progress is described in **periodic reports** which are usually written on an annual basis. In progress reports, the current status of the remediation is described and compared to previous results, the assessment of the historical data series. If necessary, the conceptual site model is updated. Furthermore, actions to enhance the remediation performance which had been taken within the reporting period are documented. Depending on the complexity of the remediation project, a short text with diagrams and graphics (e.g. water table contour lines, contaminant concentration distribution maps or time series) can be sufficient as a progress report. A more complex remediation needs a more detailed reporting.

The **final remediation report** that is prepared after termination of the active remediation measures is more comprehensive as it summarizes the remediation progress of the complete remediation period and documents that the remediation goals have been achieved, in case the remediation has been successful.

10.3.6 Completion of remediation

If a decontamination is conducted, the remediation is considered complete when the contaminated medium is treated up to a fixed target value.

Upon completion of the works, the final remediation report must be provided by the liable party to the competent authority. This step is important because it essentially constitutes a statement by the liable party that the remediation goals have been achieved and that the site is no longer to be designated as contaminated. The authorities should verify that the required standards (i.e. the target values) have been attained. Where the remediation has been completed successfully, the authorities will alter the records for the site in the register of contaminated sites and provide written confirmation that the remediation obligation has been fulfilled by the liable party.

It appears not seldom during the remediation, that the remediation goals cannot be achieved. This is mainly due to the low accessibility of the residual product phase and of contaminants having migrated into low-permeable soil strata. For these cases a **fallback scenario** is necessary. First, it will become necessary to review the data that have been used for remediation design, the remediation design itself and the performance of the remediation with the aim to identify potential optimization options. In some cases, the evaluation may reveal that more aggressive remediation technologies (e.g. thermal desorption) or even a containment would be needed. If any options arise, they need to be implemented.

If not, it becomes obvious that the remediation (applying the predefined targets) is technically not feasible. It should then be checked whether natural processes are active and monitored natural attenuation (MNA) or natural source zone depletion (NSZD) can be feasible approaches which may lead in the long-term to a decontamination of the site. The site may then be left to long-term monitoring. In any case, it must be assured that source-receptor pathways are interrupted and that the population is kept safe.

To achieve this goal, a variety of measures must be undertaken which can be summarized with the term "**institutional control**", for instance:

- Fence around the contaminated area,
- Prohibition to use the groundwater for private purposes (e.g. irrigation),
- Obligation to clean up the extracted contaminated water prior to use for industrial processes or drinking water production.

The effectiveness of these institutional control measures must be surveilled as long as the contamination is existing.

The non-achievability of the remediation targets should be presented to the competent authority for review. It is to the discretion of the authorities to decide whether the remediation can be terminated prematurely. Arguments for this can be derived from proportionality considerations. If it can be shown, for instance, that an additional remediation progress is only achievable in long periods with the consumption of high amounts of energy and process reagents and at strongly increasing costs, the active remediation may be terminated due to proportionality reasons. An additional argument to terminate the active remediation prematurely may be that it is possible to demonstrate that natural attenuation (biodegradation) is taking place. Hence, the active remediation can be stopped and the achievement of the remediation targets only by means of MNA can be pursued.

In the case of a containment, the remediation is perceived to be completed after the completion of the containment construction works by definition. A **long-term monitoring** is usually carried out subsequently.

Remediation

The remediation will be carried out based on details provided by the remediation plan. The more complex the remediation is, the more comprehensive are the requirements for operational planning. The contractor is responsible for the remediation performance including management of the field activities and compliance with the applicable regulations as well as with relevant legal and official provisions and requirements. The institutional control by the authorities is, in general, carried out within the framework of the quality control process. In addition, the competent authority will check whether the remediation goals are achieved.

The remediation comprises three phases: (i) construction of the remediation infrastructure and test-phase, (ii) regular operation and (iii) termination of remediation. The contractor is responsible for remediation operation, maintenance, repair and substitution, adjustment of operation (optimization) and delivery of consumables and energy. Optimization requires that all devices might be operated flexibly within a certain range (e.g. pumping or injection rates). This requires the so-called "adaptive design".

The remediation is terminated when the contaminated medium is treated up to a fixed target value. This has to be proved by the liable party and shall be confirmed by an official final statement provided by the competent authority. It is not uncommon for a remediation project that the remediation goals cannot be achieved. In such a case, suggestions for an alternative approach should be presented to and discussed with the competent authority, if required. The authority decides whether the remediation can be terminated prematurely.

After the baseline monitoring, the remediation is accompanied by three different types of monitoring: (i) process monitoring (checking the effectiveness of the treatment), (ii) performance monitoring (checking the effectiveness of the remediation, i.e. the decrease of the contaminant concentrations) and (iii) compliance monitoring (demonstrating that the requirements as defined in the remediation contract or the applicable laws and guidelines are met).

11 Remediation aftercare

11.1 Objective

The long-term effect of a successful remediation should be proved by means of an appropriate monitoring. In general, after termination of the active remediation, a variety of different effects may occur. First of all, the anthropogenically influenced hydrological and hydrogeochemical conditions recover to the "natural" conditions. This is true for nearly all remediation technologies. Even in the case of soil exchange, the mobilized residual contaminants drain away. For pump-and-treat, the groundwater flow velocity is slowed down allowing more time for the expression of a contaminant concentration equilibrium between sorbed and dissolved contaminants usually lying on a substantially higher level. This increase of the contaminant concertation in groundwater is referred to as rebound (see Chapter 3).

More pronounced are recoveries after termination of microbial or chemical in-situ remediation. The injected reagents may cause an ongoing contaminant degradation even months or a few years after the termination of active remediation. Hence, it takes quite a long time until the anthropogenically affected conditions recover. At the end of this period, the rebound reaches its maximum.

Monitoring the formation of anthropogenically unaffected conditions and the formation of the rebound to its maximum is referred to as **post-remediation monitoring**. After that the **aftercare monitoring** starts in which is surveilled whether any site conditions (e.g. seasonal hydrological variations) may influence the concentrations of the residual contaminants. Without any influences, these concentrations remain unchanged until the residual source is exhausted nearly completely – a process which may take decades or even centuries. In case that residual contaminants are still occurring at the site and that the aftercare monitoring has been finished, physical monitoring may be replaced by **organizational supervision**.

The costs for the entire monitoring should be taken into consideration already during the feasibility study stage (see Chapter 8.9).

11.2 Post-remediation monitoring

The duration of monitoring activities after completion of remediation depends on the type of remediation technology applied. For instance, less long aftercare is usually necessary after SVE (since this technology does not alter the biogeochemical environment substantially), whereas in the case of enhanced microbial degradation, it could take years to restore the natural conditions.

After termination of SVE, a so-called 3-point sampling is done (e.g. 4, 8 and 12 months after stop). If the data indicate no current or future rebound above the target values, the post-remediation monitoring can be terminated.

For containment measures the post-remediation monitoring is done to monitor the fate of the contaminants not contained by the construction measures. In general, these are the contaminants within the plume since the containment is limited in most cases to the source.

The measures performed during the post-remediation monitoring are defined in the monitoring plan as integral component of the remediation plan (see Chapters 9.3 and 10.3.4). After the active remediation has been completed, the monitoring plan is confirmed or updated.

The data are evaluated after each sampling event with respect to the initial questions: (i) has the biogeochemical environment completely recovered and (ii) has the rebound developed to its maximum? In addition, it will be checked whether the groundwater flow conditions remain unchanged. Based on the results, it will be evaluated whether the monitoring needs to be continued as planned or stopped and whether any optimizations are necessary.

In case the spatial distribution of the contaminants will increase posing a risk to sensitive receptors, it might be necessary to enter again in the phase of active remediation.

11.3 Aftercare monitoring

In general, during the aftercare monitoring it is only necessary to analyze the contaminants and to record the hydrogeological conditions. For containment systems, also site visits to check the ongoing functionality of the containment building are necessary (maintenance of structures and installations). In case of any observed damage, e.g. of seals, gas collectors and water chambers, a repair will be initiated.

The monitoring frequency can be gradually decreased in the aftercare monitoring and is lower than the monitoring frequency during the post-remediation monitoring, since without any external influence no substantial changes in contaminant concentrations are expected. Seasonal hydrogeological variations may have an influence on the contaminant concentrations. If it can be demonstrated by application of statistical methods that the concentrations do not change or (in the best case) decline continuously, the aftercare monitoring can be terminated. This requires in the best case at least 8 monitoring points.

11.4 Organizational supervision

In case that residual contaminants are still occurring at the site and that the aftercare monitoring has been finished, physical monitoring may be replaced by "organizational supervision" in order to prevent that the contamination will be forgotten. In case that activities in the vicinity of the historical contamination (e.g. groundwater extraction from a construction pit) are necessary, it must be assured that these do not influence the contaminant distribution in the sense of a mobilization. Therefore, the contaminated site needs to be kept in the official register of contaminated sites. The continued registration of the site provides that its development can be observed. This is called "organizational supervision".

When construction planning applications are sent to the authorities, they should check a potential influence of the planned measures on the residual contamination and should optionally request an additional (temporary) phase of active contaminant monitoring (sampling and analyses).

Remediation aftercare

The long-term effect of a remediation should be proved with an appropriate monitoring. After termination of the active remediation, the anthropogenically influenced hydrological and hydrogeochemical conditions recover to the "natural" conditions. In most cases, the contaminant concentration increases to a certain extent (rebound). Monitoring these effects is called "post-remediation monitoring". During the "aftercare monitoring", it is surveilled whether any site conditions (e.g. seasonal hydrological variations) may influence the concentrations of the residual contaminants. If (statistically proved) the concentrations show no trend to increase, the monitoring may be finished. In case that residual contaminants are still occurring at the site and that the aftercare monitoring has been finished, physical monitoring may be replaced by "organizational supervision".

12 Consideration of future site use and site development scenarios

12.1 General considerations

The prospect of a future use of industrial sites after previous operations have been terminated is an important aspect for many countries, particularly in Europe, considering the increasing efforts to reduce land consumption and sealing, e.g. of agricultural land and green areas, and to revitalize former, decommissioned industrial sites for developing new environmentally friendly and economically viable options of use. For site owners and economic operators, site (or brownfield) redevelopment provides the opportunity to convert derelict and/or contaminated land that may poses economic risks to the owner or operator into a valuable property and thus create new value out of a former "risk location".

As defined by the German Environment Agency (Umweltbundesamt, 2014), "brownfield redevelopment means the process of rehabilitating a particular piece of land for a new use, after the former use has been discontinued". According to a definition formulated by the Engineering Technology Association on Brownfields of Germany (Ingenieurtechnischer Verband für Altlastenmanagement und Flächenrecycling e.V., ITVA), brownfield redevelopment involves "usage-related reintegration of properties in the economic and natural cycle whose original usage has been lost (e.g. abandoned factory or company sites, property owned by the military, traffic infrastructure elements, etc.) via planning, environmental and/or economic measures" (ITVA, 1998).

Brownfield redevelopment is a complex process involving numerous parties. Site owners, citizens, investors, urban and spatial planners and politicians are involved and have a broad range of different interests. Moreover, responsibility often lies with several planning and permitting authorities since various types of legal frameworks are involved – namely environmental law, building permit law and spatial planning law (Umweltbundesamt, 2014).

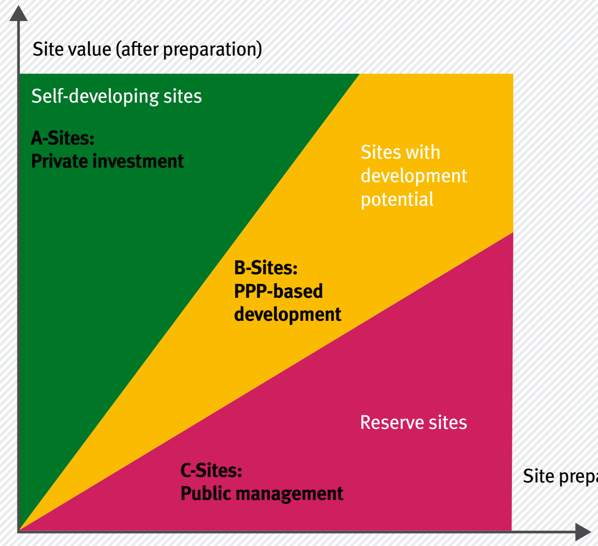
According to the German Environment Agency (Umweltbundesamt, UBA), the profitability of brownfield redevelopment is determined by local real estate prices and the revenues that can be realized in view of the respective land prices. It is often helpful to divide brownfield sites along a cost-benefit ratio into the following three categories (CABERNET, 2005):

- **Type A sites** ("self-developing sites") are sites, e.g. properties in good locations in prosperous regions, whose projected land recycling revenues exceed the projected preconstruction costs to a large extent. This type of sites attracts private investors without subsidies and other types of financial support and thus will not remain unused for long.
- **Type B sites** ("sites with development potential") are sites whose profitability is uncertain for risk-related reasons. In order to reduce such risks, to allocate costs and to accelerate the development process, it can be necessary to take action such as carrying out missing development measures or amending unsuitable parcel divisions.
- **Type C sites** ("reserve sites") are sites, e.g. in the case of a glutted real estate market, whose projected redevelopment revenues substantially fall short of the projected preconstruction costs and which can only be developed with significant public funding.

Brownfield revitalization and management strategies are based on the aforesaid classifications (according to region). Planning, economic, fiscal and legal measures related to land-take reduction are mainly focussed on "Type B sites". In such cases, strategic public-private partnerships allow for the mitigation of legal, financial and other risks – and thus provide prospects for redevelopment (Umweltbundesamt, 2014).

Figure 34:

Types of sites related to site value vs. costs for site development



Source: (Umweltbundesamt, 2014)

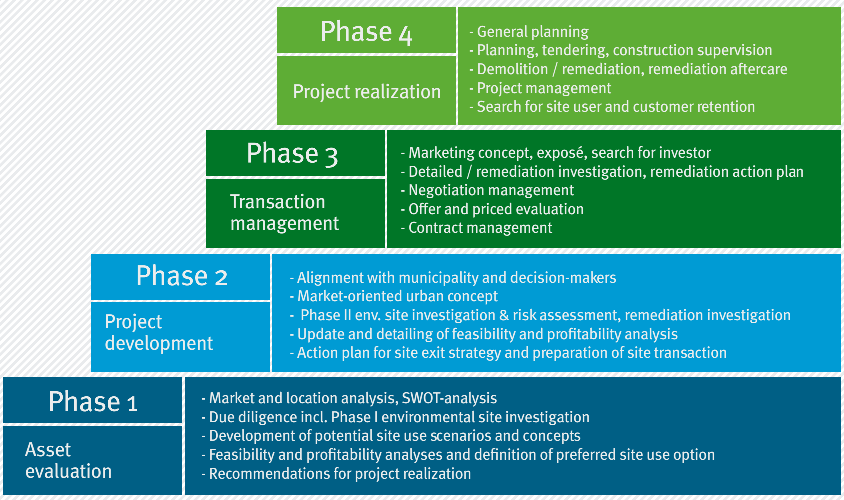
12.2 Phased approach for site development projects

The methodology for the development of former industrial and/or contaminated sites strongly depends on the type of each individual site and the respective framework conditions. There are diverse methodologies for site development and site transaction, and a comprehensive overview on brownfield redevelopment has been published by UBA in 2005 (A. Kaelber, 2005).

An example of a proven, systematic methodology is the following stepwise approach that has been applied to various site development projects, also for sites of the oil & gas industry such as tank farms and refineries. It can be divided into four phases:

Figure 35:

Phased approach for site development and transaction



Source: (Arcadis Germany GmbH, 2017)

During **Phase 1**, a first evaluation (or a "quick-scan") of the asset in terms of inherent risks, potentials for development and the general feasibility (i.e. market and location analysis, site status regarding potential contaminations, initial environmental risk assessment, identification of all site-specific risks, consideration of potential site use scenarios and a preferred development option, initial cost-benefit analysis, etc.) is carried out. The results allow a preliminary classification of the site in view of the development potential as displayed in Figure 35 (Type A: self-developing, Type B: development potential, Type C: reserve). Accordingly, the subsequent Phases 2 – 4 may only be carried out if a site can be allocated to category A or B, while for C-type sites only measures in terms of risk management (e.g. hazard prevention and mitigation of potential environmental impacts to relevant receptors, compliance with environmental regulations) may be considered.

If the outcome of Phase 1 reveals a reasonable potential for development, **Phase 2** will be carried out. This phase comprises a detailed environmental site investigation program including a comprehensive environmental risk assessment that allows a resilient quantification of risks and costs for addressing existing soil, subsoil and groundwater contaminations and also contaminations in the structural fabrics of buildings and installations (e.g. asbestos). Based upon this data and information, further alignments with important stakeholders such as municipalities, competent authorities and other important decision-makers can be made, and the site development strategy can further be developed. Possible residual risks and restrictions will be addressed, and cost-benefit analyses will be updated accordingly. The main outcome of Phase 2 shall be a plan and a schedule for a time- and cost-efficient site transaction.

The site transaction process is done in **Phase 3** and comprises all necessary marketing activities, the search for and negotiations with potential investors or future site users, proposal and price evaluations, contractual aspects and also the development and regulatory approval of a remediation plan, if the obligation for remediation is not transferred to the new site owner or investor through a private law contract. The intended outcome of Phase 3 would be a completed transaction of the site to a new site owner or investor, if the site will not continuously be used and developed by the current site owner him-/herself. In the latter case, the main variation from the site development phases as described above would be that no property sales activities are required.

Phase 4 comprises the full implementation of the new site use strategy including demolition and remediation depending on the new site use concept, planning, permitting and construction, the related project management and also the search for site users, e.g. tenants.

An important aspect of site development projects, particularly for sites such as refineries and tank farms, is the integration of demolition and related remediation activities into the development and transaction process. There are usually large quantities of steel and other materials of considerable value on these sites (e.g. storage tanks, processing facilities, pipelines, supporting infrastructure and also large quantities of concrete), and the revenues that can be obtained from the sale of scrap metal and recycling materials are to be included into the cost-benefit analysis for each site development project that involves demolition activities. These revenues may compensate a considerable part of the costs for demolition and remediation, depending on the respective market price for steel and recycling materials. This needs to be considered in the planning and scheduling of a site development project.

12.3 Integrated approach for site development projects

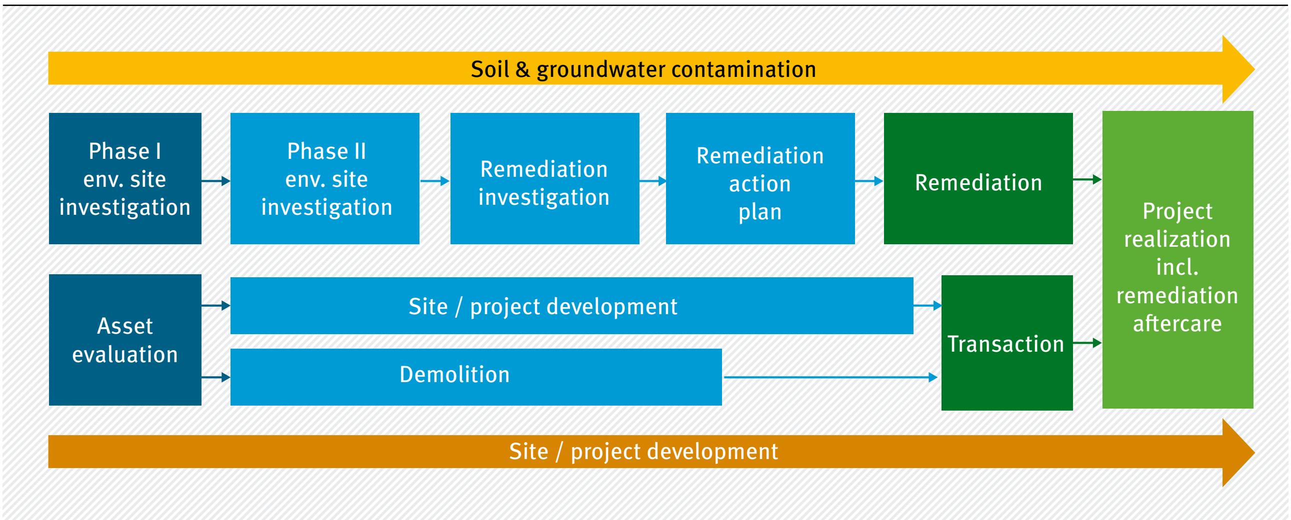
Particularly for large industrial sites, such as former refineries or tank farms or for sites that are located in less attractive locations (Type B sites), it might be required to develop such properties plot-by-plot rather than in one unit if no investor or subsequent user can be found for the entire site at once. The advantages of such an approach are:

- The risks of a successive development of individual plots (including pre-financing) usually remain limited and easier manageable,
- Smaller plots might be more attractive for a larger group of potential investors or subsequent site users, and thus it might be easier to finally sale the land,
- Contaminated hotspots which cannot be remediated in a time- and cost-efficient manner may be isolated from the remediated areas by subdivision of the entire site into several plots.

In this case, an integrated approach, where environmental site investigation, demolition and site development are carried out in parallel, can lead to significant time savings and to an increased efficiency. This approach also allows a sooner compensation of costs for site development and environmental investigation through the sale, e.g. of scrap metal, and a faster sale of already decontaminated and developed plots after project realization if the individual projects are of limited extent.

Figure 36:

Integrated approach for brownfield redevelopment



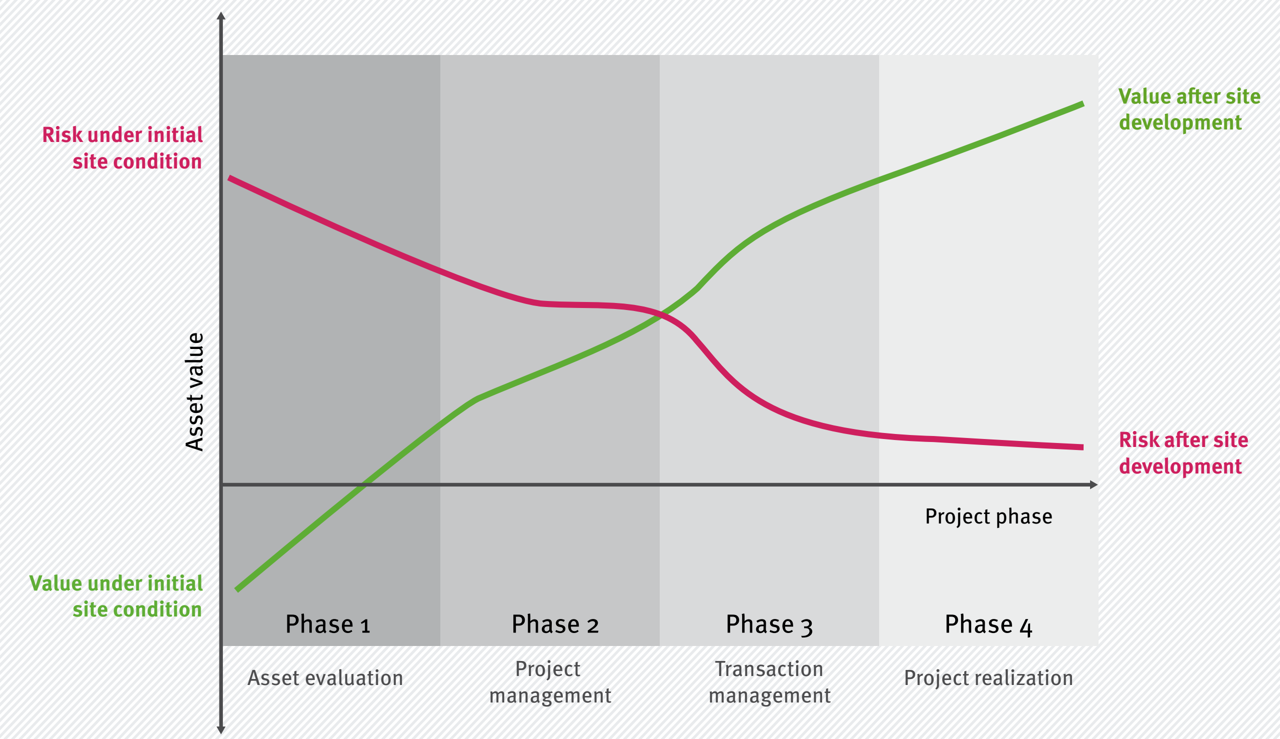
Source: Arcadis, own figure

Eventually, the selection of the appropriate site development strategy (“standard” or integrated approach, comprehensive or plot-by-plot, etc.) has to be made for each project individually and is mostly depending on the specific site characteristics such as the initial site condition (particularly regarding soil and subsoil contaminations), location, urban planning, future site use scenario, remediation goals, regulatory requirements and restrictions, etc.

At any rate, risks associated with a decommissioned industrial site shall become progressively apparent and manageable and thus shall decrease throughout the course of a structured site development project while the value of the land increases as the site development strategy is progressively developed and implemented.

Figure 37:

Diametrical "risk-vs.-value" progression in the course of a site development and transaction project



Source: (Arcadis Germany GmbH, 2017)

12.4 Influence of remediation measures on site development projects

With respect to the management of potentially contaminated and contaminated sites, the intended future use of a contaminated site has a strong influence on investigation and remediation activities and related considerations.

As already mentioned in previous chapters of this manual, it is strongly recommended to define remediation targets with respect to the future site use and based upon a solid environmental risk assessment for the relevant receptors, also taking economic criteria into account.

In case that a conversion of an industrial site into an urban area is planned, different (risk-based) remediation target values must be considered, e.g. for the source-receptor pathway soil → humans. Hence, a full understanding of the planned future site use is of paramount importance for the liable party before any remediation activities can be planned and executed, for the assurance of legal certainty.

In some cases, a contaminated site might be needed urgently, e.g. in the context of urban land development. Usually, existing contaminations complicate or even inhibit investments on these sites. On the other hand, construction activities frequently require soil excavation. If the topsoil is contaminated, a combination of remediation and construction activities may cause business-usual costs (e.g. for excavation) that would arise anyway during a construction project, and therefore could reduce the costs for remediation activities under certain circumstances.

Additional costs that are directly related to remediation may arise from:

- Disposal of the contaminated soil,
- Additional excavation of contaminated soil outside the immediate construction area,
- Backfill of the excavation pits (if the pits are not needed for the construction project such as for a cellar),
- Exchange of the contaminated topsoil in a wider area (in case that the decontamination of the entire site is required),
- Covering the contaminated soil with clean topsoil.

However, the combination of construction and remediation activities usually leads to cost savings with respect to the total project costs.

Another possibility is to integrate the implementation of an in-situ remediation into the site development project during the remediation planning phase (see Figures 35 and 36). Any remediation infrastructure might be built in the underground. In most cases, only a small area of the entire site is needed for the installation of the treatment plant. Access to the – if necessary, noise-protected – plant must be guaranteed throughout the entire duration of the remediation project.

In summary, planned investments must not inevitably be delayed or even blocked by required remediation activities.

Sometimes it is not possible to achieve the predefined remediation targets, e.g. because of the geological and hydrological site conditions or as a consequence of technical limitations. In that case, the status of the impacted site would remain "contaminated". If the contamination is limited to a rather smaller area or "hot spot" at the site, a possible solution to this dilemma would be to subdivide the site into various plots according to their level of (de)contamination and to isolate ("no use") only the area for which remediation targets cannot be reached. This would allow the immediate use of cleaned-up plots.

In case that the defined remediation targets cannot be achieved on a larger part of the site, it might be appropriate to terminate the remediation activities and to consider a modification of the site use planning in consultation with the involved stakeholders and the responsible regulating and planning authorities. This could imply that the problematic areas are not used as urban areas or for the construction of any other buildings but as green areas after the topsoils have been replaced.

At this point we refer to the possibilities and advantages of public law contracts as described in Chapter 1.5 for the implementation of achievable remediation goals in relation to suitable site use scenarios.

Consideration of future site use and site development scenarios

Brownfield redevelopment (or site development towards a new site use) plays an important role for the reduction of land consumption in general and also for creating value out of derelict and/or contaminated land that may pose economic risks to the owner or economic operator.

The profitability of brownfield redevelopment is determined by local real estate prices and the revenues that can be realized in view of the respective land prices. Brownfield sites can be divided into three categories along a cost-benefit ratio:

- Type A sites ("self-developing sites") in attractive locations, with limited risks and with a high profitability,
- Type B sites ("sites with development potential") that have an elevated risk profile and thus a rather uncertain profitability and therefore require further investments,
- Type C sites ("reserve sites") where development costs exceed the expected revenues.

Methodologies for site development are strongly depending on the type of sites and the respective framework conditions. One example for a comprehensive site development and transaction methodology is a 4-phase approach consisting of the following phases:

- Phase 1 – Asset evaluation including Phase I environmental site investigation,
- Phase 2 – Project development including Phase II environmental site investigation, environmental risk assessment and demolition,
- Phase 3 – Transaction management including remediation plan,
- Phase 4 – Project realization including remediation aftercare.

For sites with large quantities of steel and other usable materials, revenues from the sale of scrap metal and recycling materials should be considered in the cost-benefit analysis for site development projects which involve demolition activities.

For sites where the site development and transaction for the entire property is not possible, a plot-by-plot approach might be required implying a subdivision of the entire site and the successive development of the individual plots.

A variation to the 4-phases site development methodology is the integrated approach, where environmental site investigation, demolition and site development are carried out in parallel, which allows significant time savings and a higher efficiency. Ultimately, all site development activities shall lead to a significant reduction of site-related risks and a strong increase of the value of the land.

With respect to contaminated site management, the future use of a contaminated site has a strong influence on investigation and remediation activities and related considerations. Hence, the future site use should be defined prior to any remediation work, for assuring legal certainty for the liable party.

Contaminated hot spots which cannot be remediated within a time- and cost-efficient manner may be isolated from the remediated areas by subdivision of the entire site into several plots, depending on the level of decontamination. Further remediation activities might be integrated into site development considerations.

Public law contracts and public-private partnerships might be useful approaches for addressing large-scale remediation projects in conjunction with sustainable future site use concepts.

13 Requirements on health, safety, security & environment (HSSE)

Health, safety, security & environment (HSSE) are always top priorities for all work activities performed in the oil & gas industry. Consultants, contractors and subcontractors are responsible for:

- Providing and maintaining a safe work environment for employees and any other persons,
- Preventing negative impacts on the environment and
- Executing their work in compliance with...
    - national legal requirements regarding occupational health & safety, environmental protection, medical examinations, working hours, etc.,
    - technical regulations and
    - additional requirements defined by the commissioning party.

In general, every person working on site shall be authorized and encouraged to stop work if there are concerns about safe work execution. However, project managers, site work supervisors and HSSE managers should pay particular attention to potential unsafe or critical working conditions, acts or behavior of the work teams. They should always act as role models for a safe work culture and instruct and encourage their team members accordingly.

Prior to the commencement of any work activities, a **health & safety plan** (HASP) has to be prepared that includes an assessment of the site and work-specific risks and that defines risk mitigation as well as emergency actions.

In detail, a HASP that fulfils the HSSE requirements of the oil & gas industry under global HSSE standards shall contain the following objectives, specifications and elements (listed as they appear in a usual HASP):

- **Emergency response plan**: behavioral measures and information for emergency cases, including first aid, communication lists and responsibilities are defined and described;
- **Work risk assessment** (job hazard and safety analyses): identification and classification of all hazards related to the site, the processes and the work tasks; assessment of task-specific hazards and definition of risk mitigation measures for either completely avoiding or at least minimizing the residual risks during work preparation phase and/or on-site;
- Definition of the minimum **personal protective equipment** (PPE), e.g. hard hat, safety glasses, safety boots and high-visible vests; additional, task-specific PPE (e.g. safety gloves, noise protection, etc.) according to the specifications of the work risk assessment;
- **Last minute risk assessments**: personnel is trained to perform a last-minute risk assessment or safe performance self-assessments before starting a task or after working conditions have changed;
- **Work permits**: completion and approval of work permits for high-risk tasks by trained personnel –permit issuers and permit holders– prior to work, e.g. for...
    - hot works (e.g. in areas with increased risk of fire or explosion),
    - energy isolation (lock-out, tag-out, test-out),
    - excavation and trenching,
    - lifting and hoisting,
    - working at heights (usually > 2 m),
    - working in confined spaces;
- **Traffic control**: assessment of hazards caused by traffic on-site and in public areas and definition of risk mitigation actions;
- Definition of **exclusion zones**: assessment of hazards caused by heavy equipment like excavators, cranes, trucks, etc. and definition, demarcation and barricading of exclusion zones where non-essential personnel is prohibited, including depicting the zones in a map;
- **Equipment inspection**: inspection and maintenance of all equipment according to legal and technical regulations, additional checks and inspections for critical equipment like heavy equipment, lifting equipment, PPE, etc; the results of the checks are to be documented regularly in written form and attached to the HASP;

- **Hazardous substances**: relevant information on handling and storage of hazardous substances are obtained and communicated;
- Specification of **competencies of personnel and supervisors**: only individuals who can proof appropriate competence are allowed to perform the work, and the required competences should be displayed in the work scope description and/or in the HASP;
- **Subcontractor management**: description of the services that are provided by subcontractors and definition of the responsibilities for all works conducted by the contractor;
- **Training**: only appropriately trained, competent personnel under the supervision of a foreman or construction manager with oil & gas experience or an additional site safety coordinator for high-risk work activities are allowed to execute the work;
- Inexperienced workers and short service employees need to be registered and mentored;
- No driving and no work execution under (residual) alcohol and drugs;
- No use of mobile phones during work execution and while driving;
- All HSSE requirements should be addressed at an early stage and integrated into work planning;
- **Waste handling** (separation, storage, declaration and transport) needs to be done according to legal regulations or additional requirements;
- Information on **subsurface structures** (pipes, cables, foundations, etc.) including unexploded ordnance (UXO) need to be obtained prior to the commencement of the work; optionally pre-drilling or hand-augering in all critical areas need to be performed for subsurface clearance; the results need to be handed over to the drilling personal;
- Investigation and assessment regarding **UXO** as addressed in Chapter 2.4 is inevitable for working on sites of the oil & gas industry that have existed by the end of World War II or where any suspicion regarding potential UXO does exist;
- **Management of change**: mitigation of risks caused by changed procedures, schedules, circumstances, etc.;
- **Emergency exercises** (drills): execution of emergency exercises to check site-specific emergency procedures and communication;
- **Incident reporting and investigation**: all accidents, damages and occupational illnesses are investigated in detail, reported and communicated to the commissioning party and other stakeholders as agreed upon;
- **Safety monitoring and reporting**: all situations where safety could be violated are tracked, analyzed and communicated with respect to safety improvement, e.g.:
    - Recordable incidents (injuries, damages, etc.),
    - First aid cases,
    - Near misses/near losses (according to the United States Occupational Safety and Health Administration (OSHA), these are "incidents in which no property was damaged and no personal injury was sustained, but where, given a slight shift in time or position, damage or injury easily could have occurred") (Laborers' Health & Safety Fund of North America, 2013)
    - Positive interventions (pro-active, positive HSSE-related activities) e.g. by site workers,
    - Loss prevention observations (observation of activities which lead to or support the prevention of HSSE-related incidents or accidents).

Requirements on health, safety, security & environment (HSSE)

Health, safety, security & environment (HSSE) are top priorities for all works performed in the oil & gas industry.

A comprehensive health & safety plan (HASP) that contains all relevant HSSE-related documents, instructions and specifications must be prepared and communicated to the entire work teams prior to work execution.

All work activities on-site must be carefully assessed with respect to HSSE risks, and measures for avoiding or at least controlling and mitigating all hazards must be planned and surveilled accordingly through a documented risk assessment process.

Work activities with elevated risk potentials are addressed in respective permits to work.

Daily safety discussions shall ensure that the work teams have a full and common understanding of all work activities for the day and also identify and respond to possible changes of work conditions.

Each person working on site has a general responsibility for working under safe conditions. The principle of a last-minute risk assessment shall facilitate that workers on-site always think about the tasks they perform, recognize, assess and control the risks and keep health & safety first in all things.

All persons working on-site are authorized and encouraged to stop work if they have reasonable HSSE concerns regarding the work they perform.

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Annex 1: Phase I environmental site investigation report — Exemplary content breakdown

Table of contents

1 Executive summary

2 Introduction, scope of work (definition of the problem)

3 General data

- Designation
- City district, parcel, land boundaries, location, competent authorities, legal entity/owner

4 Available information prior to the Phase I environmental site investigation

5 Program of the Phase I environmental site investigation (planned approach)

6 Results of the Phase I environmental site investigation

6.1 Site operation

- Type of the potentially contaminated site
- Description of the area and changes of the area
- Period of site operation, period of disposal including disposal volume
- History of technical systems and installations, containment and disposal facilities
- General staffing and shifts, general operations
- Building materials
- Material storage – raw material storage, underground tanks
- Emissions to air – process emissions, other atmospheric emissions
- Water supply, aqueous effluents and storm water drainage
- Waste production and disposal
- Energy supply
- Health & safety
- Fire and emergency precautions
- Noise
- Site security
- Housekeeping

6.2 Site description

- Morphological data
- Geology and soil stratigraphy (soil type, regional geological classification)
- Hydrology (type of aquifer, single-layer or multi-layer aquifer, formation, thickness, permeability, groundwater pressure level, direction of groundwater flow, groundwater gradient, distance of the surface to the groundwater level, perched aquifer, class of groundwater protection, data on water quality)
- Meteorological data (average precipitation, average humidity, average groundwater recharge rate, main wind direction)
- Potential source-receptor pathways

6.3 Potential contamination (sources of harmful substances)

- Accidents and spills, known contaminated areas
- Type and quantity of hazardous substances, their spatial and temporal distribution (known, suspected), description of the substances; possibly existing and previously measured data

6.4 Data relating to site use (protective goods concerned in the case of current or planned site use)

- Soil
- Playground
- Residential area
- Agricultural use
- Recreational area
- Industrial area
- Nature and landscape protection area
- Water body
- Water protection area

7 Assessment of potential risks

- Indication of relevant resources/goods to be protected and the respective pathways
- Exclusion of irrelevant pathways or receptors
- Formal assessment
- Maps and illustrations
- History of the investigated area presented in tables

8 Summary and recommendations

Annex 2: Phase II environmental site investigation report — Exemplary content breakdown

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Annex 3: Remediation feasibility study — Exemplary content breakdown

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